An X-Band Reconfigurable Bandpass Filter Using Phase Change RF Switches
Muzhi Wang, Feng Lin, and Mina Rais-Zadeh
Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, 48109, USA

Abstract — In this paper, we report on a reconfigurable bandpass filter for X-band applications. The filter is composed of coupled λ/2 microstrip line resonators. Center frequency tuning of each resonator is achieved using an RF switch based on a phase change chalcogenide compound, germanium telluride, which switches in and out a loading capacitor. A combination of electric and magnetic coupling between the resonators realizes a near constant absolute-bandwidth as the filter is tuned. The center frequency of the filter is switched between 7.45 and 8.07 GHz, with a 3-dB bandwidth of ~500 MHz, insertion loss less than 3.2 dB, and return loss better than 18 dB. The measured third-order intermodulation intercept point (IIP3) and 1-dB power compression point (P1dB) are better than 30 dBm at frequency offset of 1 kHz and 25 dBm, respectively. Measured and simulated results are in good agreement. To our best knowledge, this is the first time implementation of a tunable filter using germanium telluride based phase change switches.

Index Terms — Germanium telluride, phase change materials, MEMS, switches, tunable filters, X band.

I. INTRODUCTION

Compact and low-loss tunable filters are needed for a number of applications including cognitive radios, modern transceivers, and anti-jamming communication systems, to name a few [1]. There have been several designs reported for implementing tunable or reconfigurable filters. The frequency tuning for such devices is achieved electronically by solid-state varactors or switches, RF microelectromechanical systems (MEMS) switches or capacitors, variable dielectric capacitors, or magnetically using yttrium-iron-garnet (YIG). Solid state tuning elements have relatively high losses at high frequencies (>10 GHz) and linearity issues limiting their application areas. MEMS electrostatic switches are proven to have high power handling capability at the cost of large DC voltages to hold them in the down state. Recently, RF switches using phase change materials have gained a lot of attention as they offer fast switching speed (<10 µs), large cut-off frequency (>1 THz), high OFF/ON resistance change ratio (amorphous/crystalline resistivity ratio of > 10^4), small size (in few µm^2 range), near-zero in-state power consumption, high power handling capability (P1dB > 25 dBm), and high linearity (IIP3 > 50 dBm) [2-4]. However, the focus so far has been on implementing the switching element and only a handful of reports exist on exploiting phase change switches in functional RF modules.

In the X band, there are many examples of planar tunable filters using MEMS switches [5], ferroelectric barium-strontium-titanate (BST) capacitors [6], or vanadium dioxide (VO2) switches [7]. As a proof of concept, in this work, we utilize germanium telluride (GeTe) phase change switches for the first time to realize a reconfigurable X-band filter.

II. TUNABLE BANDPASS FILTER DESIGN AND FABRICATION

The filter is designed for X-band military communication applications with uplink and downlink frequency bands of 7.9 – 8.4 GHz and 7.25 – 7.75 GHz, respectively. The target insertion loss of the filter is less than 4 dB. The filter
consists of two λ/2 microstrip line open-loop resonators (i.e. no vias) each loaded with a switchable capacitor (open-circuited stubs) at the end. External coupling is achieved by a coupled feed line (Fig. 1(a)).

A. Filter with Constant Absolute Bandwidth (CABW)

Fig. 1 (b) shows the equivalent-circuit model of the filter. To design a two-pole 7.5/8.15 GHz filter with a 3-dB absolute bandwidth of 500 MHz, the low-pass Butterworth prototype is first designed with elements g_i, i=0, 1, 2, 3. Given the specifications including the center frequency and the 3-dB fractional bandwidths (Δ), the desired values of external quality factors (Q_0) and coupling coefficients (k_12) of the microstrip resonators are obtained (Equations (2) and (3)). To calculate the coupling coefficients, the Y-matrix of the two-port coupled-resonator section in Fig. 1(c) is firstly derived as

\[ Y_{11} = j\omega C_{stub} + \frac{Y_{inc} + Y_{inc}}{2}, \quad Y_{12} = \frac{Y_{inc} - Y_{inc}}{2} \]  

(1a)

\[ Y_{inc,o} = Y_2 Y_{inc,o}^{\prime} + j Y_2^{\prime} \tan \theta_0 \]

(1b)

\[ Y_{inc,o}^{\prime} = \frac{Y_{inc,o}^{\prime}}{Y_{inc,o} - Y_2 \tan \theta_1 \tan \theta_2} \]

To achieve a constant bandwidth, the Y-matrix of the circuit in Fig. 1(c) should satisfy the following resonance and coupling coefficient conditions across the entire tuning range [8]:

\[ \text{Im}\left[Y_{11}\left(\omega_0\right)\right] = 0, \quad \frac{\text{Im}\left[Y_{12}\left(\omega_0\right)\right]}{b} = \frac{\Delta}{\sqrt{g_1 g_2}} = k_{12} \]  

(2)

where \( b = \frac{\omega_0}{2} \frac{\partial \text{Im}\left[Y_{11}\left(\omega_0\right)\right]}{\partial \omega} \), \( \omega_0 \) is the resonant angular center frequency. Using this configuration (Z_0=37Ω, Z_0=23.3Ω, Z_0=33Ω, \( \theta_0=55^\circ \), \( \theta_1=23^\circ \), \( \theta_2=95^\circ \) and \( \Delta=6.1\% \) at 8.15 GHz), the required and calculated coupling co-efficient \( k_{12} \) to achieve a constant bandwidth of 500 MHz at different center frequencies of coupled resonators is plotted in Fig. 2.

In addition, to maintain constant absolute bandwidth, the external quality factor \( Q_m \) of the filter should satisfy (3) [8]

\[ Q_m = \frac{b}{Y_0} \frac{\omega_0}{2Y_0} \frac{\partial \text{Im}\left[Y_{11}\left(\omega_0\right)\right]}{\partial \omega} = \frac{g_1 g_2}{\Delta} \]  

(3)

where \( Y_0 \) is the input admittance of the circuit including the external coupling element (see Fig. 1(d)). Capacitance C in Fig. 1(b) represents a source-load coupling between the feed lines and can be adjusted by changing the gap (g_i) between the feed lines to enhance the rejection close to the passband. Since there are two signal paths: inductive coupling between the resonator and capacitive source-load coupling, two transmission zeros are introduced in the \( S_{21} \) response, enhancing the near band rejection of the filter.

B. Phase Change Switch Design and Its Integration into the Microstrip Filter

The structure of the GeTe phase change switch used in the tunable filter is shown in Fig. 3 inset. Simulations of the GeTe switch is performed using Agilent HFSS. The switch consists of a single GeTe layer connecting two RF terminals laterally. An embedded heater line runs below the GeTe layer. The heater is electrically isolated from the RF signal path by a silicon nitride (Si_3N_4) layer. The GeTe layer has a thickness of approximately 150 nm, and the RF electrodes have a width of 30 μm and a separation of 1.5 μm. The GeTe layer can be thermally transitioned between amorphous (OFF) and crystalline (ON) states by applying proper current pulses to the heater. Simulated S-parameters of the phase change switch are presented in Fig. 3. In simulations, the conductivity of GeTe at on state is assumed to be \( 4.3 \times 10^4 \) S/m with OFF/ON resistance ratio of \( 4.3 \times 10^3 \). These values are extracted from resistivity measurements.

![Fig. 2](image-url) Desired k_{12} for CABW of 500 MHz

![Fig. 3](image-url) Simulated S-parameter of the GeTe switch. Inset shows the cross-section schematic of the switch.
The filter is built on a high-resistivity ($\rho > 20 \, k\Omega \cdot cm$) silicon substrate with $t_s = 11.7$ and $h = 0.5 \, mm$. The filter layout is optimized using the HFSS full-wave electromagnetic simulation tool. The width of the microstrip resonators (0.9 mm) is chosen to get a small resonator impedance of 33 $\Omega$ and a high unloaded quality factor ($Q_u$). To achieve a value close to ideal for $k_{12}$, the distance ($s$) between the two resonators and the length ($l_2$) of the coupled line are optimized, while the required $Q_{out}$ is realized by changing the width ($w_2$) of the feed lines and the gap ($g_0$) between the feed lines and resonators. To facilitate ground-signal-ground (GSG) probe measurement, two vialess microstrip to coplanar-waveguide (CPW) transitions [9] are connected at the input and output RF ports. Final dimensions of the filter are as followings: $w_1=0.4$, $w_2=0.9$, $w_3=0.55$, $h_0=0.8$, $l_1=1.42$, $l_2=1$, $l_3=2.7$, $l_4=0.47$, $g_0=0.015$, $g_1=0.077$, $s=0.057$ (all in mm). Fig. 4 shows an optical micrograph of a fabricated filter. The filter area is 10.8x3.9 mm$^2$.

When switches are ON, a lower frequency passband of 7.45 GHz (simulation: 7.5 GHz) is achieved with an insertion loss of 3.2 dB, 3-dB bandwidth of 482 MHz, and return loss $>30$ dB. When the switches are OFF, the filter is switched to the higher frequency band of 8.07 GHz (simulation: 8.15 GHz) with insertion loss of 2.6 dB, bandwidth of 520 MHz, and return loss $>18$ dB (Fig. 6). The $Q_u$ of microstrip resonators with GeTe switches estimated using Eq. (4) [10] is 59/73 in the ON/OFF states.

$$I.L \ (dB) = 4.343 \sum_{i=1}^{n} \frac{S_{i}}{FBW Q_{ui}}$$

Fig. 6. Measured and simulated S-parameters of the filter in both switch states.

**B. Linearity and Power Handling Measurement**

The IIP$^3$ is measured at the center frequency of the pass band. The extracted IIP$^3$ at 1 kHz offset is better than 30 dBm for both states (Fig. 7). Measured results also show that the tunable filter can handle more than 25 dBm of input power at both states of the switch before 1-dB compression occurs (Fig. 8).

**III. RESULTS**

**A. S-Parameter Response**

The DC resistance of GeTe switches at the ON and OFF states is measured to be ~ 5 $\Omega$ and 0.4 M$\Omega$, respectively.
TABLE I
PERFORMANCE COMPARISON OF THE REPORTED SECOND-ORDER TUNABLE FILTER

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Tuning elements</th>
<th>BW_{\text{min}} (% of f_0)</th>
<th>IL (dB)</th>
<th>Range (GHz)</th>
<th>Estimated Q_u</th>
<th>Bias voltage (V)</th>
<th>Size (mm^2)</th>
<th>Tuning Speed</th>
<th>Power Consumption</th>
<th>IIP_3 (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5]</td>
<td>MEMS switch</td>
<td>5.8</td>
<td>2.6-2.9</td>
<td>12-15</td>
<td>77-81</td>
<td>60</td>
<td>~5x4</td>
<td>~10 µs</td>
<td>Near 0</td>
<td>N/A</td>
</tr>
<tr>
<td>[6]</td>
<td>BST capacitor</td>
<td>15</td>
<td>2.0-2.7</td>
<td>10-10.56</td>
<td>&lt; 40</td>
<td>30</td>
<td>3.1x6.9</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>[7]</td>
<td>VO₂ switches</td>
<td>12-13</td>
<td>5</td>
<td>8.6-9.2</td>
<td>&lt; 20</td>
<td>60</td>
<td>9x7</td>
<td>&lt;10 µs</td>
<td>1.8 W (pulse)</td>
<td>N/A</td>
</tr>
<tr>
<td>This work</td>
<td>GeTe switches</td>
<td>6.4-6.5</td>
<td>2.6-3.2</td>
<td>7.45-8.07</td>
<td>59-73</td>
<td>15 to 20</td>
<td>3.9x10</td>
<td>&lt; 6 µs</td>
<td>0.5-1.5W (pulse)</td>
<td>30</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

A tunable bandpass filter using GeTe switches was introduced for the first time. Table I compares the performance specifications of this filter with reported filters in the X band. As shown, the proposed filter offers competitive performance. Compared to MEMS tunable filters, it shows a faster response time and requires smaller voltage pulses for actuation. Compared to ferroelectric filters, it shows a small loss for a much higher filter Q and finally, compared to VO₂ type filters, it offers better linearity and does not consume static power to stay in the ON or OFF state.

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REFERENCES


