# An X-Band to Ku-Band RF MEMS Switched Coplanar Strip Filter

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***Abstract*—Radio frequency microelectromechanical systems (RF MEMS) are key enabling technologies for miniature reconfigurable circuits such as microwave filters. We present a two-pole monolithic RF MEMS switched filter, fabricated on GaAs, that employs surface-micromachined capacitors to present a variable capacitance to a coupled coplanar strip filter, thereby switching the filter center frequency 37% between 10.7 GHz and 15.5 GHz with voltages of 20 and 0 V, respectively. This 15% bandwidth filter occupies a chip area of 2.2 × 1.5 mm and demonstrates less than 2-dB of loss, making it promising for numerous applications within these critical frequency bands.**

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

## I. INTRODUCTION

RECONFIGURABLE microwave circuits have generated great interest for both military and commercial applications because these networks allow increased system functionality with lower weight and cost than existing systems [1]. Due to their low-loss and other attractive characteristics, radio frequency microelectromechanical systems (RF MEMS) are key to meeting these objectives [1], [2]. One of the most critical elements enabled by RF MEMS is the tunable filter, of which there have been several examples. These filters have included both lumped designs [3]–[5] and distributed designs [6]–[9] at frequencies ranging from L-band to millimeter-wave. However, there have been few examples of RF MEMS-enabled filters in the 8 to 18 GHz range where numerous radar and communications applications reside. In this work, we present an RF MEMS switched filter operating in this important frequency range.

## II. RF MEMS SWITCHED CAPACITOR

This filter design is enabled by a low-loss RF MEMS switched capacitor. The device used in this work is optimized for low loss and high-Q at microwave frequencies. To enable post-processing on arbitrary substrates ranging from quartz to InP MMICs, the device was fabricated using a low-temperature surface micromachining process described in detail previously [10]. This process uses a polymer sacrificial layer and evaporated gold films to fabricate the capacitor, and a low-temperature dry etch process to release the devices. In the future, we anticipate adding thin-film resistors using a high-resistivity layer to allow individual biasing of the switches, enabling more complex and higher-order filter designs.

The switched capacitor consists of a 1.2 $\mu$m-thick gold cantilever suspended 5 $\mu$m over a ground pad coated with silicon oxynitride dielectric. A cantilever device is used to reduce sensitivity due to thermal mismatches between the substrate and device, but has not been characterized over a broad temperature range. The device is switched by increasing the actuation voltage until the plate pulls down onto the substrate at approximately 15 V. The up-state capacitance is approximately 150 fF while the down-state capacitance is approximately 400 fF at 20 V. Additionally, the downstate capacitance can be tuned between approximately 350 and 400 fF by varying the holding voltage between the pull-off voltage of 10 V and maximum voltage of 20 V, allowing approximately 10% tuning in the downstate. Even though this slight tuning is possible, in this filter application the device is used as a two-state switch for improved stability and reproducibility in the presence of vibration or bias voltage noise. This MEMS capacitor has a Q-factor of over 100 through the entire band of operation up to 25 GHz, and an extrapolated minimum self-resonant frequency of over 60 GHz in the highest capacitance state. Additionally, switching times between the down-state and up-state were measured to be under 100 $\mu$s. Finally, while the device has been operated to over a billion cycles without any charging or stiction-related failures, during the lifetime test the pull-in voltage gradually shifted from 15 to 7 V due to metal fatigue at the anchor. This reliability limitation will be addressed in future designs.

## III. FILTER DESIGN AND FABRICATION

The filter was designed as a second-order capacitively-loaded interdigital filter [11]. The resonators were grounded at one end by a large grounding capacitor for bias isolation, their lengths were chosen to be approximately 45° long at the center frequency of 12.5 GHz to allow for maximum tuning range, and the tap locations were chosen for optimum filter characteristics at 12.5 GHz. The filter elements, to take full advantage of the high performance of the switched MEMS capacitor, were fabricated in a coupled coplanar strip (CPS) configuration on a GaAs substrate [12]. Coplanar technology, rather than microstrip, was

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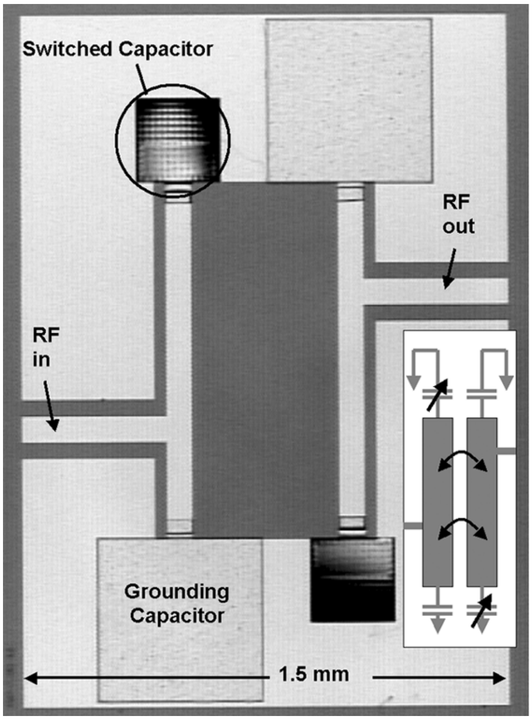

Fig. 1. Optical micrograph of the RF MEMS switched filter with an inset showing a simple equivalent circuit model of the filter. The filter dimensions are 1.5 × 2.2 mm.

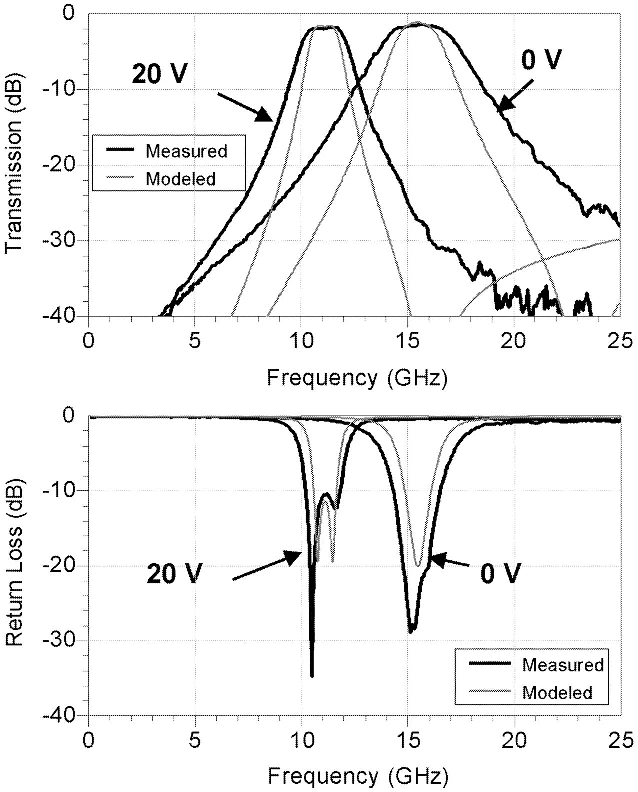

Fig. 2. Measured and modeled transmission and return loss of the switched filter.

chosen both for process simplicity and the ability to fabricate these components on arbitrary substrates. This filter differs from previously reported RF MEMS switched CPS-filters [9] in that this design is switched by changing the loading capacitors rather than by physically changing the length of the line. This approach allows for a filter layout that is up to 50% smaller at a given frequency than previous examples.

After using standard filter design techniques [13] and software to design a 15% bandwidth, 0.25-dB ripple filter, the layout accuracy was verified with a commercial 2.5D method-of-moments simulator [14] and a commercial three-dimensional (3-D) finite element simulator [15]. An optical micrograph of the filter, which occupies only 1.5 × 2.2 mm of chip area, is shown in Fig. 1, which also includes a simple sketch of the equivalent circuit as an inset. The coplanar waveguide (CPW) feedlines are designed for 50 Ω impedance, while the CPS resonators are 80 $\mu$m wide with a 35 $\mu$m gap between the signal line and the ground plane, producing a characteristic impedance of 58 Ω and an effective dielectric constant of 6.85. The resonators are 1100-$\mu$m long and separated by 450 $\mu$m, producing even and odd mode impedances of approximately 62 Ω and 52 Ω. The switched capacitors are 300× 300 $\mu$m with an initial air gap of 5 $\mu$m. Because of the short resonators (about 45°), this filter occupies less than half the chip area as earlier designs.

## IV. RESULTS

The filter was tested using coplanar Cascade probes and an HP8510C network analyzer from 50 MHz to 25 GHz. For testing, wirebonds were added across the CPW feed to suppress spurious modes at the feed junctions. The control voltage, ranging from 0 to 20 V, was introduced to the CPW center conductor through the internal bias tees on the network analyzer. The transmission and return loss properties of the filter at voltages of 0 and 20 V are shown in Fig. 2, which also shows the circuit model response. At 0 V, the filter's center frequency is 15.5 GHz, with a bandwidth of 2.2 GHz. The minimum passband loss is approximately 1.4 dB in that state, with the return loss better than 20 dB in the passband. When the switches are pulled in at 20 V, the filter center frequency is 10.7 GHz with 1.8 GHz bandwidth. In this state, the insertion loss is less than 2 dB, with in-band return loss better than 10 dB. This 37% center frequency switching is achieved with only two simple RF MEMS devices.

The rejection of the filter at two bandwidths above the center frequency is greater than 15 dB for both of the states, as expected for a two-pole filter. In similar filters operating at lower frequency, we have observed a slight decrease in stop-band rejection at three times the center frequency, but the rejection of this particular filter remains greater than 20 dB because of the electrically short resonators.

While the measured and modeled responses correspond well, there is a discrepancy between the measured and modeled bandwidths which can be accounted for by several factors. First, the circuit-level simulation does not accurately account for the coplanar-strip tees, which impact the performance of the resonators. Second, accurately accounting for the coupling between the coplanar strip resonators and end ground planes requires full 3-D electromagnetic simulation. Finally, the resonator grounds are not exactly fixed at the end of the resonator, but instead distributed across the large area of the grounding capacitor. All of these effects were captured by full electromagnetic simulation and considered in the final design, but were not incorporated into the circuit model.

The filter properties change with frequency because the physical locations and lengths of the resonators and taps are fixed. Therefore, as the filter is switched, the effective tap position and coupling coefficient vary, deviating from the ideal desired filter response. The filter was optimized for a response at 12.5 GHz, resulting in larger insertion and return losses at lower frequencies and merging of the poles at the upper frequency. Except for these slight departures from an ideal filter shape, the filter response is symmetric about the center frequency. The loss of the filter is limited by the low Q (30–40) of the coplanar strip line, rather than by losses in the switched capacitors. By using a transmission line technology with improved unloaded Q, the loss of this filter can be significantly improved.

## V. CONCLUSION

In this work, we have presented an RF MEMS enabled switched filter with 37% tuning from a center frequency of 10.7 to 15.5 GHz. The filter has a bandwidth of approximately 15% and less than 2 dB of loss in the passband. The monolithic design takes full advantage of the RF MEMS device by eliminating losses associated with off-chip connections and allowing the total filter to occupy only 3.3 $\text{mm}^2$. This filter has lower loss, smaller size, and a larger tuning range than previous RF MEMS filters of this type, and switches between two critical radar bands, enabling frequency agile radars and other systems. Future work to improve the filter passband properties is ongoing, and is expected to make this design and fabrication technique a strong candidate for insertion into advanced RF system designs.

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