A Widely Tunable RF MEMS End-coupled Filter

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***Abstract* — A three-pole tunable end-coupled filter from 6 to 10 GHz was developed with a broad 35% tuning range. This tuning range was realized by switching distributed loading structures with radio frequency microelectromechanical systems (RF MEMS) capacitive switches. By tuning the coupling capacitors as well as the loading capacitors, the filter achieved a constant fractional bandwidth of 15±0.3 % and an insertion loss ranging from 3.3 dB to 3.8 dB over the entire band. Digital switching ensured good thermal stability, and microstrip transmission lines provided lower insertion loss than with coplanar waveguide. Future improvements are expected to decrease the insertion loss to below 2.1 dB.**

***Index Terms* — Adaptive filters, microstrip filters, resonator filters, switched filters, tunable filters, microelectromechanical devices.**

I. INTRODUCTION

Military and commercial applications are continually demanding smaller, more efficient, and frequency agile devices [1]. This trend supports ongoing development of systems for lightweight and mobile applications. Radio frequency microelectromechanical systems (RF MEMS) are ideal for these applications due to their low-power consumption, low loss, and excellent linearity [2]-[4].

Previous work has shown distributed MEMS transmission line (DMTL) filters to be compact and tunable. In these filters, multiple resonators are tuned by loading transmission lines with RF MEMS varactors [5]-[6]. By varying resonator loading capacitance, the phase velocity is adjusted, causing a change in the electrical length of the resonator, thus tuning the center frequency of the filter. However, over large tuning ranges, changing only the loading capacitance of these designs fails to maintain constant bandwidth and insertion loss. By tuning the coupling between resonators in addition to varying the loading capacitance, constant bandwidth and insertion loss is achievable. In addition, analog tuning of MEMS varactors is inherently temperature and process dependent causing performance uncertainties and instabilities. Therefore, bi-stable RF MEMS switches were utilized to digitally load filter resonator sections. Also, the unloaded Q of the transmission line resonators dominates the insertion loss of coplanar waveguide (CPW) DMTL filters, limiting further improvements in the loss performance [6]. In this design, microstrip technology is used for its lower loss and reduced parasitics.

This work presents a discrete three-pole DMTL bandpass filter with relatively constant bandwidth and insertion loss over a 35% tuning range from 6.0 to 10 GHz. It employs digitally switched tuning with two-bit precision for best process yield and performance stability, and microstrip transmission lines for lowest insertion loss.

II. DESIGN

Insertion loss of various technologies was evaluated to optimize the filter performance. To calculate loss, the following equation was used [7]-[8],

$$Loss = 4.343 \cdot \sum_{i=1}^{i=n} g_i \cdot \frac{f_C}{(f_H - f_L) \cdot Q_U} \qquad (1)$$

where f_C is the center frequency, f_H and f_L are the upper and lower frequencies which determine the filter bandwidth, g_i are the low pass insertion loss prototype values, n is the number of poles, and Q_u is the unloaded Q of a resonator. Typical filter specifications will fix the values of g_i, f_C, f_H, and f_L. Therefore, to obtain the lowest loss, a high Q_u is desired. Typically, microstrip transmission lines have a much higher Q_u than their CPW counterparts, and therefore are a better choice for reduced insertion loss.

For this end-coupled filter, capacitively loading the transmission line resonators creates a slow-wave structure, with the phase velocity tuned by changing the loading capacitance [9]-[10]. To accomplish this, RF MEMS capacitive switches are periodically connected to the transmission line as shown in Fig. 1. Additional MEMS capacitive switches are used to tune the coupling capacitance between resonators.

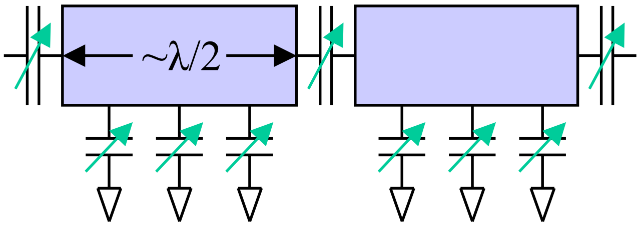

Fig. 1. Slow wave structure of a DMTL filter.

Capacitive RF MEMS switches are used to create four discrete filter states by selecting banks of microstrip stubs to load the transmission line. Stubs, rather than lumped capacitors, were used to load the transmission lines because their characteristics are well understood and they enable repeatable capacitances. Microstrip stubs also eliminate the need to use metal insulator metal (MIM) capacitors and the through-wafer grounding vias that these capacitors would require. The MEMS switches are in series with the stubs and control to what degree the microstrip stubs load the transmission line. In the up state, the small capacitance of the MEMS switch dominates the series capacitor structure ($C_{mems} << C_{stub}$). In the down state, the capacitive switch has a large capacitance value ($C_{mems} >> C_{stub}$) and therefore the capacitance of the stub will dominate.

Tuning DMTL filters over a large tuning range only by capacitively loading the transmission line is possible, but it is achieved at the cost of variable bandwidth and insertion loss. This is apparent in Fig. 2, which shows measured results of a three-pole DMTL filter tuned over the full band using constant coupling capacitors between resonators. As the capacitive loading increases, the bandwidth decreases while the insertion loss increases.

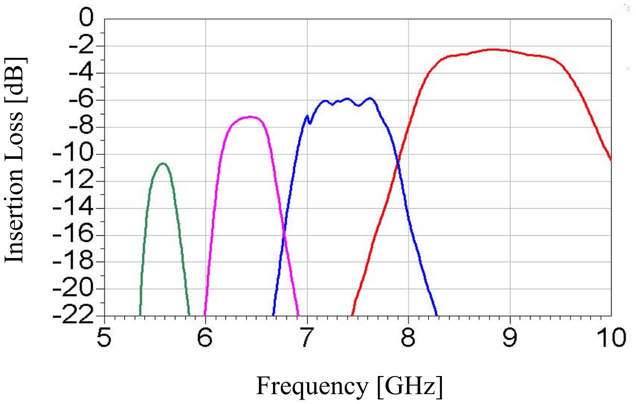

Fig. 2. Measurements demonstrating variable bandwidth and insertion loss of a DMTL filter with constant coupling capacitance.

The use of inductive inverters reduces this problem, but will not enable the wide tuning range of 35% desired. To address this problem, RF MEMS capacitive switches were used to select interdigital capacitors (IDC) in order to tune the inter-resonator coupling.

III. RESULTS

End-coupled DMTL filters, as shown in Fig. 3, were fabricated using standard semiconductor processes. First, the bias lines were deposited using a tantalum nitride layer with 1 kΩ/□ sheet resistance. The bottom contact metal was fabricated by evaporating a smooth 0.3 μm thick layer of gold. This layer was used as the interdigital capacitor

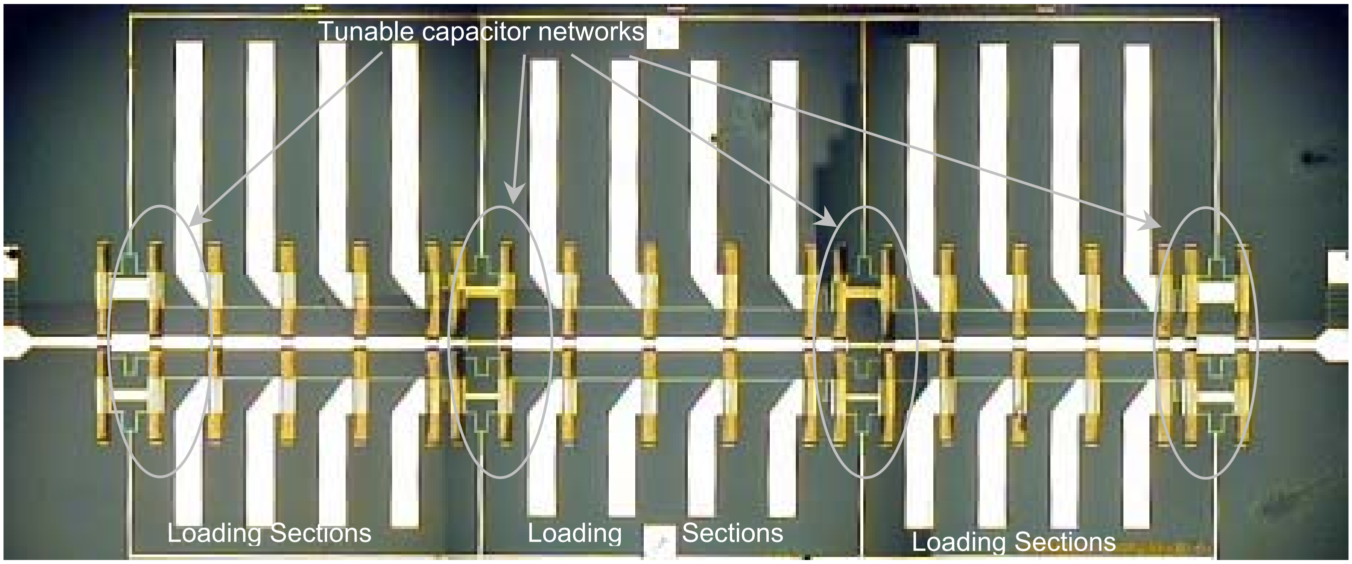

Fig. 3. Optical micrograph of the DMTL filter, with dimensions of 8.9 mm x 4.2 mm

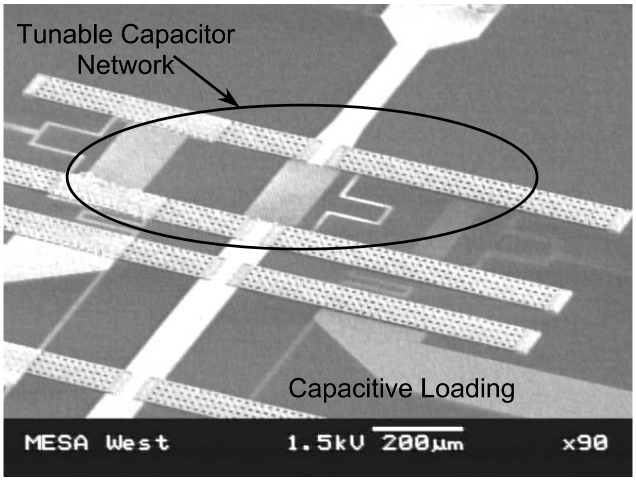

Fig. 4. SEM image showing the distributed loading of a microstrip line on Alumina using fixed beam capacitive switches and open-ended microstrip stubs. The four uppermost switches show the 2-bit coupling capacitor tuning network.

(IDC) banks used for coupling between resonators as well as the metal surface under the switch. A thin layer of 0.3 µm thick plasma-enhanced chemical vapor deposited silicon oxynitride was used to form the dielectric layer for the MEMS capacitive switches. The 2.5 µm thick gold transmission lines were then evaporated and patterned by lift-off, and a 4 µm thick sacrificial layer was used to define the up-state capacitance of the MEMS switch. The bridge was formed by sputtering a 1 µm thick layer of aluminum, which was then patterned through reactive ion etching.

This filter network included 40 RF MEMS switches. A scanning electron micrograph of the tunable IDC networks and loading structures are shown in Fig. 4. The filters were tested in a lab ambient using a cascade RF probe station and a HP 8510C network analyzer. Actuation of the RF MEMS switches was accomplished using a bipolar waveform with a magnitude of 40 V.

Measured insertion loss and return loss are shown in Fig. 5. The insertion loss of the four-state filter varies between 3.3 dB and 3.8 dB, while the filter exhibits a tuning range of 35% centered at 8.2 GHz. The ripple bandwidth over the tuning range is 1.2±0.2 GHz, such that the filter demonstrates a fractional bandwidth of 15±0.3 %.

The measured insertion loss of 3.3 dB is higher than simulated and was traced to a resistive contact between the bridge layer of the capacitive switch and the signal line. This resistance was caused by incomplete etching of the sacrificial layer underneath the bridge anchor. This contact resistance greatly reduces the Q of the switch loading the transmission line. Due to this decrease in Q, the loss of the switches dominates the filter loss. Simulations indicate that the filter should have less than 2.1 dB of insertion loss once this process issue is corrected.

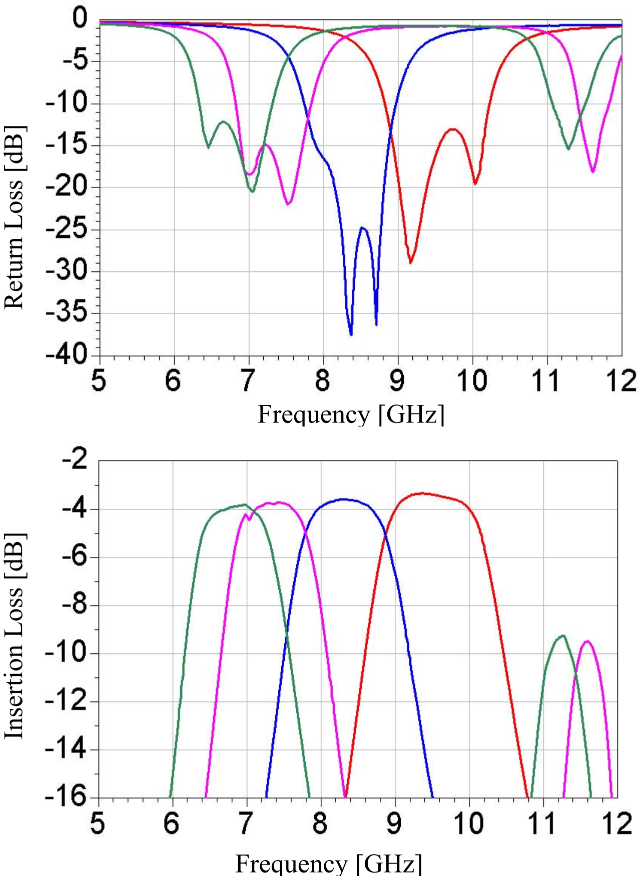

Fig. 5. Return loss (Top) and Insertion Loss (Bottom) of a distributed MEMS transmission line filter with tuned coupling capacitors.

When the filter is switched into the lowest two frequency states, there are additional resonances at approximately 11.5 GHz that are 6 dB down from the passband. While these resonances are outside of the frequency band of interest, they are still undesirable. Simulations show that the long loading stubs used to realize these two frequency states cause these resonances. Future designs will elimate these resonances by replacing the longest microstrip stubs with capacitors to ground.

V. CONCLUSION

This work presents a digitally-tuned DMTL filter with a 35% tuning range centered around 8.2 GHz. To date, this is the largest reported tuning range of any MEMS monolithic filter. With an insertion loss of 3.5±0.25 dB and a return loss > 12 dB, the loss of this filter is comparable to other reported work, but has the potential to achieve lower loss with the improvements that have been described. Digital tuning provides good stability while tunable coupling capacitors maintain a constant bandwidth across all tuning states. MEMS based filters such as this one are very attractive for many military and commercial applications due to reduced size and power consumption.

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