Development of a 6–12 GHz Tunable Band Pass Filter Using MEMS Diaphragm Actuators

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***Abstract*—A very low loss, wide bandwidth, tunable evanescent-mode cavity band pass filter (BPF) with one-octave (6–12 GHz) tuning range is presented. In order to implement a very low insertion loss with wideband operation, a new coaxial feed structure is devised in the tunable BPF. Across the entire tuning range, the achieved insertion loss is less than 0.5 dB. The tunability is realized by using silicon microelectromechanical systems (MEMS) diaphragms with slits that are electrostatically actuated.**

***Index Terms*—Tunable filter, MEMS, RF-MEMS**

I. Introduction

RAPID growth in demand for multi-band and multi-standard RF front-end modules has accelerated research activities, especially on the implementation of reconfigurable RF filters. Such activities resulted in a 12–18 GHz three-pole tunable filter that was implemented using RF MEMS capacitive switches with loaded resonators [1]. Piezoelectric disks were used on substrate integrated evanescent-mode cavities to create a tunable filter with tuning range of 0.98–3.48 GHz [2]. While a wide tuning range is highly desirable, RF filter performance such as low passband insertion loss and high stopband attenuation is needed in a small form factor. One of the critical design factors for the desired performance is a high unloaded quality factor (Q_u).

Heavily-loaded evanescent-mode cavity filters offer a very attractive solution for achieving high performance in a small form factor. A previous characterization of loaded evanescent-mode cavity resonators has been reported in [3]. The resonant frequency and Q_u are determined by the dimensions of the cavity, the loading post, and the gap between the post top and the cavity ceiling. When the gap is very small, the resonant frequency of the resonator is strongly dependent on the gap. If the cavity ceiling can be deflected by an external force, the resonant frequency can be tuned [4].

A high-Q tunable evanescent-mode cavity filter using single-crystal silicon RF MEMS diaphragms has been demonstrated to verify this concept [5]. All-silicon tunable cavity filter operating from 6.7 to 20.5 GHz has been presented using gold diaphragm with radial slits to reduce the stiffness of the diaphragm [6].

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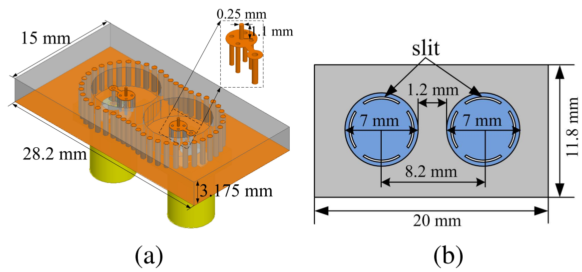


Fig. 1: Illustrations of (a) a two-pole evanescent-mode cavity and (b) MEMS diaphragms with slits.

In this letter, a very low loss tunable evanescent-mode cavity BPF with one-octave tuning range is implemented using a new integrated coaxial feed structure. The BPF has a continuous tuning range exceeding an octave (5.3–12 GHz) with a very low insertion loss of less than 0.5 dB over the majority of the frequency range. It is also shown that the tuning range increases when adding slits on the silicon diaphragm actuator.

II. Design of One-Octave Tunable BPF

A. New Coaxial-fed Evanescent-mode Cavity Filter

The layout and dimensions of the second-order, evanescent-mode BPF design is shown in Fig. 1 (a). The BPF consists of two heavily-loaded, evanescent-mode cavities with an inductive iris providing the inter-resonator coupling and two shorted coaxial feeds for the external coupling. The physical geometry of the filter design was realized using ANSYS HFSS in a 3.175-mm thick Rogers TMM3 substrate with a relative permitivity of 3.27 and a loss tangent of 0.002. The diameter and depth of the cylindrical cavity are 10 mm and 3.175 mm, respectively. The capacitive loading post is formed in two steps, the top part has a diameter of 0.25 mm and a height of 1.1 mm, the bottom part has a diameter of 2 mm and a height of 2.075 mm.

The external coupling is achieved by forming a coaxial extension into the cavity and short-circuiting to the platform of the bottom part of the post. The distance between coaxial feed line and the capacitive post is 0.56 mm. Aperture coupling method, shown in [5], results an increase in insertion loss due to radiation, and in order to limit this loss, a new coaxial feed structure is devised as shown in Fig. 1 (a). This new coaxial feed structure also allows for stronger coupling which enables

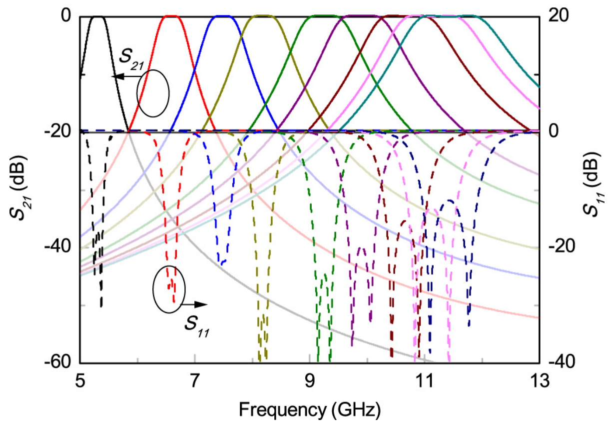


Fig. 2: Simulated return (S_{11}) and insertion (S_{21}) loss of the coaxial-fed evanescent-mode cavity band pass filter.

higher bandwidth designs. Implementing this new feed method in all-silicon design operating 8–16 GHz in [6] would be very challenging as it requires 3D patterning and selective etching of the silicon cavity in silicon microfabrication process.

The simulated filter performance is shown in Fig. 2. The return loss across the tuning range is less than 10 dB and the simulated insertion loss is 0.1 dB at 12 GHz and is less than 0.3 dB across the entire tuning range of 6–12 GHz. It should also be noted that the bandwidth increases as a function of frequency at a rate that is higher than the rate of the external coupling growth. This results in weaker coupling at the higher end of the filter tuning range.

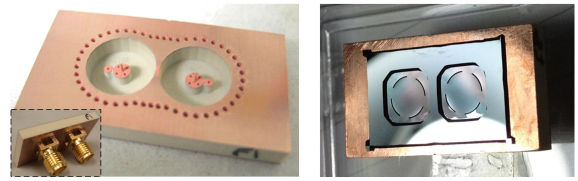
B. Design of MEMS Diaphragm Tuner

To actuate the proposed evanescent-mode cavity filter, two single-crystal silicon diaphragms covered by gold are required. These two diaphragms are fabricated on the same silicon die, which simplifies the tuner integration compared to using two individual dies on the TMM filter substrate. In order to compare the deflection of diaphragm, two different diaphragms are designed. One is a circular silicon diaphragm and the other is, as shown in Fig. 1 (b), that four slits are added around the circular diaphragm. The width of the slits is chosen to be 150 µm. Each slit spans 60° of a circle with 2.5-mm radius. The slits are located 0.5 mm away from the outer edge of the diaphragm. The slits release part of the residual stress in the diaphragm actuator, resulting in an improved tuning range.

III. Fabrication and Experiments

A. Coaxial-fed Evanescent-mode Cavity

The fabrication of the coax-fed evanescent-mode cavity filter in the 3.175-mm thick Rogers TMM3 substrate is conducted using an LPKF C100HF circuit board plotter. The first step is machining the 0.25-mm wide, 1.1-mm tall capacitive posts. These posts are challenging to machine due to the high aspect ratio. The tool-choice is critical for achieving a precise cut without breaking the posts. For this project, a 250-µm shell cutter from PreciseBits is chosen to remove the substrate material around the posts. After the material removal, the vias in the bottom post and around the cavities are drilled.



(a) (b)

Fig. 3: Pictures of (a) the evanescent-mode cavity and (b) top view of the coaxial-fed evanescent-mode cavity integrated with the proposed MEMS diaphragm.

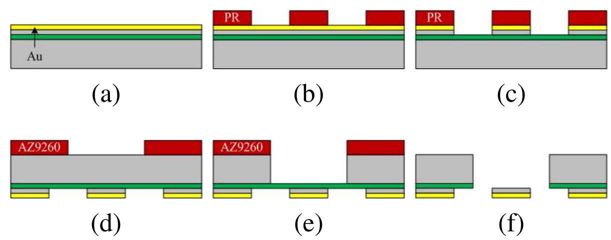


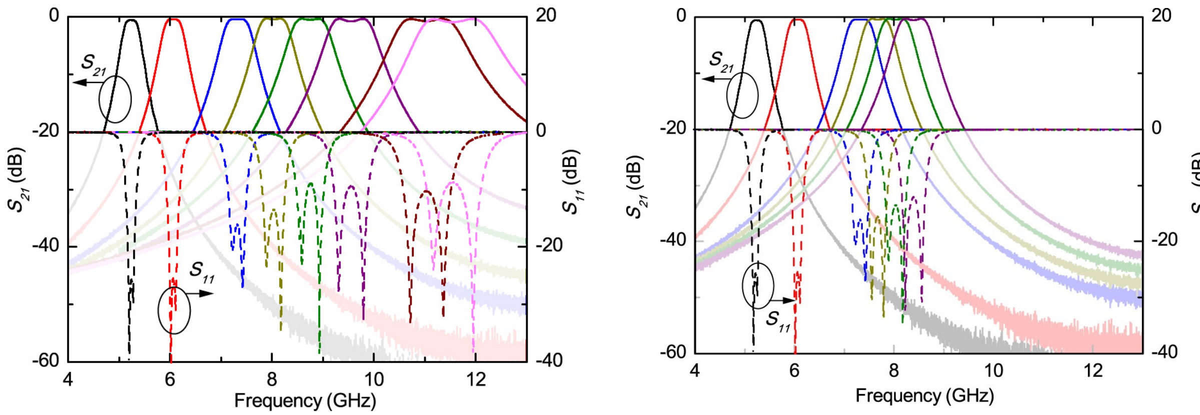
Fig. 4: Fabrication process for the diaphragm with slits: (a) gold sputter, (b) photolithography, (c) gold and silicon etch, (d) photolithography, (e) DRIE, and (e) oxide etch.(not to scale)

Following the milling, the vias and posts are bulk metallized using electroless plating and then electroplating 1.5 µm and 5 µm of copper, respectively. When the plating is finished, the bottom of the capacitive post and the RF feed lines are defined using a second milling step. The final step is mounting and soldering the two SubMiniature version A (SMA) coaxial connectors on to the cavity filter. Alignment is performed using a Finetech's FINEPLACER®pico pick and place machine after applying solder paste on the connectors. Finally, the solder is reflowed in a Manncorp reflow oven. A picture of the cavity filter with the SMA connectors is shown in Fig. 3 (a).

B. MEMS Diaphragm Tuner

The fabrication process for the silicon diaphragm without slits is depicted in [5]. The fabrication process for the MEMS diaphragm with slits is shown in Fig. 4. The MEMS diaphragm is fabricated on a silicon-on-insulator (SOI) wafer. The thickness of the silicon device layer and the buried oxide on the SOI wafer are 3 µm and 1 µm, respectively as shown in Fig. 4 (a). First, a 0.5-µm thick gold layer is deposited using DC sputtering. Then, the slits are patterned on the gold layer using photolithography and the gold and silicon device layers are etched away to form the physical slits in the silicon diaphragm. The next step is patterning the circular shape on the silicon handle layer to remove the substrate using deep reactive ion etching (DRIE). After removing the oxide layer in a buffered oxide etchant, the fabrication process for the MEMS diaphragm with slits is finalized.

The diaphragm is assembled on the cavity using a 118-09A/B-187 conductive silver epoxy from Creative Materials Inc.. The gap between the diaphragm and capacitive posts is controlled by monitoring the return loss at each port using a network analyzer in order to determine the resonant frequency of each resonator. When the desired frequency is achieved, the



(a) (b)

Fig. 5: Measured S-parameters of the BPF (a) with and (b) without slits on the gold/silicon diaphragms.

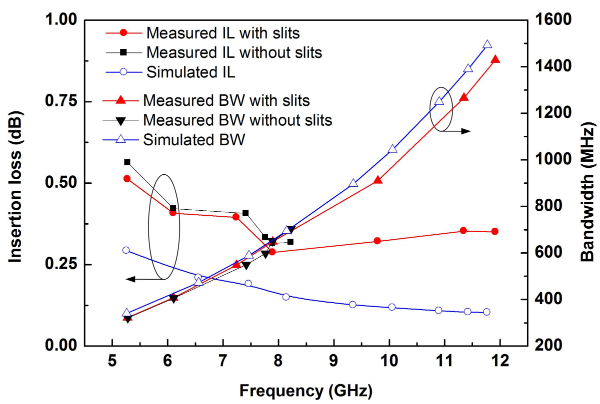


Fig. 6: Comparison of the insertion loss and bandwidth between measured and simulated results of the tunable evanescent-mode cavity BPF.

assembled filter is cured until the solvent content of the epoxy precursor fully evaporates. A picture of the evanescent-mode cavity filter integrated with the MEMS diaphragm with slits is shown in Fig. 3 (b).

C. Experimental Results

An Agilent E8361A network analyzer is used to measure the S-parameters of the tunable BPF, and Keithley 2400 Sourcemeters are used to provide the tuner biasing. The network analyzer was calibrated using the coaxial SMA calibration standards. The actuation mechanism of the MEMS diaphragm and measurement method is described in detail in [5]. The measured S-parameters of the evanescent-mode tunable BPF with and without slits are shown in Fig. 5 (a) and (b), respectively. As shown in Fig. 5 (a), the entire tuning range of 6–12 GHz can be achieved when using the silicon diaphragms with slits. When adding the slits to the diaphragms, the tuning range increases by 3.6 GHz (from 8.7 to 12.3 GHz). As can be seen in Fig. 6, the insertion loss in the passband is less than 0.5 dB from 6 GHz to 12 GHz. The measured bandwidth agrees well with the simulated bandwidth. The difference between the measured and simulated insertion loss ($< 6\,\%$) can be attributed to the non-ideal behavior of the metal composition of the gold and silver epoxy, and the solder connection between the SMA connector center pin and capacitive post in the cavity. Furthermore, comparison of the measured insertion loss of the samples with the two different diaphragm shows that the impact from the slits is negligible in terms of loss performance. The resulting effective Q_u of the BPF is between 355 and 600. The required actuation voltage is less than 140 V for both diaphragms.

IV. Conclusion

In this letter, a one-octave (6–12 GHz) tunable evanescent-mode cavity band pass filter has been designed, fabricated, and measured. In order to achieve a very low insertion loss in the passband ($\leq$0.5 dB), a new coaxial feed lines are integrated into the BPF. The tuning capability is realized by using electrostatic force on single-crystal silicon RF MEMS diaphragms. When adding slits on the silicon diaphragms, tuning range of the BPF increases by 3.6 GHz. This low loss and wideband filter technique enables the use of tunable filters prior to low noise amplifiers in receiver systems with minimal impact on the system sensitivity.

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