MONOLITHIC INTEGRATION OF PHASE CHANGE MATERIALS AND ALUMINUM NITRIDE CONTOUR-MODE MEMS RESONATORS FOR HIGHLY RECONFIGURABLE RADIO FREQUENCY SYSTEMS

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To my family and those who have supported me during my research (NE)
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ABSTRACT

The problem today in the world of RF systems is the extremely crowded and rapidly changing modern military and commercial spectral environment. This increases the demand for highly reconfigurable, miniaturized, and low power RF system elements such as resonators and filters significantly [1]. As a solution to this issue, resonators and filters with a switching element, integrated on the same substrate, can be used to build dynamically reconfigurable filters that can operate around different center frequency bands, and then within each frequency band, the roll-off, bandwidth, and order of the filter response can be programmed. The integration of a capacitor, switch, and resonator into a single device will reduce the insertion loss and size requirement of the system by minimizing the number of physically separated RF components. This thesis presents a unique solution by monolithically integrating phase change material switches and aluminum nitride contour-mode resonators to produce reconfigurable resonators for the realization of intrinsically switchable and reconfigurable filter banks.
I. INTRODUCTION

A) Project Motivation

The demand for highly reconfigurable, miniaturized, and low-power radio frequency (RF) systems that can operate in the extremely crowded and rapidly changing modern commercial and military spectral environment has been growing steadily. In this context, the implementation of high performance microacoustic resonators with monolithically integrated switching and reconfiguration functionalities will dramatically reduce loss associated with the filtering element enabling new radio architectures with enhanced spectrum coverage and reduced component count and development cost compared to conventional multi-band radios.

B) Resonator Selection

MEMS resonator technologies based on both electrostatic [2]-[3] and piezoelectric [4]-[7] transduction have been investigated. Among these, the piezoelectric Aluminum Nitride (AlN) contour-mode resonator (CMR) technology [3], [8] has emerged as one of the most promising in enabling the fabrication of multiple frequency and high performance resonators on the same silicon chip. Nevertheless, no dynamically reconfigurable solutions based on AlN micro-acoustic resonant devices have been demonstrated to date due to the intrinsic static nature of such resonant structures: the operating frequency and electrical impedance of the device are set by material properties and geometrical dimensions that cannot be dynamically controlled to a large extent. Only very limited frequency tuning due to piezoelectric [9]-[11] and thermal effects has been demonstrated [12]-[14]. A broader coverage of the RF spectrum could potentially be achieved by developing a bank of multi-frequency AlN micro-acoustic resonators in an electrically
programmable matrix in which RF switches are used for frequency selection. The major limitation to the implementation of such reconfigurable architectures is the need of a dense integration of resonators and switches which necessarily increases size and complexity of the system and negatively affects its RF performance due to the resistive losses and capacitive loading effects introduced by the switches and the interconnections. In this perspective, the monolithic integration of RF switches and AlN MEMS resonators in a single technology platform is highly desirable since it would eliminate the loading effect introduced by the conventional hybrid integration with other RF CMOS-MEMS tunable components (i.e. switches and capacitors), and significantly reduce the area required, allowing the achievement of the highest level of reconfigurability with minimum possible effect on the resonator electromechanical performance.

C) Integrated Designs

Therefore, in recent years, a significant research effort has been devoted towards the development of technology platforms in which high performance AlN resonators and RF switches are monolithically integrated to minimize complexity and losses to enable new radio architectures with enhanced spectrum coverage [7], [15]-[17].

In particular, effective ON/OFF switching of the acoustic resonance, with minimal effect on the electromechanical performance of the device, has been recently demonstrated with the monolithic integration of chalcogenide phase change material (PCM) switches in the design of an AlN MEMS resonator [16]-[20]. Chalcogenide PCMs demonstrate a significant change in resistance (ON/OFF ratio \( \sim 10^6 \)) between the amorphous (OFF, high resistance) and crystalline (ON, low resistance) states upon specific heat treatment by means of electrical pulses (by Joule heating). Reversible switching behavior can be achieved by applying low voltage pulses of proper duration (direct heating) across the PCM [21]-[24]. Due to this property, PCMs have been investigated for use as RF switches [23], [25] and have been incorporated in the design of reconfigurable RF
components such as inductors [26] and circuits such as voltage controlled oscillators [27].

While the achievement of high reliability is recognized as the main challenge to mainstream use of these PCM switches, several groups have made significant progress, demonstrating ON resistance values of less than $1\ \Omega$ [28], the ability to cycle between ON and OFF states over 10,000 times [29], insertion loss values of less than 0.2 dB [30], and a figure of merit as high as 12.5 THz which is rapidly approaching the best reported (~40 THz) for RF MEMS switches [31].
II. CONTOUR-MODE RESONATORS

A conventional static contour-mode resonator consists of an AlN micro-plate sandwiched between a top interdigital (IDT) metal electrode and a bottom metal plate electrode (Figure 1-a,c). When an alternating current (ac) signal is applied across the thickness $T$ of the AlN film, a contour-extensional mode of vibration is excited through the equivalent $d_{31}$ piezoelectric coefficient of AlN.

![Figure 1: 3D schematic representation and top view of contour-mode resonator design with bottom electrode plate and top interdigital electrodes that connect to one or both terminals or ports.](image)

Given the equivalent mass density, $\rho_{eq}$, and Young’s modulus, $E_{eq}$, of the material stack that forms the resonator, the center frequency, $f_0$, of this laterally vibrating mechanical structure is set by period $W_0$ of the top IDT and can be approximately expressed as:

$$f_0 = \frac{1}{2W_0} \sqrt{\frac{E_{eq}}{\rho_{eq}}} \quad (1)$$

In order for a contour-mode of vibration to be excited in a piezoelectric AlN resonator, the electric field must be applied across the thickness of the piezoelectric material. This
electric field will be translated to a lateral, in-plane mechanical vibration at a resonant frequency set by the geometric dimensions of the resonant plate. The equivalent circuit for the contour-mode resonator is derived from Mason’s model (Figure 2) [32].

![Equivalent circuit diagram](image)

Figure 2: Conventional Mason lumped circuit model for a piezoelectric transducer [32].

In the Mason model, the physical parallel plate capacitor formed by the electrodes and the dielectric (which has piezoelectric functionality), is represented by an intrinsic capacitance, $C_0$. The transformer turn ratio, $\eta$, is a representation, at a specific point (typically the maximum displacement point), of the conversion between the electrical and mechanical variables of the resonator. The motional branch represents the mechanical variables of the resonator, with the motional capacitance ($C_m$) representing the reciprocal of the compliance ($1/k_{eq}$), the motional resistance ($R_m$) representing the damping ($c_{eq}$), the motional inductance ($L_m$) representing the mass ($m_{eq}$) and $\varepsilon_p$ representing the permittivity of the piezoelectric material.

<table>
<thead>
<tr>
<th>Mechanical Variable</th>
<th>Symbol</th>
<th>Electrical Representation</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>$F$</td>
<td>Voltage</td>
<td>$V$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$V$</td>
<td>Current</td>
<td>$I$</td>
</tr>
<tr>
<td>Compliance</td>
<td>$1/k_{eq}$</td>
<td>Capacitance</td>
<td>$C_m$</td>
</tr>
<tr>
<td>Damping</td>
<td>$c_{eq}$</td>
<td>Resistance</td>
<td>$R_m$</td>
</tr>
<tr>
<td>Mass</td>
<td>$m_{eq}$</td>
<td>Inductance</td>
<td>$L_m$</td>
</tr>
</tbody>
</table>

The following equations can be used to convert from the mechanical variables to the electrical representation [32].
\[ C_0 = \varepsilon_p \frac{\text{Electroded Area}}{\text{Thickness of Electroded Area}} \]  

(2)

\[ \eta = \frac{F}{V} = \frac{I}{v} \]  

(3)

\[ C_m = \frac{1}{k_{eq}} \]  

(4)

\[ R_m = c_{eq} \]  

(5)

\[ L_m = m_{eq} \]  

(6)

If the Mason model (Figure 2) is terminated in a short circuit, which represents a perfectly reflective boundary, such as air, in the acoustic domain, the equivalent circuit for the one-port piezoelectric resonator can be derived [32]. In this configuration (one-port design), the static capacitance, \( C_0 \), is in parallel to the resonant branch (\( R_m, L_m, \) and \( C_m \)). With this equivalent circuit, the Modified Butterworth Van Dyke model (Figure 3), the value of the device static capacitance depends on the electrode area, as long as fringing fields are neglected.

Figure 3: Modified Butterworth Van Dyke equivalent circuit for a one-port piezoelectric contour-mode resonator.

For a contour-mode resonator design, the patterning of the electrodes is very important,
as it determines not only the motional impedance for the resonator, but also selects the 
excitation mode of the resonator, as well as determining the electromechanical coupling 
coefficient ($k_t^2$) [32].

$$k_t^2 \propto \frac{W_{\text{res}}}{W_{\text{el}}} \left[ \sin \left( \frac{\pi}{2} \frac{W_{\text{el}}}{W_{\text{res}}} \right) \right]^2$$ (7)

Where $W_{\text{res}}$ is the width of the resonator pitch and $W_{\text{el}}$ is the width of the electrode.

Therefore, the design requires a trade-off between $k_t^2$, $R_m$, and spurious mode excitation 
(excitation of any frequency other than the desired value). For a one-port contour-mode 
resonator employing either Lateral Field or Thickness Field Excitation, the equivalent 
circuit (Figure 2) parameters can be derived using the following equations [32], [33]:

$$C_0 = n \cdot \varepsilon_p \frac{W_{\text{res}}L}{T}$$ (8)

$$\eta = 2d_{31}E_{\text{eq}}L$$ (9)

$$C_m = n \cdot \frac{2}{\pi^2} \frac{W_{\text{res}}}{LT} \frac{1}{E_{\text{eq}}} = \frac{8}{\pi^2} C_0 k_t^2$$ (10)

$$R_m = \frac{1}{n} \frac{\pi}{2} TL \sqrt{E_{\text{eq}} \rho_{\text{eq}}} \frac{1}{Q} = \frac{\pi^2}{8} \frac{1}{2\pi f_0 C_0} \frac{1}{k_t^2 Q}$$ (11)

$$L_m = \frac{1}{n} \frac{\rho_{\text{eq}}}{2} LW_{\text{res}}T = \frac{\pi^2}{8} \frac{1}{(2\pi f_0)^2} \frac{1}{C_0 k_t^2}$$ (12)

Table 2: Variables for equivalent circuit equations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Number of interdigital electrodes</td>
</tr>
<tr>
<td>$W_{\text{res}}$</td>
<td>Pitch of resonator</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of resonator</td>
</tr>
<tr>
<td>$T$</td>
<td>Thickness of piezoelectric layer</td>
</tr>
<tr>
<td>$E_{\text{eq}}$</td>
<td>Equivalent Young’s Modulus of material stack</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>Piezoelectric coefficient</td>
</tr>
<tr>
<td>$\rho_{\text{eq}}$</td>
<td>Equivalent density of material stack</td>
</tr>
<tr>
<td>$Q$</td>
<td>Quality factor</td>
</tr>
</tbody>
</table>
For the two-port resonator design, the equivalent circuit can be represented by two cascaded Mason models, or two resonators coupled at a location that has infinite stiffness. From this cascaded circuit, the equivalent circuit model for the two-port contour-mode resonator can be derived (Figure 3).

\[ C_0,\text{in} = n_{in} \varepsilon_{33} \varepsilon_0 \frac{W_{res} L}{T} \]

\[ C_0,\text{out} = n_{out} \varepsilon_{33} \varepsilon_0 \frac{W_{res} L}{T} \]

However, with set static capacitances, \( C_{0,\text{in}} \) and \( C_{0,\text{out}} \), and given quality factor, \( Q \), electromechanical coupling, \( k_t^2 \), and operating frequency, \( f_0 \), the impedance of the 2-Port device can be determined using the following equations [33]:

\[ Z = \frac{1}{j \omega C_0,\text{in}} + \frac{1}{j \omega C_0,\text{out}} + \frac{1}{j \omega L_m} + \frac{1}{R_m} \]

\[ \frac{1}{Q} = \frac{1}{j \omega C_{0,\text{in}}} + \frac{1}{j \omega C_{0,\text{out}}} + \frac{1}{\omega L_m} + \frac{1}{\omega R_m} \]

Figure 4: Equivalent circuit for a two-port piezoelectric contour-mode resonator.
\[ R_m = \frac{\pi T}{8 L} \frac{\rho_{eq}^{3/2}}{E_{eq}^{3/2} d_{31}^2} \frac{n_{in} + n_{out}}{n_{in}^2} = \frac{\pi^2}{8} \frac{1}{2\pi f_0 c_{0,in}} \frac{n_{in} + n_{out}}{n_{in}} \frac{1}{k_t^2 Q} \]  
(15)

\[ L_m = \frac{W_{res} T}{8 L} \frac{\rho_{eq}}{E_{eq}^{2} d_{31}^2} \frac{n_{in} + n_{out}}{n_{in}^2} = \frac{\pi^2}{8} \frac{1}{(2\pi f_0)^2 c_{0,in} k_t^2} \frac{n_{in} + n_{out}}{n_{in}} \]  
(16)

\[ C_m = \frac{8}{\pi^2} \frac{W_{res} L}{T} E_{eq} d_{31}^2 \frac{n_{in}^2}{n_{in} + n_{out}} = \frac{8}{\pi^2} C_{0,in} k_t^2 \frac{n_{in}}{n_{in} + n_{out}} \]  
(17)

Therefore, for given geometries of the AlN resonant micro-plate and electrodes (Figure 1), the equivalent electrical impedance of this laterally vibrating electromechanical structure is univocally set by the terminal connections of the top and bottom electrodes determining the distribution of the electric field across the piezoelectric material, hence the values of \( C_0 \) and \( k_t^2 \). For this design, the terminal connections of either the top or bottom electrodes can be adjusted to determine the device electrical impedance, ON/OFF state of the admittance or transmission, and/or the operating frequency.

Linearity in contour-mode resonators has been extensively characterized, especially in regard to their effect on the phase noise of oscillators [34]. It was determined that the close-to-carrier phase noise for the oscillator at lower power levels was primarily due to the \( 1/f \) or flicker noise of the resonator. The physical origin of this flicker noise is still under dispute by several research groups. Contour-mode resonators use only a piezoelectric transduction, which means that the only nonlinearity present is the mechanical linearity. The \( d_{31} \) piezoelectric coefficient of aluminum nitride remains linear under even large electric fields. Shift of center frequency and peak amplitude of the resonator response were examined under varying power levels in [34].
III. PHASE CHANGE MATERIALS

Chalcogenide phase change materials (PCMs), which are the type of PCMs relevant to radio frequency (RF) applications, are a special type of material that can be configured to present in two or more states or phases. The two main phases are the amorphous phase, which acts as a capacitor with the material measuring a high resistivity, and the crystalline phase, which acts as a resistance with the material measuring low resistivity. Some phase change materials, such as Germanium Antimony Telluride (GST) have an intermediate state that presents as a medium resistance and depends on the crystalline structure of the material [35]. In order to switch between the different states, the phase change material must be heated to a certain temperature. To transition between the amorphous and crystalline states, the PCM must be heated slowly to the crystallization temperature (varies slightly based on film composition and thickness, but is typically between 190 °C and 250 °C), and then slowly cooled to allow the atoms to coalesce into an organized crystalline structure. This organized structure reduces the resistivity of the film and provides the PCM with conductor-like properties with a typical resistance of ~0.1 – 100 Ω. Once transitioned to a crystalline state, no heat or power is required to keep the PCM in this state. The PCM will remain in a crystalline form until the melting point of the material is reached. If the material is quickly heated to the melting point of the material (~700 °C for bulk material) [36], and then immediately quenched, the material will be shocked out of the crystal structure, breaking up the atoms, and attaining a high resistivity amorphous state. In the amorphous state, the PCM demonstrates insulator-like properties, with a high resistance typically between $10^4$ and $10^7$ Ω (Figure 5).
PCMs have been investigated for many years, focusing on applications in the field of non-volatile memories [22]. The phases of the PCM, mainly GST for this application, are used to toggle and store data by switching between the different states. In addition to GST, other PCMs have been characterized to determine parameters such as ON/OFF resistance ratio, crystallization temperature, and crystalline resistance values [37]. More recently (the last two or three years), research has expanded to investigate the possible application of phase change materials in the world of RF systems.

PCMs are being investigated for RF switch applications for several reasons. Several PCM properties such as a low ON state resistance, high ON/OFF resistance ratio, and low OFF state capacitance lend themselves well to RF switch applications. A low ON state resistance will allow for a low insertion loss in systems that require switch components. The low OFF capacitance will provide excellent isolation for other components in the system, reducing the interference of the switches in the signal or response of other components. The high ON/OFF resistance ratio will reduce the leakage current through the switch, reducing the power consumed by the system in general. While the power used to heat the PCM switch designs is typically a bit higher than other types of RF switches currently being utilized, they do have unique advantage over the more frequently used
switches such as solid state or MEMS designs. One of the main advantages of PCM switches is that they do not require continuous power to maintain the ON or OFF state. Therefore, even if each switch cycle draws more power, that power draw only lasts for 10s or 100s of microseconds, rather than a very small power being drawn continuously. This significantly reduces any leakage current, like that limiting the performance of solid state designs that involve transistors and subthreshold current limits [38]. Such a unique property can be extremely beneficial for operations that are run using battery power or those that remain in a passive state where extremely small or no power consumption is desirable.

While GST is one of the best known PCMs, along with several metal oxides, the PCM that seems the most promising for RF switch applications is Ge$_{50}$Te$_{50}$ (GeTe), due to its low ON state resistance, high ON/OFF resistance ratio, and the fact that it has only two distinct states (Figure 6) [21].
The PCM switch design showcased in this thesis is based on the direct heating switching method [40]. This switch design utilized a fairly simple 6-step fabrication process, starting with a 1 µm aluminum nitride (AlN) deposition to form a passivation layer on the silicon substrate. This passivation layer was chosen due to the fact that AlN has high thermal conductivity. A heater layer of titanium nitride (TiN) is then deposited and patterned (thickness not specified). A 125 nm layer of GeTe is deposited using sputtering, patterned, and then annealed at 250 °C to obtain a crystalline film. The RF electrodes, 500 nm gold, sandwiched within thin layers of titanium that act as diffusion barriers, were then deposited to form a horizontal signal path through the GeTe. A second layer of 125 nm GeTe was deposited and then annealed at 250 °C to crystallize the PCM. The final step involved depositing and patterning a second TiN heater layer (thickness not specified) to form a vertical path for the current from the transition pulses [40]. The PCM gap switch in this case was patterned to be 0.6 µm x 12 µm.

After fabrication, the initial resistance measured (crystalline state) was 3.9 Ω. In this design, a voltage pulse (voltage difference applied to the top and bottom heater electrodes, causing current to flow directly through the PCM layers) of ~8.5 V amplitude and 2 µs duration (73 mW) was used to transition from the crystalline to the amorphous state, obtaining an OFF resistance of 8 kΩ - 100 kΩ, and therefore an ON/OFF resistance of > 0.2 x 10⁴. To transition from the amorphous state to the crystalline state, a voltage pulse of 9 V amplitude and 400 µs duration (9 mW) was used. This switch was reportedly cycled at least 200 times, as seen in Figure 7a-b.

For this design, the isolation was found to be > 18 dB from 0-20 GHz and the insertion loss was found to be < 0.5 dB from 0-20 GHz (Figure 7c-d). The FOM of this switch was found to be > 4 THz. This direct heating design demonstrates an acceptable figure of
merit, a fairly simple fabrication, a low insertion loss, reasonable isolation, and lower power consumption than the indirect heating design [40].

Figure 7: (a, b) Switching Cycles, (c) Isolation, and (d) Insertion Loss from [40].

Currently, PCM switches show great promise as a competitor in the world of RF switching technologies. They have several unique advantages and generally good performance. A table with comparisons of key performance parameters of PCM, MEMS, and solid-state switches can be found in Table I.

Table 3: Comparison of PCM, RF MEMS, and Solid-State Switch Technologies [41], [28]

<table>
<thead>
<tr>
<th>Key Performance Parameter</th>
<th>Monolithic PIN Diode</th>
<th>GaAs MMIC</th>
<th>CMOS SOI/SOS</th>
<th>RF MEMS</th>
<th>GaN MMIC</th>
<th>PCM RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Loss (dB)</td>
<td>0.3-1.5</td>
<td>0.3-2.5</td>
<td>0.3-2.5</td>
<td>0.1-5</td>
<td>0.1-1.5</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Isolation (dB)</td>
<td>&gt; 30</td>
<td>&gt; 25</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>&gt; 35</td>
</tr>
<tr>
<td>Power Consumption Level</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Switching Speed</td>
<td>ns - μs</td>
<td>ns - μs</td>
<td>μs</td>
<td>μs</td>
<td>ns</td>
<td>μs</td>
</tr>
<tr>
<td>FOM (THz)</td>
<td>1.59</td>
<td>0.71</td>
<td>0.64</td>
<td>0.36</td>
<td>40</td>
<td>12</td>
</tr>
</tbody>
</table>
Currently, the main barrier to making PCM switches, especially GeTe switches, viable for widespread use, is the lack of reliability or low number of switching cycles before failure or degradation. In order to improve the number of successful switching cycles, further investigation into the failure mechanisms and causes must be performed. Once the sources of failure in PCM RF switches are well characterized and documented, the design of PCM RF switches can be tailored to avoid these issues and maximum the efficiency of the switch design. Reduction of power consumption and switching time can also be beneficial to the progress of PCM RF switches. Nonlinearity has been analyzed for these switch designs [25].

Once these issues are addressed, if reliable, low power, fast switching speed PCM switches can be developed with a fairly simple fabrication process that allows for easy integration with RF components and systems, PCM RF switches present great potential for operation alongside or replacement of the current RF MEMS and solid state switch technologies.
IV. INTEGRATED DESIGN THEORY

This thesis explores the concept of monolithically integrating contour-mode resonators and phase change material switches into a single reconfigurable device that can obtain effective ON/OFF states, device impedance, and operating frequency. Three design iterations are covered in this thesis, the first design integrating the phase change material into the already-present aluminum nitride vias to change the connections between the bottom electrode and the terminals of the device. Changing these connections will enable the programming of the device impedance and ON/SHORT switching of the device admittance. Design two involves integrating the phase change switches to connect each individual interdigital electrode to a single terminal through a silicon dioxide layer, enabling effective ON/OFF switching of the admittance (for 1-Port devices) or transmission (for 2-Port devices), and programming of the device impedance. Finally, the third design demonstrates integration of phase change material switches between each individual interdigital electrode and both terminals, in order to change the terminal connections of each finger and therefore provide effective ON/OFF switching, programming of device impedance, and reconfiguration of operating frequency.

A) Integrated Design #1

This design is an innovative device concept in which 2 chalcogenide phase change material (Germanium Telluride, Ge\textsubscript{50}Te\textsubscript{50}) programmable vias are monolithically integrated with a piezoelectric MEMS resonator technology (Figure 9) and used to dynamically reconfigure the electrical connections of the device top and bottom electrodes, which directly affects the distribution of the electric field across the piezoelectric transducer and therefore determine the equivalent electrical impedance of the device. Such effective reconfiguration of the AlN MEMS resonator is achieved
without increasing the complexity of the device fabrication process (only 1 additional mask required) or requiring substantial modification of the device layout (only one probing pad per via is required for programming) compared to conventional static devices. This innovative approach demonstrates that the monolithic integration of PCM switches in the design of an AlN MEMS resonator can be exploited not only to achieve ON/OFF switching of the acoustic resonance but also effective reconfiguration of the device electrical impedance enabling the implementation of highly reconfigurable filter architectures, exclusively based on the same micro-acoustic resonator technology, in which order, bandwidth and roll-off can be dynamically adjusted to adapt to the needs of different wireless communication standards: filter order can be modified by reconfiguring into a short circuit of one or more resonators composing the filter, while the positions of the poles and zeroes that set the filter bandwidth and roll-off can be adjusted by reconfiguring the electromechanical coupling coefficient, $k_r^2$, and static capacitance, $C_0$, of the individual resonant elements.

Figure 9: Scanning Electron Microscope (SEM) picture of: (a) the entire device; (b) a closer view of the PCM via; (c) shows 3D schematic view of the device and cross-section of a PCM via.
By programming each of the two vias independently, the device can be reconfigured to operate in 4 different states: *Lateral Field Excitation Mode (LFEM)* where both vias are in the OFF state (bottom electrode is electrically floating, lateral field excitation (LFE) scheme [42] is implemented – relatively low value of device static capacitance $C_0$, therefore high impedance, Fig. 7-a); *Thickness Field Excitation Mode-High Impedance (TFEM-HI)* where only via 1 is in the ON state (thickness field excitation (TFE) scheme [42] is implemented by the bottom plate and the one top interdigital electrode connected to via 2 – higher value of $C_0$, Fig. 7-b); *Thickness Field Excitation Mode-Low Impedance (TFEM-LI)* where only via 2 is in the ON state (TFE scheme [42] is implemented by the bottom plate and the two top interdigital electrodes connected to via 1 – highest value of $C_0$, Fig. 7-c); and *SHORT* where both vias are in the ON state (bottom electrode electrically shorts the resonator terminals, Fig. 7-d).

Figure 10: Schematic representation of device terminal connections, equivalent circuits of the reconfigurable resonator, and FEM COMSOL simulation of electric field distribution of device in (a) LFEM, (b) TFEM-HI, (c) TFEM-LI and (d) SHORT states. $R_s$ is the resistance of the Pt plate (deposited film resistivity, ~5X bulk value). $C_{sw}/R_{sw}$ are the capacitance/resistance of the PCM via switch in the OFF/ON state. $R_s$ is the electrical resistance of the Al. $C_0/R_{0p}$ are static capacitance/resistance of the piezoelectric transducer. $R_m$, $C_m$, and $L_m$ represent the motional branch. For the FEM simulations, red indicates the presence of electric field and grey indicates the absence.
The programmable resonator presented in this work was fabricated using a simple 4-mask, post-CMOS compatible fabrication process shown in Figure 11. The fabrication process started with a high resistivity Silicon (Si) substrate (resistivity > 10,000 Ω·cm). A 5 nm/95 nm Titanium/Platinum (Ti/Pt) layer was deposited via RF/DC sputtering and patterned by lift-off to create the bottom electrode plate. Next, 420 nm of high quality c-axis oriented AlN was deposited on top of the patterned Ti/Pt layer. Inductively Coupled Plasma (ICP) etching, using Cl₂ based chemistry, was used to define the dimensions of the AlN micro-plate (200 µm × 60 µm) and open vias (10 µm × 10 µm) to the bottom Ti/Pt layer. DC pulse/DC sputtering and lift-off were then used to deposit and pattern 100 nm/10 nm of Ge₅₀Te₅₀/Ti in the AlN vias. For the top electrode and probing pad, 220 nm Aluminum (Al) was deposited and patterned using DC sputter and lift-off. Finally, the device was released from the substrate by isotropic etching of Si in Xenon Difluoride (XeF₂).

Figure 11: Fabrication process flow as described in Section II-B. (1) Sputter deposition and lift-off of bottom Platinum electrode; (2) Sputter deposition and ICP etch of Aluminum Nitride; (3) DC sputter deposition and lift-off of Ge₅₀Te₅₀; (4) Sputter deposition and lift-off of top Aluminum electrode; (5) Isotropic etching of Si and release of resonator structure using XeF₂.
B) Integrated Design #2

This design implements the phase change material switches to connect each individual interdigital electrode to one terminal or port. Therefore, electrodes one and three connect to terminal or port 1 (input) and electrode 2 connects to terminal or port 2 (output). Individual operation of these switches allows for effective ON/OFF switching of the device admittance or transmission and programming of the device impedance. This fabrication only requires two steps more than the static contour-mode resonator design.

Figure 12: (a) 3D schematic of Integrated Design #2 and (b) fabrication process for Integrated Design #2. 6-mask fabrication process: (1) High resistivity Si wafer; (2) Sputter deposition and lift-off of 100 nm Pt as bottom electrode; (3) Sputter deposition of 500 nm AlN and dry etch to form vias and resonator body; (4) Sputter deposition and lift-off of 100 nm Al to form interdigital electrode bottom electrode of PCM switches; (5) PECVD deposition and ICP etching of SiO₂ to form insulation for PCM switches; (6) DC pulse sputtering and lift-off of 100 nm PCM; (7) Sputter deposition and lift-off of 100 nm Cu as top electrode; (8) Release in XeF₂.

a. Integrated Design #2 – 1-port Design

The RF MEMS resonator utilized in this design is a contour-mode resonator consisting of an AlN thin-film (500 nm) sandwiched between a top Aluminum (Al) interdigital electrode (IDT) (with three fingers) and a bottom Platinum (Pt) plate electrode. Three 2 µm × 2 µm programmable PCM vias are employed to connect each of the metal fingers composing the top aluminum IDT to the corresponding device terminal through a 300 nm
SiO$_2$ layer: the two outer fingers are connected to Terminal 1 through PCM vias 1 and 3 and the center finger is connected to Terminal 2 through PCM via 2 (Fig. 9-a, 10). Each programmable PCM via is composed of a 100 nm thick Ge$_{50}$Te$_{50}$ film deposited in a 2 $\mu$m $\times$ 2 $\mu$m via (etched in a 300 nm SiO$_2$ isolation layer) and sandwiched between a bottom Al electrode and a top Copper (Cu) electrode.

Ge$_{50}$Te$_{50}$ was chosen as the PCM for the programmable vias due to its high ON/OFF ratio ($\sim 10^6$) and low loss at radio frequencies [23], [21]. When all the vias are OFF (OFF State), the terminals of the device are ideally completely isolated. Therefore, a high impedance path (ideally approaching an open circuit) is formed between the device terminals (determined by the combination of the capacitances of the PCM vias in the OFF state and parasitics) and no resonance is excited. When via 1 is in the ON state (State 1), the corresponding metal finger is connected to Terminal 1, introducing an additional capacitive contribution to the high impedance path formed between the device terminals. When vias 1 and 2 are in the ON state (State 2), the corresponding two metal fingers are connected to Terminal 1 and Terminal 2 respectively, effectively inducing an electric field across the AlN plate that mainly couples to the 3$^{rd}$ order contour-extensional mode.

Figure 13: Scanning Electron Microscope (SEM) picture of: (a) the entire device; (b) a closer view the programmable electrode fingers; and (c) a closer view of the PCM via.
of vibration of the AlN plate (a weak coupling to the 1st, 2nd, 4th, and 5th order modes is also induced). For State 3, where all three vias are in the ON state, the polarity of the interdigital electrode best matches the strain field of the 3rd order contour-extensional mode of vibration (very weak coupling to the 1st and 5th order modes is also induced).

b. Integrated Design #2 – 2-port Design

Differently from previous demonstrations, a 2-port configuration is chosen since it enables the synthesis of reconfigurable narrow-band filters by simply electrically cascading multiple switchable resonator stages. The lateral-extensional mode resonator is composed of an AlN thin-film (500 nm) sandwiched between a bottom (Pt) plate electrode connected to electrical ground and top interdigital electrode (Al) patterned in 3 parallel fingers: 2 of which are connected to form the input port and 1 is connected to form the output port. 3 programmable PCM vias are employed to connect each of the metal fingers to the corresponding device terminal through a 250 nm SiO2 layer (Figure 14).

Figure 14: Scanning Electron Microscope (SEM) image of (a) reconfigurable 2-port resonator, (b) switchable electrodes, (c) PCM via, and (d) 3D schematic of resonator design.
Fabrication of this switchable 2-port piezoelectric MEMS resonator was completed with a post-CMOS, 6-mask fabrication process (Figure 12-b). Starting with a high resistivity silicon wafer ($\rho > 20,000 \, \Omega$), 100 nm of platinum (Pt) was deposited and patterned to form the bottom electrode. 500 nm aluminum nitride (AlN) was deposited and etched to form the vias to the Pt and the dimensions of the resonant micro-plate. The interdigital electrodes (100 nm aluminum (Al)) were deposited and patterned. An electrical insulator layer of 250 nm silicon dioxide (SiO2) was PECVD deposited and etched, followed by the deposition of the PCM layer ($Ge_{50}Te_{50}$) to form the via switches. The top electrode of the switches and the probing pads (100 nm copper (Cu)) was deposited and patterned, and finally the silicon was isotropically etched in XeF$_2$ to release the device.

This simple and CMOS-compatible fabrication process lends itself very well to the monolithic integration required to design highly reconfigurable resonator structures.

C) Integrated Design #3

![Image](image.png)

Figure 15: Scanning Electron Microscope (SEM) image of (a) the reconfigurable resonator with probing pads for 12 PCM switches; (b) close-up of single PCM via.

A conventional static contour-mode resonator consists of an aluminum nitride (AlN)
micro-plate sandwiched between two metal electrodes: a top interdigital (IDT) electrode and a bottom plate electrode that is electrically floating (Figure 1,5a). A contour-extensional mode of vibration is excited through the d$_{31}$ piezoelectric coefficient of the AlN when an alternating current signal is applied across the thickness of the piezoelectric material (AlN). For the contour-extensional mode, the center operating frequency, $f_0$, of the laterally vibrating mechanical structure is determined by the equivalent mass density, $\rho_{eq}$, and Young’s modulus, $E_{eq}$, of the material stack forming the resonator, as well as the period $W$ of the top IDT as expressed in Equation (1).

Therefore, for given geometries of the AlN resonant micro-plate and electrodes, the operating frequency and the equivalent electrical impedance of this laterally vibrating electromechanical structure is univocally set by the terminal connections of the top IDT. For this reconfigurable design, the top aluminum interdigital electrode is composed of $n=6$ metal fingers. The IDT fingers completely cover the resonant body of the device, extending up to the anchoring regions, where they are overlapped by the electrical terminal of the resonator, separated by a SiO$_2$ insulating layer. 12 $2 \mu m \times 2 \mu m$ Ge$_{50}$Te$_{50}$ PCM vias are used to connect the six metal fingers of the interdigital electrode to the device terminals (through the SiO$_2$ insulation layer), as shown in Figure 15. Therefore, reconfiguration of the device operating frequency and equivalent electrical impedance can be achieved by independently programming each of the 12 PCM vias to reconfigure the terminal connections of the IDT (9 possible electrode configurations are shown in Figure 16).
Figure 16: Electrode configurations for nine different experimentally obtained states.

Figure 17: Fabrication process flow: (1) Si wafer; (2) Sputter and lift-off of 100 nm Pt; (3) Sputter of 500 nm AlN and dry etch; (4) Sputter and lift-off of 100 nm Al; (5) PECVD deposition and ICP etching of SiO₂; (6) DC pulse sputter and lift-off of 100 nm PCM; (7) Sputter and lift-off of 100 nm Cu; (8) Release in XeF₂.

The device was fabricated using a simple 6-mask process (Figure 17). The fabrication process started with a high resistivity Silicon (Si) substrate (resistivity > 10,000 Ω·cm). A 5 nm/95 nm Titanium/Platinum (Ti/Pt) layer was deposited via RF/DC sputtering and patterned by lift-off to create the bottom electrode plate. Next, 500 nm of high quality c-axis oriented AlN was deposited on top of the patterned Ti/Pt layer. Inductively Coupled Plasma (ICP) etching, using Cl₂ based chemistry, was used to define the dimensions of the AlN micro-plate (200 μm × 60 μm) and open vias (10 μm × 10 μm) to the bottom Ti/Pt layer. For the top interdigital electrode, 100 nm Aluminum (Al) was deposited and patterned using DC sputter and lift-off. PECVD was used to deposit 300 nm of Silicon Dioxide (SiO₂), which was then etched using CHF₃ based chemistry to form the vias for the switches. DC pulse/DC sputtering and lift-off were then used to deposit and pattern
100 nm/10 nm of Ge₅₀Te₅₀/Ti in the vias. For the top electrode and probing pad, 10/100 nm Chrome/Copper (Cr/Cu) was deposited and patterned using DC sputter and lift-off. Finally, the device was released from the substrate by isotropic etching of Si in Xenon Difluoride (XeF₂).
V. EXPERIMENTAL RESULTS AND ANALYSIS

This section discusses the results obtained from fabrication and testing of the three integrated designs discussed in Section IV.

A) Integrated Design #1

The electrical response of the programmable AlN MEMS resonator was measured using an Agilent E5071C network analyzer after performing an open-short-load calibration on a reference substrate. The transition temperature needed for the ON/OFF switching of the PCM vias (reversible switching between amorphous and crystalline states) was achieved by direct heating (using DC probes to pass current directly through the PCM, joule heating).

![Image](image_url)

Figure 18: Measurement setup and heating pulse waveforms for switching of PCM vias. (a) For the pulse application, DC probes were used to apply a voltage pulse between the top and bottom electrodes of the via switch through probing pads. Pulses were generated using an Agilent Frequency Generator. (b) Heating pulse waveforms applied for crystallization and amorphization of vias. (c) Schematic representation of DC pulse application and joule heating of PCM.

A relatively long and low voltage pulse (~4 V or 5 V for a duration of 500 µs with a
rise/fall time of 100 ns) was used to slowly heat the PCM in the 10 µm × 10 µm via up to the crystallization temperature (measured to be ~230 °C) and then slowly cool it down to form an organized crystal structure. When a voltage of at least 2 V (threshold voltage) was applied, the resistance of the switches dropped to ~450 Ω, however, maximum crystallization was not achieved until a 4 V pulse was applied to via 1 and a 5 V pulse to via 2, for which the minimum DC resistance values were measured. The difference in voltage levels required to achieve maximum crystallization of the two PCM vias can be attributed to the different lengths of the Pt routing lines connecting the bottom electrode of each via to the corresponding probing pad. Considering this resistance drop at threshold voltage and the final voltage applied to achieve the maximum possible crystallization, the power used to turn this via ON is ~55 mW, and this power is applied for ~500 µs to achieve a transition to the crystalline state.

A relatively short and high voltage pulse (~5.8 V pulse with a duration of 6 µs and a rise/fall time of 5 ns) was required to heat the PCM up to its melting point [36] and quench it rapidly, disrupting the crystalline structure and returning the material to the amorphous state. A higher power consumption of ~550 mW was required to quickly (~6 µs) heat the PCM to the melting point of the material.

For the 4 states, the measured electrical responses were fitted (Fig. 16-a,b, Table 4) using the equivalent circuits shown in Fig. 2. The measured data in Fig. 5 clearly demonstrates the effectiveness of the proposed design in reconfiguring the resonator static capacitance, $C_0$, (from ~484 fF in the LFEM state to ~1459 fF in the TFEM-LI state) and electromechanical coupling coefficient, $k_t^2$, (from ~0.85 % in the TFEM-HI state to ~2.02 % in the LFEM state) as well as the capability of readily reconfiguring the device into a short circuit (SHORT state). Such experimental verification can be considered a stepping stone towards the demonstration of dynamically reconfigurable filter architectures whose order, bandwidth, and roll-off can be dynamically adjusted.
Figure 19: (a, b) Measured admittance and phase response for all 4 states, as well as a shorted device with no PCM in the vias (which has a slightly different center frequency due to the fact that it was fabricated on a separate wafer) and fitting based on equivalent circuits in Figure 10. (c, d) Comparison between Finite Element Method (FEM) simulated (COMSOL) and experimentally extracted values of $C_0$ and normalized $k_t^2$ for the 3 device ON states (relative change from LFEM-both switches OFF). This first device prototype could only be reconfigured 7 times due to failure of the PCM vias (attributed to diffusion and melting of Al electrodes along with the large size of the via). Future work will be focused on addressing this important reliability issue through investigation of optimal electrode materials and barrier layers as well as optimization of the via size.

Table 4: Fitted Values of Obtained States Based on Equivalent Circuits

<table>
<thead>
<tr>
<th>State</th>
<th>$R_m$</th>
<th>$L_m$</th>
<th>$C_m$</th>
<th>$R_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFEM</td>
<td>320 Ω</td>
<td>82 μH</td>
<td>7.9 fF</td>
<td>20 Ω</td>
</tr>
<tr>
<td>TFEM-HI</td>
<td>470 Ω</td>
<td>166 μH</td>
<td>3.9 fF</td>
<td>50 Ω</td>
</tr>
<tr>
<td>TFEM-LI</td>
<td>155 Ω</td>
<td>41 μH</td>
<td>16 fF</td>
<td>50 Ω</td>
</tr>
<tr>
<td>SHORT</td>
<td>390 Ω</td>
<td>82 μH</td>
<td>7.9 fF</td>
<td>20 Ω</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>$C_0$</th>
<th>$R_{0p}$</th>
<th>$Q_m$</th>
<th>$k_t^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFEM</td>
<td>483.6 fF</td>
<td>23 Ω</td>
<td>299</td>
<td>2.02 %</td>
</tr>
<tr>
<td>TFEM-HI</td>
<td>563.6 fF</td>
<td>720 Ω</td>
<td>439</td>
<td>0.85 %</td>
</tr>
<tr>
<td>TFEM-LI</td>
<td>1459 fF</td>
<td>250 Ω</td>
<td>328</td>
<td>1.34 %</td>
</tr>
<tr>
<td>SHORT</td>
<td>483.6 fF</td>
<td>23 Ω</td>
<td>--</td>
<td>--</td>
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<tr>
<td>Switch values</td>
<td>$C_{\text{OFF, via 1}}$</td>
<td>$C_{\text{OFF, via 2}}$</td>
<td>$R_{\text{ON, via 1}}$</td>
<td>$R_{\text{ON, via 2}}$</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td></td>
<td>1260 fF</td>
<td>1500 fF</td>
<td>15 $\Omega$</td>
<td>15 $\Omega$</td>
</tr>
</tbody>
</table>

The relatively low extracted Q values can be attributed to a non-optimized resonator design, and they are not associated to the introduction of the PCM vias in the resonator design. Indeed, static devices fabricated on the same chip (without PCM vias) showed similar Q values.

The resistance values of the PCM vias in the ON state were extracted by measuring the electrical admittance of the device in the SHORT state and comparing it to a reference device based on the same design but without PCM in the two vias (shorted vias). The measured admittances were fitted using the equivalent circuit in Figure 10-d (Figure 19), with the SHORT state of the PCM device showing a ~30 $\Omega$ higher value for the resistance connecting the device terminals. Therefore, the ON resistance of each 10 $\mu$m $\times$ 10 $\mu$m PCM via switch was readily extracted to be $R_{\text{PCM}} = \sim 15 \, \Omega$.

Such relatively large value of the switch ON resistance is attributed to non-uniform crystallization of the PCM due to the relatively large via size. While the relatively large values of the extracted switch OFF capacitances, $C_{\text{sw 1}} \sim 1260 \, \text{fF}$ and $C_{\text{sw 2}} \sim 1500 \, \text{fF}$, are due to an extended overlap between the top and bottom metal electrodes across the AlN (Figure 20). The total capacitance associated with this overlap area results from the parallel combination of three parallel plate capacitors (Figure 20): $C_{\text{AlN}}$, due to electrode overlap across the AlN dielectric; $C_{\text{AlN/PCM}}$, due to the electrode overlap across the AlN/PCM dielectric stack; and $C_{\text{PCM}}$, due to the electrode overlap across the PCM (the actual OFF capacitance of the PCM switch).

According to this simple model, the contribution of the actual PCM-filled via to $C_{\text{sw}}$ was estimated to be $\sim 190 \, \text{fF}$ considering dielectric constant values of $\sim 21.3$ for the Ge$_{50}$Te$_{50}$ [23] and $\sim 8.5$ for the AlN [43]).
Figure 20: (a) SEM image of resonator and PCM vias, illustrating overlap that results in higher $C_{\text{OFF}}$ for both vias in the equivalent circuit fittings. (b) Via 1, on the left of the top image, has a total area of $86 \, \mu\text{m} \times 65 \, \mu\text{m}$ (marked in blue). From calculations using ideal dielectric constants of 8.5 for AlN and 21.3 for PCM, the calculated value of $C_{\text{sw1}} \sim 1150 \, \text{fF}$ ($C_{\text{AlN}} \sim 750 \, \text{fF}$, $C_{\text{AlN/PCM}} \sim 213 \, \text{fF}$, and $C_{\text{PCM}} \sim 190 \, \text{fF}$). The AlN/PCM overlap capacitance area is $40 \, \mu\text{m} \times 35 \, \mu\text{m}$ for both vias (marked in purple), and the PCM switch area is $10 \, \mu\text{m} \times 10 \, \mu\text{m}$ for both switches (marked in red). (c) Via 2, on the right of the top image, has a total area of $100 \, \mu\text{m} \times 69 \, \mu\text{m}$ (marked in blue). The calculated value of $C_{\text{sw2}} \sim 1390 \, \text{fF}$ ($C_{\text{AlN}} \sim 985 \, \text{fF}$, $C_{\text{AlN/PCM}} \sim 213 \, \text{fF}$, and $C_{\text{PCM}} \sim 190 \, \text{fF}$). The ideal calculated values only vary from measurement by 8.6 % for via 1 and 7.6 % for via 2, which is well within an acceptable margin of error.

2D finite element method (FEM) simulations were performed in COMSOL to verify the correlation between the measured electrical impedances of the resonator in each state and the corresponding programmed electrode terminal connections (Figure 19-c,d). Despite the fact that ideal open and short circuits were employed to build the 2D FEM models of the device in the different states, the measured electromechanical coupling coefficient and impedance variations along the different states closely follow the ones predicted by FEM simulations, confirming the proper functionality of the reconfigurable resonator according to the proposed design. In the SHORT state, a low-impedance path, instead of an ideal short-circuit, is formed between the resonator terminals (in parallel with the
static and motional branches of the resonator) due to the limited ON resistance values of the PCM switches and the relatively large resistance associated to the bottom Pt electrode (deposited film resistivity, ~5X bulk value). Therefore, although the response of the device is dominated by the low-impedance path through the bottom electrode, a resonant mode is still excited in the resonator.

The effect of self-switching (OFF-to-ON) of the PCM vias due to Joule heating on the device linearity was also experimentally analyzed. Due to the non-zero OFF capacitance, $C_{sw}$, of the PCM vias in the OFF state (present in the LFEM, TFEM-HI, TFEM-LI states), part of the delivered RF power is dissipated in the vias as Joule heat. The portion of the delivered RF power dissipated in the vias is inversely proportional to the ratio of the static capacitance, $C_0$, and the capacitance associated with the combination of all PCM vias in the OFF state, $C_S$, (except at the resonance frequency for which the great majority of the RF power is dissipated in the low impedance motional branch of the resonator).

Table 5: Capacitance Values and Ratios for Non-SHORT States

<table>
<thead>
<tr>
<th>State</th>
<th>$C_0$</th>
<th>$C_S$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFEM</td>
<td>483.6 fF</td>
<td>685 fF</td>
<td>0.706</td>
</tr>
<tr>
<td>TFEM-HI</td>
<td>563.6 fF</td>
<td>1500 fF</td>
<td>0.376</td>
</tr>
<tr>
<td>TFEM-LI</td>
<td>1459 fF</td>
<td>1260 fF</td>
<td>1.158</td>
</tr>
</tbody>
</table>

When the level of RF power dissipated in a programmable via in the OFF state is such to heat the PCM up to the crystallization temperature, an OFF-to-ON transition is triggered, causing a self-reconfiguration of the device. In order to characterize the linearity of the fabricated AlN/PCM reconfigurable resonator prototype, the device was configured in TFEM-HI state (most critical case due to the lowest $C_0/C_S$ ratio (Table 5), hence largest portion of delivered power dissipated in the OFF PCM via) and its electrical response was measured for different values of the input available power (from -20 dBm to 10 dBm).
The measurement results in Figure 21 demonstrate that no self-reconfiguration of the device took place for input power levels as high as 10 dBm (i.e. the device is not reconfigured into a SHORT state due to an OFF-to-ON self-switching of via 2). DC resistance measurements of the vias performed after the high driving power test further confirmed that the PCM remained in the amorphous state (~500 kΩ). Once these measurements were completed, via 2 was successfully switched to the ON state (RPCM ~15 Ω), confirming that the operation of the PCM was not permanently affected by the application of the higher input RF power.

This result demonstrates that, despite the relatively large OFF capacitance of the switch (due to a non-optimum design of this first prototype), the linearity of the device is maintained for available input power levels up to 10 dBm. Lower values of OFF capacitance for the AlN PCM vias are expected to be achieved by optimization of via size and reduction of overlap area and capacitance, guaranteeing unchanged electromechanical performance and linearity of the reconfigurable AlN/PCM resonator compared to the static case.
**B) Integrated Design #2 – 1-port Design**

The device was fabricated using the process shown in Figure 10-b and tested in a RF probe station. Its electrical impedance was measured using a network analyzer. Voltage pulses of 1 V, 200 µs duration and 100 ns rise/fall time were used to turn the PCM switches ON (~5 Ω) and pulses with 2.5 V amplitude, 4 µs duration, and 5 ns rise/fall time were used to turn the PCM switches OFF (~40 MΩ, ~10 fF calculated capacitance).

![Equivalent circuit model of the device in the (a) OFF state and State 1, and (b) State 2 and State 3.](image)

*Figure 22: Equivalent circuit model of the device in the (a) OFF state and State 1, and (b) State 2 and State 3. Cp, Rp (~28 Ω), and Rpp represent the high impedance path between the resonator terminals created by the total capacitance associated with the combination of PCM via switches in the OFF state and other parasitics. Rs (~5 Ω in ON states) is the loss introduced by the combination of PCM vias in the ON state – note that Rs has minimal effect on resonator performance. C0 and R0p are static capacitance/resistance of the piezoelectric transducer. Rm, Cm, and Lm represent the motional branch of the resonator.*

Four states were achieved by programming each via independently: *OFF State* (device capacitance, $C \sim 48 \text{ fF}$, electromechanical coupling, $k_t^2 \sim 0\%$), *State 1* ($C \sim 87 \text{ fF}$, $k_t^2 \sim 0\%$), *State 2* ($C \sim 327 \text{ fF}$, $k_t^2 \sim 1.08\%$), and *State 3* ($C \sim 439 \text{ fF}$, $k_t^2 \sim 1.45\%$). The electrical response of the device was measured for each state (Figure 23-a) and fitted to the equivalent circuit models shown in Figure 22 (Figure 24).
Figure 23: (a) Measured Response for all three states with modes of vibration labelled. (b) Simulation results for State 2 and State 3 with modes of vibration labelled.

The measured data was compared with the 2D finite element method (FEM) simulation results. Despite the fact that ideal open and short circuits were employed to build the 2D FEM models of the device in the different states, the measured electromechanical coupling coefficient and impedance variations among the different states closely follow the ones predicted by FEM simulations, confirming the proper functionality of the reconfigurable resonator according to the proposed design (Figure 23-b, Figure 25).
Figure 24: Equivalent circuit fitting for (a) OFF State, (b) State 1, (c) State 2, and (d) State 3 using equivalents circuits from Figure 22.

<table>
<thead>
<tr>
<th>State</th>
<th>Comparisons with FEM Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured Values</td>
</tr>
<tr>
<td></td>
<td>$C_0$ (pF)</td>
</tr>
<tr>
<td>State 2</td>
<td>278</td>
</tr>
<tr>
<td>State 3</td>
<td>391</td>
</tr>
</tbody>
</table>

Figure 25: Comparison of $C_0$ and $k_x^2$ from Experimental results and 2D FEM COMSOL simulations. Even though the absolute values differ due to imperfections in the model and material coefficients used in the simulation, the experimental results follow the proper trend, verifying the operation of the switchable resonator.
C) Integrated Design #2 – 2-port Design

The transition temperature needed for the switching of the PCM vias was achieved by passing current directly through the PCM (direct heating [20]). Voltage pulses of 1.5 \( V \) amplitude and 200 \( \mu s \) duration were used to turn the PCM switches ON while pulses of 4.7 \( V \) amplitude and 2 \( \mu s \) duration were used to trigger the ON-to-OFF transition.

Effective ON/OFF switching of the device transmission (\(~42dB\) variation for fixed 50 \( \Omega \) termination) was demonstrated (Figure 6), due to the monolithic integration of 3 ultra-miniaturized (2 \( \mu m \times 2 \mu m \)) PCM switches with radio frequency (RF) performance superior to the one of more conventional RF switch technologies: an ON-state resistance of 2 \( \Omega \) (a low \( R_{\text{ON}} \) minimizes the insertion loss of the resonator design) with an OFF-state capacitance and resistance of 22 \( fF \) and \(~20 M\Omega\), respectively, were measured for the PCM switches of this work resulting in an RF switch cutoff frequency of 3.6 \( THz \) and an improved figure of merit (\( FOM = R_{\text{ON}}C_{\text{OFF}} \sim 44 \text{ fs} \)) compared to the \(~100s \text{ fs} \) of typical solid-state RF switches [28]. An equivalent circuit was developed for the two-port design based off of the typical two-port equivalent circuit [33].

![Figure 26: Equivalent circuit for transmission response in all four states. \( C_f \) represents the feedthrough capacitance from the input to output port. \( C_{\text{0,in}} \) and \( C_{\text{0,out}} \) represent the static capacitance at the input and output port respectively. \( R_m \), \( L_m \), and \( C_m \) represent the motional branch of the resonator. \( C_{\text{p1}} \) represents the combination of all switches in the OFF state connected to the input port as well as any parasitics. \( C_{\text{p2}} \) represents the combination of all switches in the OFF state connected to the output port as well as any parasitics.](image-url)
represents the combination of all switches in the OFF state connected to the output port as well as any parasitics.

Figure 27: (a) Transmission for all states and equivalent circuit fittings (Figure 26). The quality factor is comparable to other devices on the same wafer, which indicates that the Q is not negatively impacted by the integration of the PCM. (b) Input port admittance and equivalent circuit fitting using the MBVD equivalent circuit for all states. The capacitance ratio between OFF State and State 3 is over 21X.

When all three PCM switches are turned OFF, this device demonstrates > 50 dB rejection at the resonance peak for the OFF state. Insertion loss for the ON state (when all three PCM switches are turned ON), was ~10 dB for a fixed 50 Ω termination which corresponds to only ~2.5 dB for a matched termination of 571 Ω (this could be decreased with optimization of the resonator design, as this resonator only demonstrated a Q of 420). For the admittance of the input port, a capacitance ratio (C\text{ON}/C\text{OFF}) of ~21X was calculated from the difference in total capacitance for each state (C\text{ON}=1444 fF, C\text{OFF}=70 fF) (Figure 27-b). Such a low capacitance in the OFF state reduces the leakage current through the resonator when all the switches are in the OFF state. The high capacitance ratio will enable filter designs created solely from monolithically integrated AlN/PCM resonators with reconfigurable bandwidth, roll-off, and order.

D) Integrated Design #3

For this design, with 12 integrated PCM switches, the transition temperature for ON/OFF
switching of each PCM via (reversible switching between amorphous and crystalline states) was achieved by direct heating of the PCM: a voltage pulse was applied across the via to pass current directly through the PCM and change its temperature by joule heating. To transition from the amorphous (OFF) state to the crystalline (ON) state, a pulse of 0.5 V amplitude, 2 $\mu$s duration, and 5 ns rise/fall was used to achieve an ON resistance of $\sim$2 $\Omega$ for an individual 2 $\mu$m×2 $\mu$m PCM via switch. To switch from the ON state to the OFF state (with an extracted $C_{OFF}$=22 fF from a single switch of the same size and structure), a pulse of 1 V amplitude, 2 $\mu$s duration, and 5 ns rise/fall was used. The reconfigurable resonator was programmed to operate in nine states (Figure 16, Figure 28): State 1 (6 vias ON, 6$^{th}$ order contour-extensional mode of vibration, $f_1$=181.3 MHz, $C$$\sim$1,135 fF, $k_t^2$$\sim$1.24 %), State 2 (6 vias ON, 3$^{rd}$ order contour-extensional mode of vibration, $f_2$=385.4 MHz, $C$$\sim$715 fF, $k_t^2$$\sim$1.32 %), States 3-7 (1-5 vias ON, 125 fF<$C<$635 fF), and OFF (all vias OFF).

Figure 28: Admittance response for nine states achieved.

The electrical response of the device in each state was measured using an Agilent E5071C network analyzer after performing an open-short-load calibration on a reference substrate, and then fitted to the equivalent circuit models shown in Figure 29. The equivalent circuit in Figure 8b was used to fit the OFF State and State 7, while the circuit
in Figure 8c (a modified Butterworth Van Dyke model) was used to fit States 1-6. The values of the resonator static capacitance, \( C_0 \), were estimated by 2D Finite Element Method (FEM) simulations using COMSOL while the values of the other circuit components were extracted from the measured data. The measured frequencies and the extracted values of the equivalent circuit components and electromechanical performance in each state are shown in Table 6.

![Figure 29: (a) 3D schematic image of reconfigurable resonator and (b,c) equivalent circuit models of the device. \( C_p, R_m, \) and \( R_{pp} \) represent the high impedance path between resonator terminals created by the total capacitance associated with the combination of PCM via switches in the OFF state and other parasitics. \( R_S \) (~2 Ω) is the loss introduced by the combination of PCM vias in the ON state – note that \( R_S \) has minimal effect on resonator performance. \( C_0/R_{op} \) are static capacitance/resistance of the piezoelectric transducer. \( R_m, C_m, \) and \( L_m \) represent the motional branch of the resonator.]

<table>
<thead>
<tr>
<th>State</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_5 ) (MHz)</td>
<td>181</td>
<td>385</td>
<td>385</td>
<td>386</td>
<td>386</td>
<td>386</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( R_m ) (Ω)</td>
<td>250</td>
<td>600</td>
<td>800</td>
<td>1800</td>
<td>3000</td>
<td>3200</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( L_m ) (µH)</td>
<td>155</td>
<td>39.9</td>
<td>53.6</td>
<td>115</td>
<td>188</td>
<td>226</td>
<td>--</td>
<td>--</td>
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<tr>
<td>( C_m ) (fF)</td>
<td>4.97</td>
<td>4.27</td>
<td>3.17</td>
<td>1.47</td>
<td>0.90</td>
<td>0.75</td>
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<tr>
<td>( C_0 ) (fF)</td>
<td>496</td>
<td>410</td>
<td>366</td>
<td>229</td>
<td>155</td>
<td>147</td>
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<td>--</td>
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<tr>
<td>$R_0$ ($\Omega$)</td>
<td>5</td>
<td>95</td>
<td>95</td>
<td>95</td>
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<tr>
<td>$C_p$ ($\mu F$)</td>
<td>639</td>
<td>494</td>
<td>355</td>
<td>143</td>
<td>140</td>
<td>143</td>
<td>153</td>
<td>125</td>
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<tr>
<td>$R_{ppp}$ ($k\Omega$)</td>
<td>9.5</td>
<td>28</td>
<td>2.5</td>
<td>13</td>
<td>14</td>
<td>10</td>
<td>40</td>
<td>35</td>
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<tr>
<td>$R_p$ ($\Omega$)</td>
<td>28</td>
<td>650</td>
<td>650</td>
<td>208</td>
<td>188</td>
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<tr>
<td>$Q_m$</td>
<td>707</td>
<td>161</td>
<td>163</td>
<td>156</td>
<td>152</td>
<td>171</td>
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<tr>
<td>$k_t^2$ (%)</td>
<td>1.24</td>
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<td>1.07</td>
<td>0.79</td>
<td>0.72</td>
<td>0.63</td>
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<td>$R_S$ ($\Omega$)</td>
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<td>2</td>
<td>2</td>
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<td>--</td>
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</tr>
</tbody>
</table>

It is worth noting that fairly constant electromechanical coupling coefficient, $k_t^2$, was achieved for the two different operating frequencies (State 1,2, Table 6).
VI. APPLICATIONS AND PRACTICAL USES

The extracted equivalent circuit of the device fabricated for the Integrated Design #3 was used to simulate the response of an AlN/PCM filter architecture with reconfigurable bandwidth and roll-off (Figure 30), demonstrating the great potential of this technology for the implementation of single chip, multi-band reconfigurable RF systems.

Figure 30: Simulated response of 4th order filter based on architecture shown. (a) Reconfigurable filter bandwidth using experimental variable capacitance and frequency states (Figure 28) for RES 3. (b) Reconfigurable filter roll-off using experimental variable capacitance states (Figure 28) for RES 2. Filter bandwidth can be adjusted by reconfiguring the static capacitance of RES 3 when its operating frequency is set to be far from the filter passband (385 MHz, States OFF, 2-7 in (a, Figure 28)). Filter roll-off can be adjusted by reconfiguring the static capacitance of RES 2 (b, Figure 28) or by configuring RES 3 to operate at a frequency close to the filter passband (181 MHz) which introduces a zero in the filter transfer function (State 1 in (a, Figure 28)).
The monolithic integration of phase change material switches and 2-port aluminum nitride piezoelectric MEMS resonators enables the design of easily fabricated devices with low resistive losses and minimal capacitive loading effects, reducing the signal loss and leakage current in potential systems created from these monolithically integrated components (compared to typical systems utilizing resonators and switches as separate RF components). The small size and easy fabrication of these PCM switches enables for effective integration, reducing the number of RF components in complex RF systems such as filters, and setting a milestone towards the development of AlN/PCM single-chip multi-band RF systems with the highest level of reconfigurability and minimum possible effect on the RF performance. The three integrated designs showcased in this thesis demonstrate the potential for these monolithically integrated devices to create simply fabricated, highly reconfigurable resonator elements that can be further integrated to create low power, highly reconfigurable, and minimal size RF systems.

In order to further improve these integrated designs, further improvement of the PCM switch designs should be investigated and implemented, with the main focus being the improvement of the switch reliability. Increasingly dense integration will improve the number of frequencies available for reconfiguration, and filters should be designed and fabricated in order to test the combination of several monolithically integrated resonators.
VIII. REFERENCES


