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Abstract

Transition from research to application requires understanding of the basic behavior of transducers, field generators, and in particular, the magnetization process, domain dynamics, and polarization switching of ME effects to applied electric or magnetic fields. The CME (converse magnetoelectric) effect is investigated for the first time here in the context of three different multiferroic heterostructures with the goal of promoting their application in devices, such as transducers, sensors, and field generators. This investigation demonstrates experimentally and theoretically that tuning of magnetic properties of the heterostructures can be controlled through applied electric field. Significant CME effect is found in all three heterostructures: FeCoV/PZN-PT (31 Oe cm kV$^{-1}$), Metglas/PMN-PT (23 Oe cm kV$^{-1}$), and FeGa/PMN-PT (12.5 Oe cm kV$^{-1}$). The tunabilities of remanence ($M_r$), coercivity ($H_c$), and squareness (SQ = $M_r / M_s$) are demonstrated. A sensitive dependence of CME effect on the magnitude of the applied electric field is discovered in the time and frequency domains, especially near the electric coercive field, and an alternative path to magnetization reversal is identified. The change in sign of magnetization is shown in the vicinity of magnetic coercivity. Tuning of induced magnetic fringe field (4.5 Oe cm kV$^{-1}$) is shown for the FeGa/PMN-PT heterostructure, which could be used as a magnetic field
generator. Results of low temperature characteristics of magnetization and magnetostriction of a novel terbium-doped FeGa alloy show this material can be applied to actuators and sensors requiring operability in wide temperature ranges. Indirect electric-field tuning can also be applied to patch antennas with a dielectric substrate. A novel low-profile ($\lambda_0/17$) rectangular patch antenna with a corrugated metallization layer is designed here using a genetic algorithm optimization. The reflection coefficient of the simulated antenna is replicated using an antenna fabricated based on the optimized model. The morphology of the corrugated layer is shown to induce coupling modes in the antenna, which can in turn result in the enhancement and tuning of transverse magnetic mode resonances. This antenna prototype provides a cheaper and lighter alternative to existing planar patch antennas with magnetic substrates.
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Chapter 1:

Static Converse Magnetolectric (CME) Effect in Multiferroic Transducers

1.1 Introduction

Multiferroic (MF) materials that simultaneously display ferroelectric and ferromagnetic (or antiferromagnetic) behavior can typically be realized by two materials design paths: ‘natural’ (single phase) MF compounds or ‘artificial’ MF composites (e.g., heterostructures). However, most single phase MF materials exhibit a magnetoelectric coupling response at low temperatures [1] that severely hinder their practical utility. In contrast, artificially structured materials, typically constructed as multilayered heterostructures or as granular composites, often exhibit large magnetolectric coupling at or above room temperature [2-5]. These artificial MF composites are particularly attractive as a pathway to realizing multifunctional devices [6-9]. Furthermore, the artificial MF heterostructures are relatively simple and cost-effective to design and fabricate. As a result there has been a considerable amount of interest in
understanding both the fundamental physics as well as the engineering potential of such materials [10-13].

During the past decade, a number of important applications based on the magnetoelectric effect (ME) have been proposed and/or demonstrated, mostly derived from MF heterostructures. Among these applications are ac and dc magnetic field sensors, transformers and gyrators, actively tunable microwave devices, the latter include filters, phase shifters and delay lines, as well as hybrid spintronic MF devices as potential MRAM elements [14-17]. In recent years, in particular, there has been a large body of research on multiferroic heterostructures [4, 18, 19] that employ a wide range of magnetostrictive and ferroelectric materials, including the first ME heterostructures based on semiconductor substrates (e.g., GaAs) [3]. It is noteworthy that conventional MF heterostructures, in their most common constructs, consist of ferromagnetic magnetostrictive elements mechanically coupled to piezoelectric elements. Magnetostrictive materials play an important role in providing a medium to couple magnetic fields to strain, whereas the piezoelectric element serves to convert strain to voltage. Such elements function in a bidirectional fashion in which magnetic fields are generated in response to the applied electric fields, as well as electric fields generated in response to the magnetic fields. Due to the availability of high quality, inexpensive, single crystal piezoelectric materials, such as lead magnesium niobate–lead titanate (PMN–PT), lead zinc niobate–lead titanate (PZN–PT) and lead
zirconate titanate (PZT) ceramics, supporting substrates of MF heterostructures are commonly piezoelectric elements. The magnetostrictive element is typically bonded, or in some cases deposited directly on the surface, to piezoelectric substrate [20].

The effect and potential tunability of magnetic hysteresis loops under the application of an electric field for MF heterostructures are important for eventually realizing multifunctional electronic devices. Previous studies have mostly focused on physical parameters, such as ferromagnetic resonance frequency, tuned by an electric field. It is now clear that the transition from research to practical applications will require a sound understanding of the basic behavior of such systems and in particular magnetization processes, domain dynamics and polarization switching of the ME to applied electric or magnetic fields. This work aims to build the fundamental knowledge base necessary to accelerate the development of MF structures towards practical engineering applications.

The CME effect manifests itself as a strain induced magnetization when an electric field is applied across the piezoelectric, which is in contrast to the ME effect in which an applied magnetic field causes polarization of the piezoelectric. The ME and CME effects in composites are extrinsic effects and are dependent on the microstructure of the magnetic and piezoelectric phases and on the coupling of these two phases at their interface. The CME response can be quantified by introducing a CME coupling coefficient, $\alpha_{CME} = \alpha_E = \partial H/\partial E$. It
represents the stress-induced magnetic field per applied electric field. The transfer of mechanical stress is achieved by bonding the piezoelectric and magnetostrictive components in a laminated form. This connectivity scheme can be realized either by using an epoxy layer or by growing the magnetostrictive and piezoelectric materials in epitaxial layers. Bonding the layers with an epoxy is simple and low-cost. It allows for more flexibility in the choice of a connectivity scheme in the heterostructure. It has been shown previously that ME coupling increases with decreasing thickness of the magnetostrictive material in a certain range of the ratio of magnetostrictive to piezoelectric thickness [21]. This can be attributed to a substrate clamping effect. So the thickness of the magnetostrictive layer must be carefully adjusted in order to maximize its usefulness in a MF heterostructure.

In this chapter, the CME effect is investigated in the case of three different MF heterostructures. It will be shown that tuning of their magnetic properties is possible through the application of an electric field. Significant CME effect is found to be present in the FeCoV/PZN-PT, Metglas/PMN-PT, and FeGa/PMN-PT heterostructures.
1.2 The FeCoV/PZN-PT Heterostructure [2]

FeCoV alloys possess superior magnetic and mechanical properties at elevated temperatures and have found use in magnetic bearings, transformers, and electrical generators that operate under high stress and at high temperatures [22].

A new multiferroic heterostructure consisting of the FeCoV alloy thick film and lead zinc niobate-PT (PZN-PT) single crystal is designed. In contrast to prototypical ME constructs, this system demonstrates significant CME coupling, which is defined as a change in magnetization due to an external electric field. A CME coupling constant of 31 Oe/kV cm$^{-1}$ is observed. This effect was verified by static magnetic measurements using a vibrating sample magnetometer (VSM) under the application of electric fields as opposed to the more common measurement by ac modulation or ferromagnetic resonance.

1.2.1 Design and Materials

In the present study, a 350 μm thick Fe$_{48}$Co$_{50}$V$_2$ cold-rolled strip was employed as the magnetostrictive element. To gain an optimum combination of mechanical and magnetic properties, the FeCoV alloy was heat treated at 600 to 700 °C in a H$_2$ gas atmosphere and polished to a 70 μm thickness.
To produce strong ME coupling in the proposed heterostructure, it was crucial to select a high functioning piezoelectric crystal as the substrate. We chose a relaxor-based ferroelectric single crystal, Pb(Zn$_{1/3}$Nb$_{2/3}$)O$_3$–PbTiO$_3$, consisting of a rhombohedral symmetric PZN and a tetragonal symmetry ferroelectric PT. This crystal features exceptional dielectric and electromechanical properties: e.g., $k_{33} = 0.86$, $d_{31} = 1100$ pC/N, $d_{32} = -2700$–$3200$ pC/N, $d_{33} = 1500$ pC/N, $K^T > 5000$, and tan δ < 0.01 at 1 kHz [23].

Finally, this multiferroic heterostructure was designed to operate in the L-T ME coupling mode (i.e., longitudinal magnetized/transverse polarized) and consisted of a laminated structure of a FeCoV film and PZN-6%PT single crystal poled along the [011] direction. The two components were bonded with quick curing ethyl cyanoacrylate. The magnetic properties were measured using a Lakeshore vibrating sample magnetometer with the magnetic field direction aligned parallel to the [100] direction ($d_{32}$). Electric fields from ~8 to +8 kV/cm were applied across two electrodes. Each electrode consists of NiCr (25–40 nm) and AuPd (250 nm) layers. Measurement for the CME coupling was performed in the field and geometry configurations depicted in Figure 1.1(a).
Figure 1.1: (a) Schematic diagram of the FeCoV/PZN-PT multiferroic heterostructure, (b) 3D magnetic domain image for FeCoV film by MFM, and (c) magnetic hysteresis loops under application of an electric field strength $E = 8$ kV/cm (dash line: ----) and no electric field (solid line: —) [2].
An external magnetic field \( (H) \) was applied along the [100] \( (d_{32}) \) direction of the PZN-PT crystal, whereas the [011] \( (d_{33}) \) is perpendicular to the heterostructure plane. The thicknesses of the FeCoV film and PZN-PT crystal were 70 and 500 μm, respectively. The optimized ratio of thickness is a prerequisite in obtaining large CME coupling [21].

### 1.2.2 Results and Discussion

Figure 1.1(b) depicts a three-dimensional magnetic force microscopy (MFM) image illustrating the morphology of the magnetic domain structure of the FeCoV film. It reveals a branched domain pattern common to Co-based magnetic alloys [24]. Figure 1.1(c) presents basic static magnetic properties measured by VSM. The magnetic film has a saturation magnetization \( 4\pi M_s \) of 20 ± 0.2 kG \( (H = 10 \text{ kOe}) \) and a coercivity \( H_c \) of 15 Oe in the absence of an electric bias field. The application of an electric field results in significant changes to magnetic hysteresis. This phenomenon will be discussed below.

The correlation between magnetization \( (M \text{ at } H = 500 \text{ Oe}) \) and electric field is presented in Figure 1.2(a). The typical butterfly-shaped loop is associated with the dependence of strain on electric field in the PZN-PT crystal [25]. This result stems from ferroelectric hysteresis. It is evident that the \( M-E \) curve corresponds closely to the ferroelectric hysteresis loop \( (P-E \text{ curve}) \), as depicted in Figure 1.2 (dashed line). It is
noteworthy that the electric coercivity \( E_c \) is about 5.2 kV/cm, which results in two shoulders in the \( M-E \) curve. Clearly, the application of electric field results in a reduction in magnetization by 10%. Figure 1.2(b) illustrates the variations in remanence \( (M_r) \) and magnetization loop squareness (SQ) with the application of an electric field. The remanent magnetization and loop SQ display a complicated dependence with applied electric field, which contains two broad peaks in the vicinity of 5–7 kV/cm. In this heterostructure, the induced magnetic field obtained is based on the so-called Villari effect, i.e., a reverse magnetostriction [26]. Due to the hysteresis behavior of ferromagnetic materials, the magnetostriction process also exhibits hysteresis, which strongly mirrors the magnetization process. Furthermore, it is assumed that the appearance of the peaks is associated with both the nonlinear relationships between strain and stress, and strain and electric field, in the PZN-PT crystal [27, 28]. Previous work indicated a complex relationship between magnetic hysteresis and stress even in the absence of an electric bias field [29, 30]. Nevertheless, a maximum electric field tunability in both remanence and SQ of 37% and 23%, respectively, was demonstrated in response to a 2 kV/cm change in electric field strength.
Figure 1.2: (a) Dependence of magnetization ($M$) at $H = 500$ Oe on the applied electric field ($E$) in the laminated FeCoV/PZN-PT heterostructure (solid line: ——) and the polarization hysteresis loop for the ferroelectric PZN-PT crystal used in the heterostructure (dash line: ---). (b) Variation in remanence ($M_r$) and SQ under an electric field strength ($E$) for the FeCoV/PZN-PT heterostructure [2].
Figure 1.3(a) presents the electric field dependence of $H_c$ for the FeCoV film. This clearly shows an irreversible loop similar to the $M-E$ loop depicted in Figure 1.2. Coercivity $H_c$ dramatically increases from 15.2 to 26.5 Oe with an applied electric field of 8 kV/cm. This corresponds to an increase of 71% and a coercivity tunability of 1.4 Oe/kV cm$^{-1}$ or 9%/kV cm$^{-1}$. The correlation between coercivity and electric field was not adequately addressed in previous ME studies; however, it essentially reflects the dependence of coercivity upon stress, which has been extensively studied [31, 32]. As a result, a stress dependence of coercivity is determined by the following factors: (1) the direction of the stress-induced field ($H_0^E$) relative to an external field ($H$), (2) the coercivity mechanism, i.e., irreversible rotation or domain wall displacement, and (3) the stress-induced change in the orientation, magnitude, and distribution of magnetic anisotropy fields. Here, $H_0^E$ is assumed to be perpendicular to $H$, and the coercivity is predominately attributed to irreversible domain wall motion, which is evident in the field configurations and magnetic domain patterns of Figure 1.1(a) and Figure 1.1(b). These results clearly illustrate an increase in coercivity in response to an electric bias field, where a compressive stress results in a large enhancement in coercivity that was not predicted or measured in earlier studies [31].
Figure 1.3: (a) Dependence of coercivity ($H_c$) on an electric field strength ($E$) and (b) correlation between the stress-induced magnetic field ($H_{c}^{\epsilon}$) and external magnetic field ($H$) for the FeCoV/PZN-PT heterostructure [2].
It is understandable that the stress-induced anisotropy field is critical in determining the coercivity of the magnetic material. We therefore attempt to calculate the stress-induced field in the FeCoV film by considering the strain inside the PZN-PT crystal created by application of the electric bias field. This induced field is expressed as [33]

\[
H^E_\sigma = 3 \frac{\partial \lambda}{\partial M} \sigma (\cos^2 \varphi - \nu \sin^2 \varphi),
\]

where \( \varphi \) is the angle between magnetization and stress and \( \nu \) denotes Poisson ratio of the magnetic material. In this structure, \( \varphi \) and \( \nu \) are 90° and 0.41, respectively. The magnetostriction coefficient \( (\lambda) \) and saturation magnetization \( (M_s) \) are 60 ppm and 1590 G, respectively. The stress \( (\sigma) \) in the FeCoV film is roughly derived from a simple relation: \( \sigma = d_{32}EY \), where \( Y \) (the Young’s modulus) is \( 2 \times 10^{12} \) dyn/cm\(^2\) [34], \( d_{32} = -2800 \) pC/N, and \( E = 8 \) kV/cm. Applying these relations, the stress-induced field is \( H^E_\sigma = -224 \) Oe, where a negative sign represents the induced field transverse to an external field (the magnetization direction) [31] [see Figure 1.1(b)]. In fact, a larger estimate of the induced field \( H^E_\sigma \) can be expected because \( H^E_\sigma \) depends on \( \partial \lambda / \partial M \).

Figure 1.3(b) shows the correlation between external magnetic field and stress-induced magnetic field, which was extracted from Figure 1.1(c). A significant increase in the induced field emerges in the external fields below 300 Oe. It is potentially valuable that an 8 kV/cm electric field strength enables the heterostructure to generate an induced magnetic
field of \( \sim 240 \) Oe under a small biased magnetic field. This corresponds to a CME coupling constant of 31 Oe/kV cm\(^{-1}\), which is among the largest values reported for ME heterostructures [35]. It is also noticed that the measured value is very close to the estimated value of 224 Oe. Additionally, the CME coupling is likely to be enhanced by employing an epoxy having a Young’s modulus close to the magnetic material instead of the ethyl cyanoacrylate employed here.

### 1.3 The Metglas/PMN-PT Heterostructure [36]

An electric field tunable magnetic hysteresis loop is studied in a multiferroic heterostructure consisting of a 25 μm thick Metglas® ribbon affixed to a lead magnesium niobate–lead titanate (PMN–PT) crystal. The strength of the CME effect can be defined as

\[
CME = \frac{M(E) - M(0)}{M(0)},
\]

where \( M(E) \) and \( M(0) \) represent magnetizations with and without the application of an electric field \( (E) \), respectively [36]. This multiferroic heterostructure exhibits a strong converse magnetoelectric effect, \( CME = -80\% \), and a converse magnetoelectric coupling constant, \( \alpha_E = 23 \) Oe cm kV\(^{-1}\), in the vicinity of the saturation electric polarization. This work systematically demonstrates the tunability of magnetic parameters.
including magnetization, coercivity, remanence and squareness, under the application of an electric field of 0–8 kV cm\(^{-1}\). Additionally, the physical mechanism of the CME is discussed. These results provide useful resources for the design of a new generation of electrically controlled devices.

### 1.3.1 Design and Materials

A ferromagnetic magnetostrictive Metglas® ribbon affixed to a piezoelectric PMN–PT single crystal substrate. The amorphous Metglas® ribbon, i.e. Metglas Inc. 2605C0, has a thickness of 23–30 μm, saturation magnetization \(4\pi M_s = 18 \text{ kG}\) and saturation magnetostriction coefficient \(\lambda_s = 35 \text{ ppm}\). The substrate is a \((1-x)\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-x\text{PbTiO}_3\) single crystal, with \(x = 28–32\% \text{ PT}\), having \(d_{31}\) of \(\sim-1000 \text{ pC N}^{-1}\) for \(<001>\) poling and \(\sim-1500 \text{ pC N}^{-1}\) for \(<011>\) poling, featuring anisotropic in-plane piezoelectric coefficients \(d_{31}\) and \(d_{32}\), i.e. \(d_{31} = -1500 \text{ pC N}^{-1}\) and \(d_{32} = 900 \text{ pC N}^{-1}\), when poled in the \(<011>\) direction. Here, we employed a \(<011>\)-type PMN–PT crystal with dimensions of \(L10 \times W5 \times T 0.5 \text{ mm}\), coated with Au electrodes as a means of applying electric fields. This MF heterostructure was designed to operate in the L–T magnetoelastic coupling mode and consisted of a laminated structure of a Metglas® ribbon and a 0.7PMN–0.3PT single crystal poled along the \(<011>\) direction. The two components were bonded with quick curing ethyl
cyanoacrylate-based adhesive. Measurement of the converse magnetoelectric coupling was performed in the field and geometry configurations depicted in Figure 1.4. An external magnetic field (H) was applied along the <100> (d_{31}) direction of the PMN–PT crystal, while the <011> (d_{33}) direction aligned perpendicular to the heterostructure plane. For the structure of this study, the thickness ratio is 0.05, where t = 25 μm for the Metglas® ribbon and t = 500 μm for the PMN–PT crystal.

Figure 1.4: Schematic diagram of a Metglas®/PMN–PT MF heterostructure [36].
The magnetic properties were measured using a vibrating sample magnetometer (VSM, Lakeshore Model 7400) with the magnetic field direction aligned parallel to the \(<100\) direction \((d_{31})\). The applied voltage ranged from \(-400\) to \(400\) V across the PMN–PT crystal, corresponding to an electric field \((E)\) of \(-8\) to \(+8\) kV cm\(^{-1}\). The electric field dependence of polarization was measured by a ferroelectric measurement system (Radiant Technologies, Inc.). The magnetic domain structure was observed by a magnetic force microscope (Ambios Technology USPM, Model 2SAAVO) with a distance of \(~100\) nm between the tip and the sample surface. The as-produced Metglas® ribbon was polished to a root mean square (RMS) roughness of \(<10\) nm.

1.3.2 Results and Discussion

1.3.2.1 Magnetic and ferroelectric properties of the Metglas®/PMN–PT heterostructure

Figure 1.5(a) and Figure 1.5(b) depict magnetic force microscopy images illustrating the magnetic domain structure of the Metglas® ribbon surface for a free-standing and bonded configuration (i.e. bonded to a PMN–PT substrate), respectively. Both reveal domain patterns commonly observed in metallic glass ribbons [24]. In such amorphous materials, the
domain structure is typically determined by the stress state of the magnetic ribbon. As such, there are two kinds of domain patterns, the wide striped domains with 180° walls that follow the in-plane magnetization of Figure 1.5(a) and the narrow spiked domains of Figure 1.5(b), indicating that the easy axis of magnetization aligns out of the ribbon surface [16].

Figure 1.5: Magnetic domain images on the surface of a 25 μm thick Metglas® ribbon scanned by MFM: (a) free-standing sample and (b) bonded on PMN–PT substrate [36].
No uniform component of the stress tensor can be presented in the absence of external forces; therefore, the domain configurations of Figure 1.5 must be necessarily inhomogeneous if the internal stresses are in fact the dominant source of magnetic anisotropy. From elastic boundary conditions, the stress tensor at the surface must be planar and characterized by two principal axes and a characteristic angle. For positive magnetostriction materials, such as Metglas® ribbons, a perpendicular easy axis is generated if the two principal stresses are negative (i.e. compressive stress). This leads to the domain pattern shown in Figure 1.5(a) even when the ribbon is free standing. The pattern in Figure 1.5(b) exhibits an obvious change in the ratio of black and white domains compared with the image for the free-standing ribbon. The change in magnetic domains reflects the change in an induced anisotropy field arising from the stress at the bonding interface between the Metglas® ribbon and the PMN–PT substrate. Furthermore, the compressive forces in the bonded ribbon result in the broadening of domains in one direction (white stripes, see Figure 1.5(b)) and hence this becomes the initial state of magnetization for the ME measurements performed in this study.

Figure 1.6 presents the basic static magnetic properties of the MF heterostructure measured by VSM. The magnetic ribbon has a saturation magnetization, \(4\pi M_s\), of 18 kG, and a coercivity, \(H_c\), of 1.13 Oe (in the absence of an electric bias field). These data indicate superior soft magnetic properties while retaining a high magnetostriction coefficient of
35 ppm. Metglas® ribbons are therefore excellent candidate materials for the magnetostrictive components of MF heterostructures. The application of an electric field to the PMN–PT substrate gives rise to significant changes in the shape of the magnetic hysteresis loop which is presented as the dashed line in Figure 1.6. The magnetic ribbon appears ‘harder’ when the substrate is biased by an electric field.

![Magnetic hysteresis loops](image)

**Figure 1.6:** Magnetic hysteresis loops under application of an electric field $E = 8$ kV cm$^{-1}$ (dashed line ----) and no electric field (solid line ———) [36].

Figure 1.7 presents the ferroelectric hysteresis loops at different frequencies, $f = 0.5, 1, 2, 3.3, 5, 10, 20$ and $33$ Hz, for an untreated $<0 11>$-type PMN–PT substrate. With increasing frequency, the electric...
polarization (P) at an applied electric field of 8 kV cm\(^{-1}\) decreases from 40 to 17 \(\mu\)C cm\(^{-2}\), whereas the electric coercive field \((E_c)\) increases from 4.4 to 5.2 kV cm\(^{-1}\), corresponding to 220 – 260 V. A ‘knee’ appears in the loop near \(\sim 4\) kV cm\(^{-1}\) which we attribute to the abrupt strain experienced by the PMN–PT crystal under the application of an instantaneous electric field [37].

![Electric polarization hysteresis loops at different frequencies](image)

**Figure 1.7:** Electric polarization hysteresis loops at different frequencies for a PMN–PT crystal used in the heterostructure [36].
1.3.2.2 Static CME

As depicted in Figure 1.6, the magnetic hysteresis loop can be substantially altered by an applied electric field of $E = 8 \text{ kV cm}^{-1}$ across the PMN–PT substrate. According to the results illustrated in Figure 1.6, we conclude that the induced magnetic easy axis is transverse to the external magnetic field, which is sketched in Figure 1.4. It is worth noting that the external magnetic field (sometimes called the magnetic bias field) strongly influences the strength of the CME. Figure 1.8(a) and Figure 1.8(b) display the dependence of the CME and the stress-induced internal magnetic field ($\delta H_E$) on a magnetic field, respectively. Here, $\delta H_E$ is obtained from the change in the applied magnetic field when an electric field is applied. Clearly, a peak in the CME appears at $H \approx 20 \text{ Oe}$ with a maximum value of 80%. This result is promising due to the relatively small magnetic bias field of 20 Oe, which is easily obtained in practical electronic systems. The bias field dependence of the CME was first measured by Srinivasan et al for a NiZn ferrite–PZT composite [38]. At the same time, the heterostructure of the present work exhibits an induced magnetic field, $\delta H_E = 180 \text{ Oe}$, corresponding to a bias field of 60 Oe (see Figure 1.8(b)). Figure 1.8(a) and Figure 1.8(b) can be considered the starting point for the design of magnetoelectric devices. To optimize operating conditions for some magnetoelectric devices, for example magnetic field transducers, they must be based on the conditions illustrated in Figure 1.8(b). In
contrast, those applications involving electrical control of magnetization start from the curve depicted in Figure 1.8(a).

![Figure 1.8: (a) Applied magnetic field dependence of the ME at a biased field of 20 Oe and (b) applied magnetic field dependence of the stress-induced magnetic field ($\delta H_E$) for the Metglas®/PMN–PT heterostructure. The applied electric field is 8 kV cm$^{-1}$ [36].](image)

Figure 1.8(b) shows the correlation between the external magnetic field and the stress-induced magnetic field. A significant increase in the induced field is evident with external magnetic fields above 30 Oe. It is advantageous that an 8 kV cm$^{-1}$ electric field induces a magnetic field of
more than 180 Oe under magnetic bias fields of 20 – 60 Oe. These values are among the lowest bias fields reported for MF heterostructures to date [39]. Importantly, such a significant induced field yields a considerably larger converse magnetoelectric coupling constant of 23 Oe/(kV cm). The converse magnetoelectric coupling can likely be further enhanced by employing an epoxy having a Young’s modulus closer to that of the magnetic material instead of the quick curing ethyl cyanoacrylate (Y = 0.5 × 10^{12} dyn cm^{-2}) employed here.

As shown in Figure 1.8(a), a 20 Oe bias field maximizes the CME for the heterostructure. Most of the following experiments are conducted at this bias field. The electric field dependence of CME is demonstrated in Figure 1.9, where the electric field amplitude is swept from +8 to −8 kV cm^{-1}. Electric hysteresis of the ME is evident, corresponding closely to the ferroelectric hysteresis loop of Figure 1.7. This loop has historically been referred to as the ‘butterfly’ loop. Note, the switching of CME occurs near E = 4–5 kV cm^{-1} and corresponds to the electric coercive fields measured for the PMN–PT crystal (see Figure 1.7). The CME magnitude shows a slight decrease when the electric field is reduced from 8 kV cm^{-1} to 4 kV cm^{-1} and then experiences a precipitous drop to near zero for E < 4 kV cm^{-1}. However, when the electric field reverses direction, the CME initially remains constant and then slightly increases until E > 5 kV cm^{-1}. The butterfly loop is largely symmetric, which is determined by the strain
versus $E$ curve for the piezoelectric material, as shown in [24]. This phenomenon has been observed in similar MF composites [18].

![Graph showing the variation of ME with an applied electric field ($E$) at a biased magnetic field of 20 Oe for a Metglas®/PMN–PT heterostructure.](image)

**Figure 1.9:** Variation of ME with an applied electric field ($E$) at a biased magnetic field of 20 Oe for a Metglas®/PMN–PT heterostructure [36].

Static magnetic measurements provide basic magnetic properties, such as saturation magnetization, remanence magnetization, coercivity, and hysteresis loop squareness, etc. Figure 1.10 illustrates the changes in these magnetic parameters in response to an electric field applied across the PMN–PT substrate. All the curves shown in Figure 1.10(a)–(d) feature similar butterfly loops. Additionally, the electric tunability of magnetic parameters is unambiguous. For example, the remanence and the
squareness decrease by 54% and 56%, respectively, whereas the coercivity increases by 170% in response to the applied electric field. These changes correspond to a tunability of $\sim 10\%/\text{kV cm}^{-1}$ for $M_r$ and SQ and $\sim 34\%/\text{kV cm}^{-1}$ for $H_c$.

An important feature of the CME is that it can irreversibly be transformed from a high magnetoelectric state to a low magnetoelectric state when polarized by an electric field larger than the critical value near the coercive field, $E_c = 4–5 \text{kV cm}^{-1}$. This feature points to the common nature of relaxor and normal piezoelectric materials. Both kinds of materials generally exhibit a nonlinear correlation between strain and electric field, which mirrors a ferroelectric hysteresis loop.

Figure 1.10(c) presents the electric field dependence of magnetic coercivity for the heterostructure. The data show a hysteresis loop, reflecting the ferroelectric polarization process described in the $P$–$E$ loop depicted in Figure 1.7. The magnetic coercive field increases from 1.13 to 2.48 Oe under the application of an electric field of 8 kV cm$^{-1}$. This implies a coercive tunability of 0.19 Oe/(kV cm$^{-1}$) or 17%/ (kV cm$^{-1}$). The correlation between coercivity and electric field has not been satisfactorily addressed in previous studies [21]; however, it essentially reflects the dependence of coercivity upon applied stress, which has been extensively studied in magnetic materials for many years [40]. The stress dependence of the coercivity is determined by the following factors: (1) the direction of
\( \delta H_E \) relative to an external field (H), (2) the coercivity mechanism, i.e. irreversible rotation or domain wall displacement, and (3) the stress-induced change in the orientation, magnitude and distribution of magnetic anisotropy fields. In the present case, \( \delta H_E \) is assumed to be transverse to H, and the coercivity is predominately attributed to irreversible domain wall motion, as surmised from the magnetic field configurations of Figure 1.4 and magnetic domain patterns of Figure 1.5. These results clearly indicate an increase in coercivity in response to increasing electric field, where a compressive stress results in a large enhancement of coercivity that was neither predicted nor adequately addressed in earlier studies [41].
Figure 1.10: Dependence of (a) magnetization ($M_s$) at $H = 400$ Oe, (b) remanence ($M_r$), (c) coercivity ($H_c$), (d) and squareness (SQ) on the applied electric field ($E$) for the Metglas®/PMN–PT heterostructure [36].

It is well known that a stress-induced anisotropy field is crucial in determining the coercivity of the magnetic material. We therefore attempt to calculate the stress-induced field in the Metglas® ribbon by considering...
the strain created by the application of the electric bias field on the PMN–PT crystal. This induced field can be expressed as [33]

$$\delta H_E = 3 \frac{\partial \lambda}{\partial M} \sigma (\cos^2 \varphi - \nu \sin^2 \varphi),$$

(1.3)

where $\varphi$ is the angle between the magnetization and the applied stress (here $\varphi = 0^\circ$), and $\nu$ denotes the Poisson ratio of the magnetic material. In this structure, we conjecture that the deformation of the Metglas® ribbon mirrors that experienced by the PMN–PT substrate. Note that Eq. (1.3) predicts that the stress-induced magnetic field is proportional to the derivative of the magnetostriction coefficient ($\lambda$) with respect to the magnetization ($M$). For the Metglas® ribbon used here $\lambda = 35$ ppm and $M = 890$ G. The stress ($\sigma$) in the Metglas® ribbon is approximated from the relation $\sigma = d_{31} E Y$, where $Y$ (Young’s modulus) is $1.1 \times 10^{12}$ dyn cm$^{-2}$ [42], $d_{31} = -1500$ pC N$^{-1}$ and $E = 8$ kV cm$^{-1}$. Applying these relations, the stress-induced field is $\delta H_E \approx -160$ Oe, where the negative sign represents the induced field transverse to the externally applied magnetic field (the magnetization direction, see Figure 1.4). The calculation matches closely the experimental maximum value of $\delta H_E = 180$ Oe. The results presented here are important for applications of magnetoelectric devices that may take advantage of different tunable parameters, e.g. magnetization, coercivity, remanence, squareness, permeability, etc, tuned by an electric field.
1.4 The FeGa/PMN-PT Heterostructure [43]

The CME effect of a multiferroic laminated heterostructure composed of a Fe-Ga magnetostrictive layer and a PMN-PT piezoelectric layer is examined. Such a heterostructure is potentially useful as a magnetic field generator, which can be used in the tuning of microwave devices. Magnetization, magnetic coercivity, remanence, and squareness are shown to exhibit pronounced hysteretic behavior and potential for tuning with an applied electric field, with a CME coupling coefficient of $\alpha_E = 12.5 \text{ Oe cm kV}^{-1}$. The deformation of the PMN-PT under an applied electric field results in an internal stress-induced magnetic field, with an experimentally determined value of $\sim 100 \text{ Oe}$. The tunable range of fringe fields generated by the stress-induced field is predicted to be 104 Oe. The results will establish a foundation in the design of E-field tunable magnetic devices.

Galfenol have been studied previously, and a low temperature dependence of the magnetostriction has been observed [44]. The magnetostrictive strain can be as high as 300 ppm. The Terfenol-D rare-earth iron alloy, which has one of the highest magnetostriction coefficients, is sometimes used as a magnetostrictive layer. However, Terfenol-D is more brittle than Galfenol. Therefore, Galfenol can be a better choice in high temperature-high stress environments [45]. Previously, Galfenol has
been used in combination with PZT in laminates, such as in Galfenol/PZT ac magnetic field sensors [46], in a tachometer able to withstand harsh environmental conditions [45], and in the investigation of the CME effect [47]. Spin-spray deposition of Fe$_3$O$_4$ ferrite thin-film on ferroelectric substrates has also resulted in large CME effect [41]. A good substitute for PZT is PMN-PT because of its large piezoelectric constants and electromechanical coupling factors. The piezoelectric properties of single crystal PMN-PT, including the strain as a function of electric field, are reported in prior work [48]. E-field tuning of ferromagnetic resonance is demonstrated for FeGaB thin-films on PMN-PT [49]. The ME effect in epitaxial Fe-Ga film on PMN-PT is shown to be around 13.4 (G cm)/V [50]. The dynamic response of the ME effect in the laminated Fe-Ga/PMN-PT heterostructure is also reported in the literature [51]. CME effect on such a heterostructure is not investigated previously, but it has great potential for applications such as a field generator [8].

### 1.4.1 Design and Materials

A thinly polished slab of magnetostrictive Fe-Ga (Galfenol) with dimensions 4.5 mm x 3 mm x 100-130 μm is glued to a piezoelectric PMN-PT single crystal substrate. The substrate features anisotropic in-plane piezoelectric coefficients $d_{31}$ and $d_{32}$, i.e. $d_{31} = -1500$ pCN$^{-1}$ and $d_{32} = 900$ pCN$^{-1}$, when poled in the <011> direction. We use a <011> poled PMN-PT single crystal with dimensions of 10 mm x 5 mm x 0.5 mm. The top
and bottom sides of the PMN-PT slab are coated with gold electrodes to allow for an applied electric field parallel to the <011> direction. The magnetostriction strain as a function of applied magnetic field is obtained by placing the Galfenol in an electromagnet. The Galfenol is a polycrystalline material with (110)-preferred orientation. To assemble the heterostructure, the polished Galfenol is glued to the PMN-PT substrate with a fast-dry ethyl cyanoacrylate adhesive. The thickness of the bond layer is 20-50 μm. The geometry of the heterostructure is shown in the inset of Figure 1.11. The magnetic properties are measured using a vibrating sample magnetometer (VSM, Lakeshore Model 7400). Magnetic field direction is aligned along the <100> direction, so that the heterostructure operates in an L-T mode. The voltage across the PMN-PT is varied from -400 to +400 V, corresponding to an electric field (E) of -8 to +8 kV/cm.
1.4.2 Results and Discussion

In Figure 1.11, a shift in the magnetic hysteresis loop is observed with the application of an electric field. It indicates that a stress-induced magnetic field is not entirely in the same direction as the external magnetic field, yielding the reduction in magnetic moment measured. This results in field dependence of the CME effect with maximum response occurring at a bias magnetic field of 370 Oe, as can be seen from the change in magnetic moment as a function of applied magnetic field (Figure 1.12).
A maximum CME (~15%), as calculated by Eq. (1.2), is measured at an electric field of \( E = 6 \text{ kV/cm} \) (Figure 1.13). The polarization of PMN-PT also reaches a maximum at \( E = 6 \text{ kV/cm} \) [36]. This is evidence of the coupling of magnetization and electric polarization, i.e. ME coupling. In addition, the CME effect achieves maximum hysteretic behavior at the value of electric coercivity, which is at \( E = 4 \text{ kV/cm} \). This is further proof of ME coupling, since there is a pronounced switching effect of magnetic properties around the electric coercivity. It can be concluded that the applied electric field does, indeed, drive the magnetic behavior of the heterostructure.

A number of magnetic parameters are obtained from the magnetic hysteresis loop. The saturation magnetization, remanence, coercivity, and squareness as functions of applied electric field are shown in Figure 1.14. All curves in Figure 1.14 exhibit a “butterfly” hysteresis, maximums at \( E = 6 \text{ kV/cm} \), and maximum hysteretic behavior at the electric coercivity \( (E = 4 \text{ kV/cm}) \). The change in saturation magnetization is about 1.7%. However, the remanence and coercivity increase by 25% and 30%, respectively, with the application of an electric field. Therefore, the tunability for remanence and coercivity is about 4.2% / (kV/cm) and 5% / (kV/cm), respectively. The absolute values of remanence and coercivity depend on the intrinsic properties of the material, and even though they are rather small, their usefulness is determined by the type of application.
Figure 1.12: Difference in magnetization between the two hysteresis loops shown in Figure 1.11 as applied electric field is switched from $E = 0$ to $E = 8$ kV/cm [43] © 2011 IEEE.

A plot of squareness shows an increase of ~42% with applied electric field (Figure 1.14(d)), which corresponds to a tunability of 7% / (kV/cm). This is determined by an induced anisotropy field. The curves presented above exhibit a characteristic “butterfly” shape, which is indicative of the non-linearity of magnetostriction. We note that the squareness is measured with zero magnetic bias. This is a desirable property for self-biased devices, since a significant change in the squareness occurs despite the absence of an external biasing field.
An important characteristic of the CME effect in the MF heterostructure is the presence of a stress-induced magnetic field with components parallel and transverse to longitudinal dimension of the Fe-Ga layer. The parallel component of the induced field shift due to the applied electric field is derived from the magnetization curves in Figure 1.11. The result is plotted in Figure 1.15. Here, $\delta H_E$ is effectively the internal magnetic field induced by the electric field, since $\delta H_E$ is obtained at a given $4\pi M$. Therefore, the demagnetizing field is subtracted out when calculating the field shift from the magnetization curves in Figure 1.11.

Figure 1.13: Change of CME with an applied electric field at a bias of 370 Oe [43] © 2011 IEEE.
Figure 1.14: Hysteresis loops for coercivity ($H_c$), saturation magnetization ($M_s$), remanence ($M_r$), and squareness (SQ) as functions of applied electric field [43] © 2011 IEEE.

The maximum induced magnetic field is ~100 Oe at $H_{bias} = 450$ Oe, which yields $\alpha_E = 12.5$ Oe cm/kV. Thus, the heterostructure can function as field generator for tuning applications. It is possible to obtain a theoretical value for $\delta H_E$ [10]:

$$\delta H_E = \frac{3\lambda Y d_{31} E_3}{M_s} = \alpha_E E,$$  \hspace{1cm} (1.4)
where $Y$ is Young’s modulus for Fe-Ga and $\lambda$ is the magnetostrictive strain. For $d_{31} = 1500$ pC N$^{-1}$, $E = 8$ kV cm$^{-1}$, $Y = 6.5 \times 10^{11}$ dynes cm$^{-2}$ in the [100] ($d_{31}$) direction [52], and $M_s = 1098$ G, we obtain $\delta H_E \approx 320$ Oe. This value has the same order of magnitude as the experimentally determined induced field, but somewhat higher than the measured value. This discrepancy can be attributed to the effect of shear lag (i.e. load transfer) and demagnetization [53, 54].

A numerical simulation is performed to determine the fringe fields that result from the induced internal magnetic field (Figure 1.16). The change in fringe fields is obtained as a function of applied electric field at a distance of 0.05 mm from the edge of the Fe-Ga layer in the longitudinal direction. The simulation shows a maximum change of 104 Oe with the application of an electric field. Given the design of a two-unit multiferroic heterostructure, fringe field is expected to be larger and more uniform between the two multiferroic structures.
Therefore, pronounced electric field tuning of magnetic parameters has been demonstrated in a laminated Fe-Ga/PMN-PT heterostructure. The results presented here are valuable to the design of new magnetic field generators based on the ME effect, since the existence of a stress-induced magnetic field can result in the formation of fringe magnetic fields external to the magnetostrictive layer [8]. Such a heterostructure can be made into a transducer, which can in turn tune ferrite filters and other microwave components by varying an applied electric field.
Figure 1.16: Change in simulated stress-induced fringe field as a function of applied electric field at a distance of 0.05 mm from the edge of the magnetic layer in the direction of $d_{31}$, as can be seen from the above inset. The asterisk at the tip of the arrow denotes the location of a gauss probe. Note that the inset drawing is not to scale [43] © IEEE 2011.
Chapter 2: Dynamic Effects in Multiferroic Transducers

2.1 Dynamic CME Effect in a Metglas/PMN-PT Heterostructure [55]

2.1.1 Introduction

Continued miniaturization of conventional solid-state electronic devices is largely achieved by reducing the physical size of active elements (i.e., memory elements, logic gates, transistors, etc.). This can also be achieved through the use of new materials in the development of multifunction devices capable of performing more than one operation or function within the same or smaller active volume. Among systems experiencing cooperative phenomena, i.e., magnetic ordering, electric ordering, piezoelectricity, etc., multiferroic (MF) materials offer unique potential for innovation in new electronic applications and technologies [35, 56]. For clarification purposes, here we refer to materials and constructs having ferromagnetic and ferroelectric components as multiferroic, while the effect derived from the coupling of electric to
magnetic fields (vice versa) or associated effects on functional properties will be referred to as the magnetoelectric (ME) effect.

In recent years, researchers have begun to acknowledge the importance of the dynamic response of the magnetoelectric effect [11, 38, 57, 58]. Most studies have focused on the direct magnetoelectric effect (not converse magnetoelectric effect) and PZT-based MF constructs [59, 60].

It is now clear that the transition from research to practical applications will require a complete understanding of the dynamic behavior of such systems, and in particular, domain dynamics, polarization switching, and temporal response of the CME effect to applied electric or magnetic fields. This work aims to build the fundamental knowledge base necessary to accelerate the development of MF structures towards practical engineering applications. Here, we present results of studies of the low frequency time domain response of the converse magnetoelectric effect of a MF heterostructure consisting of a Metglas® ribbon affixed to a lead magnesium niobate–lead titanate (PMN-PT) single crystal. In contrast to conventional MF constructs, the present work addresses the dynamic response of converse magnetoelectric (CME) coupling in the laminated composite structure.

A multiferroic heterostructure, consisting of a 25 μm thick Metglas® ribbon affixed to a lead magnesium niobate–lead titanate (PMN-PT) crystal, is systemically studied to investigate the time response of
converse magnetoelastic coupling under the application of electric fields at low frequencies (0.05 < f < 10 Hz). This multiferroic heterostructure exhibits a considerably strong converse magnetoelastic effect, CME = −80% (see Eq. (1.2)), and a CME coupling constant, $\alpha_E = 22.5$ Oe-cm/kV, at frequencies below 1 Hz and near saturation electric polarization. A switching time $t_s$, representing the response time of the CME coupling, is measured to be 0.6 seconds for this heterostructure under the application of instantaneous electric fields. The switching time results in significant influences on the magnetoelastic effect especially at frequencies higher than 2 Hz. The dynamic response of CME coupling is predominantly determined by ferroelectric relaxation within the PMN-PT crystal, as opposed to the magnetic relaxation of the Metglas® ribbon. A model is used to describe the dynamic behavior of CME coupling in disordered systems such as PMN-PT.

### 2.1.2 Experiment

The present work focuses on the dynamic properties of a layered multiferroic structure consisting of a ferromagnetic magnetostrictive Metglas® ribbon affixed to piezoelectric PMN-PT single crystal substrate. The amorphous Metglas® ribbon, Metglas Inc. 2605C0, has a thickness of 23~30 μm, saturation magnetization $4\pi M_s = 18$ kG, and saturation magnetostriction coefficient $\lambda_s = 35$ ppm. It is noteworthy that the (1−
$x$Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$–xPbTiO$_3$ single crystal, with $x = 28$–$32\%$ PT, not only has a large $d_{31}$ of $\sim 1000$ pC/N for $<001>$ poling and $\sim 1500$ pC/N for $<011>$ poling, but also features anisotropic in-plane piezoelectric coefficients $d_{31}$ and $d_{32}$, i.e., $d_{31} = 1500$ pC/N and $d_{32} = 900$ pC/N, when poled in the $<011>$ direction [61]. In comparison, the more widely used lead zirconate titanate (PZT) ceramics have a piezoelectric coefficient, $d_{31}$, far smaller at $\sim 200$ pC/N. As a result, PMN-PT crystals have attracted much interest in due to the relatively large electromechanical coefficients. In particular, the anisotropic $<011>$-type PMN-PT crystals have naturally become favored candidates for use in ultrasensitive magnetoelectric devices [62, 63]. Here, we employed the $<011>$-type PMN-PT crystal with dimensions of $L10 \times W5 \times T0.5$ mm, coated with Au electrodes as a means of applying electric fields. This multiferroic heterostructure was designed to operate in the L-T ME coupling mode (i.e., longitudinal magnetized/transverse polarized) and consisted of a laminated structure of a Metglas ® ribbon and 0.7PMN-0.3PT single crystal poled along the $<011>$ direction. The two components were bonded with quick curing ethyl cyanoacrylate-based adhesive. Measurement of the converse magnetoelectric coupling was performed in the field and geometry configurations depicted in Figure 2.1. An external magnetic field ($H$) was applied along the $<100>$ ($d_{31}$) direction of the PMN-PT crystal, while the $<011>$ ($d_{33}$) direction aligned perpendicular to the heterostructure plane. It is noteworthy that an optimized thickness ratio of the magnetic and
ferroelectric components is a prerequisite for obtaining large CME [21].

For the heterostructure of the present study, a thickness ratio of 0.05, where $t = 25 \, \mu m$ for the Metglas® ribbon and $t = 500 \, \mu m$ for the PMN-PT crystal, was used.

![Figure 2.1: Schematic diagram of a Metglas/PMN-PT multiferroic heterostructure](image)

The magnetic properties were measured using a vibrating sample magnetometer (VSM, Lakeshore Model 7400), with the magnetic field direction aligned parallel to the $<100>$ direction ($d_{31}$). Applied voltage ranged from $–400$ to $400 \, V$ across the PMN-PT crystal, corresponding to an electric field strength ($E$) of $–8$ to $+8 \, kV/cm$. Low frequency
magnetoelectric response was measured by VSM while alternating electric fields were applied across the PMN-PT crystal as a square wave, generated by a BK Precision 4011A Functional Generator and a High-Voltage Power Amplifier (Trek Model 609B-3). Electric field dependence of polarization was measured by a ferroelectric measurement system (Radiant Technologies, Inc.).

### 2.1.3 Results and Discussion

As sketched in Figure 2.1, an induced magnetic easy axis is transverse to the external magnetic field [36]. It is worth noting that the external magnetic field (sometimes called the magnetic bias field) strongly influences the strength of the converse magnetoelectric effect. In this experiment, a 20 Oe biased field is used to induce a maximum CME effect. Details of the static CME measurements have been published in [36].
Figure 2.2: Dependence of magnetization ($M$) with time under an application of different electric fields with square waveform at $f = 0.5$ Hz and $H = 20$ Oe [55].

In this work, the focus is on the electric field dependence of the CME effect under low frequency square wave excitations. Figure 2.2
shows the time evolution of the magnetization under square wave electric field having an amplitude of $E = 8$ kV/cm applied across the PMN-PT crystal. Due to a DC offset, the square wave consists of only positive values of electric field, varying from 0 to +8 kV/cm. A time window of 300 seconds is captured for a drive frequency of 0.5 Hz. The magnetization reveals an obvious time effect, especially for $E = 5–6$ kV/cm. Within such a 300-second observation window, the magnetization decays by 10%, which corresponds to an enhancement of the CME effect in the present experiment. However, either high ($E > 6$ kV/cm) or low ($E < 5$ kV/cm) values of electric field result in a negligible decay in magnetization. Furthermore, time dependences of the magnetization for an electric field drive frequency of 1, 0.05 and 0.1 Hz are shown in Figure 2.3 and Figure 2.4. In addition to a slight enhancement in the CME effect for a higher electric field, i.e., $E = 8$ kV/cm (see Figure 2.4(a) and Figure 2.4(c)), there is an obvious decay of magnetization at $E \sim 6$ kV/cm, as evident in Figure 2.4(b) and Figure 2.4(d). An electric field dependence of polarization ($P$ vs. $E$) with different frequencies can be referred to [36]. All of the data in Figure 2.2 through Figure 2.4 were measured at a bias magnetic field of 20 Oe in order to maximize the CME effect. Possible mechanism responsible for this behavior, including time evolution of the magnetization, electric polarization, and the CME effect are discussed below in detail.
Figure 2.3: Dependence of magnetization \( M \) with time under an application of different electric fields with square waveform at \( f = 1 \) Hz and \( H = 20 \) Oe [55].
Figure 2.4: Dependence of magnetization ($M$) with time under an application of different electric fields with square waveform at $f = 0.1$ and 0.05 Hz, respectively ($H = 20$ Oe) [55].
The variation of CME with frequency is of utmost importance to many practical applications. An important question is whether a large CME effect can be sustained over a broad range of frequencies. Figure 2.5 shows a remarkable dependence of the CME effect upon frequency in which CME values drastically reduce above 2 Hz. A strong CME effect in excess of 80% can only be observed at very low frequencies. This outcome highlights the limitations of multiferroic heterostructures investigated here for practical applications, especially at high frequencies.

Figure 2.5: Variation of the magnetoelectric effect (ME) with a frequency under a square wave electric field [55].
Figure 2.6: (a) Time response of magnetization ($M$) under the abrupt change of an electric field, (b) a representative waveform for a jump of an electric field ($E = 8$ kV/cm), (c) calculated magnetoelectric effect within different time domains, and (d) calculated magnetoelectric effect at different frequencies [55].
Figure 2.6(a) depicts the time response of magnetization to an instantaneous electric field excitation of amplitude $E = 8$ kV/cm (see Figure 2.6(b)) applied across the PMN-PT crystal. Clearly, the magnetization does not follow the abrupt transition in electric field but rather experiences a delay of 0.6 seconds in magnetoelectric response. This 0.6 s time, defined here as the switching time, $t_s$, signals the near saturation of CME coupling in each $E$-field cycle and we believe it is unique to each multiferroic heterostructure. The CME effect was calculated to be increasing within the time window of 0.6 seconds. These data and best fit are provided in Figure 2.6(c). Additionally, the frequency response of the ME transition is illustrated in Figure 2.6(d), where the individual CME effect frequency components were derived from the calculated curve in Figure 2.6(c). Within the critical time of $t_s = 0.6$ s the applied electric fields at frequencies greater than 1 Hz are unable to induce the maximum CME effect. Only low frequency signals of $f \leq 1$ Hz result in a maximum CME effect. The conclusions of the time domain analysis of the CME effect for the present MF construct are fully consistent with above experimental observations.

We next attempt to understand the underlying physical mechanisms of the observed time domain behavior of the CME effect. The possible mechanisms include temporal relaxation processes of the PMN-PT crystal, Metglas® ribbon, and the interface between the PMN-PT crystal and magnetic material. The Metglas® ribbon demonstrates a very
short magnetic relaxation time, on the order of $10^{-6}$ seconds, making this a negligible contribution to the observed transition time of 0.6 seconds. It is noteworthy that the PMN-PT crystal exhibits a significant response time, up to 20 seconds, depending on the amplitude of the applied electric field. A systematic investigation of the time response of polarization under different magnitudes of electric field for the PMN-PT crystal as well as other ceramic materials was carried out by Jullian [64]. This work demonstrated an obvious time dependence of the polarization when the applied electric field ($E$) was either less than or close to the electric coercive field ($E_c = 5$ kV/cm [36]). A broad range of charging times, on the order of magnitude from $10^{-1}$ to $10^1$ seconds, depending on the magnitude of applied electric field, was reported. Fast response of the polarization, within about $10^{-6}$ seconds, was observed only for high magnitudes of electric field ($E \gg E_c$). The time dependence of the polarization is simultaneously transformed to the time-dependence of strain in such a piezoelectric crystal. Therefore, these early experimental results provide important insights into the time evolution of the CME effect. Our experimental results indicate that an electric field of 8 kV/cm is insufficient to fully saturate the polarization of the ferroelectric crystal, which leads to a time delay of the polarization in response to an abrupt change in electric field. However, the contribution of the interface to time delay of magnetization, and in turn the CME effect in the multiferroic heterostructure, remains unclear. Further work is needed to quantitatively
evaluate the influence of the interface region on CME effects. Nevertheless, we believe that the time dependence of the CME effect is predominately determined by the PMN-PT substrate in our experiments.

![Graph showing variation of CME effect with applied electric field](image)

**Figure 2.7:** Variation of the magnetoelectric effect (ME) with an applied electric field \( (E) \) at different frequencies \( (f = 0.05, 0.1, 0.5, \text{ and } 1 \text{ Hz}) \) [55].

As the experimental data illustrates, the magnitude of the CME effect varies not only with frequency, but also with the strength of applied electric field. In fact, the CME effect increases rapidly for applied electric field values between 5 and 7 kV/cm as shown in Figure 2.7. With further increases in electric field strength, only small gains are observed in the
CME effect. On the other hand, the CME effect exhibits only a slight dependence upon frequency in the range of 0.05–1 Hz. Additionally, the CME effect does not show a saturation state after one cycle of applied electric field. The time (or number of cycles) dependence of the magnetization or CME effect is extremely sensitive to frequency when the applied electric field is near the coercive field value of $E_c = 5$ kV/cm. A typical example is taken from the case of $E = 5.6$ kV/cm for $f = 0.5$ Hz as depicted in Figure 2.2. A significant decay of magnetization with time or cycles is observed.

Our experiments further indicate that the magnetization decay depends upon frequency, electric field strength, and magnitude of the CME effect, as is illustrated in Figure 2.8. It is noted that the higher the electric field is for $E > E_c$, the shorter the after-effect is. This behavior could be related to the intriguing and controversial aging effect observed in relaxor ferroelectric materials, such as PMN-PT [65-67]. Possible mechanisms of aging/fatigue effects for the PMN-PT crystal have been identified. It may arise from ferroelectric-like polar nanoregions (PRNs) in this crystal [68]. In general, the time dependence of the polarization decay following an electric field step is well described by the stretched power law behavior of $P(t) = P_0 \cdot exp[-(t/\tau)^\beta]$, with $\beta < 1$. In our experiment, since the increase in the ME effect with time is attributed to the enhancement of strain under an applied electric field, an unsaturated polarization is likely responsible for the time-dependence of the magnetoelectric effect [69]. A
polarization-independent aging behavior, as postulated in the literature [70], is likely insignificant in this MF heterostructure.

**Figure 2.8:** Variation of aging strength of the magnetoelectric effect with an applied electric field ($E$) at different frequencies ($f = 0.05$, 0.1, 0.5, and 1 Hz) [55].

From Figure 2.8, the time effect is more apparent when the electric field is slightly higher than the coercive field ($E_c$). The field dependence of the CME effect is more sensitive than the frequency dependence. Of course, time effect of ME coupling is measured by means of the magnetization with time under an electric field. As mentioned above, the magnetization achieves a constant value only after many cycles of the electric field excitation. The time dependence of the magnetization can be
described by an exponential decay function: \( M(t) = M_0 \cdot \exp[-(t/\tau)^\beta] \), where \( \tau \) is a time constant. Figure 2.9 shows the time constant (\( \tau \)) obtained from the above exponential decay function fitting to the experimental data under applied electric field, \( E = 6 \text{ kV/cm} \). A linear increase of the time constant (\( \tau \)) with increasing frequency is observed. The data suggest that the ME effect has a characteristic memory, i.e., it requires more cycles to stabilize the effect at higher frequencies. This time window is apparently different from those at lower frequencies, which therefore suggests that the after-effect is not simply determined by a constant time domain. This phenomenon is quite similar to previously reported observations in PMN-PT crystals and other ferroelectric materials [71], in which a loss of electric polarization with time was determined to be proportional to \( N/f^2 \) (\( N \) and \( f \) denote the number of cycles and frequency, respectively). This infers that at high frequency excitations there is a small change in the polarization that is reflected in the change in magnetization representing the ME effect. In comparison of the aging effects and decay time, a small aging effect corresponds to a long decay time, as indicated in Figure 2.8 and Figure 2.9.
Figure 2.9: Frequency dependence of decay time constant ($\tau$) for the magnetoelectric effect at application of an applied electric field of $E = 6 \text{ kV/cm}$. Dashed line is a linear fit to the experimental data [55].

2.1.4 Conclusion

In summary, the static and dynamic converse magnetoelectric effects in a multiferroic heterostructure (Metglas®/PMNPT crystal) were investigated experimentally by measurements of the frequency and time response of the CME effect at different applied electric fields. The experiments indicate a sensitive dependence of the CME effect upon the magnitude of the applied electric field, especially in the vicinity of electric coercive field ($E_c$), which is related to a critical behavior near the coercive field. The multiferroic heterostructure demonstrates a strong converse ME
coupling, yielding a coupling constant $\alpha_e = 22.5$ Oe cm/kV. A CME effect of ~80% was measured at $E = 8$ kV/cm. Importantly, the heterostructure exhibits a switching time of 0.6 seconds under the application of an instantaneous square wave form electric field excitation. The time delay results in a reduction of the CME effect at frequencies above 1 Hz, which is assumed to arise from a relaxation effect of the PMN-PT crystal. In addition, aging behavior of the CME effect as a function of cycle frequency, amplitude, and number, are observed and discussed.

2.2 Magnetization Switching in a FeCoV/PMN-PT Heterostructure [72]

2.2.1 Introduction

Electric field control of magnetization, often referred to as the converse magnetoelectric effect, has received considerable attention [73]. A key motivating factor is that magnetic fields are not required for magnetization switching. Techniques for electric control of magnetization include the spin-torque effect in spin-valves [74] and magnetic tunnel junctions [75], and electric field control of magnetization in single phase multiferroic materials [5, 76] and in ferromagnetic/ferroelectric heterostructures [77, 78].
An attractive approach toward electric field control of magnetization takes advantage of elastic coupling [4, 18, 79, 80] either as magnetostrictive coupling or as elastostrictive coupling. Here, it is shown that piezomagnetism in a FeCoV alloy film/piezoelectric PMNPT crystal heterostructure can be used to manipulate the magnetic easy axis in the ferromagnetic film by simply changing the amplitude of the voltage applied to the piezoelectric crystal. Importantly, the highly efficient coupling between electric, magnetic, and strain degrees of freedom in the ferromagnet/piezoactuator heterostructure allows reversible switching of the magnetization, other than a simple change in amplitude of the magnetization as has been repeatedly demonstrated [2, 80, 81]. As such, this effect, demonstrated at room temperature, is of particularly fundamental and technological interest and utility.

2.2.2 Experiment

The electric field control of magnetization reversal of a layered multiferroic heterostructure consisting of a ferromagnetic magnetostrictive FeCoV ribbon affixed to a piezoelectric PMN-PT single crystal substrate is demonstrated. The Fe$_{48}$Co$_{48}$V$_2$ ribbon has a thickness of 120 μm, saturation magnetization of $4\pi M_s = 20$ kG, and saturation magnetostriction coefficient of $\lambda_s = 60$ ppm. The (1−x)Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$−xPbTiO$_3$ single crystal, with $x = 28$–$32\%$ PT, features anisotropic in-plane piezoelectric coefficients, $d_{31}$ and $d_{32}$, where $d_{31} = -1500$ pC/N and $d_{32} =$
900 pC/N when poled in the <011> direction. We employed a <011>-type PMN-PT crystal of dimensions L10 × W5 × T0.5 mm³ coated with Au electrodes as a means of applying electric bias. This multiferroic heterostructure was designed to operate in the L-T ME coupling mode and consisted of a laminated structure of FeCoV/0.7PMN-0.3PT poled along the <011> direction. The two components were bonded with quick curing ethyl cyanoacrylate-based adhesive. Measurement of the converse magnetoelectric coupling was performed in the geometry depicted as the inset to Figure 2.10. Specifically, an external magnetic field (H) was applied along \( d_{32} \) of the PMN-PT crystal, while the \( d_{33} \) direction aligned perpendicular to the heterostructure plane. For the heterostructure of the present study, a thickness ratio of 0.24, where \( t = 120 \mu m \) for the FeCoV ribbon and \( t = 500 \mu m \) for the PMN-PT crystal, was used.

Magnetic properties were measured using a vibrating sample magnetometer (VSM, Lakeshore Model 7400) with the magnetic field aligned parallel to \( d_{31} \). The applied voltage ranged from -400 to 400 V across the PMN-PT crystal corresponding to an electric field strength (E) of -8 to +8 kV/cm. Low frequency magnetoelectric response was measured by the VSM while alternating square wave electric fields were applied across the PMN-PT crystal (BK Precision 4011A Functional Generator with High-Voltage Power Amplifier, Trek Model 609B-3). Electric field dependence of polarization was measured by a ferroelectric measurement system (Radiant Technologies, Inc.).
2.2.3 Results and Discussion

2.2.3.1 Origin and Strength of Magnetization Switching

Figure 2.10 presents a representative magnetic hysteresis loop of the MF heterostructure under the application of electric voltages across the PMN-PT crystal. The magnetic ribbon, affixed to the ferroelectric slab,
showed a coercivity of \( \sim 10 \) Oe while the applied magnetic field was 500 Oe. There appeared a relatively abrupt step in the demagnetizing curve when a reverse magnetic field was applied near the value of the magnetic coercivity, \( H_c \). The net magnetization vector undergoes a reversal from positive to negative through \( H_c \). This experiment also demonstrated a reduction in coercivity by \( \sim 20\% \) when an electric voltage of 300 V was applied. Thus, we can take advantage of the abrupt change in magnetization in the vicinity of coercivity in order to achieve a magnetization reversal, other than a simple change in magnitude of the magnetization as has been shown previously [81]. The latter is sometimes called magnetization switching but is more accurately described as a change in magnetization.

For the next experiment, a saturation magnetic field of 500 Oe was applied. The sample returned to its remanent state and a voltage of 400 V was applied as the reverse magnetic field approached -4 Oe. As shown in the inset to Figure 2.10, point a on magnetization curve 1 abruptly drops to point b on segment 2 due to the application of voltage. More importantly, the precipitous drop in magnetization implies an apparent magnetization reversal that is evidenced by the change in sign of magnetization. In this instance, an electric field was insufficient to complete reversal of all spins unless a reverse saturation magnetization occurred. However, the detectable change in sign of magnetization arises from the reorientation of spins. The inset to Figure 2.10 illustrates possible configurations of spins.
in two magnetization states, corresponding to points $a$ and $b$. This switching reflects a converse magnetoelectric coupling coefficient of 
\[ \alpha = \mu_0 (dM/dE) = 1.6 \times 10^{-7} \, \text{s m}^{-1} \] which is comparable to the largest direct ME coupling with sharp domain switching, $\Delta P/\Delta H \sim 10^{-9} \, \text{s m}^{-1}$ [82, 83], and the recently reported room temperature value of $\alpha \sim 2 \times 10^{-8} \, \text{s m}^{-1}$ for a La$_{0.67}$Sr$_{0.33}$MnO$_3$/BaTiO$_3$ film heterostructure [56]. Additionally, this result compares favorably with other laminated heterostructures with direct ME coupling without magnetization switching, such as Pb(Zr,Ti)O$_3$/terfenol-D, $\sim 10^{-8} \, \text{s m}^{-1}$ [84-86]. Since the strength of ME coupling is a function of external magnetic field, this heterostructure yields a maximum CME coupling, $\alpha = 2.2 \times 10^{-7} \, \text{s m}^{-1}$, under the application of a magnetic field $\sim 160$ Oe. However, the CME response does not occur coherently with magnetization reversal, but rather as an abrupt change in magnitude of the magnetization.

Similarly, curves 3 and 4 in Figure 2.10 represent voltage off and on states, respectively. It is unsurprising that the switching between curves 3 and 4 is similar to that between curves 1 and 2 due to the symmetric nature of the hysteresis loop. As a result, magnetization switching is reversible in the multiferroic heterostructure. Reversible or irreversible switching is affected by design considerations that include field configuration and geometry of the heterostructure, as well as the intrinsic properties of the piezoelectric and piezomagnetic materials.
The strength of the magnetization switching is proportional to the converse magnetoelastic coupling coefficient, which depends upon the slope of the demagnetizing curve near the magnetic coercive field. In the present case, a stress-induced anisotropy field is assumed to be aligned along the direction of the applied magnetic field. Thus, the stress-induced anisotropy field is expressed as [33],

\[ H_\sigma = \sigma \left\{ \frac{3}{2} \lambda + (e_{zz}^{me})_0 \right\} (\cos^2 \varphi - \nu \sin^2 \varphi) \]  \hspace{1cm} (2.1)

where \( \sigma \) and \( \lambda \) are the induced stress and magnetostriction coefficient in the magnetic material, respectively, \( \nu \) is the Poisson’s ratio, \( (e_{zz}^{me})_0 \) is the magnetostrain in the demagnetized state, while \( \varphi \) represents the angle between the magnetization and the stress axes. The stress produced by an applied electric field is \( \sigma = d_{32} Y U / t \), where \( Y \), \( U \) and \( t \) denote Young’s modules, applied voltage, and thickness of PMN-PT crystal, respectively.

Given an ideal transformation of strain from the PMN-PT crystal to the magnetic film, the stress-induced anisotropy field due to the applied electric voltage is expressed as

\[ H_{\sigma}^E = \frac{3 \cdot d_{32} \cdot Y \cdot U}{2t} \frac{\partial \lambda}{\partial M} (\cos^2 \varphi - \nu \sin^2 \varphi) \]  \hspace{1cm} (2.2)

This expression relates the derivative of the magnetostriction with respect to magnetization to the applied magnetic field. These experiments show a reduction in coercivity due to the application of an electric field, which suggests that an external electric field enables reversal of the magnetization. When the magnetic field strength approaches the coercive
field, spins become frustrated and easily flipped, as sketched in the inset to Figure 2.10. The response of magnetization switching is triggered by an induced magnetic field, of presumably merely a few Oersted. This is due to substantive values of $\lambda$ and $M$ under the application of low bias fields.

2.2.3.2 Magnetization Switching with a Pulsed Electric Field

Low frequency switching, 0.02–1 Hz, of magnetization in this heterostructure was investigated. Accordingly, while the magnetization switching is driven by a pulsed electric field a small reverse bias magnetic field of $H_b = -4$ Oe is required. Subsequently, a square wave of amplitude 300 V was applied to the MF heterostructure, with no change in polarity of electric voltage (see Figure 2.11). The electric field-induced magnetization is shown to switch in response to the pulsed electric field. This indicates a switching of the magnetization vector, though it does not imply a 180° rotation of spins. In fact, the reversal of the measured magnetization is generated by a stress-induced magnetic anisotropy field. Note that the switching is reversible, which is determined by the vector configuration of internal anisotropy field, bias magnetic field, and stressed-induced magnetic field. Investigation of the underlying physical mechanisms of this effect is underway.

Moreover, we discuss two phenomena observed in these measurements. One, the induced signal evolves to a triangle-like waveform with increasing frequency, typically higher than 0.5 Hz. Second,
the change in amplitude of induced magnetization decreases slightly with frequency. Correspondingly, the CME coupling coefficient reduces from $6 \times 10^{-8} \text{ s m}^{-1}$ at $f = 0.02 \text{ Hz}$ to $4.2 \times 10^{-8} \text{ s m}^{-1}$ at $f = 1 \text{ Hz}$, as shown in Figure 2.12. Both effects result from ferroelectric relaxation in the piezoelectric crystal and are dependent upon the applied E. This has been verified in previous experiments of the time and frequency domain response of a PMN-PT based heterostructure [11, 55]. However, an electric field sufficient to saturate the electric polarization in the piezoelectric crystal can effectively reduce the relaxation time.
Figure 2.11: Magnetization switching under application of a square waveform electric field at different frequencies [72].
2.2.4 Conclusion

In summary, we have demonstrated an alternative path to magnetization reversal by the application of electric field in a multiferroic heterostructure. The switching of magnetization, i.e., the change in sign of magnetization, is shown to occur near magnetic coercivity of the magnetostrictive layer, in this case FeCoV. With the assistance of a small magnetic bias field of merely a few Oersted, one observes magnetization switching having a CME coupling of \( \alpha \sim 1.7 \times 10^{-7} \text{ s m}^{-1} \). Importantly, this demonstration of magnetization reversal in a multiferroic heterostructure
enables the development of a generation of magnetic devices dynamically controlled by electric fields.
Chapter 3: Tunable Fringe Magnetic Fields Induced in a FeGa/PMN-PT Multiferroic Transducers [87]

3.1 Introduction

Although the static CME effect has been the focus in the past years, investigation of the fringe magnetic fields of a multiferroic heterostructure has been largely overlooked. Recently, the tuning of ferrite phase shifters using the induced magnetic fields of a Terfenol-D/PMN-PT laminated transducer was demonstrated [8], where the fringe field played the important role of active tuning of the phase shifter while reducing power consumption and increasing switching speed. The Fe-Ga/PMN-PT laminate heterostructure discussed here has also shown potential for electric field assisted tuning of magnetization and other magnetic parameters [43].

The fringe magnetic field, induced by magnetoelectric coupling in a bilayer Fe-Ga/\(\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{PbTiO}_3\) (PMN-PT) multifunctional composite, was investigated. The induced external field is characterized
as having a butterfly hysteresis loop when tuned by an applied electric field. A tuning coefficient of the electrically-induced fringe magnetic field is derived from the piezoelectric and magnetostrictive properties of the composite. A measured maximum tuning coefficient, 4.5 Oe / (kV cm\(^{-1}\)), is found to agree well with theoretical prediction. This work establishes a foundation in the design of transducers based on the magnetoelectric effect.

### 3.2 Experiment

A bilayer laminated heterostructure, consisting of a polished polycrystalline FeGa alloy layer with dimensions of 15 mm x 10 mm x 0.4 mm and single crystal PMN-PT layer with dimensions of 15 mm x 10 mm x 0.5 mm, was assembled. The PMN-PT substrate was obtained commercially. A fast-dry ethyl cyanoacrylate adhesive was used as a bonding material between the two elements, with thickness of 20-30 µm. The PMN-PT layer was poled along the [011] direction, which is normal to the 15 mm x 10 mm surface. This single-crystal PMN-PT possesses a piezoelectric coefficient \( d_{33} < 500 \) pC/N along the poling direction, and a transverse extension (TE) mode piezoelectric coefficient \( d_{31} = 2300 \) pC/N. This type of cut was chosen because of its superior piezoelectric performance [88]. The two faces, with normal vectors parallel and
antiparallel to [011], were plated with gold electrodes. The FeGa/PMN-PT heterostructure was positioned between the pole pieces of an electromagnet, so that the direction of the bias magnetic field coincided with the longitudinal direction of the composite. The bias field was incremented in steps of 25 Oe, and then for each bias field, an electric field applied across the PMN-PT was varied over a range of -8 kV/cm to 8 kV/cm. The measurement of the fringe magnetic field exterior to the FeGa layer along a direction parallel to the applied bias magnetic field was accomplished using a Gauss meter. A schematic of the multiferroic composite can be seen in Figure 3.1. Data were also collected for the fringe field with an out-of-plane bias magnetic field.

![Gauss Probe](image)

**Figure 3.1:** The graphical representation of the multiferroic transducer [87].
3.3 Results and Discussion

The strain ($\varepsilon$) versus electric field (E) of the PMN-PT component was obtained for the $d_{31}$ direction and presented in Figure 3.2. The non-linear behavior of electrically induced strain seen in Figure 3.2 is due to the hysteretic behavior of electronic polarization in the PMN-PT. The strain coercivity can be defined as the electric field at which the measured strain in the PMN-PT reverses polarity. The coercivity is observed to be between 2 kV/cm and 3 kV/cm. The relatively large magnitude of coercivity can be attributed to the difficulty in electric field-assisted domain switching, since the two possible domains are mostly perpendicular to each other [89]. The maximum positive strain is measured at $|E| = 2$ kV/cm.
The magnetostrictive element, i.e. FeGa alloy of the heterostructure, can be synthesized by the substitution of Ga atoms for Fe atoms in the body-centered-cubic Fe lattice [44]. The addition of Ga enhances the magnetocrystalline anisotropy of the lattice, which results in the stabilization of an easy axis of magnetization along the <100> direction [90]. The elastic response of FeGa is also anisotropic, increasing in the direction of higher electron density distribution, which is maximized in single crystals and strongly textured polycrystalline forms [91]. The alloy used here is stress-annealed, which improves the magnetostrictive strain through a build-up of internal stress, as compared to the FeGa without pre-stress treatment. The FeGa used in this experiment is additionally
strongly textured along the <110> crystallographic direction, which coincides with the longitudinal dimension of the structure (Figure 3.3). A sufficiently strong compressive pre-stress along <100> is typically required to overcome the magnetocrystalline anisotropy. Once the anisotropy is overcome, the magnetic moments are free to align perpendicular to the axis of pre-stress [92]. An applied magnetic field along the longitudinal direction rotates magnetic moments along the magnetization direction, which leads to maximum magnetostriction. It should be noted that the addition of pre-stress results in not only an increased magnetostriction but also an increased bias magnetic field needed for reorienting the magnetic moments in the direction of applied magnetic field [93]. Therefore, there is a tradeoff between larger tuning of the fringe field, depending on the magnetostriction, and smaller bias magnetic fields. The B-H loop and magnetostriction versus applied magnetic field for FeGa are shown in Figure 3.4(a) and Figure 3.4(b), respectively. The B-H curve has a shape typical of a soft magnetic material and exhibits saturation at bias fields greater than 500 Oe. Accordingly, the magnetostriction is also saturated near H=500 Oe. The large saturation field and small slope of the magnetostriction curve are attributed to a weak <100> texturing in the longitudinal dimension, compared to that in the out-of-pane (Figure 3.3).
Figure 3.3: The x-ray diffraction scans along the longitudinal and out-of-plane directions of the magnetostrictive FeGa alloy [87].

The fringe magnetic field as a function of applied electric field is shown in Figure 3.5(a), with the Gauss probe positioned as illustrated in Figure 3.1. An important characteristic of the external field plot is a pronounced butterfly hysteresis between -4 kV/cm and 4 kV/cm, with two maximums at +/-2 kV/cm. A direct link between the stress-induced magnetic field and electrically-induced strain can be observed by comparing the plots in Figure 3.2 and Figure 3.5(a), as both curves follow the same pattern of hysteresis. Two distinct maximums of the fringe field for a given bias field, as seen in Figure 3.5(a), coincide with the peaks of the electrically-induced strain in the PMN-PT. The presence of fringe
magnetic field at zero applied electric field is due to the magnetization induced in the FeGa alloy with the applied magnetic field. It is pointed out that the effect of the demagnetizing field, which opposes any magnetization in the direction of applied bias field, must be considered. The demagnetization factor for a ferromagnetic rectangular prism can be determined analytically [94]. For the given dimensions, the demagnetization factor in the magnetization direction is \( N_1 \approx 0.035 \). To obtain an effective bias field, the demagnetizing field is subtracted from the applied magnetic field.

The electric field-tunable behavior of the stress-induced fringe field, \( h^\sigma(V) \), can be quantified using the following metric:

\[
\alpha_f = \frac{h^\sigma(V_0) - h^\sigma(0)}{\Delta E},
\]

where \( \Delta E = E_0 = 8 \text{ kV cm}^{-1} \). The coefficient in Eq. (3.1) is plotted as a function of bias field in Figure 3.5(b). The induced fringe field reaches a maximum, \( \alpha_f = 4.5 \text{ Oe / (kV cm}^{-1}) \), at a bias of 125 Oe. A similar response of the induced internal field as a function of applied bias magnetic field was observed previously [43]. A CME tuning coefficient can be derived from the constitutive relations of the piezoelectric and magnetostrictive components, and the boundary conditions for the stress and strain at the interface of the two elements of the heterostructure [21]. Following a similar procedure, the tuning coefficient for the fringe field is given by
\[ \alpha_f = \alpha_{31}^f = \frac{\partial h^q_1}{\partial E_3} = \frac{d_{31} q_{11}^*}{(\mu_0 - \mu_{11}^T)(s_{11}^H + \frac{t_m s_{11}^E}{t_p}) + q_{11}^* q_{11}}, \] (3.2)

where \( h^q_1 \) is the component of the induced fringe magnetic field parallel to the longitudinal dimension of FeGa, \( E_3 \) is the applied electric field, \( d_{31} \) is the piezoelectric coefficient of PMN-PT, \( q_{11} \) is the piezomagnetic coefficient, \( q_{11}^* \) is the stress sensitivity of the magnetic layer, \( s_{11}^H \) and \( s_{11}^E \) are the elastic compliance coefficients at constant magnetic and electric field, and \( \mu_{11}^T \) is the permeability of FeGa at constant stress. In Eq. (3.2), \( t_m = 0.4 \) mm and \( t_p = 0.5 \) mm are the thicknesses of the magnetostrictive and piezoelectric components, respectively. We have assumed that \( q_{11}^* \approx q_{11} \) for the stress and bias field under consideration. Using \( d_{31} = -2300 \) pC/N, \( q_{11} = 9 \) nm/A, \( \mu_{11}^T = 15\mu_0 \), \( s_{11}^H = 15 \) pm\(^2\)/N, and \( s_{11}^E = 126 \) pm\(^2\)/N, the fringe field tuning coefficient is predicted to be 13 Oe / (kV cm\(^{-1}\)). The piezoelectric coefficient is obtained from the slope of Figure 3.2, i.e. \( d_{31} = \partial \varepsilon / \partial E \). The piezomagnetic coefficient is determined from the \( \lambda-H \) curve in Figure 3.4(b), i.e. \( q_{11} = \partial \lambda / \partial H_i \), where \( H_i = H_a - N_1 M \) is the internal field. The result predicted by Eq. (3.2) is within the same order of magnitude as the experimentally determined value of 4.5 Oe / (kV cm\(^{-1}\)). The theoretical coefficient is derived using the magnetic field at the surface of the FeGa layer, and since the magnetic layer can be viewed as an approximation of a large magnetic dipole, the external magnetic field is expected to decrease with increasing distance from the lateral side of the heterostructure. Therefore, it is acceptable that the slight discrepancy in
tuning coefficient between the measured and predicted value arises from an error in measuring position.

The experimentally determined fringe field tuning coefficient for an out-of-plane bias is shown in Figure 3.6. There is an upward trend with increasing bias field. However, the magnitude of the coefficient is much lower in comparison to the tuning coefficient obtained with an in-plane bias magnetic field. It should be noted that this field configuration corresponds to a transversely magnetized-transversely poled (T-T) mode. In this case, the coupling is pronouncedly determined by both the piezoelectric coefficient $d_{33}$ and the out-of-plane magnetostrictive coefficient ($\lambda_{oop}$). It is clear that either $d_{33}$ or $\lambda_{oop}$ is much smaller than $d_{31}$ or the in-plane magnetostrictive coefficient ($\lambda_{ip}$). Additionally, the bias magnetic field is transverse to the measured fringe field, intruding an extra torque on the magnetic dipoles. It also acts to reduce the in-plane fringe field. As a result, an observation of low fringe field and ME coupling is predictable. Furthermore, the maximum tuning coefficient occurs at an applied field of more than 2000 Oe for an out-of-plane measurement. This can be explained by the large demagnetization factor of 0.9 in the thickness dimension.
Figure 3.4: The magnetic induction loop (a) and magnetostriction curve (b) of the FeGa alloy as functions of the in-plane bias magnetic field [87].
Figure 3.5: Measured fringe magnetic field at the edge of the transducer (a), as well as tuning coefficient of the fringe field (b) for an in-plane bias magnetic field [87].
3.4 Conclusion

It is concluded that the FeGa/PMN-PT laminate composite can produce electrically- tunable external magnetic field. When the external field is plotted as a function of applied electric field for a given bias magnetic field, we observe a butterfly hysteresis that is also typical of the electrically induced strain in the piezoelectric PMN-PT. This is suggestive of the strain-mediated magnetoelectric effect. It is shown that an in-plane bias magnetic field produces the largest in-plane fringe magnetic field.
This work has established a foundation for future work on the tuning of devices using a fringe magnetic field induced by the magnetoelectric effect. Further work needs to be done to determine the uniformity of the fringe field, especially in the presence of more than one multifunctional composite in a planar configuration.
Chapter 4:

Terbium-doped Galfenol: An Alternative Magnetostrictive Component in MF Heterostructures

4.1 Introduction

FeGa (i.e., Galfenol) alloys, which are some of the most important functional magnetic materials, have been widely used for many years in sonar systems [95]; force, displacement, and torque sensors [96, 97]; and acoustic and tactile sensors [98]. However, the alloys have been of increasing interest in the emerging applications based on the magnetoelectric effect. Particularly, FeGa alloys possess the potential to be used effectively in multiferroic (MF) transducers, magnetic field generators, and sensors under extreme environmental conditions due to their high tensile strength and ductility, as well as low hysteresis [52, 99-101]. In addition to these superior mechanical properties, Galfenol single crystals possess large magnetostriction of over 350 ppm, with peaks in magnetostriction at 19 or 28 at. % Ga content [102, 103]. The large magnetostriction in FeGa can be attributed to directional short-range
interactions between the Ga atoms [104], as well as nanodispersion of a DO$_3$ phase in the bcc A2 structure of Galfenol with 19 at. % Ga [105-107]. As a new application of Galfenol, we have recently demonstrated two new multiferroic structures consisting of FeGa alloy and other ferroelectric materials. One is a multiferroic magnetic field generator by means of converse magnetoelectric effect (CME) [8, 87], the other is high sensitivity magnetic field sensor without bias DC field based on the direct magnetoelectric effect (DME) [108]. In practical applications, multiferroic sensors or transducers are required to work over a broad range of temperatures (-40~120 °C). This in turn requires magnetostrictive materials having high thermal stability, i.e. low temperature coefficient of magnetostriction, well-behaved derivative of magnetostriction with respect to magnetic field, as well as large magnetic permeability [100, 109].

With development of the multiferroic devices, new magnetostrictive materials have been investigated continuously. Very recently, we reported a large enhancement in magnetostriction coefficient of FeGa alloy with low level doping of terbium [110]. This compound has the potential to replace its parent compound as a material of choice for the magnetostrictive component of the multiferroic heterostructure. However, temperature dependence of this novel material has increasingly become a concern as we attempt to employ the material for application of practical devices. In this study, we focus on the temperature stability of magnetic and magnetostrictive properties for the [110]-textured polycrystalline alloy,
Fe\textsubscript{81}Ga\textsubscript{19}Tb\textsubscript{x} (x=0.3), and its parent compound, Fe\textsubscript{81}Ga\textsubscript{19}. Previous work indicated that the low level doping of x=0.3 can maximize magnetostrictive coefficient at room temperature, yielding more than a two-fold enhancement in magnetostriction [110]. However, no previous study has investigated the temperature characteristics of low Tb-doped Galfenol alloys, which was found to have significant advantages over its parent compound. The thermal stability is easily quantified by a temperature coefficient of magnetostriction. In addition, it is noticed that the FeGa or FeGa-Tb alloys reveal an unexpected phenomenon in that large magnetoresistance effect is observed at low temperatures. The thermally driven behavior in magnetic or electric properties has not been uncovered until current work. It is believed that this work may shed new light on understanding of fundamental physics and applications for the magnetostrictive alloys.

4.2 Experiment

Bulk samples of polycrystalline Fe\textsubscript{81}Ga\textsubscript{19} and Fe\textsubscript{81}Ga\textsubscript{19}Tb\textsubscript{x} (x=0.3) alloys were produced by vacuum electric arc-melting and the directional solidification (DS) technique [110]. The magnetic hysteresis loops were measured at room temperature using a LakeShore Vibrating Sample Magnetometer (VSM). For an applied field of 1000 Oe, the magnetic
moment was recorded as a function of temperature in the range of 10 K to 1000 K using the Quantum Design’s Physical Property Measurement System (PPMS). Saturation magnetization was obtained for temperatures up to 100 K. A strain gauge bonded longitudinally on Galfenol samples (Figure 4.1) was used to determine the magnetostrictive coefficient along growth direction of the samples, with a temperature ranging from 10 K to 350 K varied by PPMS.

Figure 4.1: Stain gauge glued to a Tb-doped Galfenol slab.

A Vishay Micro-Measurements P3 Strain Indicator recorded the magnetostrictive strain as the field was swept from 0 to 5000 Oe for a predefined temperature sequence. Strain measurements were initiated
only after the zero-field magnetostriction was stable at a given temperature in the PPMS sequence. X-ray diffractometer was employed to determine structure and texture of the polycrystalline alloys. Resistivity of the alloy bulk samples was then recorded by employing the four-point probe method. First the samples were cooled to 10 K, and then resistivity was recorded by the PPMS for temperatures up to 300 K with no applied magnetic field. Resistivity was then measured again as the temperature was cooled back to 10 K, with an applied nonzero magnetic field. Measurements of AC susceptibility in the 20-300 K temperature range at frequencies of $f = 10, 20, 30, 50, 100$ and 1000 Hz were done using the PPMS in order to investigate a phase transition likely occurring at low temperatures.

4.3 Structural and Magnetic Properties

X-ray diffraction data presented was derived from scanning of the sample plane perpendicular to the growth direction. The single phase bcc structure of the FeGa alloys is identified with the three strongest peaks indexed to (110), (200), and (211) reflection planes, as shown in Figure 4.2. It is noticed that the polycrystalline Galfenol samples exhibit slight [110]-preferred crystallographic orientation along the crystal growth direction. It was previously reported that terbium favors to grow along with
[200] axis [110], which is exemplified by an increase in relative intensity of the (200) reflection. The XRD pattern is of the typical bcc A2 structure as found in Galfenol with 19 at % of Ga. With limit of the XRD resolution, DO₃ tetragonal phase was not clearly observed in evidence of the characteristic peaks near 31° and 64°, corresponding to the reflections of (200) and (400) planes [111].

Figure 4.2: XRD plots of Fe₈₁Ga₁₉ and Fe₈₁Ga₁₉Tbₓ (x=0.3) taken in the growth direction. The [110]-texturing is evidenced by the large (110) peak of the Fe₈₁Ga₁₉ sample, as compared to the much smaller peaks at the (200) and (211) planes. Optimal Tb doping is exemplified by a large (200) peak in the Fe₈₁Ga₁₉Tbₓ (x=0.3) polycrystalline alloy.
Doping with Tb has a significant effect on the magnetic properties of polycrystalline Galfenol. According to the magnetic hysteresis loop (Figure 4.3), doping with Tb increased the saturation magnetization by 7%, as compared to the un-doped Galfenol parent alloy. As shown in the inset to Figure 4.3, the Tb doping of x=0.3 can maximize saturation magnetization. Additionally, it has been reported that x=0.2-0.3 have the highest magnetostrictive coefficients for Fe\textsubscript{83}Ga\textsubscript{17}Tb\textsubscript{x} [110]. Further increase of Tb doping reduces the saturation magnetostrictive coefficient due to the formation of a Tb-rich secondary phase at the grain boundaries.

![Magnetization hysteresis loops for Galfenol (Fe\textsubscript{81}Ga\textsubscript{19}) and Tb-doped Galfenol. Shown in the inset is the saturation moment as a function of Tb doping amount.](image)

Figure 4.3: Magnetization hysteresis loops for Galfenol (Fe\textsubscript{81}Ga\textsubscript{19}) and Tb-doped Galfenol. Shown in the inset is the saturation moment as a function of Tb doping amount.
The magnetization as a function of temperature is provided in Figure 4.4. Measurements are collected at a field of 1000 Oe, which is far below a saturation magnetic field. It is clear that the magnetization stability at temperatures below 300 K is improved in the Tb-doped Galfenol; whereas, for Fe$_{81}$Ga$_{19}$, a noticeable dip in the magnetic moment is observed at temperatures near 70-100 K, which may be suggestive of a phase transition. This remarkable dip was not observed for the Tb-doped sample. According to our previous experiments, the Curie temperature for Fe$_{81}$Ga$_{19}$ is near 970 K [112], which is within 20 K of the value derived from Figure 4.4. Furthermore, our measurement indicates that Tb enables an increase in Curie temperature, 100-200 K for the Fe$_{81}$Ga$_{19}$ alloy, as depicted in Figure 4.4. It is apparent that the ferromagnetic A2 structure of the doped Galfenol is sustained for temperatures below ~1100 K. Due to instrumental limitation, the magnetic moment could not be measured at temperatures above 1000 K.
Magnetostriction and the Temperature

Coefficient of Magnetostriction

Next, a study of magnetostriction was carried out for temperatures between 10 K and 350 K. In Figure 4.5(a), the magnetostrictive strain of polycrystalline Fe$_{81}$Ga$_{19}$ is plotted for a set of selected temperatures as a function of applied magnetic field. The magnetostriction curves for Tb-doped Galfenol are plotted in Figure 4.5(b). There is a characteristic kink in the magnetostriction curve for Fe$_{81}$Ga$_{19}$ centered at 1800 Oe (~50 % of
the saturation field), which is attributed to the displacement of 90°
magnetic domain walls. In contrast, Tb-doped Galfenol does not present
such a kink. The trend of magnetostriction with a magnetic field is
phenomenally independent of temperature. However, the saturation
magnetostriction ($\lambda_s$) and its associated saturation field vary significantly
with temperature. For Fe$_{81}$Ga$_{19}$, the magnetostriction saturation field is
reduced by 18 % as the temperature is increased from 10 K to 350 K. At
300 K, the saturation field is $\sim$3600 Oe. For the Tb-doped Galfenol, the
reduction is 8 %, with a saturation field of 3000 Oe at room temperature.
Therefore, the saturation filed is more independent of temperature in the
case of the Tb-doped Galfenol alloy. The temperature stability of the
magnetostriction curve is important for sensor and actuator applications.
Figure 4.5: Magnetostriction as function of magnetic field at different temperatures for (a) Galfenol, and (b) Tb-doped Galfenol.
A plot of saturation magnetostrictive coefficient ($\lambda_s$) measured in the direction of the crystallographic [110] direction (i.e. the direction of texture) over a temperature range of 10 K – 350 K is shown in Figure 4.6 for Fe$_{81}$Ga$_{19}$ and Fe$_{81}$Ga$_{19}$Tb$_x$ ($x=0.3$). The Tb-doped Galfenol exhibits $\lambda_s = 85$ ppm at $T = 300$ K, while Fe$_{81}$Ga$_{19}$ exhibits $\lambda_s = 34$ ppm at $T = 300$ K. In general, the maximal magnetostriction for the Galfenol alloy is measured along <100> axes for a single crystal [104]. However, in this case, it is important to confirm that the saturation magnetostriction for Fe$_{81}$Ga$_{19}$ is within reasonable bounds for a [110]-textured polycrystalline material. Assuming the approximation of only dipole-dipole interactions inside the material, the magnetostrictive coefficient, $\lambda$, is expected to be close to the values given by Eqs. (4.1) and (4.2), [113]:

$$\lambda_{110} = \frac{1}{4} \lambda_{100} + \frac{3}{4} \lambda_{111}, \quad (4.1)$$

$$\bar{\lambda} = \frac{2}{5} \lambda_{100} + \frac{3}{5} \lambda_{111}. \quad (4.2)$$

Eq. (4.1) reflects the magnetostriction measured in the [110] direction of a cubic single crystal. Eq. (4.2) is the average magnetostriction of a polycrystalline material measured in any given direction. The $\lambda_{100}$ and $\lambda_{111}$ are the strains in the [100] and [111] crystallographic directions, respectively. For Fe$_{81}$Ga$_{19}$ without any compressive pre-stress, $(3/2)\lambda_{100} = 215$ ppm [114] and $(3/2)\lambda_{111} \approx -20$ ppm [103]. Eqs. (4.1) and (4.2) result in
\[ \lambda_{110} = 26 \text{ ppm and } \bar{\lambda} = 49 \text{ ppm. Therefore, the measured magnetostrictive coefficient } (\lambda_{110}^{t}) \text{ of 34 ppm for the [110]-textured Galfenol is close to the expected values, and} \]

\[ \lambda_{110}^{t} = 34 \approx (1.17)\lambda_{110}. \quad (4.3) \]

It is now possible to estimate a maximal magnetostrictive coefficient, \((3/2)\lambda_{100}\), for the Terbium-doped Galfenol in terms of the measured \(\lambda_{100}\) in the [100] crystallographic direction. The factor of 3/2 is due to the definition of magnetostriction as a deformation from the demagnetized state. Using Eq. (4.1) and Eq. (4.3), as well as \((3/2)\lambda_{111} \approx -20 \text{ ppm, an optimal magnetostrictive coefficient is predicted to be } (3/2) \lambda_{100} \approx 568 \text{ ppm for } \text{Fe}_{81}\text{Ga}_{19}\text{Tb}_{x} (x=0.3). \text{ It should be pointed out that the calculation for Tb-FeGa alloy is assumed to have similar texturing degree to that of pure FeGa alloy. The experiments indicate that } \text{Fe}_{81}\text{Ga}_{19}\text{Tb}_{x} (x=0.3) \text{ alloy has demonstrated a } \sim 250\% \text{ increase in room temperature saturation magnetostriction, compared to that of the un-doped } \text{Fe}_{81}\text{Ga}_{19}. \text{ It is predictive that further enhancement in magnetostriction may be achieved by the application of a compressive pre-stress or quenching during cooling process [111, 115].} \]
Temperature dependence of magnetostriction is crucial especially for practical applications, but fundamental research on thermal behavior has been limited so far. Previously, it has been reported that magnetostriction ($\lambda_{100}$) decreases phenomenally as $\sim T^3$ for various Galfenol alloys, such as Fe$_{83}$Ga$_{17}$ and Fe$_{87}$Ga$_{13}$ [44]. However, physical explanation is essentially lacking. In this chapter, we attempt to describe the temperature dependence of magnetostriction in terms of a power law, similar to the one governing the temperature dependence of magnetization. As known, near magnetic saturation, magnetostriction is
predominately attributed to a rotation of magnetic domains, and as such [113],

$$\lambda \sim \lambda_0 \left( \frac{M}{M_0} \right)^2.$$ \hfill (4.4)

In addition, the magnetization for $T < T_c$ is given by the following expression with critical coefficients $\alpha$ and $\beta$:

$$M(T) = M_0 \left[ 1 - \left( \frac{T}{T_c} \right)^\alpha \right]^\beta.$$ \hfill (4.5)

Eq. (4.5) is simplified to an expression similar to the Bloch Law for $T \ll T_c$.

Combining Eqn. (4.4) and (4.5), the magnetostriction as a function of temperature is expressed as

$$\lambda(T) \approx \lambda_0 \left[ 1 - \left( \frac{T}{T_c} \right)^\alpha \right]^{2\beta}.$$ \hfill (4.6)

Finally, a regression analysis was applied to the data in Figure 4.6 with the exponents, $\alpha$ and $\beta$, as fitting parameters, while the low temperature saturation magnetostriction ($\lambda_0$) for $T \to 0$ and the Curie temperature ($T_c$) were set as constants. Note, Eq. (4.6) can fit to the curves in Figure 4.6 very well with coefficients of determination ($R^2$) greater than 0.99 for Fe$_{81}$Ga$_{19}$ and Fe$_{81}$Ga$_{19}$Tb$_x$ ($x=0.3$). The results of the regression analysis are given in Table 4.1 for both materials. It should be stated that the precession of the Curie temperature is not critical, as long as the
exponents $\alpha$ and $\beta$ can be modified in order to maximize the goodness of fit.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$\lambda_0$ [ppm]</th>
<th>$T_c$ [K]</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$R_\lambda(T = 300K)$ $\times 10^{-3} K^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$<em>{81}$Ga$</em>{19}$</td>
<td>44.5</td>
<td>990</td>
<td>2.69</td>
<td>3.35</td>
<td>-2.52</td>
</tr>
<tr>
<td>Fe$<em>{81}$Ga$</em>{19}$Tb$_x$ (x=0.3)</td>
<td>112</td>
<td>~1100</td>
<td>1.96</td>
<td>1.65</td>
<td>-1.83</td>
</tr>
</tbody>
</table>

Table 4.1: List of model parameters used in Eq. (4.6) and temperature coefficients ($R_\lambda$) at room temperature derived from Eq. (4.8).

The total reduction in the saturated strain with increasing temperature for Fe$_{81}$Ga$_{19}$Tb$_x$ (x=0.3) and Fe$_{81}$Ga$_{19}$ over the temperature range studied was 28 %, and 34 %, respectively. These measurements reveal a slight increase in the absolute value of the temperature coefficient $R_\lambda$ of magnetostriction, which can be defined as

$$R_\lambda(T) = \frac{1}{\lambda(T)} \frac{d\lambda}{dT}$$  \hspace{1cm} (4.7)

Using the magnetostriction model of Eq. (4.6), as well as Eq. (4.7), the temperature coefficients for the two alloys can then be written as

$$R_\lambda(T) \approx -2\alpha\beta \frac{\left(\frac{T}{T_c}\right)^\alpha}{T \left[1 - \left(\frac{T}{T_c}\right)^\alpha\right]}, \quad T < 350 \, K$$  \hspace{1cm} (4.8)

where $\alpha$ and $\beta$ are the coefficients derived from the nonlinear regression analysis. According to Eq. (4.8), $|R_\lambda(T)|$ is monotonically increasing for $T > \ldots
0. At room temperature (300 K), the temperature coefficient for Fe$_{81}$Ga$_{19}$ is given as \(-2.52 \times 10^{-3} \, K^{-1}\), while for the Tb-doped Galfenol, the coefficient is calculated to be \(-1.83 \times 10^{-3} \, K^{-1}\) (Table 4.1), which is a reduction of 27\% with Tb doping.

In addition, it can be deduced from the fitted data and Eq. (4.8) that $|R_A(T)|$ for the Tb-doped alloy is smaller than the one for Fe$_{81}$Ga$_{19}$ for all observed temperatures greater than 190 K. It is clear that the addition of terbium reduces the temperature coefficient of magnetostriction over a range of temperatures useful in practical applications, while significantly enhancing the magnitude of magnetostriction. Therefore, one may conclude that terbium doping of Galfenol leads to significant improvement in the temperature stability of magnetostriction.

### 4.5 The Approach to Saturation Magnetostriction

Another characteristic distinguishing the Tb-doped Galfenol from its parent composition, Fe$_{81}$Ga$_{19}$, is the relationship between magnetostriction and magnetization. This is best exemplified by the plots in Figs. 6(a) and 6(b). In a magnetization process, magnetostrictive strain is first initiated as a result of the displacement of 90° magnetic domain walls, and subsequently by the rotation of magnetic domains. The displacement of 90° domain walls is usually shown as a linear
dependence of the magnetostriction with respect to the magnetization. Alternatively, the rotation magnetization is represented by a quadratic relationship, similar to the one given in Eq. (4.4) [113]. In contrast, the displacement of 180° domain walls has no effect on the elongation of the bulk sample. It is also clear that 180° domain walls are displaced much easier than the 90° domain walls, which is the reason for the delayed 90° domain wall displacement [113]. It should be noted that Galfenol has an easy axis along any of the six <100> crystallographic directions. It follows that the displacement of 90° domain walls is initiated at roughly a third of the saturation moment, since if an alloy with cubic symmetry is magnetized in the [110]-textured direction, the [−1 0 0] and [0 −1 0] domain walls reorient by the application of the magnetic field along the [100] and [010] directions, respectively. In both materials, the magnetostriction is mainly due to magnetization rotation. However, in the case of Fe$_{81}$Ga$_{19}$ (see Figure 4.7(a)), domain rotation is initiated much later in the magnetization process, or when the alloy is magnetized to ~85% of the saturation. For Tb-doped Galfenol, the displacement of 90° magnetic domain walls is shown to have a minor role in magnetostriction saturation (see Figure 4.7(b)). This could be due to Tb impurities at a grain boundary, acting as pinning sites, which would impede domain wall motion. As a result, the doped FeGa alloy has a smooth transition from displacement of 90° domain walls to domain rotation.
Figure 4.7: Normalized magnetostriction as a function of normalized magnetization for (a) Galfenol, and (b) Tb-doped Galfenol.
4.6 Spin Stabilization at Low Temperatures in Tb-doped Galfenol

The Galfenol alloy has also displayed interesting electron transport properties at low temperatures below 100 K. As the parent compound of Galfenol is warmed from 10 K to room temperature with no magnetic field and then cooled with a nonzero magnetic field, a significant negative magnetoresistance (MR) was observed around 75 K. For a given temperature, the magnetoresistance can be defined as

\[ MR = \frac{\rho(H) - \rho(0)}{\rho(0)}, \]  

(4.9)

where \( \rho(0) \) is the resistivity at zero field and \( \rho(H) \) is the resistivity at an applied field \( H \). As can be seen from Figure 4.8(a), the MR can reach a level of -25%. Magnetoresistance is saturated for fields greater than 3000 Oe (Figure 4.8(b)). The MR is negative and approaching zero asymptotically as a function of increasing temperature. This was correlated to the resistivity, obtained by a four-point measurement, which was lower with an applied nonzero magnetic field parallel to the four-point probe, as compared to the resistivity with no field applied (Figure 4.8(c)). Interestingly, there was a lack of any significant MR effect in the Tb-doped Galfenol (Figure 4.8(d)). Previously, large MR has been observed in
multilayer magnetic thin films containing an antiferromagnetic pinning layer [116], as well as in granular materials [117].

Figure 4.8: (a) Magnetoresistance of \( \text{Fe}_{81}\text{Ga}_{19} \) as a function of temperature. (b) The maximum magnitude of magnetoresistance as a function of magnetic field. (c) The change in resistivity with temperature and magnetic field for \( \text{Fe}_{81}\text{Ga}_{19} \). The inset is a zoomed in region of resistivity around 75 K, which is where greatest MR is recorded. (d) Magnetoresistance of \( \text{Fe}_{81}\text{Ga}_{19}\text{Tb}_x \) (\( x=0.3 \)) as a function of temperature.
In the case of the textured polycrystalline Fe$_{81}$Ga$_{19}$ alloy, a possible antiferromagnetic (AFM)/ferromagnetic (FM) coexistence is found for temperatures lower than 100 K. This is evidenced by the remanent magnetization (inset to Figure 4.9(a)) as well as the antiferromagnetic behavior of magnetization for applied magnetic fields up to 1000 Oe (Figure 4.9(a)). The remanence at room temperature was $\sim$0.73 emu/g, which is more than three times the average remanent magnetization for temperatures below 100 K. The antiferromagnetic ordering at low temperature and low magnetic fields could be the reason for the unusually large resistivity, leading to large negative magnetoresistance in Fe$_{81}$Ga$_{19}$. Microscopically, the AFM ordering may be a manifestation of increased scattering due to nonaligned ferromagnetic entities, which is seen in granular materials [117]. In an analogy to magnetically inhomogeneous granular materials studied previously, the textured polycrystalline Galfenol alloy produced by the directional solidification technique contained grains separated by nonmagnetic grain boundaries composed of Gallium, or Gallium and Terbium in the case of Fe$_{81}$Ga$_{19}$Tb$_x$ (x=0.3) [110]. AFM/FM coexistence at low temperatures was still present in the Tb-doped Galfenol, but the dip in moment occurred at a lower temperature ($\sim$40 K) and was not as pronounced (Figure 4.9(b)). Therefore, it can be inferred that the Tb-doping resulted in spin stabilization at low temperatures, which would offer a possible explanation for the lack of magnetoresistance in Fe$_{81}$Ga$_{19}$Tb$_x$ (x=0.3), as depicted in Figure 4.9(b). For high fields, it can be
seen that the AFM state, in the case of both compounds, is diminished, with only ferromagnetic behavior observed at magnetic saturation (Figure 4.9(c)). Accordingly, the saturation of magnetoresistance, as shown in Figure 4.8(b), can be explained by the increased FM ordering at the expense of AFM ordering at higher magnetic fields. Another possible consequence of AFM/FM coexistence is emergence of magnetic frustration of some spins in the crystal lattice [118]. This is a necessary condition for a spin glass state. In fact, AC susceptibility measurements made on the Fe$_{81}$Ga$_{19}$ alloy provide some evidence for a spin glass transition. A sharp peak, whose location is a function of frequency, of the real part of the AC susceptibility was observed near the freezing temperature ($T_f$). From Figure 4.9(d), $T_f \approx 32$ K. Furthermore, the shape of the susceptibility curves was invariant with frequency for temperatures greater than ~80 K.
Figure 4.9: Magnetization of Fe$_{81}$Ga$_{19}$ (a) and Fe$_{81}$Ga$_{19}$Tb$_x$ (x=0.3) (b) for a field of 1 kOe. The remanent magnetizations for the two alloys are given in the insets. (c) The saturation magnetization for low temperature. Near magnetic saturation, only ferromagnetic ordering is observed. (d) The real part of AC susceptibility as a function of temperature exhibiting a possible spin glass state near 32 K.

4.7 Conclusion

In summary, a significant increase (250 %) of magnetostriction was measured for the [110]-textured polycrystalline alloy, Fe$_{81}$Ga$_{19}$Tb$_x$ (x=0.3), as compared to the parent compound, Fe$_{81}$Ga$_{19}$. Tb doping resulted in an
increase in magnetization, a reduction of saturation field, as well as a
decrease in magnitude of the magnetostriction temperature coefficient. These characteristics can have beneficial effect in practical applications, such as sensors and actuators requiring operability in wide temperature ranges. In addition to the temperature stabilization of magnetostriction, Tb doping may reduce magnetic frustration of the spins at low temperatures. Interestingly, pure FeGa alloy demonstrates a large magnetoresistance at low temperature (~75 K), which may stem from the spin frustration and phase transition.
Chapter 5:

Antenna Optimization and Tuning Through Changes in Material Morphology

5.1 Motivation and Background

The goal of the following investigation was to design a low-profile patch antenna with desirable directivity and bandwidth (BW), as determined by the return loss measured at a coaxial feed with 50 Ohm input impedance. The antenna is made to radiate efficiently in the 2-4 GHz band (S-band) of the electromagnetic spectrum and can potentially be used in point-to-point telecommunications. Another design goal was to use a non-magnetic substrate, in order to reduce cost and physical weight. In order to achieve a large bandwidth, a change in material morphology between the radiating patch and the ground plane is realized, which is directly related to the electric fields generated by the antenna. The electromagnetic field configuration beneath the antenna and the fringe fields surrounding the antenna are modified by a corrugated plane of metallic patches midway between the radiating patch and the ground plane. It was found that the corrugated plane is not detrimental to the directivity and gain.
The process of finding an optimal corrugation pattern was achieved through the use of the Genetic Algorithm (GA) optimization technique, which played a central role in realizing the desired antenna characteristics.

The final antenna model was then compared with a standard radiating rectangular patch of the same dimensions, but without the inclusion of a corrugated plane.

In summary, creation of the antenna was motivated by the following design principles:

1. Low-profile (thickness << \( \lambda_0 / 4 \))
2. Large bandwidth (>> BW of standard rectangular patch antenna)
3. Good directivity and gain
4. S-band operability
5. Non-magnetic substrate
6. Simplicity of radiating patch and feeding mechanism
7. Cost

Some of the above goals are interconnected, e.g. the use of non-magnetic substrate and the cost of raw materials. In the statement of the first principle, \( \lambda_0 \) is the wavelength of the resonant frequency of the antenna.

One last challenge was an attempt to modify the bandwidth and tune the antenna without the help of a magnetic substrate. Modification of the
bandwidth in such a manner, while at the same time preserving the low profile of the antenna, was accomplished by changing the radiating fringe fields of the antenna through the addition of a parasitic metallic patch.

5.2 Introduction

Low-profile planar antennas serve an important role in military and commercial applications where the reduction of physical size and weight are critical in the design of portable antenna systems. A low-profile rectangular patch antenna placed on top of a fragmented ground plane is designed and simulated using Ansys’s HFSS 12.1 electromagnetics solver. A genetic algorithm (GA) is used in parallel with HFSS in the optimization of the design process. The antenna is tuned to operate in the S-band of the electromagnetic spectrum. Traditional designs of rectangular patch antennas can only achieve bandwidths of roughly a few percent. For an antenna backed only by a perfect electric conductor (PEC) ground plane, the height of the antenna should be λ/4 in order to avoid destructive wave interference due to the 180° phase shift caused by the PEC. This is especially problematic for the design of a low-profile S-band antenna, since the λ/4 restriction would result in a height of several centimeters. Height reduction, without sacrificing gain, can be achieved by placing an electromagnetic bandgap (EBG) metamaterial between the
antenna and the PEC ground plane [119]. Good radiation characteristics can be achieved with an antenna height less than $\lambda/10$. The EBG acts as a perfect magnetic conductor, which effectively eliminates the phase shift caused by the PEC. Thus, the antenna can be located very close to the EBG ground plane. However, the antenna bandwidth is limited by the bandwidth of the EBG.

Here we show that a corrugated plane of metallic square patches can lead to large bandwidth, as defined by the reflection coefficient of the antenna, as well as the gain and radiation efficiency. The most obvious physical difference between the corrugated metallic plane used in this investigation and the EBG is in the distribution of the patch elements. In an EBG, metallic patches are arranged in a periodic structure, while in the fragmented metallic plane, the patches have a random distribution. In addition, there is no reliance on vias connecting the metallic elements to ground, which simplifies the design and processing. The antenna presented in this letter is a multilayer system, requiring two layers of dielectric substrates. A genetic algorithm is developed for the purpose of optimizing the thickness of the substrates, the coax-feed location, as well as the size and distribution of the patch elements in the fragmented metallization layer beneath the radiating patch.
5.2.1 Antenna Metrics

The antenna, as defined by the IEEE Standard Definitions of Terms for Antennas (IEEE Std 145-1983), can be viewed as a device for radiating or receiving radio waves. However, as a more basic definition, the antenna can also be understood as a transitional device separating the RF transmission line and free-space. The excitation electromagnetic fields within the antenna cause acceleration of electric charge which is then subsequently decelerated by the physical discontinuities of the antenna. This process causes electric fields to be generated and detached as free-space waves. It is these waves that form the electromagnetic radiation produced by the antenna.

There exist three field regions surrounding an antenna. The region closest to the antenna is the reactive near-field, the region further out is the radiation near-field (Fresnel) region, and the one furthest out is the far-field region. In this chapter, we concern ourselves with only the far-field region. For an antenna with size $D$ and resonant wavelength $\lambda$, the far-field can be defined as all points in space at a distance $R$ from the antenna, for which

$$R > \frac{2D^2}{\lambda}.$$  \hfill (5.1)
The radiation patterns obtained by the simulations and physical measurements in this chapter are all taken at the far zone. The radiation intensity in the far-field is defined as [120]

\[
U = r^2 W_{\text{rad}} \approx \frac{r^2}{2\eta} \left[ \left| E_\theta(r, \theta, \varphi) \right|^2 + \left| E_\varphi(r, \theta, \varphi) \right|^2 \right],
\]

(5.2)

where \( W_{\text{rad}} \) is the radiation density of the antenna, \( E_\theta \) and \( E_\varphi \) are the far-field electric field components, and \( \eta \) is the intrinsic impedance of the medium. Another important metric is the directivity of an antenna, which is defined as the ratio of the radiation intensity in a given direction to the radiation intensity over all directions. In mathematical terms,

\[
D = 4\pi \frac{U}{P_{\text{rad}}},
\]

(5.3)

where \( P_{\text{rad}} \) is the total radiated power.

As will be seen later, the antennas designed here do not have an omnidirectional pattern. Therefore, it is useful to define the directivity in terms of the half-power beamwidths (HPBW) of the primary radiation lobe. An example of the HPBW is shown in Figure 5.1. Assuming rotational symmetry and angles in units of radians, the directivity for a radiation pattern with main lobe is approximated as

\[
D \approx \frac{4\pi}{(\Theta_{3\text{ dB}})^2}.
\]

(5.4)
In Eq. (5.4), $\theta_{3\,dB}$ is the half-power beamwidth in a cross-section of the beam.

Figure 5.1: The Half-power beamwidth (HPBW) of a radiation pattern [121].

Another important metric is the efficiency of an antenna. The efficiency takes into account conduction and dielectric losses within the antenna, as well as reflection losses due to impedance mismatch between the transmission line and the antenna at the input terminals. It is defined as

$$e = e_{\text{cond}}e_{\text{die}}(1 - |\Gamma|^2) = e_{\text{rad}}(1 - |\Gamma|^2).$$  \hspace{1cm} (5.5)
In the above equation, the conduction and dielectric efficiencies are grouped as the radiation efficiency \(\varepsilon_{\text{rad}}\), since the conduction and dielectric losses determine how much of the power that goes into the antenna is radiated. In Eq. (5.5), \(\Gamma\) is the voltage reflection coefficient measured at the input terminals, which is defined as

\[
\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}. \tag{5.6}
\]

Here, \(Z_0\) is the characteristic impedance of the transmission line, \(Z_{in}\) is the input impedance of the antenna. A useful parameter that can be related to the voltage reflection coefficient is the voltage standing wave ratio (VSWR):

\[
\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}. \tag{5.7}
\]

The return loss is the effectiveness of power delivery from a transmission line to an antenna and is a function of the incident power to the reflected power [122]:

\[
RL = 10 \log_{10} \left( \frac{P_{in}}{P_{ref}} \right) dB = -20 \log_{10} |\Gamma| dB. \tag{5.8}
\]

In terms of the VSWR, Eq. (5.8) takes the following form:

\[
RL = 20 \log_{10} \frac{\text{VSWR} + 1}{\text{VSWR} - 1} dB. \tag{5.9}
\]
The negative of the return loss is equivalent to the reflection coefficient in decibels, or the S-parameter $S_{11}$ from the theory describing two-port networks. Therefore, $S_{11} = -RL$. The $S_{11}$ of an antenna can also be obtained from simulation (i.e., Ansys’s HFSS), or from measurements taken using a Vector Network Analyzer (VNA).

One commonly used definition for bandwidth of an antenna is derived from the continuous frequency band ($f_{\text{low}}$ to $f_{\text{high}}$) for which $S_{11} < -10 \text{ dB}$. For such a frequency band, the fractional bandwidth is given as

$$BW = \frac{f_{\text{high}} - f_{\text{low}}}{(f_{\text{high}} + f_{\text{low}})/2} \times 100 \% \quad (5.10)$$

Finally, the gain of an antenna takes into account both the directivity and the efficiency. So,

$$G = 4\pi \frac{U}{P_{\text{acc}}} = e_{\text{rad}}D \quad (5.11)$$

If reflection losses are taken into account, we can define an absolute gain, or realized gain (used in HFSS), so that

$$G_{\text{abs}} = (1 - |\Gamma|^2)e_{\text{rad}}D = (1 - |\Gamma|^2)G \quad (5.12)$$

Therefore, the magnitudes of the directivity, gain, and absolute gain can be related as $G_{\text{abs}} < G < D$. 

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The directivity (and gain) can be represented by the sum of orthogonally polarized components in the far-field, since from Eqs. (5.2) and (5.3),

\[
D \approx \frac{4\pi}{P_{rad}} \left( \frac{r^2}{2\eta} \right) \left( |E_\theta|^2 + |E_\varphi|^2 \right)
\]

\[
= \frac{4\pi}{P_{rad}} \left( \frac{r^2}{2\eta} |E_\theta|^2 \right) + \frac{4\pi}{P_{rad}} \left( \frac{r^2}{2\eta} |E_\varphi|^2 \right) 
\]

\[
= \frac{4\pi}{P_{rad}} U_\theta + \frac{4\pi}{P_{rad}} U_\varphi = D_\theta + D_\varphi 
\]

Therefore, it becomes relatively easy to represent co- and cross-polarization components of a radiation pattern.

5.2.2 The Microstrip Patch Antenna

The rectangular microstrip patch antenna is a type of planar antenna, which consists of a thin radiating metallic patch with dimensions \( L \times W \times t \) situated over a metallic ground plane at some height \( h \) (Figure 5.2). The thickness of the patch is much smaller than the free-space wavelength of the resonant frequency \( t \ll \lambda_0 \). The patch and the ground plane are usually separated by a dielectric sheet, called a substrate, with a dielectric constant \( \varepsilon_r \). In general, the shape of a patch can be square, rectangular, circular, triangular, bow-shaped, etc [120]. The microstrip patch antennas are low-profile, conformal to differently-shaped surfaces, inexpensive to manufacture using printed-circuit technology. They do have
some disadvantages, such as presence of cross-polarization components, low efficiency, low power, narrow frequency bandwidth [120]. There are various feeding mechanism, but the most commonly used are coaxial probe, microstrip line, aperture coupling, and proximity coupling [120, 123-128]. Proximity coupling facilitates the largest bandwidth. However, it is most difficult to fabricate. In the coax probe feed, the inner conductor of the coax connector makes contact with the radiating patch, while the outer conductor is connected to the ground plane. The coaxial feed has the following advantages:

1. Ease of fabrication
2. Relatively easy to match impedance to transmission line
3. Low spurious radiation

However, the coaxial feed also has a few disadvantages:

1. Difficult to model
2. Narrow bandwidth
3. Cross-polarization due to inherent asymmetry

Due to ease of fabrication, we have decided to use the coaxial feeding method in this chapter.

Some of the disadvantages of the microstrip antennas and the probe-feed method can be overcome by a choice of substrate thickness and dielectric constant, use of cavities [129, 130], adding parasitic elements [131], and stacking [132-134]. A thicker substrate can provide
larger bandwidth, while smaller dielectric constant can lead to better efficiency [126].

Figure 5.2: Rectangular patch antenna fed with a coaxial probe.

The three most popular methods for microstrip antenna analysis are the transmission-line model [120, 124], cavity model [120, 135], and full-wave analysis using integral equations and the moment method [136, 137]. The transmission-line model can be used to understand the
resonance behavior of the antenna, obtain the resonant frequency of the
dominant mode, and account for electric field fringing effects. Full-wave
analysis using integral equations can give the most accurate results, but it
is also the most sophisticated and complex method. In fact, it was used to
solve the stacked patches antenna problem, whose results can be applied
to some of antenna designs in this chapter [138].

The cavity model can be used to obtain the excitation modes and
their resonant frequencies. In addition, it provides good approximations for
the radiated fields in the far-field. In the cavity mode, the antenna system
has to be viewed as a dielectric-loaded cavity with perfect electric
conductors (PEC) on the top and bottom, and perfect magnetic conductors
(PMC) on the sidewalls. The ground plane and substrate are assumed to
be horizontally truncated to the size of the radiating patch.

![Microstrip patch antenna as a dielectric-loaded cavity.](image)

Figure 5.3: Microstrip patch antenna as a dielectric-loaded cavity.
In the cavity model, one has to first solve the inhomogeneous Helmholtz wave equation for the $z$-component of the vector potential:

$$\nabla^2 A_z + k^2 A_z = 0$$  \hfill (5.14)

Assuming harmonic functions as solutions, and then applying the PEC and PMC boundary conditions, Eq. (5.14) leads to a constraint equation for the wavenumbers, which gives the resonant frequencies of the cavity modes [120]:

$$(f_r)_{mnp} = \frac{1}{2\pi \sqrt{\mu\varepsilon}} \sqrt{k_x^2 + k_y^2 + k_z^2}$$

$$= \frac{v_0}{2\pi \sqrt{\varepsilon_r}} \sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{W}\right)^2 + \left(\frac{p\pi}{h}\right)^2}$$  \hfill (5.15)

In Eq. (5.15), $m$, $n$, and $p$ are zero or positive integers, with the added constraint that they cannot be all zero.

The solution to Eq. (5.14) is given by the following electromagnetic fields within the cavity:
\[ E_x = E_{0x} \sin(k_x x) \cos(k_y y) \sin(k_z z) \]

\[ E_y = E_{0y} \cos(k_x x) \sin(k_y y) \sin(k_z z) \]

\[ E_z = E_{0z} \cos(k_x x) \cos(k_y y) \cos(k_z z) \]

\[ H_x = H_{0x} \cos(k_x x) \sin(k_y y) \cos(k_z z) \]

\[ H_y = H_{0y} \sin(k_x x) \cos(k_y y) \cos(k_z z) \]

\[ H_z = 0 \]

Using Eq. (5.15) and Eq. (5.16), the four lowest-order TM\(^2\) modes are \(TM_{100}^2\), \(TM_{010}^2\), \(TM_{200}^2\), and \(TM_{020}^2\). The existence and location of a given mode in the frequency spectrum can be determined either through a calculation of the resonance frequency using Eq. (5.15), or by observing the field pattern obtained from a numerical simulation and then comparing it to the electromagnetic fields in Eq. (5.16).

### 5.2.3 Design Approach

The antenna design problem posed in the beginning of the Introduction, which involves the random distribution of metallic patches underneath a radiating patch, requires a full-wave analysis for finding an accurate reflection coefficient and radiation pattern. In this specific case, a complete reliance on the cavity model is not possible, since the metallization layer below the radiating patch would violate the substrate
truncation requirement of the cavity model. However, the electromagnetic standing waves beneath the radiating patch can still serve as an approximation to the fields in Eq. (5.16) depending on the amount of metallization. Furthermore, a scheme for the configuration of the corrugated metallic plane needs to be devised, so that an optimal reflection coefficient, radiation pattern, and gain can be found.

5.2.3.1 Design from First Principles

The problem of stacked metallic patches has been analyzed previously [138]. Barlatey et al. gave a full-wave treatment using a mixed-potential integral equation for two stacked microstrip patches in a double-layer substrate. Near and far field waves, as well as surface waves were characterized. They achieved fractional bandwidths of ~15% and total antenna thickness of ~λ₀/10. This method does not require the inclusion of PMC walls, and so it is possible to obtain theoretical results for various antenna metrics. Nevertheless, numerical methods are still required in the solution of the Green’s functions. A full-wave treatment of a many-patch problem for the purpose of obtaining an optimized design would be extremely complex. A more tractable and efficient approach is to use an optimization technique in conjunction with a finite element method (FEM) solver, such as the High Frequency Structural Simulator (HFSS) from Ansys.
5.2.3.2 Global Optimization

If a specific problem has a finite and relatively small set of possible solutions, i.e., a small search space, then it may be possible to find the best optimal solution. Deterministic algorithms can be used in these cases to find the local optimum reasonably fast. However, if the problem to be optimized contains many variables and a large search space, then another technique may be required.

In the global optimization technique, a possible solution \( x' \), which is part of a set of possible solutions \( S \), is assumed to have an optimal value for some fitness function \( f \). For a minimization problem, an attempt is made to find the solution \( x' \), such that for any other possible solution \( x \) [139],

\[
x \neq x' \Rightarrow f(x') \leq f(x)
\]  
(5.17)

There are numerous techniques to find the global optimum, such as heuristics, stimulated annealing (randomized heuristics), combinatorial optimization, local search algorithms, etc. The problem with these algorithms is their heavy reliance on the local neighborhood structure of the search space. However, a type of optimization algorithm exists, called a genetic algorithm (GA), which is able to discover optimal solutions through the use of nonuniform probability distributions functions in the process of generating new potential solutions. Therefore, a genetic algorithm can be a good candidate to solve the problem posed in Eq. (5.17).
5.2.4 The Genetic Algorithm

The genetic algorithm uses the principles of genetics and evolution and an associated fitness function in order to find a global optimum. It is best suited for dealing with large and discontinuous search spaces [139]. A genetic algorithm begins by generating a set of random members of the search space \((S)\), called a population \((P)\). The set \(P\) is taken as finite and much smaller than \(S\). Fitness of each member in the population is evaluated according to a predetermined fitness function. At this point, a select number of members, defined as parents, are chosen out of the population and are then mixed together using recombination and mutation operators. The resulting members are called children, whose fitness is evaluated using the fitness function. Finally, the population undergoes some form of replacement in order to keep the population size in check. The whole process is then repeated until a member of the population satisfies the fitness criterion. Thus, an optimal solution is found.

Each member in the population possesses a set of characteristics, which define its appearance in the actual problem. These characteristics are called genes. Common real-world representations of genes are binary and real numbers. Recombination and mutation operators are designed for the purpose of modifying these genes.

Recombination operators take two or more parents and mix them together to form children. One commonly used recombination operator for
binary representations is the one-point crossover (Figure 5.4), in which a random number \( r \) is chosen in the range \([1, l - 1]\), where \( l \) is the length of the binary sequence. The two parents are then split at that point, and the tails exchanged to form two children [139, 140]. Whole arithmetic recombination can be used for genes represented by real numbers. It is defined by the following schema, where for each gene \( x \in \text{Child 1} \) and \( y \in \text{Child 2} \):

\[
\text{Child 1} = a \cdot x + (1 - a) \cdot y
\]

(5.18)

\[
\text{Child 2} = a \cdot y + (1 - a) \cdot x
\]

In Eq. (5.18), \( a \) represents the amount of mixing between the two parents, and is usually given by a random real number between 0 and 1.

Figure 5.4: One-point crossover of two 3x3 binary matrices.
Mutation operators act to introduce variation in the population, so that a larger extent of the search space can be explored. In the case of the binary representation, the mutation operator is simply a binary bit flip with some probability of occurrence \( p_m \) that is applied to each gene. For real numbers, a non-uniform mutation can be used, in which a real number drawn from a random number probability distribution (i.e. Gaussian distribution) with a mean of zero and a small standard deviation is added to the value of the gene. The amount of mutation is controlled by the standard deviation of the probability distribution.

The choice of parent selection is important, since a proper algorithm should be able to control selection pressure and prevent premature convergence to a solution. One of the most common selection algorithms is the tournament selection operator, which compares the fitness of potential parents taken \( k \) at a time and selects parents with the highest fitness [139-141] (Figure 5.5).

```
set current_member = 1;
WHILE ( current_member ≤ Size (P) ) DO
    Pick \( k \) members randomly, with or without replacement;
    Select the best of these \( k \) comparing their fitness values;
    Denote the best member as \( i \);
    set mating_pool[current_member] = i;
    set current_member = current_member + 1;
END WHILE
```

Figure 5.5: Pseudocode for tournament selection algorithm [139].
Picking individuals with replacement entails that selected parents are put back into the population after mating. Selection pressure and convergence can be controlled by the tournament size ($k$). A subtype of tournament selection is the binary tournament ($k = 2$), which only compares two potential parents at a time. The tournament selection algorithm has the advantage that it does not require knowledge of the whole population. It only compares the fitness of potential parents.

Finally, at the end of GA loop, the population has to undergo some form of replacement. One simple choice is the age-based replacement, in which all parents in the population are replaced by the children. This type of replacement preserves population size.

### 5.3 Finding an Optimal Antenna Model

In order to tune and optimize the antenna for use in the S-band, a genetic algorithm is coded in the C++ programming language (See Appendix A). In addition, GA optimization allows for the inclusion of constraints in the design parameters, which can be included conveniently in the code itself [142]. Genetic algorithms have been used successfully in problems involving patch antennas [143-145]. The design of a patch
antenna with a fragmented ground plane is well suited for such an optimization, since the number of possible permutations of the corrugated metallization layer is extremely large. In addition, there are a number of other parameters in the antenna design, which are optimized concurrently with the patch distribution.

The parameters to be optimized are given by genes in the GA, which are represented as either binary or real numbers in the C++ code. The parameters are the thicknesses and permittivity constants of the dielectric substrates, the position of the coaxial feed, and the patch size and patch distribution in the corrugated metallization layer sandwiched between radiating patch and the ground plane. The patch sizes and patch distribution in the metallization layer are represented by real and binary $N \times N$ matrices, respectively. The matrix describes the patch distribution in one of the quadrants (Q1) underneath the antenna, with the other quadrants being mirror images across the x- and y-axes (Figure 5.6). This is done in order to preserve the symmetry of the radiation pattern.
Figure 5.6: Structure of metallization layer situated below the radiating patch, but above the ground plane. Quadrant Q1 is derived from the patch size and distribution matrices. Q2 is a mirror image of Q1, Q3 is a mirror image of Q2, and Q4 is a mirror image of Q3.

The GA algorithm is initialized with a set of randomized genes for each population member. The fitness \( F \) of each member is evaluated according to the following equation:

\[
F = - \sum_{f} L(f),
\]

(5.19)

where

\[
L(f) = \begin{cases} 
\rho(f), & \rho(f) > -10 \text{ dB} \\
-10, & \rho(f) \leq -10 \text{ dB} 
\end{cases}
\]
In Eq. (5.19), $\rho(f)$ is the reflection coefficient, or $S_{11}$, for a given frequency $f$, with the sum performed over all frequencies in the desired bandwidth. An optimal solution is discovered if only if Eq. (5.19) is maximized, and if the realized gain is larger than zero for any given frequency. In order to evaluate the fitness, an antenna model created by a VBScript code is fed into HFSS (See Appendix B), which then returns the simulated reflection coefficient and gain back to the genetic algorithm program. This process is repeated until an optimal solution is found. A flowchart of the operation as described above is given in Figure 5.7(a). A pseudo-code of the GA is also shown in Figure 5.7(b).

Figure 5.7: (a) Flow chart of optimization process. (b) Pseudo-code of genetic algorithm (GA).
Parent selection is accomplished through binary tournaments using the algorithm in Figure 5.5. Mating of chosen parents is done using one-point crossover for antenna parameters requiring a binary representation, such as the distribution of patches in the metallization layer, and arithmetic recombination for the real-valued antenna parameters. Mutation with a small finite probability of a bit flip is only applied to single bits of binary genes, while non-uniform mutation with a Gaussian distribution is performed on the real-valued genes. The probability of mutation is kept small but non-zero in order to prevent significant loss of genetic material. At the completion of each loop cycle, the entire parent population is replaced by the offspring. The platform size, dimensions of the radiating patch, and the radius of the ring structure surrounding the probe feed are kept constant during the optimization process.

5.4 Results and Discussion

We have designed two antenna models, in order to test the theory set forth in the previous sections. The first model, Model A, is designed and simulated entirely using HFSS and the genetic algorithm. Model B was also simulated using HFSS and the GA, but it in addition to that it was chosen for fabrication due to its smaller profile and simpler design. The
results for Model B are obtained from both numerical simulations and experimental measurements. A “control” antenna, which is identical to Model B except for a lack of corrugated metallization layer, is also designed and fabricated.

5.4.1 Model A

A radiating rectangular patch with dimensions 2.6 x 5.2 cm is placed on top of a corrugated metallization layer, which is sandwiched between two dielectric layers with different permittivity constants. The lower substrate uses a Duroid dielectric with permittivity of 6.15 and thickness of 0.8 cm. The upper substrate is simulated with a Duroid dielectric with permittivity of 9.2 and thickness of 0.2 cm. A dielectric loss tangent of 0.002 is assigned to both dielectrics. There is a solid metallic ground plane below the lower substrate. The HFSS antenna model, as shown in Figure 5.8, has dimensions of 10 x 10 x 1 cm (without the dimensions of radiation box). The excitation is accomplished through a waveport at the bottom of a coaxial connector beneath the ground plane. The impedance of the coaxial feed is matched for a 50 Ω transmission line. A top view of the antenna is given in Figure 5.9(a). Also shown is the cross-sectional view of the antenna (Figure 5.9(b)). A coaxial connector is used at the bottom of the metallic ground plane. As can be seen in Figure 5.9(a), there is a ring cutout on the patch antenna centered at the feed point. This ring structure has shown to be important for tuning out reactive
impedance [146]. The size of the ring is chosen to match the antenna impedance to that of the coaxial feed.

Figure 5.8: HFSS model of the low-profile antenna with a corrugated metallization layer. The corrugated layer is sandwiched between two dielectric substrates.

HFSS simulations are performed using a Driven Modal solution type and a discrete frequency sweep. The reflection coefficient of the optimal solution is shown in Figure 5.10. The bandwidth, as defined by Eq. (5.10), is an impressive 53% (1.8 – 3.1 GHz), which is much higher than the typical bandwidth (a few percent) of a rectangular patch antenna backed by a PEC ground plane. The antenna is well matched for an input impedance of 50 Ω. Two main resonances can be identified in Figure 5.10, one at 2.2 GHz and another one at 2.5 GHz.
Figure 5.9: (a) Top view of the antenna system. A capacitive ring can be seen around the coaxial feed point. (b) Cross-sectional view of the antenna showing the two dielectric substrate layers, along with the coax connector.

Simulations without the ring structure centered at the feed point result in sizable impedance mismatch due to capacitive loading. This kind of loading can be attributed to the small height of the antenna above the
ground plane and the coupling between the patch antenna and the fragmented metallization layer. In the genetic algorithm, the total thickness of the substrates is restricted to be less than \( \lambda_{\text{low}}/10 \), and so the capacitive loading is significant and effectively acts as an offset in the fitness calculations, which rely on the reflection coefficient. Therefore, the presence of the ring or a similar structure that affects the reactance of the antenna is necessary in the optimization process.

![Reflection Coefficient](image)

**Figure 5.10**: Reflection coefficient at the antenna feed point. The bandwidth is approximately 53%.

The E-plane (x-z plane) and H-plane (y-z plane) radiation patterns for a frequency of 2.5 GHz are given in Figure 5.11(a) and Figure 5.11(b),
respectively. Maximum gain of 2.6 dB is achieved in the out-of-plane direction. Good radiation characteristics of the patch antenna are maintained at and near resonance despite the very low height. The resonance behavior centered at 2.5 GHz is due to the geometry of the radiating patch and associated standing wave modes, since the observed directivity is typical for rectangular patch antennas. The bandwidth, for which there is both a maximum directivity and positive gain in the out-of-plane direction, is 17% (2.32 – 2.74 GHz) (Figure 5.12).

![Resonance behavior centered at 2.5 GHz](image)

**Figure 5.11:** (a) E-Plane realized gain at 2.5 GHz. (b) H-Plane realized gain at 2.5 GHz. Both radiation plots show positive gain within ±20˚ of the out-of-plane direction.
The maximum realized gain of the antenna as a function of frequency is shown in Figure 5.12. The gain is greater than zero for frequencies higher than 1.78 GHz. The plot is derived from the peak-realized gain of the HFSS simulation. The bandwidth, as defined by Eq. (5.10) and the additional requirement that $G_{abs} > 0$, is determined to be ~43% (1.8 – 2.78 GHz). This is a major improvement over the bandwidth of a PEC-backed patch antenna with a similar height above the ground plane. Part of this bandwidth includes the resonance at 2.2 GHz, which can be attributed to interaction of electromagnetic modes with the fragmented ground plane. The directivity of the 2.2 GHz resonance, not shown in the paper, is offset from the out-of-plane direction. In addition, the antenna exhibits excellent efficiency of over 88% (Figure 5.13), despite the small total thickness of 1 cm ($\lambda_0/12$). It is known that the radiation capabilities of a patch antenna are increased when its fringe fields are loosely bound [126]. Therefore, the high gain and efficiency could be due to coupling between the patch antenna and the fragmented metallization layer that acts to delocalize the fringe fields.
Figure 5.12: Peak and out-of-plane realized gains as functions of frequency. The peak gain for a given frequency is the maximum gain obtained in any direction. The out-of-plane realized gain is the gain in the far-field in the direction for which $\varphi = 0$ and $\theta = 0$. The positive gain bandwidth in the out-of-plane is $\sim 17\%$.

Figure 5.13: The radiation efficiency ($P_{\text{radiated}}/P_{\text{incident}}$) is shown as a function of frequency. The efficiency is over 88% in the bandwidth of interest.
5.4.2 Model B

An antenna was designed and optimized using HFSS and the GA. For this model, \( N = 3 \) was chosen as the dimension for the \( N \times N \) patch distribution matrix \( (GPD) \) and the patch size matrix \( (GSD) \). Since Model B was designed with fabrication in mind, additional physical constraints were placed on the optimization process. For example, the choice of a Duroid dielectric substrate placed constraints on the allowed thicknesses and dielectric constants, since Duroid substrates are manufactured with very specific physical parameters. Additionally, the radiating patch was initialized with dimensions of 2.6 cm × 5.2 cm, same as in Model A. The capacitive ring cutout around the feed probe had an inner radius of 0.3 cm and an outer radius of 0.35 cm. The coax connector had an inner radius of 0.065 cm and an outer radius of 0.205 cm. The GA was executed with the goal of finding an optimization for an S-band antenna.

The corrugated metallization layer, whose appearance is controlled by the \( GPD \) and the \( GSD \) genes, was sandwiched halfway between the two dielectric substrates. The GA produced a lower substrate with a thickness of 0.3048 cm and dielectric constant of 2.94 (RT/duriod 6002). The upper substrate was also RT/duriod 6002 with the same thickness. Therefore, the total thickness of the antenna system was 0.6096 cm. The GA came up with the following patch distribution matrix:
\[ GPD = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} \quad (5.20) \]

The corresponding size distribution matrix was:

\[ GSD = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 2.08 \\ 0 & 0 & 0.896 \end{pmatrix} \quad (5.21) \]

Note that that sizes are given in centimeters, which is the default length unit in the GA.

The presence of “empty” space in the metallization layer gave us the opportunity to modify the lateral size of the ground plane and the substrate and observe the effect of reducing the platform size. The platform is defined as the ground plane and substrate layers. The two chosen platform sizes were 15 cm × 15 cm² and 7 cm × 12 cm². The structure of the 7 cm × 12 cm antenna is shown in Figure 5.14.
Figure 5.14: (a) Top view of Model B with 7 cm x 12 cm platform and the rectangular radiating patch. (b) View of the corrugated metallization layer midway between the radiating patch and the ground plane.

The reflection coefficients at the coax terminal are given in Figure 5.15. It can be concluded that the platform size has little effect on the reflection coefficient, $S_{11}$. The bandwidth of the antenna with a smaller platform is ~30%. Therefore, it is advantageous to use the smaller platform in order to reduce the profile of the antenna.
Figure 5.15: Reflection coefficients ($S_{11}$) of Model B with (a) 7 x 12 cm platform, and (b) 15 x 15 cm platform.

The total thickness of the antenna can be stated as $\lambda_0/17$, where $\lambda_0$ is the wavelength corresponding to the central frequency of the bandwidth obtained from Figure 5.15 and Eq. (5.10). This is on par or better than similar designs of low-profile patch antennas [135, 138].

It is also important to compare the performance of Model B pictured in Figure 5.14 to the performance of an equivalent antenna without a corrugated metallization layer. This other antenna can serve as a “control” for the effect and significance of the corrugated layer. Simulation results of the reflection coefficients from Model B and the control antenna are
displayed in Figure 5.16. It can be clearly seen that the corrugated metallization layer results in significant improvement in bandwidth.

![Figure 5.16: Simulated S11 for Model B and a control antenna with no corrugated metallization layer.](image)

The peak realized gain (Figure 5.17) and the radiation pattern (Figure 5.18) were obtained for both Model B and the control at a few different frequencies. Most importantly, in the case of the Model B antenna, high values of peak realized gain (> 6 dBi) are sustained for frequencies up to 3.4 GHz. This is significant because, in addition to facilitating larger bandwidths, the corrugated metallization layer does not
act to suppress the gain produced by the antenna. In fact, the gain is enhanced for frequencies higher than the resonance of the control antenna (2.7 GHz). This is suggestive of coupling between radiating element and the corrugated layer.

![Figure 5.17: Simulated peak realized gain for Model B and the control antenna.](image)

**Figure 5.17:** Simulated peak realized gain for Model B and the control antenna.
As can be seen from Figure 5.18, the realized gain radiation pattern is focused in the out-of-plane at 2.6 GHz, and split into two beams along the H-plane (y-z plane) at higher frequencies, which would suggest the emergence of a higher resonance mode.

To gain deeper insight into the polarization characteristics of the Model B antenna, the far-field orthogonal components of realized gain (see Eq. (5.13)) at two different frequencies are plotted in Figure 5.19. In spherical coordinates, the far-field orthogonal components are \((G_{\text{abs}})_{\phi}\) and \((G_{\text{abs}})_{\theta}\). According to Figure 5.19(a), the dominant polarization in the E-plane (x-z plane) is the phi component of the realized gain, with a max gain of \((G_{\text{abs}})_{\phi} \approx 7.5\, \text{dBi}\). In the H-plane (Figure 5.19(b)), the theta component is dominant, but only in a narrow cone of ±10° with respect to the out-of-plane direction (\(\theta = 0\)). For a frequency of 3 GHz, it is the phi component that is dominant. However, as expected from Figure 5.18(b),
the realized gain is extremely low \((G_{abs})_\varphi \leq 0\) in the E-plane (Figure 5.19(c)). Conversely, the H-plane realized gain is large \((G_{abs})_\theta > 5 \text{ dBi}\) and concentrated in two beams centered at ±40° from the out-of-plane. Additionally, there is relatively low cross-polarization \((G_{abs})_\theta < -5 \text{ dBi}\) in close proximity to the two beam maximums (±40° ± 10°).

Figure 5.19: Far-field orthogonal components of realized gain for (a) E-plane radiation at 2.6 GHz, (b) H-plane radiation at 2.6 GHz, (c) E-plane radiation at 3 GHz, and (d) H-plane radiation at 3 GHz.
Now that the reflection coefficient and absolute gain have been determined, the next natural step would be to examine the radiation efficiency (see Eq. (5.5)) of the Model B antenna and compare it to the control antenna. The radiation efficiency is in general different from the total efficiency, as it only includes losses within the antenna and does not depend on the impedance mismatch at the excitation port (i.e., the interface between the coax connector and the transmission line). HFSS provides a convenient parameter, radiation efficiency, defined as

\[ e = \frac{P_{\text{rad}}}{P_{\text{acc}}} \]  

(5.22)

A plot comparing the radiation efficiency of Model B and the control antenna is shown in Figure 5.20. Simulated efficiency is > 95% in the frequency range of 2.6 GHz to 3.4 GHz. On the other hand, the radiation efficiency of the control antenna is marked by a steep decline above 3 GHz, which is not due to the reflection mismatch at the excitation port, but is most likely due to the limitation of the antenna as a broadband radiator.
In order to fully understand the reason for the bandwidth, efficiency, gain enhancement in the Model B antenna, as compared to the control, an investigation of the electromagnetic interactions between the radiating patch, the individual elements of the corrugated metallization layer, and the ground plane is required. As hinted previously, enhancement of antenna performance can be due to an emergence of coupling modes. The most basic coupling mode, which is also found in the control antenna, is the TM$_z$ mode predicted by the cavity model (see the Antenna Metrics section) as a natural consequence of equating the patch antenna/ground plane system to a dielectric-loaded cavity. Even though the cavity model
cannot be used directly in this case due to violation of the PMC boundary condition, it can still serve as an approximation and a basis. So, potentially, the radiating patch can be coupled to the following elements:

1. Ground plane (TM$^z$ modes).
2. The small patches in the corrugated metallization layer.
3. The large patches in the corrugated metallization layer.

It is conceivable that all three interactions form coupling modes, which can affect the bandwidth, efficiency, and gain of the antenna characterized by Model B. The most obvious mode is the TM$^z$, which represents the classic resonance mode of a patch antenna backed by a ground plane. The presence of two such modes was hinted by a shape change in the radiation pattern (Figure 5.18) that occurred between 2.6 GHz and 3 GHz, and more precisely by the first two dips in the reflection coefficient (Figure 5.16). However, since no significant change in the radiation pattern is observed at 3.4 GHz (Figure 5.18(c)), it is likely that no higher TM$^z$ mode is associated with the third dip in the reflection coefficient.

To facilitate the discovery of TM$^z$ modes, electric field vectors below the surface of the radiating patch are produced at phases $\varphi_1 = \varphi_0 + 90^\circ$ and $\varphi_2 = \varphi_0 + 270^\circ$, where $\varphi_0$ is the initial phase of the electric excitation current. A plot of the electric field vectors at 2.7 GHz is given in Figure 5.21 for the control antenna. According to the chosen coordinate system
and Eq. (5.16), it can be concluded that a $TM_{10}^2$ mode is excited at 2.7 GHz.

Figure 5.21: Electric field vectors below the radiating patch of the control antenna with phases (a) $\varphi_1 = \varphi_0 + 90^\circ$, and (b) $\varphi_2 = \varphi_0 + 270^\circ$. 
Interestingly, according to Eq. (5.15) and the cavity model, the $TM_{10}^z$ mode is normally found at $\sim 3.36$ GHz for a rectangular patch antenna and a substrate with dielectric constant of 2.94. The shift could be due to the capacitive ring cutout, which surrounds the feed probe.

A similar plot of electric field vectors can be constructed for Model B. In this case, as expected, two TM$^z$ modes are found, one at 2.6 GHz (Figure 5.22), and another one at 2.94 GHz (Figure 5.23), whose locations correspond to the dips in the reflection coefficient. The electric field configuration shown in Figure 5.22 corresponds to the $TM_{10}^z$ mode, while the field configuration in Figure 5.23 is attributed to the $TM_{02}^z$ mode.
Figure 5.22: Electric field vectors below the radiating patch of Model B at 2.6 GHz with phases (a) $\varphi_1 = \varphi_0 + 90^\circ$, and (b) $\varphi_2 = \varphi_0 + 270^\circ$. 
According to Eq. (5.15) and the fact that $W = 2L$, there should be a degeneracy for the $TM_{10}^z$ and $TM_{02}^z$ modes, since

$$ (f_r)_{10} = (f_r)_{02} \approx 3.36 \text{ GHz} \quad (5.23) $$
This degeneracy is broken in Model B, which could be due to another type of interaction, a coupling between the radiating patch and small patches of the corrugated metallization layer. The small patches are situated parallel to the width dimension of the radiating patch (Figure 5.14(b)), and since they are partially underneath the radiating patch, it is conceivable that they would have some effect on the TM\textsuperscript{2} modes.

A plot of the electric current density vectors on the surface of the metallic patches can be used in pinpointing any coupling between the corrugated layer and the radiating patch. In fact, it is found that the direction of current vectors on the surface of the small patches follows the direction of the current vectors on the radiating patch. Although small, the induced current density is present for all test frequencies. A plot to illustrate this coupling at a frequency of 2.6 GHz is given in Figure 5.24. It is noted that the TM\textsuperscript{2}\textsubscript{10} mode in Model B is shifted from 2.7 GHz down to 2.6 GHz, a shift of 100 MHz from its location in the control antenna. Therefore, the TM\textsuperscript{2}\textsubscript{10} resonance mode is tuned by 4% due to coupling between the radiating patch and the corrugated metallization layer.
Lastly, coupling between the radiating patch and the large patches in the corrugated metallization layer is also observed through an induced current in the large patches. Two unique modes are found, one at 3 GHz (Figure 5.25), and another at 3.4 GHz (Figure 5.26). We can call the mode at 3 GHz, an *even mode*, since the current vectors belonging to the large patches on each side of the radiating patch are oriented in the *same* direction as the current vectors on the corresponding section of the radiating patch. Thus, they act to enhance the $TM_{02}^z$ mode. Conversely, at 3.4 GHz, an *odd mode* emerges, in which the current vectors belonging to the large patches on each side of the radiating patch are oriented in the *opposite* direction to the current vectors on the corresponding section of the radiating patch. Therefore, the odd mode couples destructively to the...
$TM_{02}^z$ mode. One can argue that the even mode couples to the $TM_{02}^z$ mode constructively, enhancing the bandwidth, gain, and efficiency. This process continues until an excitation of the odd mode at 3.4 GHz, which marks the start of rapid deterioration of antenna performance. Similar even and odd modes have been observed in the case of a simpler stacked patch configuration [135].

Figure 5.25: Coupling between the electric current density vectors in the large patches and the vectors in the radiating patch at a frequency of 3 GHz.
In order to test out the validity of the simulation, versions of Model B and the control were fabricated and tested. The radiating patch and corrugated metallization layers were etched on separate pieces of RT/duroid 6002 substrate. One substrate, which had a ground plane etched on side, and nothing on the other, was used as the lower half of the control antenna (Figure 5.27). The lower half of Model B included an etched ground plane on one side and the corrugated metallization layer on the other side (Figure 5.28). Fabrication of the separate lower and upper halves of the antennas was outsourced to E-Fab, Inc.
Figure 5.27: Antenna layers for control antenna. On the left side, shown are the upper and lower sides of bottom half of antenna. On the right side, shown are the upper and lower sides of the top half of the antenna.

Figure 5.28: Antenna layers for Model B. On the left side, shown are the upper and lower sides of bottom half of antenna. On the right side, shown are the upper and lower sides of the top half of the antenna.
The assembling of the antenna, which involved connecting the two halves by applying small amounts of Loctite Gel Control Super Glue, was accomplished in CM3IC. A small gauge wire was inserted through a drill hole in the antenna at the location of the feed probe, after which an SMA coax connector was soldered to the wire and antenna ground plane (Figure 5.29).

![Figure 5.29: Assembled antenna.](image)

Agilent vector network analyzer (VNA) was used for the purpose of recording the reflection coefficients of Model B and the control antenna. A plot of VNA data is given in Figure 5.30. The bandwidth of the fabricated control antenna is 7%, which is significantly smaller than the simulated control (15%). However, the bandwidth of the fabricated version of Model
B is 32%, which is very close to the simulated result (30%). The VNA data, plotted together with HFSS simulation data, is shown in Figure 5.31.

![Graph showing reflection coefficients](image)

**Figure 5.30:** Reflection coefficients of fabricated versions of Model B and the control antenna.
Figure 5.31: Reflection coefficient for the simulated and fabricated antennas.

5.5 Conclusion

Two different low-profile rectangular patch antennas were designed using an efficient process involving the use of the genetic algorithm optimization technique along with Ansys’s finite element method solver (HFSS v12.1). HFSS’s role as a means of evaluating a fitness function within the genetic algorithm provided a convenient way of minimizing the reflection coefficient of the proposed patch antennas for use in the S-band. The final antenna solutions (Model A and Model B) possessed a corrugated metallization layer sandwiched between the radiating patch
and the ground plane. A bottom layer substrate (substrate 1) was situated between the ground plane and the corrugated metallization layer. The top layer substrate (substrate 2) was sandwiched between the corrugated layer and the radiating patch. A fabricated version of Model B was also tested. The physical characteristics of Model A and Model B are summarized in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Model A (simulated)</th>
<th>Model B (fabricated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch size</td>
<td>2.6 $\times$ 5.2 cm$^2$</td>
<td>2.6 $\times$ 5.2 cm$^2$</td>
</tr>
<tr>
<td>Platform size</td>
<td>10 $\times$ 10 cm$^2$</td>
<td>7 $\times$ 12 cm$^2$</td>
</tr>
<tr>
<td>Total thickness</td>
<td>1 cm ($\lambda_0/12$)</td>
<td>0.6096 cm ($\lambda_0/17$)</td>
</tr>
<tr>
<td>$\varepsilon_1, \tan \delta_1$</td>
<td>6.15, 0.002</td>
<td>2.94, 0.0012</td>
</tr>
<tr>
<td>$\varepsilon_2, \tan \delta_2$</td>
<td>9.2, 0.002</td>
<td>2.94, 0.0012</td>
</tr>
<tr>
<td>$S_{11}$ bandwidth</td>
<td>53% (1.8 – 3.1 GHz)</td>
<td>30% (2.5 – 3.38 GHz)</td>
</tr>
<tr>
<td>Peak realized gain</td>
<td>3 dBi</td>
<td>8.8 dBi</td>
</tr>
<tr>
<td>Main resonances</td>
<td>2.2, 2.5 GHz</td>
<td>2.6 ($TM_{10}^z$), 2.94 ($TM_{02}^z$) GHz</td>
</tr>
</tbody>
</table>
An analysis of Model B showed that in addition to the two resonances resulting from coupling between the radiating patch and the ground plane, there were two other distinct modes that were due to strong coupling between the radiating patch and the large elements of the corrugated metallization layer. Another type of weak coupling was associated with an induced current in the small patches of the corrugated metallization layer. This type of coupling was potentially responsible for a downward shift (~4%) in the $TM_{10}^2$ resonance mode. Therefore, the morphology of the corrugated layer is shown to induce coupling modes in the antenna, which can in turn result in the enhancement and tuning of transverse magnetic mode resonances. This antenna prototype provides a cheaper and lighter alternative to existing planar patch antennas with magnetic substrates.
Appendix A

A.1 chromosome.h

#ifndef CHROMOSOME_H
#define CHROMOSOME_H

#include <random>
#include <vector>
#include "rand_def.h"

typedef std::vector<std::vector<bool>> boolMatrix;
typedef std::vector<std::vector<double>> doubleMatrix;
typedef std::vector<double> doubleArray;

class Chromosome {
public:
    Chromosome();
    Chromosome& operator=(const Chromosome &);
    void recombine(Chromosome &, randEngine &);
    void mutate(randEngine &);
    double evaluateFitness(void);
    double getFitness(void) const;
    void randomize(randEngine &);
    bool isOptimal(void) const;
    void printPattern(void) const;

private:
    // Define size of 2D genes and number of singlet genes
    static const int MAT_SIZE;
    static const int NUM_SINGLET_GENES;
    static const int NUM_REAL_MAT_GENES;

    // Define names of real singlet genes
    static const int GT1;
    static const int GT2;
    static const int GP1;
    static const int GP2;
    static const int GCP;

    // mutation probability for binary genes
    // (between 1/POP_SIZE and 1/(MAT_SIZE^2))
    static const double pm;

    // Define antenna parameters
    // (physical dimensions are in centimeters, unless noted otherwise)
    static const double c;
static const double fmin;
static const double fmax;
static const double freqSteps;
static const double lmin;
static const double lmax;
static const double antLength;
static const double antWidth;
static const double platformSize;
static const double quadrantSize;

// Define coaxial feed parameters
static const double coaxLength;
static const double coaxRad;
static const double coaxPinRad;

// Define capacitive ring structure
static const double ring_ir;
static const double ring_or;

// GSD resolution
static const double maxGSD;
static const double minGSD;
static const double sigmaGSD;

// GT1 and GT2 resolutions
static const double lmid;

static const double maxGT1;
static const double minGT1;
static const double sigmaGT1;

static const double maxGT2;
static const double minGT2;
static const double sigmaGT2;

// GP1 and GP2 resolutions
static const double maxGP1;
static const double minGP1;
static const double sigmaGP1;

static const double maxGP2;
static const double minGP2;
static const double sigmaGP2;

// GCP resolution
static const double maxGCP;
static const double minGCP;
static const double sigmaGCP;

// binary distribution
static distUniInt bd;

// integer distribution
static distUniInt id;

// uniform real distributions
static distUniReal rdGSD;
static distUniReal rdGT1;
static distUniReal rdGT2;
static distUniReal rdGP1;
static distUniReal rdGP2;
static distUniReal rdGCP;
static distUniReal rdProb;

// normal distributions
static distNorm ndGSD;
static distNorm ndGT1;
static distNorm ndGT2;
static distNorm ndGP1;
static distNorm ndGP2;
static distNorm ndGCP;

// keeps track of chromosome number
// when recording near optimal fitness
static int cNum;

// Define genes
boolMatrix GPD;
doubleMatrix GSD;
doubleArray singletGenes;

double fitness;
bool optimal;

void mutateBin(randEngine &);
void mutateReal(randEngine &);
void onePointCrossover(Chromosome &, randEngine &);
void uniformCrossover(Chromosome &, randEngine &);
void recombineReal(Chromosome &, randEngine &);

double conformToRealRange(double, const double, const double, distNorm &, randEngine &)
const;
double conformPermittivity(double) const;

void writeDataToFile(void);

};

#endif

A.2 chromosome.cpp

#include <iostream>
#include <fstream>
#include <string>
#include <sstream>
#include <time.h>
#include <direct.h>
#include "math_def.h"
using std::string;
using std::cout;
using std::endl;

#include "chromosome.h"

// Define size of 2D genes and number of singlet genes
const int Chromosome::MAT_SIZE = 6;
const int Chromosome::NUM_SINGLET_GENES = 5;
const int Chromosome::NUM_REAL_MAT_GENES = 1;

// Define names of real singlet genes
const int Chromosome::GT1 = 0;
const int Chromosome::GT2 = 1;
const int Chromosome::GP1 = 2;
const int Chromosome::GP2 = 3;
const int Chromosome::GCP = 4;

// mutation probability for binary genes
const double Chromosome::pm = 1.0 /
    (((Chromosome::MAT_SIZE)*(Chromosome::MAT_SIZE)) * 0.6);

// Define antenna parameters
// (physical dimensions are in centimeters, unless noted otherwise)
const double Chromosome::c = 300000000; // speed of light in vacuum in
// units of m/s
const double Chromosome::fmin = 2000; // minimum frequency [MHz]
const double Chromosome::fmax = 4000; // maximum frequency [MHz]
const double Chromosome::freqSteps = 20;
const double Chromosome::lmin = Chromosome::c / Chromosome::fmin / 10000;
const double Chromosome::lmax = Chromosome::c / Chromosome::fmax / 10000;
const double Chromosome::antLength = 2.6;
const double Chromosome::antWidth = 5.2;
const double Chromosome::platformSize = 10;
const double Chromosome::quadrantSize = 3.5;

// Define coaxial feed parameters
const double Chromosome::coaxLength = 0.95;
const double Chromosome::coaxRad = 0.205;
const double Chromosome::coaxPinRad = 0.065;

// Define capacitive ring structure
const double Chromosome::ring_ir = 0.3;
const double Chromosome::ring_or = 0.35;

// GSD resolution
const double Chromosome::maxGSD = Chromosome::quadrantSize /
    Chromosome::MAT_SIZE;
const double Chromosome::minGSD = Chromosome::maxGSD / 4;
const double Chromosome::sigmaGSD = (Chromosome::maxGSD -
    Chromosome::minGSD) / 10;

// GT1 and GT2 resolutions
const double Chromosome::lmid = (Chromosome::lmin + Chromosome::lmax)/2;
const double Chromosome::maxGT1 = Chromosome::lmid / 20;
const double Chromosome::minGT1 = Chromosome::lmid / 40;
const double Chromosome::sigmaGT1 = (Chromosome::maxGT1 - Chromosome::minGT1) / 10;
const double Chromosome::maxGT2 = Chromosome::lmid / 20;
const double Chromosome::minGT2 = Chromosome::lmid / 40;
const double Chromosome::sigmaGT2 = (Chromosome::maxGT2 - Chromosome::minGT2) / 10;

// GP1 and GP2 resolutions
const double Chromosome::maxGP1 = 6.15;  // Has to be included in
   // conformPermittivity function
const double Chromosome::minGP1 = 2.17;  // Has to be included in
   // conformPermittivity function
const double Chromosome::sigmaGP1 = (Chromosome::maxGP1 - Chromosome::minGP1) / 10;
const double Chromosome::maxGP2 = 3.0; // Has to be included in
   // conformPermittivity function
const double Chromosome::minGP2 = 2.17;  // Has to be included in
   // conformPermittivity function
const double Chromosome::sigmaGP2 = (Chromosome::maxGP2 - Chromosome::minGP2) / 10;

// GCP resolution
const double Chromosome::maxGCP = Chromosome::antLength/2 - Chromosome::coaxRad;
const double Chromosome::minGCP = 0;
const double Chromosome::sigmaGCP = (Chromosome::maxGCP - Chromosome::minGCP) / 10;

// binary distribution
distUniInt Chromosome::bd(0,1);

// integer distribution
distUniInt Chromosome::id(0, Chromosome::MAT_SIZE-1);

// uniform real distributions
distUniReal Chromosome::rdGSD(Chromosome::minGSD, Chromosome::maxGSD);
distUniReal Chromosome::rdGT1(Chromosome::minGT1, Chromosome::maxGT1);
distUniReal Chromosome::rdGT2(Chromosome::minGT2, Chromosome::maxGT2);
distUniReal Chromosome::rdGP1(Chromosome::minGP1, Chromosome::maxGP1);
distUniReal Chromosome::rdGP2(Chromosome::minGP2, Chromosome::maxGP2);
distUniReal Chromosome::rdGCP(Chromosome::minGCP, Chromosome::maxGCP);
distUniReal Chromosome::rdProb(0, 1);

// normal distributions
distNorm Chromosome::ndGSD(0, Chromosome::sigmaGSD);
distNorm Chromosome::ndGT1(0, Chromosome::sigmaGT1);
distNorm Chromosome::ndGT2(0, Chromosome::sigmaGT2);
distNorm Chromosome::ndGP1(0, Chromosome::sigmaGP1);
distNorm Chromosome::ndGP2(0, Chromosome::sigmaGP2);
distNorm Chromosome::ndGCP(0, Chromosome::sigmaGCP);

int Chromosome::cNum = 1;
Chromosome::Chromosome()
    : GPD(MAT_SIZE, std::vector<bool> (MAT_SIZE, false)),
      GSD(MAT_SIZE, std::vector<double> (MAT_SIZE, 0.0)),
      singletGenes(NUM_SINGLET_GENES, 0.0)
{
    fitness = 0;
    optimal = true;
}

Chromosome& Chromosome::operator=(const Chromosome &rhs)
{
    this->fitness = rhs.fitness;
    this->optimal = rhs.optimal;
    this->GPD = rhs.GPD;
    this->GSD = rhs.GSD;
    this->singletGenes = rhs.singletGenes;

    return *this;
}

void Chromosome::recombine(Chromosome &c, randEngine &re)
{
    //uniformCrossover(c, re);
    onePointCrossover(c, re);
    recombineReal(c, re);
}

void Chromosome::onePointCrossover(Chromosome &c, randEngine &re)
{
    bool temp1;
    double temp2;
    int u;
    int v;

    do {
        u = id(re);
        v = id(re);
    } while (u == (MAT_SIZE - 1) && v == (MAT_SIZE - 1));

    for (int i = 0; i <= u; i++) {
        for (int j = 0; j <= v; j++) {
            // crossover binary patch pattern
            temp1 = c.GPD[i][j];
            c.GPD[i][j] = GPD[i][j];
            GPD[i][j] = temp1;
            
            // crossover matrix of real patch sizes
            temp2 = c.GSD[i][j];
            c.GSD[i][j] = GSD[i][j];
        }
    }
}
void Chromosome::uniformCrossover(Chromosome &c, randEngine &re)
{
    int mask;
    bool temp1;
    double temp2;

    for (int i = 0; i < MAT_SIZE; i++) {
        for (int j = 0; j < MAT_SIZE; j++) {
            mask = bd(re);
            if (mask == 1) {
                // crossover binary patch pattern
                temp1 = GPD[i][j];
                GPD[i][j] = c.GPD[i][j];
                c.GPD[i][j] = temp1;

                // crossover matrix of real patch sizes
                temp2 = GSD[i][j];
                GSD[i][j] = c.GSD[i][j];
                c.GSD[i][j] = temp2;
            }
        }
    }
}

void Chromosome::recombineReal(Chromosome &c, randEngine &re)
{
    double temp;
    double a = rdProb(re);

    // do a "whole arithmetic recombination" of the singlet genes
    for (int i = 0; i < NUM_SINGLET_GENES; i++) {
        temp = singletGenes[i];
        singletGenes[i] = a*singletGenes[i] + (1-a)*c.singletGenes[i];
        c.singletGenes[i] = a*c.singletGenes[i] + (1-a)*temp;
    }
}

void Chromosome::mutate(randEngine &re)
{
    mutateBin(re);
    mutateReal(re);
}
void Chromosome::mutateBin(randEngine &re)
{
    double r;

    for (int i = 0; i < MAT_SIZE; i++) {
        for (int j = 0; j < MAT_SIZE; j++) {
            r = rdProb(re);
            if (r < pm)
                GPD[i][j] = !GPD[i][j];
        }
    }
}

void Chromosome::mutateReal(randEngine &re)
{
    unsigned int u;
    unsigned int v;

    u = id(re);
    v = id(re);

    // Do nonuniform mutation with Gaussian distribution
    // with mean = 0 and standard deviation = sigma

    GSD[u][v] = conformToRealRange(GSD[u][v],
                                   minGSD, maxGSD, ndGSD, re);
    singletGenes[GT1] = conformToRealRange(singletGenes[GT1],
                                           minGT1, maxGT1, ndGT1, re);
    singletGenes[GT2] = conformToRealRange(singletGenes[GT2],
                                           minGT2, maxGT2, ndGT2, re);
    singletGenes[GP1] = conformToRealRange(singletGenes[GP1],
                                           minGP1, maxGP1, ndGP1, re);
    singletGenes[GP2] = conformToRealRange(singletGenes[GP2],
                                           minGP2, maxGP2, ndGP2, re);
    singletGenes[GCP] = conformToRealRange(singletGenes[GCP],
                                           minGCP, maxGCP, ndGCP, re);

    // Conform the GP1 and GP2 genes to the given set of available
    // permittivities
    singletGenes[GP1] = conformPermittivity(singletGenes[GP1]);
    singletGenes[GP2] = conformPermittivity(singletGenes[GP2]);
}

double Chromosome::conformToRealRange(double val, const double min,
                                        const double max, distNorm &nd, randEngine &re) const
{
    double sum;
    sum = val + nd(re);

    if (sum < min) {
        return min;
    } else if (sum > max) {
        return max;
    }
double Chromosome::conformPermittivity(double perm) const
{
    // list of available permittivities
    const double permArray[] = {
        2.17, 2.2, 2.33, 2.5, 2.94,
        3, 3.02, 3.2, 3.27, 3.5, 3.55, 3.66,
        4.5,
        6, 6.15,
        9.2, 9.8,
        10.2};

    const size_t permArraySize = sizeof(permArray)/sizeof(permArray[0]);
    unsigned int counter = 0;
    do {
        if (permArray[counter]/perm > 1) {
            if (perm > (permArray[counter]-permArray[counter-1])/2)
                perm = permArray[counter];
            else
                perm = permArray[counter-1];
        }
    } while (counter < permArraySize);
    return perm;
}

double Chromosome::evaluateFitness(void)
{
    double s11_cutoff = 10.0;
    double f_min, f_max;
    double f, s11;
    double gain;
    string tmp;
    string stream;

    std::istringstream ss;
    std::istringstream gs;
    std::stringstream strmStream;
    int batch_run;
    time_t start, end;
    double diff;

    // Output the results to file
    writeToFile();
// Call HFSS script

//
time(&start);
batch_run = system("run_script.bat");
time(&end);
diff = difftime(end, start);

// Read in s11.csv file header
std::ifstream inReturnLossFile("s11.csv", std::ios::in);
if ( !inReturnLossFile) {
    std::cerr << endl << "s11.csv" << " could not be opened!" << endl;
    exit(1);
}
inReturnLossFile >> tmp;
do {
inReturnLossFile >> tmp;
} while (tmp != "[]");

// Read in peak_gain.csv file header
std::ifstream inGainFile("peak_gain.csv", std::ios::in);
if ( !inGainFile) {
    std::cerr << endl << "peak_gain.csv" << " could not be opened!" << endl;
    exit(1);
}
do {
inGainFile >> tmp;
} while (tmp != "Theta='0deg'"");

// assume an optimal solution
optimal = true;

// zero the fitness
fitness = 0;
while (inReturnLossFile.good()) {
    getline(inGainFile, stream, ',');
    ss.clear();
    ss.str(stream);
    ss >> f;
    getline(inGainFile, stream, '\n');
ss.clear();
ss.str(stream);
ss >> gain;

generate line from return loss file, parse, and update fitness
getline(inReturnLossFile, stream, ',');
ss.clear();
ss.str(stream);
ss >> f;

generate line from return loss file, parse, and update fitness
getline(inReturnLossFile, stream, '\n');
ss.clear();
ss.str(stream);
ss >> s11;
if (s11 >= -s11_cutoff)
    fitness = fitness - s11;
else {
    fitness = fitness + s11_cutoff;
}
if (s11 > -s11_cutoff && optimal == true)
    optimal = false;
if (gain < 0 && optimal == true)
    optimal = false;
if (f == fmax / 1000)
    break;

inReturnLossFile.close();
inGainFile.close();

// Zero the fitness if HFSS exited prematurely
if (diff < 15) {
    fitness = 0;
}

// save the near optimal fitness results
if (fitness/((freqSteps + 1) * s11_cutoff) > 0.85) {
    if (chdir("near_optimal") != 0)
        mkdir("near_optimal");
    ofstream ooof( "fitness_index.txt", std::ios::app );

    // exit program if unable to create file
    if ( !ooof ) {
        std::cerr << endl << "fitness_index.txt" << " could not be opened!" << endl;
        exit(1);
    } // end if

oof << cNum << " " << fitness << endl;

oof.close();

strStream << cNum;

std::string fn1;
fn1.append("s11_");
fn1.append(strStream.str());
fn1.append(".csv");
chdir("..");
std::ifstream ifs1("s11.csv", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs1(fn1, std::ios::binary);
ofs1 << ifs1.rdbuf();
ifs1.close();
ofs1.close();

std::string fn2;
fn2.append("peak_gain_");
fn2.append(strStream.str());
fn2.append(".csv");
chdir("..");
std::ifstream ifs2("peak_gain.csv", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs2(fn2, std::ios::binary);
ofs2 << ifs2.rdbuf();
ifs2.close();
ofs2.close();

std::string fn3;
fn3.append("smith_chart_");
fn3.append(strStream.str());
fn3.append(".jpg");
chdir("..");
std::ifstream ifs3("smith_chart.jpg", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs3(fn3, std::ios::binary);
ofs3 << ifs3.rdbuf();
ifs3.close();
ofs3.close();

std::string fn4;
fn4.append("S11_");  // S11.jpg is a common file name for S11 data
fn4.append(strStream.str());
fn4.append(".jpg");
chdir("..");
std::ifstream ifs4("S11.jpg", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs4(fn4, std::ios::binary);
ofs4 << ifs4.rdbuf();
ifs4.close();
ofs4.close();

std::string fn5;
fn5.append("GA_out_");
fn5.append(strStream.str());
fn5.append(".txt");
chdir("..");
std::ifstream ifs5("GA_out.txt", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs5(fn5, std::ios::binary);
ofs5 << ifs5.rdbuf();
ifs5.close();
ofs5.close();

std::string fn6;
fn6.append("peak_gain_");
fn6.append(strStream.str());
fn6.append(".jpg");
chdir("..");
std::ifstream ifs6("peak_gain.jpg", std::ios::binary);
chdir("near_optimal");
std::ofstream ofs6(fn6, std::ios::binary);
ofs6 << ifs6.rdbuf();
ifs6.close();
ofs6.close();

cNum++;
chdir("..");
}

return fitness;
}

double Chromosome::getFitness(void) const
{
    return fitness;
}

void Chromosome::writeDataToFile(void)
{
    // ofstream constructor opens file
    std::ofstream of( "GA_out.txt", std::ios::out );

    // exit program if unable to create file
    if ( !of ) {
        std::cerr << endl << "GA_out.txt" << " could not be opened!"
                   << endl;
        exit(1);
    } // end if

    // Output the antenna parameters
    of << MAT_SIZE << endl;
    of << fmin << endl;
    of << fmax << endl;
    of << freqSteps << endl;
    of << lmin << endl;
    of << lmax << endl;
    of << antLength << endl;
    of << antWidth << endl;
    of << platformSize << endl;
    of << quadrantSize << endl;
    of << coaxLength << endl;
// Empty line
// Output singlet genes
for (int i = 0; i < NUM_SINGLET_GENES; i++) {
    of << singletGenes[i] << endl;
}

// Empty line

// Output the corrugated surface
for (int i = 0; i < MAT_SIZE; i++) {
    for (int j = 0; j < MAT_SIZE; j++) {
        // DEBUG
        GSD[i][j] = maxGSD;
        // DEBUG
        of << GSD[i][j] << ",";
    }
    of << endl;
}

of.close();

void Chromosome::randomize(randEngine &re)
{
    for (int i = 0; i < MAT_SIZE; i++) {
        for (int j = 0; j < MAT_SIZE; j++) {
            GPD[i][j] = bd(re);
            GSD[i][j] = rdGSD(re);
        }
    }
    singletGenes[GT1] = rdGT1(re);
    singletGenes[GT2] = rdGT2(re);
    singletGenes[GP1] = rdGP1(re);
    singletGenes[GP2] = rdGP2(re);
singletGenes[GCP] = rdGCP(re);

// Conform the GP1 and GP2 genes to the given set of available // permittivities
singletGenes[GP1] = conformPermittivity(singletGenes[GP1]);
singletGenes[GP2] = conformPermittivity(singletGenes[GP2]);

}

bool Chromosome::isOptimal(void) const
{
    return optimal;
}

void Chromosome::printPattern(void) const
{
    cout << endl;
    for (int i = 0; i < MAT_SIZE; i++) {
        for (int j = 0; j < MAT_SIZE; j++) {
            cout << GPD[i][j];
        }
        cout << endl;
    }
    cout << endl;
}

A.3 population.h

#ifndef POPULATION_H
#define POPULATION_H

class Population {

public:
    Population(randEngine &);
    void randomize(void);
    void select(void);
    void reproduce(void);
    const Chromosome* evaluate(int, int, double);
    void replace(void);
    double getAvFitness(void);

private:

    static const double pc; // crossover probability
    static const double ps; // parent selection probability

    static const int popSize; // population size
    static const int kSize; // tournament size

#endif

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static distUniReal probDist;
static distUniInt intDist;

randEngine& randE;
std::vector<Chromosome> pop;
std::vector<int> matingPool;  // index of population members
                             // selected for reproduction

double avFitness;  // average fitness for the population

void recombine(void);
void printPopStatus(int, int, int, double, double, double);

};
#endif

A.4 population.cpp

#include <iostream>
using namespace std;
#include "chromosome.h"
#include "population.h"

const double Population::pc = 0.7;
cost double Population::ps = 1;

cost int Population::popSize = 40;  // MUST BE EVEN!
cost int Population::kSize = 2;

distUniReal Population::probDist(0,1);
distUniInt Population::intDist(0,Population::popSize-1);

Population::Population(randEngine& re) :
    randE(re),
    pop(popSize),
    matingPool(popSize, 0)
{
}

void Population::randomize(void)
{
    for (int i = 0; i < popSize; i++) {
        pop[i].randomize(randE);
    }
}

void Population::select(void)
{
// use tournament selection with replacement

std::vector<int> sArray(kSize);
double max;
int maxMember;

int i;
int currentMember = 0;

while (currentMember < popSize) {

    // pick k random members (with replacement)
    for (i = 0; i < kSize; i++) {
        sArray[i] = intDist(randE);
    }

    // Find member with maximum fitness in tournament of size k
    maxMember = sArray[0];
    max = pop[maxMember].getFitness();
    for (i = 1; i < kSize; i++) {
        if (pop[sArray[i]].getFitness() > max) {
            maxMember = sArray[i];
            max = pop[maxMember].getFitness();
        }
    }

    matingPool[currentMember] = maxMember;
    currentMember++;
}

const Chromosome* Population::evaluate(int gen, int totGens,
                                         double prevGenAvFitness) {

    Chromosome *c;
    bool optimal = false;
    double max;

    double fitness;
    double fitnessSum;

    fitnessSum = 0;

    for (int i = 0; i < popSize; i++) {
        pop[i].evaluateFitness();

        fitness = pop[i].getFitness();
        fitnessSum = fitnessSum + fitness;

        printPopStatus(i+1, gen, totGens, fitness, fitnessSum/(i+1),
                        prevGenAvFitness);
        pop[i].printPattern();

        if (pop[i].isOptimal()) {
            c = &pop[i];
            optimal = true;
        }
    }

    return c;
}
break;
}
}
avFitness = fitnessSum / popSize;
if (!optimal) {
    max = pop[0].getFitness();
    c = &pop[0];
    for (int i = 0; i < popSize; i++) {
        if (pop[i].getFitness() > max) {
            max = pop[i].getFitness();
            c = &pop[i];
        }
    }
    return c;
}

void Population::recombine(void)
{
    std::vector<Chromosome> popCopy(popSize);
    for (int i = 0; i < popSize; i++)
        popCopy[i] = pop[i];
    Chromosome c1;
    Chromosome c2;
    double r;
    for (int i = 0; i < popSize; i+=2) {
        c1 = popCopy[matingPool[i]];
        c2 = popCopy[matingPool[i+1]];
        r = probDist(randE);
        if (r < pc)
            c1.recombine(c2, randE);
        pop[i] = c1;
        pop[i+1] = c2;
    }
}
void Population::reproduce(void)
{
    recombine();
    for (int i = 0; i < popSize; i++) {

pop[i].mutate(randE);
}

void Population::replace(void)
{
    // do nothing, age-based replacement is
    // done in the recombination phase
}

void Population::printPopStatus(int i, int gen, int totGens,
                                double fitness, double genAv, double prevGenAv)
{
    const int totDiv = 20;   // total number of
    // divisions in the status bar

    double divSize1 = (double) totDiv / popSize;
    double numDiv1 = floor(divSize1 * i);

    double divSize2 = (double) totDiv / totGens;
    double numDiv2 = floor(divSize2 * gen);

    cout << endl << endl
    << " Member " << i << " "/" << popSize << endl << endl;
    cout << " [";
    for (int j = 0; j < (int) numDiv1; j++) {
        cout << ";
    }
    for (int j = 0; j < (totDiv - (int) numDiv1); j++) {
        cout << "-";
    }
    cout << "]" << " " << floor((double) i / popSize * 100) << ";%";

    cout << endl << endl
    << " Generation " << gen << " "/" << totGens << endl << endl;
    cout << " [";
    for (int j = 0; j < (int) numDiv2; j++) {
        cout << ";
    }
    for (int j = 0; j < (totDiv - (int) numDiv2); j++) {
        cout << "-";
    }
    cout << "]" << " " << floor((double) gen / totGens * 100) << ";%";
    cout << endl << endl;
    cout << " Fitness (current member) = " << fitness << endl;
    cout << " Fitness (current gen mean) = " << genAv << endl;
    cout << " Fitness (previous gen mean) = " << prevGenAv << endl <<

double Population::getAvFitness(void) {
    return avFitness;
}

A.4 main.cpp

#include <iostream>
#include <fstream>
#include <direct.h>

using std::cout;
using std::cin;
using std::endl;
using std::ofstream;
using std::ios;

#include "chromosome.h"
#include "population.h"

int main() {
    std::random_device rd;
    randEngine re(rd());
    Population p(re);
    const Chromosome *c;

    int totGens;       // total number of generations
    int gen = 1;       // (it should be an even number)
    double prevGenAvFitness = 0;

    char e;
    int batch_run;

    //cout << "Chromosome size: " << C_SIZE << endl;
    //cout << "Population size: " << POP_SIZE << endl << endl;

    cout << "Enter number of generation (even #): ";
    cin >> totGens;

    if (totGens < 2) {
        cout << endl
             << "Number of generations needs to be 2 or greater!"
<< endl << "Enter (q) to exit: ";
cin >> e;
return 1;
}

//srand(time(0));
p.randomize();
c = p.evaluate(gen, totGens, prevGenAvFitness);
prevGenAvFitness = p.getAvFitness();
c->printPattern();
cout << "Is it optimal? " << c->isOptimal() << endl;
ofstream outGnuplot("plot_fitness.gnuplot", ios::out);
ofstream outFitnessFile("gen_fitness.txt", ios::out);
outFitnessFile << gen << " " << prevGenAvFitness << endl;
while ((c->isOptimal() == false) && gen <= (totGens-1)) {
    p.select();
p.reproduce();
gen++;
c = p.evaluate(gen, totGens, prevGenAvFitness);
prevGenAvFitness = p.getAvFitness();
outFitnessFile << gen << " " << prevGenAvFitness << endl;
c->printPattern();
cout << "Is it optimal? " << c->isOptimal() << endl;
}
outFitnessFile.close();
outGnuplot.close();
cout << "Enter (q) to exit: ";
cin >> e;
return 0;
A.5 math_def.h

#ifndef MATH_DEF_H
#define MATH_DEF_H

int delta(double);

// The delta function: if x = 0, delta(x) = 1, else delta(x) = 0
int delta(double x)
{
    if (x == 0)
        return 1;
    else
        return 0;
}
#endif

A.6 rand_def.h

#ifndef RAND_DEF_H
#define RAND_DEF_H

#include <random>

typedef std::mt19937 randEngine;
typedef std::normal_distribution<double> distNorm;
typedef std::uniform_int_distribution<int> distUniInt;
typedef std::uniform_real_distribution<double> distUniReal;
#endif

Appendix B

************************ RFSS Script for the antenna GA ************************
*v.2.5 (last edit: 11-14-2013)

************************ Function to perform round up operation ****************************

function Ceil( Number )
Ceil = Int(Number)
if Ceil <> Number then
  Ceil = Ceil + 1
end if
end function

*****************************************
' Function to parse CSV text
*****************************************

Function CSVParse(ByVal strLine)
  ' Function to parse comma delimited line and return array
  ' of field values.
  Dim arrFields
  Dim blnIgnore
  Dim intFieldCount
  Dim intCursor
  Dim intStart
  Dim strChar
  Dim strValue
  Const QUOTE = ""
  Const QUOTE2 = ""
  ' Check for empty string and return empty array.
  If (Len(Trim(strLine)) = 0) then
    CSVParse = Array()
    Exit Function
  End If
  ' Initialize.
  blnIgnore = False
  intFieldCount = 0
  intStart = 1
  arrFields = Array()
  ' Add "," to delimit the last field.
  strLine = strLine & ","
  ' Assume last entry if followed by a comma ",".
  ' Walk the string.
  For intCursor = 1 To Len(strLine)
    ' Get a character.
    strChar = Mid(strLine, intCursor, 1)
    Select Case strChar
    Case QUOTE
      ' Toggle the ignore flag.
      blnIgnore = Not blnIgnore
    Case ","
      If Not blnIgnore Then
        ' Add element to the array.
        ReDim Preserve arrFields(intFieldCount)
        ' Makes sure the "field" has a non-zero length.
        If (intCursor - intStart > 0) Then
          ' Extract the field value.
          strValue = Mid(strLine, intStart, _
            intCursor - intStart)
          ' If it's a quoted string, use Mid to
          ' remove outer quotes and replace inner
          ' doubled quotes with single.
          If (Left(strValue, 1) = QUOTE) Then
            arrFields(intFieldCount) = _
              Replace(Mid(strValue, 2, Len(strValue) - 2), QUOTE2, QUOTE)
          Else
            arrFields(intFieldCount) = strValue
          End If
        Else
          ' An empty field is an empty array element.
          arrFields(intFieldCount) = Empty
        End If
      Else
        ' increment for next field.
        intFieldCount = intFieldCount + 1
        intStart = intCursor + 1
      End If
    Case Else
    End Select
  Next intCursor
End Function
End Select
Next
' Return the array.
CSVParse = arrFields
End Function

'*****************************************
' Function to test for intersection
' between a circle and a rectangle
'*****************************************
Function intersects(cX, cY, cR, rX, rY, rW, rH)
circleDistanceX = Abs(cX - rX)
circleDistanceY = Abs(cY - rY)
If (circleDistanceX > (rW/2 + cR)) Then
intersects = False
Exit Function
End If
If (circleDistanceY > (rH/2 + cR)) Then
intersects = False
Exit Function
End If
If (circleDistanceX <= (rW/2)) Then
intersects = True
Exit Function
End If
If (circleDistanceY <= (rH/2)) Then
intersects = True
Exit Function
End If

cornerDistance_sq = (circleDistanceX - rW/2)^2 + (circleDistanceY - rH/2)^2
intersects = (cornerDistance_sq <= (cR^2))
End Function

Dim oAnsoftApp
Dim oDesktop
Dim oProject
Dim oDesign
Dim oEditor
Dim oBoundaryModule
Dim oAnalysisModule
Dim oRadFieldModule
Dim oReportModule
Dim oMeshModule
Dim oDefinitionManager
Set oAnsoftApp = CreateObject("AnsoftHfss.HfssScriptInterface")
oAnsoftApp.SetNumberOfProcessors(4)
Set oDesktop = oAnsoftApp.GetAppDesktop()
oDesktop.NewProject
Set oProject = oDesktop.GetActiveProject()
oProject.InsertDesign "HFSS", "HFSSDesign1", "DrivenModal", ""
Set oDesign = oProject.SetActiveDesign("HFSSDesign1")
Set oBoundaryModule = oDesign.GetModule("BoundarySetup")
set oAnalysisModule = oDesign.GetModule("AnalysisSetup")
Set oRadFieldModule = oDesign.GetModule("RadField")
Set oReportModule = oDesign.GetModule("ReportSetup")
' oDesign.SetSolutionType "DrivenTerminal"
Set oMeshModule = oDesign.GetModule("MeshSetup")
' oMeshModule.InitialMeshSettings _
Dim path_to_script

' Use this when running the genetic algorithm
path_to_script = "E:\Trifon's Documents\CM3IC\Fragmented Antenna\11-15-12\near_optimal\"

' Design variables

Dim freq1, bw, step_size, wavelength
Dim box_y_length, box_x_length
Dim rad_box_height

' patch antenna parameters

Dim h

' Temp variables

Dim faceid(4)

' Read fragmented pattern from file and create pattern

dim filesys, file, stream_str, strItem

' Format for GA_out.txt:

' MAT_SIZE
' fmin
' fmax
' lmin
' lmax
' antLength
' antWidth
' platformSize
' quadrantSize
' coaxLength
' coaxRad
' coaxPinRad
' ring_ir
' ring_or
' maxGSD
' GT1
' GT2
' GP1
' GP2
' GCP
' GPD matrix
' GSD matrix
Variables corresponding to above values:

dim num_elements
dim fmin
dim fmax
dim wavelength_min
dim wavelength_max
dim L
dim W
dim platform_size
dim quadrant_size
dim coax_length
dim coax_rad
dim pin_rad
dim ring_ir
dim ring_or
dim max_patch_size
dim sub1_t
dim sub2_t
dim sub1_perm
dim sub2_perm
dim coax_y_pos

Set filesys = CreateObject("Scripting.FileSystemObject")
Set file = filesys.GetFile(path_to_script & "GA_out_control_thin.txt")
Set txtstream = file.OpenAsTextStream(1,0)

' Read the GA_out.txt file
'
' Start with antenna parameters
num_elements = CInt(txtstream.ReadLine)
fmin = CDbl(txtstream.ReadLine) * 1000000
fmax = CDbl(txtstream.ReadLine) * 1000000
wavelength_min = CDbl(txtstream.ReadLine) / 100
wavelength_max = CDbl(txtstream.ReadLine) / 100
L = CDbl(txtstream.ReadLine) / 100
W = CDbl(txtstream.ReadLine) / 100
platform_size = CDbl(txtstream.ReadLine) / 100
quadrant_size = CDbl(txtstream.ReadLine) / 100
coax_length = CDbl(txtstream.ReadLine) / 100
coax_rad = CDbl(txtstream.ReadLine) / 100
pin_rad = CDbl(txtstream.ReadLine) / 100
ring_ir = CDbl(txtstream.ReadLine) / 100
ring_or = CDbl(txtstream.ReadLine) / 100
max_patch_size = CDbl(txtstream.ReadLine) / 100

' Empty line
stream_str = txtstream.ReadLine

' Read in the singlet genes
sub1_t = CDbl(txtstream.ReadLine) / 100
sub2_t = CDbl(txtstream.ReadLine) / 100
sub1_perm = CDbl(txtstream.ReadLine)
sub2_perm = CDbl(txtstream.ReadLine)
coax_y_pos = CDbl(txtstream.ReadLine) / 100

' Empty line
stream_str = txtstream.ReadLine

' Read corrugated plane
dim pattern_str()
redim pattern_str(num_elements-1)
For row = 1 to num_elements
    pattern_str(row-1) = txtstream.ReadLine
Next
* Empty line
stream_str = txtstream.ReadLine

* Read the patch size matrix

    dim patch_size_array()
    redim patch_size_array(num_elements, num_elements)
    For row = 0 to (num_elements-1)
        stream_str = txtstream.ReadLine
        col = 0
        For Each strItem In CSVParse(stream_str)
            patch_size_array(row, col) = CDbl(strItem) / 100
            col = col + 1
        Next
    Next

    txtstream.Close

* Init design variables

    ' 2 GHz -> 15 cm wavelength
    ' 600 MHz -> 50 cm wavelength
    freq1 = (fmin + fmax) / 2
    freqsol = fmax
    step_size = (fmax-fmin)/10
    wavelength = 3e8 / freq1

    sub1_t = 0.00127
    sub2_t = 0.00127
    sub1_perm = 6.15
    sub2_perm = 6.15
    sub1_losstan = 0.0027
    sub2_losstan = 0.0027
    coax_y_pos = 0.005015
    'coax_x_pos = coax_y_pos*W/L
    coax_x_pos = 0
    coax_gap = 0.004

    rad_box_height = sub1_t + sub2_t + wavelength_min / 4

    h = sub1_t + sub2_t

    *R = "50ohm"

    dim xstart, ystart
    box_x_length = platform_size
    box_y_length = platform_size
    'rad_box_x_length = box_x_length + 0.115
    'rad_box_y_length = box_y_length + 0.115
    rad_box_x_length = box_x_length
    rad_box_y_length = box_y_length
    ground_x_length = box_x_length
    ground_y_length = box_y_length

    xstart = -quadrant_size
    ystart = -quadrant_size
dim name_str, name_count, name_str_1, name_str_1_1
name_str = ""
name_str_1 = ""
name_str_1_1 = ""
name_count = 0

dim patch_pattern()
redim patch_pattern(num_elements, num_elements)
dim patch_name()
redim patch_name(num_elements, num_elements)

For row = 1 to num_elements
    For col = 1 to num_elements
        patch_pattern(row-1, col-1) = CInt(mid(pattern_str(row-1), col, 1))
        If patch_pattern(row-1, col-1) = 1 Then
            name_count = name_count + 1
            If name_str = "" Then
                name_str = "f1_" & name_count
                name_str_1 = "f1_" & name_count & "_1"
                name_str_1_1 = "f1_" & name_count & "_1_1"
            Else
                name_str = name_str & "," & "f1_" & name_count
                name_str_1 = name_str_1 & "," & "f1_" & name_count & "_1"
                name_str_1_1 = name_str_1_1 & "," & "f1_" & name_count & "_1_1"
            End If
            patch_name(row-1, col-1) = "f1_" & name_count
        End If
    Next
Next

If name_count <> 0 Then
    oEditor.CreateRectangle_ 
        Array("NAME:RectangleParameters", _
            "IsCovered:=", true, _
            "XStart:=", xstart + (row-1)*max_patch_size + 
            (max_patch_size - patch_size_array(row-1,col-1))/2, _
            "YStart:=", ystart + (col-1)*max_patch_size + 
            (max_patch_size - patch_size_array(row-1,col-1))/2, _
            "ZStart:=", sub1_t, _
            "Width:=", patch_size_array(row-1,col-1), _
            "Height:=", patch_size_array(row-1,col-1), _
            "WhichAxis:=", "Z"), _
        Array("NAME:Attributes", _
            "Name:="; patch_name(row-1, col-1), _
            "Flags:="; "", _
            "Color:="; "(255 102 0)"), _
            "Transparency:="; 0, _
            "PartCoordinateSystem:="; "Global", _
            "SolveInside:="; true)
    oEditor.DuplicateMirror_ 
        Array("NAME:Selections", _
            "Selections:="; name_str, _
            "NewPartsModelFlag:="; "Model"), _
        Array("NAME:DuplicateToMirrorParameters", _
            "DuplicateMirrorBaseX:="; 0, _
            "DuplicateMirrorBaseY:="; 0, _
            "DuplicateMirrorBaseZ:="; 0, _
            "DuplicateMirrorNormalX:="; "1mm", _
            "DuplicateMirrorNormalY:="; "0mm", _
            "DuplicateMirrorNormalZ:="; "0mm"), _
        Array("NAME:Options", _
            "DuplicateAssignments:="; true)
    oEditor.DuplicateMirror_ 
        Array("NAME:Selections", _
            "Selections:="; name_str_1, _
            "NewPartsModelFlag:="; "Model"), _
        Array("NAME:DuplicateToMirrorParameters", _
            "DuplicateMirrorBaseX:="; 0, _
"DuplicateMirrorBaseX": 0,
"DuplicateMirrorBaseY": 0,
"DuplicateMirrorBaseZ": 0,
"DuplicateMirrorNormalX": "0mm",
"DuplicateMirrorNormalY": "0mm",
"DuplicateMirrorNormalZ": "0mm"
),
Array("NAME:Options",
"DuplicateAssignments": true)

oEditor.DuplicateMirror _
Array("NAME:Selections",
"Selections": name_str_1_1,
"NewPartModelFlag": "Model"),
Array("NAME:DuplicateToMirrorParameters",
"DuplicateMirrorBaseX": 0,
"DuplicateMirrorBaseY": 0,
"DuplicateMirrorBaseZ": 0,
"DuplicateMirrorNormalX": "-1mm",
"DuplicateMirrorNormalY": "0mm",
"DuplicateMirrorNormalZ": "0mm"
),
Array("NAME:Options",
"DuplicateAssignments": true)

End If

Dim del_list
del_list = ""
For row = 1 to num_elements
For col = 1 to num_elements
If patch_pattern(row-1, col-1) = 1 Then
  ' Note that coax probe is in 4th quadrant
  patch_x = ((num_elements + 1 - row) - 1/2) * max_patch_size
  patch_y = ((num_elements + 1 - col) - 1/2) * max_patch_size

  If intersects(coax_x_pos, coax_y_pos, _
    pin_rad, patch_x, patch_y, _
    patch_size_array(row-1, col-1),
    patch_size_array(row-1, col-1)) Then
    If del_list = "" Then
      del_list = patch_name(row-1, col-1) & "_1_1"
    Else
      del_list = del_list & "," &
      patch_name(row-1, col-1) & "_1_1"
    End If
  Else If coax_x_pos <= pin_rad Then
    del_list = del_list & "," &
    patch_name(row-1, col-1) & "_1_1"
  End If
  Else If coax_y_pos <= pin_rad Then
    del_list = del_list & "," &
    patch_name(row-1, col-1) & "_1"
  End If
  Else If ((coax_x_pos <= pin_rad) And _
    (coax_y_pos <= pin_rad)) Then
    del_list = del_list & "," &
    patch_name(row-1, col-1)
  End If
End If
End If
Next
If del_list <> "" Then
  oEditor.Delete Array("NAME:Selections", "Selections": del_list)
End If

' Delete the patches which intersect with coax probe
'}
Assign finite conductivity to fragmented pattern

```vba
dim obj_names
obj_names = oEditor.GetMatchedObjectName("f1_*")
obj_deleted = oEditor.GetMatchedObjectName(del_list)

If ((UBound(obj_names) <> UBound(obj_deleted)) And (name_count <> 0)) Then
    oBoundaryModule.AssignFiniteCond
        Array("NAME:FiniteCond3", _
            "UseMaterial": true, _
            "Material": "copper", _
            "InfGroundPlane": false, _
            "Objects": obj_names)
    End If
```

Create radiation box

```vba
oEditor.CreateBox
    Array("NAME:BoxParameters", _
        "XPosition": -rad_box_x_length / 2, _
        "YPosition": -rad_box_y_length / 2, _
        "ZPosition": 0, _
        "XSize": rad_box_x_length, _
        "YSize": rad_box_y_length, _
        "ZSize": rad_box_height), _
    Array("NAME:Attributes", _
        "Name": "rad_box", _
        "Color": "(204 255 255)", _
        "Transparency": 0.8, _
        "PartCoordinateSystem": "Global", _
        "MaterialName": "vacuum", _
        "SolveInside": true)
```

Create lower substrate

```vba
oEditor.CreateBox
    Array("NAME:BoxParameters", _
        "XPosition": -box_x_length / 2, _
        "YPosition": -box_y_length / 2, _
        "ZPosition": 0, _
        "XSize": box_x_length, _
        "YSize": box_y_length, _
        "ZSize": sub1_t), _
    Array("NAME:Attributes", _
        "Name": "substrate1", _
        "Color": "(1 200 1)", _
        "Transparency": 0, _
        "PartCoordinateSystem": "Global", _
        "MaterialName": "Rogers RT/duroid 6006 (tm)", _
        "SolveInside": true)
```

Add material

```vba
oDefinitionManager.AddMaterial
    Array("NAME:sub_mat_1", _
        "CoordinateSystemType": "Cartesian", _
        Array("NAME:AttachedData"), _
        Array("NAME:ModifierData"), _
        "permittivity": sub1_perm, _
        "dielectric_loss_tangent": sub1_losstan)
```

Assign material
Array("NAME:Selections",  
"Selections:="; "substrate1"), _
Array("NAME:Attributes",  
"MaterialValue:="; "sub_mat_1" & Chr(34) & "substrate1"), _
"SolveInside:="; true)

' Create upper substrate
'

oEditor.CreateBox  
Array("NAME:BoxParameters",  
"XPosition:="; box_x_length / 2, _  
"YPosition:="; box_y_length / 2, _  
"ZPosition:="; sub1_t,  
"XSize:="; box_x_length, _  
"YSize:="; box_y_length, _  
"ZSize:="; sub2_t), _
Array("NAME:Attributes",  
"Name:="; "substrate2", _  
"Flags:="; "", _  
"Color:="; "(1 250 1)"), _  
"Transparency:="; 0.5, _  
"PartCoordinateSystem:="; "Global", _  
"MaterialName:="; "Rogers RT/duroid 6006 (tm)"), _  
"SolveInside:="; true)

oDefinitionManager.AddMaterial  
Array("NAME:sub_mat_2",  
"CoordinateSystemType:="; "Cartesian", _  
Array("NAME:AttachedData"), _  
Array("NAME:ModifierData"), _  
"permittivity:="; sub2_perm, _  
"dielectric_loss_tangent:="; sub2_losstan)

oEditor.AssignMaterial  
Array("NAME:Selections",  
"Selections:="; "substrate2"), _
Array("NAME:Attributes",  
"MaterialValue:="; "sub_mat_2" & Chr(34) & "substrate2"), _
"SolveInside:="; true)

' Create ground plane
'

oEditor.CreateRectangle  
Array("NAME:RectangleParameters",  
"IsCovered:="; true, _  
"XStart:="; -ground_x_length / 2, _  
"YStart:="; -ground_y_length / 2, _  
"ZStart:="; 0, _  
"Width:="; ground_x_length, _  
"Height:="; ground_y_length, _  
"WhichAxis:="; "Z"), _
Array("NAME:Attributes",  
"Name:="; "ground_plane", _  
"Flags:="; "", _  
"Color:="; "(255 102 0)"), _  
"Transparency:="; 0, _  
"PartCoordinateSystem:="; "Global", _  
"SolveInside:="; true)

' Assign finite conductivity to ground plane
'

oBoundaryModule.AssignFiniteCond  
Array("NAME:FiniteCond1",  
"UseMaterial:="; true, _  
"Material:="; "copper", _  
"InfGroundPlane:="; false, _  
"Objects:="; Array("ground_plane"))
Create patch antenna

```
oEditor.CreateRectangle Array("NAME:RectangleParameters", _
  "IsCovered:=", true, _
  "XStart:=", -W / 2, _
  "YStart:=", -L / 2, _
  "ZStart:=", 0, _
  "Width:=", W, _
  "Height:=", L, _
  "WhichAxis:=", "Z"), _
Array("NAME:Attributes", _
  "Name:=", "pa1", _
  "Flags:=", "", _
  "Color:=", "(255 102 0)", _
  "Transparency:=", 0, _
  "PartCoordinateSystem:=", "Global", _
  "SolveInside:=", true)
```

Assign finite conductivity to patch antenna

```
oBoundaryModule.AssignFiniteCond Array("NAME:FiniteCond2", _
  "UseMaterial:=", true, _
  "Material:=", "copper", _
  "InfGroundPlane:=", false, _
  "Objects:=", Array("pa1"))
```

Create coax feed

```
oEditor.CreateCircle Array("NAME:CircleParameters", _
  "IsCovered:=", true, _
  "XCenter:=", coax_x_pos, _
  "YCenter:=", coax_y_pos, _
  "ZCenter:=", 0, _
  "Radius:=", coax_rad, _
  "WhichAxis:=", "Z", _
  "NumSegments:=", "0"), _
Array("NAME:Attributes", _
  "Name:=", "coax_cutout", _
  "Flags:=", "", _
  "Color:=", "(132 132 193)", _
  "Transparency:=", 0, _
  "PartCoordinateSystem:=", "Global", _
  "MaterialName:=", "vacuum", _
  "SolveInside:=", true)
```

Subtract

```
oEditor.Subtract Array("NAME:Selections", _
  "Blank Parts:=", "ground_plan", _
  "Tool Parts:=", "coax_cutout"), _
Array("NAME:SubtractParameters", _
  "KeepOriginals:=", false)
```

Create cylinder

```
oEditor.CreateCylinder Array("NAME:CylinderParameters", _
  "XCenter:=", coax_x_pos, _
  "YCenter:=", coax_y_pos, _
  "ZCenter:=", -(coax_length + coax_gap), _
  "Radius:=", coax_rad, _
  "Height:=", coax_length, _
  "WhichAxis:=", "Z", _
  "NumSides:=", "0"), _
Array("NAME:Attributes", _
  "Name:=", "coax", _
  "Flags:=", "", _
  "Color:=", "(132 132 193)", _
  "Transparency:=", 0, _
  "PartCoordinateSystem:=", "Global", _
  "MaterialName:=", "vacuum", _
  "SolveInside:=", true)
```
coEditor.CreateCylinder
   Array("NAME:CylinderParameters", _
      "XCenter:=" , coax_x_pos , _
      "YCenter:=" , coax_y_pos , _
      "ZCenter:=" , -coax_gap , _
      "Radius:=" , coax_rad , _
      "Height:=" , coax_gap , _
      "WhichAxis:=" , "Z", _
      "NumSides:=" , "0" ), _
   Array("NAME:Attributes", _
      "Name:=" , "coax_gap" , _
      "Flags:=" , "", _
      "Color:=" , "(132 132 193)", _
      "Transparency:" , 0, _
      "PartCoordinateSystem:=" , "Global", _
      "MaterialName:=" , "air", _
      "SolveInside:=" , true)
   
coEditor.CreateCylinder
   Array("NAME:CylinderParameters", _
      "XCenter:=" , coax_x_pos , _
      "YCenter:=" , coax_y_pos , _
      "ZCenter:=" , -(coax_length + coax_gap), _
      "Radius:=" , pin_rad , _
      "Height:=" , coax_length + coax_gap , _
      "WhichAxis:=" , "Z", _
      "NumSides:=" , "0" ), _
   Array("NAME:Attributes", _
      "Name:=" , "coax_pin" , _
      "Flags:=" , "", _
      "Color:=" , "(132 132 193)", _
      "Transparency:=" , 0, _
      "PartCoordinateSystem:=" , "Global", _
      "MaterialName:=" , "copper", _
      "SolveInside:=" , false)
   
coEditor.CreateCylinder
   Array("NAME:CylinderParameters", _
      "XCenter:=" , coax_x_pos , _
      "YCenter:=" , coax_y_pos , _
      "ZCenter:=" , 0, _
      "Radius:=" , pin_rad , _
      "Height:=" , sub1_t , _
      "WhichAxis:=" , "Z", _
      "NumSides:=" , "0" ), _
   Array("NAME:Attributes", _
      "Name:=" , "coax_probe1" , _
      "Flags:=" , "", _
      "Color:=" , "(132 132 193)", _
      "Transparency:=" , 0, _
      "PartCoordinateSystem:=" , "Global", _
      "MaterialName:=" , "copper", _
      "SolveInside:=" , false)
   
coEditor.CreateCylinder
   Array("NAME:CylinderParameters", _
      "XCenter:=" , coax_x_pos , _
      "YCenter:=" , coax_y_pos , _
      "ZCenter:=" , sub1_t , _
      "Radius:=" , pin_rad , _
      "Height:=" , sub2_t , _
      "WhichAxis:=" , "Z", _
      "NumSides:=" , "0" ), _
   Array("NAME:Attributes", _
      "Name:=" , "coax_probe2" , _
      "Flags:=" , "", _
      "Color:=" , "(132 132 193)", _
      "SolveInside:=" , true)
oEditor.Subtract
  Array("NAME:Selections", _
  "Blank Parts:=" , "substrate1", _
  "Tool Parts:=" , "coax_probe1" ), _
  Array("NAME:SubtractParameters", _
  "KeepOriginals:" , true)

oEditor.Subtract
  Array("NAME:Selections", _
  "Blank Parts:=" , "substrate2", _
  "Tool Parts:=" , "coax_probe2" ), _
  Array("NAME:SubtractParameters", _
  "KeepOriginals:" , true)

oEditor.Subtract
  Array("NAME:Selections", _
  "Blank Parts:=" , "coax", _
  "Tool Parts:=" , "coax_pin" ), _
  Array("NAME:SubtractParameters", _
  "KeepOriginals:" , true)

oEditor.Subtract
  Array("NAME:Selections", _
  "Blank Parts:=" , "coax_gap", _
  "Tool Parts:=" , "coax_pin" ), _
  Array("NAME:SubtractParameters", _
  "KeepOriginals:" , true)

' Make capacitive ring around coaxial feed '

oEditor.CreateCircle
  Array("NAME:CircleParameters", _
  "IsCovered:" , true, _
  "XCenter:" , coax_x_pos, _
  "YCenter:" , coax_y_pos, _
  "ZCenter:" , h, _
  "Radius:" , ring_ir, _
  "WhichAxis:" , "Z", _
  "NumSegments:" , "0" ), _
  Array("NAME:Attributes", _
  "Name:" , "cap_inner_circle", _
  "Flags:" , "", _
  "Color:" , "(132 132 193)" , _
  "Transparency:" , 0, _
  "PartCoordinateSystem:" , "Global", _
  "MaterialName:" , "vacuum", _
  "SolveInside:" , true)

oEditor.CreateCircle
  Array("NAME:CircleParameters", _
  "IsCovered:" , true, _
  "XCenter:" , coax_x_pos, _
  "YCenter:" , coax_y_pos, _
  "ZCenter:" , h, _
  "Radius:" , ring_or, _
  "WhichAxis:" , "Z", _
  "NumSegments:" , "0" ), _
  Array("NAME:Attributes", _
  "Name:" , "cap_outer_circle", _
  "Flags:" , "", _
  "Color:" , "(132 132 193)" , _
  "Transparency:" , 0, _
  "PartCoordinateSystem:" , "Global", _
  "MaterialName:" , "vacuum", _
  "SolveInside:" , true)
oEditor.Subtract
  Array("NAME:Selections",
    "Blank Parts:="", "cap_outer_circle", _
    "Tool Parts:="", "cap_inner_circle"), _
Array("NAME:SubtractParameters", _
  "KeepOriginals:="", false)

oEditor.Subtract
  Array("NAME:Selections",
    "Blank Parts:="", "pa1", _
    "Tool Parts:="", "cap_outer_circle"), _
Array("NAME:SubtractParameters", _
  "KeepOriginals:="", false)

' Make a wave port
'
Dim port_faceid

oEditor.CreateCircle
  Array("NAME:CircleParameters", _
    "IsCovered:="", true, _
    "XCenter:="", coax_x_pos, _
    "YCenter:="", coax_y_pos, _
    "ZCenter:="", -(coax_length + coax_gap), _
    "Radius:="", coax_rad, _
    "WhichAxis:="", "Z", _
    "NumSegments:="", "0"), _
Array("NAME:Attributes", _
  "Name:="", "p1", _
  "Flags:="", "", _
  "Color:="", ".(132 132 193)"", _
  "Transparency:="", 0, _
  "PartCoordinateSystem:="", "Global", _
  "MaterialName:="", "vacuum", _
  "SolveInside:="", true)

oBoundaryModule.AssignWavePort
  Array("NAME:p1", _
    "Objects:="", Array("p1"), _
    "NumModes:="", 1, _
    "RenormalizeAllTerminals:="", true, _
    "UseLineAlignment:="", false, _
    "DoDeembed:="", false, _
    Array("NAME:Modes", _
      Array("NAME:Mode1", _
        "ModeNum:="", 1, _
        "UseIntLine:="", false), _
      "ShowReporterFilter:="", false, _
      "ReporterFilter:="", Array(true), _
      "UseAnalyticAlignment:="", false)

' Get face id’s that will be used for the radiation boundary
'
faceid(0) = oEditor.GetFaceByPosition(Array("NAME:FaceParameters", _
  "BodyName:="", "rad_box", _
  "XPosition:="", rad_box_x_length / 2, _
  "YPosition:="", 0, _
  "ZPosition:="", rad_box_height / 2))

faceid(1) = oEditor.GetFaceByPosition(Array("NAME:FaceParameters", _
  "BodyName:="", "rad_box", _
  "XPosition:="", 0, _
  "YPosition:="", rad_box_y_length / 2, _
"ZPosition:=", rad_box_height / 2))

faceid(2) = oEditor.GetFaceByPosition(Array("NAME:FaceParameters", _
  "BodyName":", "rad_box", _
  "XPosition":", -rad_box_x_length / 2, _
  "YPosition":", 0, _
  "ZPosition":", rad_box_height / 2))

faceid(3) = oEditor.GetFaceByPosition(Array("NAME:FaceParameters", _
  "BodyName":", "rad_box", _
  "XPosition":", 0, _
  "YPosition":", -rad_box_y_length / 2, _
  "ZPosition":", rad_box_height / 2))

faceid(4) = oEditor.GetFaceByPosition(Array("NAME:FaceParameters", _
  "BodyName":", "rad_box", _
  "XPosition":", 0, _
  "YPosition":", 0, _
  "ZPosition":", rad_box_height))

  ' Assign radiation boundary to radiation box

  oBoundaryModule.AssignRadiation _
  Array("NAME:Rad1", _
    "Faces":", Array(faceid(0),faceid(1),faceid(2),faceid(3),faceid(4)))

  ' Insert a driven setup

  oAnalysisModule.InsertSetup "HfssDriven", _
  Array("NAME:Setup1", _
    "Frequency":", freqsol, _
    "PortsOnly":", false, _
    "MaxDeltaE":", 0.02, _
    "MaximumPasses":", 10, _
    "MinimumPasses":", 1, _
    "MinimumConvergedPasses":", 1, _
    "PercentRefinement":", 30, _
    "IsEnabled":", true, _
    "BasisOrder":", 1, _
    "DoIterativeSolver":", false, _
    "DoLambdaRefine":", true, _
    "DoMaterialLambda":", true, _
    "SetLambdaTarget":", false, _
    "Target":", 0.3333, _
    "UseMaxTetIncrease":", false, _
    "MaxTetIncrease":", 1000000, _
    "EnableSolverDomains":", false, _
    "ThermalFeedback":", false, _
    "UsingNumSolveSteps":", 0, _
    "ConstantDelta":", "0s", _
    "NumberOfSolveSteps":", 1)
"GenerateFieldsForAllFreqs": false, "ExtrapToDC": false

oAnalysisModule.InsertFrequencySweep "Setup1", AnArray("NAME:Sweep1", "IsEnabled": true, "SetupType": "LinearStep", "StartValue": fmin, "StopValue": fmax, "StepSize": step_size, "Type": "Discrete", "SaveFields": true, "ExtrapToDC": false)

Insert far field sphere

oRadFieldModule.InsertFarFieldSphereSetup AnArray("NAME:Infinite Sphere1", "UseCustomRadiationSurface": false, "ThetaStart": "-180deg", "ThetaStop": "180deg", "ThetaStep": "10deg", "PhiStart": "0deg", "PhiStop": "360deg", "PhiStep": "10deg", "UseLocalCS": false)

Create report of results

CreateReport "Smith Chart", "Terminal Solution Data", "Smith Chart", "Setup : Sweep1", AnArray(), AnArray("Freq": AnArray("All"), "Polar Component": AnArray("St(p1,p1)"), AnArray()

CreateReport "S11", "Terminal Solution Data", "Rectangular Plot", "Setup : Sweep1", AnArray("Domain": "Sweep"), AnArray("Freq": AnArray("All"), AnArray("X Component": "Freq", "Y Component": "dB(St(p1,p1))"), AnArray()

CreateReport "PeakGain", "Far Fields", "Rectangular Plot", "Setup : Sweep1", AnArray("Context": "Infinite Sphere1"), AnArray("Freq": AnArray("All"), "Phi": AnArray("0deg"), "Theta": AnArray("0deg"), AnArray("X Component": "Freq", "Y Component": "dB(PeakRealizedGain)"), AnArray()

Analyze the setup
'WScript.Sleep(5000)
'oDesign.Analyze "Setup1"

' Export S11 to file
'oReportModule.ExportImageToFile _
'   "Smith Chart", _
'   path_to_script & "smith_chart.jpg", 991, 531
'oReportModule.ExportImageToFile _
'   "S11", _
'   path_to_script & "S11.jpg", 991, 531
'oReportModule.ExportImageToFile _
'   "PeakGain", _
'   path_to_script & "peak_gain.jpg", 991, 531

'oReportModule.ExportToFile "S11", path_to_script & "s11.csv"
'oReportModule.ExportToFile "PeakGain", path_to_script & "peak_gain.csv"

'WScript.Sleep(5000)
'oProject.SaveAs path_to_script & "control_thin.hfss", true
'oProject.Close
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