MEMS-Tunable Highly-Loaded Cavity Bandstop Filters for X Band and Beyond

Eric Naglich[1*], Xiaoguang Liu[2*], Dimitrios Peroulis[1], and William Chappell[1]

****E. Naglich and X. Liu had equal contributions to the work in this paper.***

1. Purdue University, Birck Nanotechnology Center, West Lafayette, IN, U.S.A. 47907 enaglich@purdue.edu

2. University of California, Davis Davis, CA, U.S.A. 95616

Abstract: *Highly-loaded cavity bandstop filters have been shown that combine high quality factor, octave-wide tuning ranges, and dynamic response shape reconfiguration capability. These past filters operated in the 1 GHz to 6 GHz frequency range and were tuned using piezoelectric actuators. This paper presents highly-loaded cavity bandstop filters that operate over the 6 GHz to 21 GHz frequency range and are tuned using silicon MEMS diaphragm tuners that practically eliminate tuning hysteresis and frequency drift under static bias.*

Keywords: Electrostatic actuation; tunable cavity filters; microelectromechanical systems (MEMS); bandstop filters

Introduction

Tunable bandstop filters enable microwave systems to operate in the presence of dynamic interference that would otherwise saturate their receivers. Several tunable bandstop filter designs have been presented in response to an increasingly crowded spectral environment and interest in cognitive radio systems [1]. Many of these designs [2], [3] operate below 6 GHz and use solid-state varactors as tuning mechanisms. This choice of tuning mechanism can work well at low frequencies, but filter performance suffers significantly at high frequencies due to loss and parasitic capacitance associated with physical properties of the solid-state materials.

MEMS varactors have been shown that can extend the operating frequency of tunable bandstop filters to X band (8 GHz-12 GHz) while retaining good filter performance [4]. However, at such high frequencies, the quality factor (Q) of filters tuned with MEMS varactors is moderate (~100). In order to obtain very high (1,000-10,000) Q widely tunable bandstop filters at X band frequencies or higher, Yttrium-Iron-Garnet (YIG) filters are often used [5]. However, the use of YIG filters is sometimes undesirable due to their large power requirements for magnetic biasing and temperature control.

One bandstop resonator technology that is scalable to high frequencies while retaining wide tuning ranges and high (300-1000) Q values is the highly-loaded coaxial cavity resonator [6]. A model of a highly-loaded coaxial cavity resonator can be seen in Figure 1. Figure 1 a) shows that

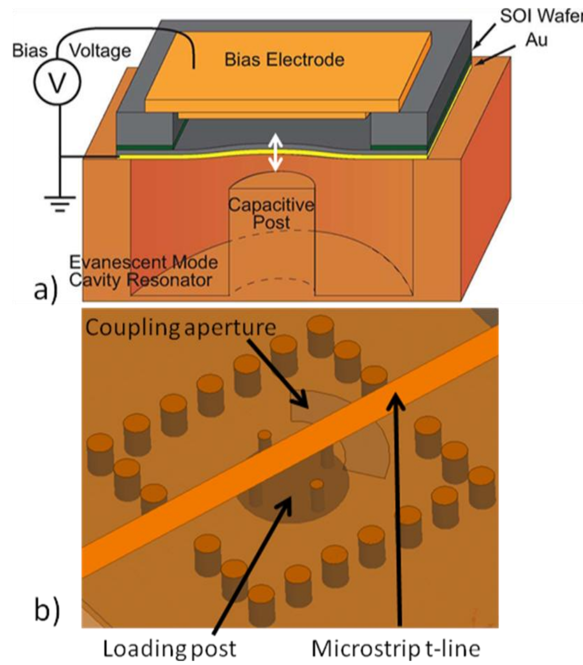

Figure 1. a) 3-D model of highly-loaded coaxial cavity with MEMS tuner and bias electrode. b) Substrate-integrated bandstop implementation

the structure is a conductor-walled, dielectric filled cavity with a loading element that is almost as tall as the cavity. A small air gap exists between the top of the loading post and the top wall of the cavity. When the air gap is small, the capacitance added to the cavity by the loading element is large enough to dominate the cavity capacitance. If the top wall of the cavity is made to be flexible, the air gap can be adjusted in order to tune the cavity over wide frequency ranges. The flexible top wall can be electromechanically tuned through the use of a bias electrode like the one shown in Figure 1 a) [6]. Figure 1 b) shows an example of a substrate-integrated implementation, where the conductive parts of the cavity are formed using plated vias. Figure 1 b) also shows a common external coupling mechanism, which is an aperture in the ground plane of a microstrip transmission line, where the ground plane also serves as a wall of the cavity. The flexible membrane would be on the bottom of the resonator in Figure 1 b), opposite the microstrip line. More information about practical substrate-integrated bandstop filter designs can be found in [6] - [8].

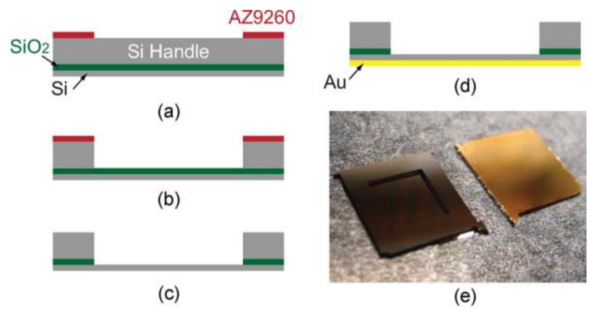

Figure 2. Fabrication process for MEMS diaphragm. a) AZ9260 patterning. b) DRIE. c) Oxide etch. d) Au sputter. e) Fabricated MEMS diaphragm.

This paper shows highly-loaded coaxial cavity bandstop filters that are scaled in frequency to operate in the 6 GHz to 21 GHz band. The filters are tuned with Silicon-On-Insulator (SOI) MEMS diaphragm tuners that practically eliminate tuning hysteresis and frequency drift under static bias. Such filter designs are promising in the space where high Q is required, the operating frequency is too high to use more standard varactor-tuned bandstop filters, and the power budget is too low to use YIG filters.

MEMS Diaphragm Tuners and Bias Electrodes

SOI MEMS diaphragm tuners were first shown in [6], where they were applied to filters in the low GHz frequency range. Figure 2 outlines the fabrication process of the tuners. First, an AZ9260 photoresist layer is patterned on the handle layer side of an SOI wafer as an etching mask for deep reactive ion etching (DRIE) (Figure 2 a)). The handle layer is then etched with DRIE (Figure 2 b)). The buried oxide layer has very high selectivity (> 200:1) to silicon in the DRIE process and serves as an etch stop layer. Next, the oxide layer is etched in buffered oxide etchant (Figure 2 c)). The device silicon layer is released after the removal of the oxide layer. The released diaphragm is flat due to the extremely low residual stress in the device silicon layer. Finally, a 1-μm-thick Au layer is deposited on top of the released silicon diaphragm by DC sputtering (Figure 2 d)). The sputtering condition is carefully controlled to achieve a low tensile stress in the metal layer. The stress- and defect-free nature of the single-crystal silicon device layer allows it to be a flexible yet robust mechanical support for the gold layer. Both sides of fabricated MEMS diaphragms can be seen in Figure 2 e). The total side length is 9.5 mm, and the side length of the flexible membrane inner part is 5 mm.

The bias electrode consists of two Au-sputtered pieces of silicon bonded together. Figure 3 shows both pieces and outlines the fabrication process. The smaller piece is shown in Figure 3 a), and its thickness, h, is controlled by timed wet etching in a 25% tetramethylammonium hydroxide (TMAH) solution at 80 ˚C. The etching condition ensures < 0.1-μm thickness control and a very smooth surface finish. The smaller piece fits into the recess in the MEMS diaphragm where the handle and oxide layers were etched away. The tight control of etching rates allows the fit and gap between the diaphragm and the bias electrode to be well controlled. Both pieces are then metalized with Au on both sides (Figure 3 b) and then bonded together by Au–Au thermal-compression bonding at 350 ˚C and 50-MPa pressure (Figure 3c)). A layer of 2-μm Parylene-C is deposited on the smaller piece side to create an insulation layer for biasing (Figure 3 d)). Figure 3 e) shows a completed bias electrode.

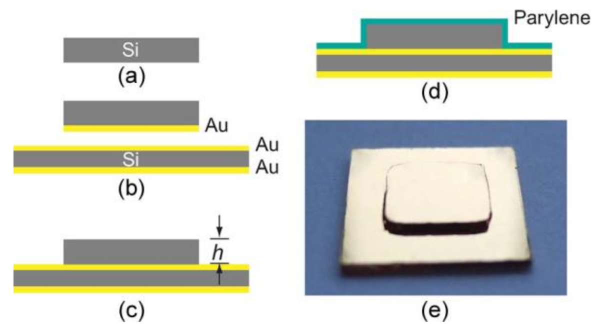

Figure 3. Fabrication process for bias electrodes. a) Top silicon piece. b) Au sputter. c) Au-Au thermal compression bonding. d) Parylene deposition. e) Fabricated electrode.

In order to deflect the gold-silicon membrane, a static bias voltage is applied to a bias electrode after it is placed such that the smaller piece of the electrode rests in the recess in the membrane. Since the membrane is grounded, an electrostatic force is produced that bends the membrane toward the bias electrode. The actuation is hysteresis-free, which makes potential control algorithms simpler. The tuners shown in this paper are frequency-scaled versions of the tuners in [6]. [6] shows calculations and/or measurements of important operational parameters of MEMS diaphragms of various sizes including but not limited to creep, tuning speed, and pull-in voltage.

Filter Design

2-pole and 4-pole narrowband Butterworth filters with a tuning range of 6 GHz to 12 GHz were designed and fabricated using the substrate-integrated, highly loaded cavities and SOI MEMS tuners described above. In addition, a 2-pole filter with a tuning range of 12 GHz to 21 GHz was designed and fabricated with similar technology. The MEMS tuners were attached to the cavities using conductive silver epoxy. All resonators were designed to have the same surface area (6.75 mm x 6.75 mm) so that a single MEMS tuner design could be used with all filter designs. This was possible through varying the size of the loading post in the cavities and the thickness of the substrate used to house the cavities.

Photographs of the 2-pole filter that could tune from 12 GHz to 21 GHz with and without MEMS tuners can be seen in Figure 4, along with a measurement fixture designed to give the filter mechanical stability under the stress and torque of connections to a network analyzer. The

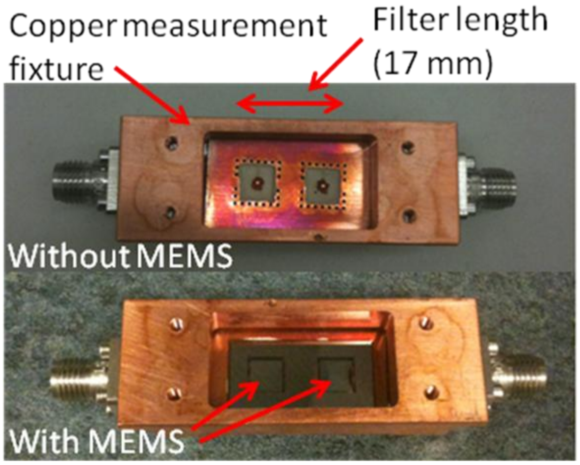

Figure 4. Photographs of the 12 GHz to 21 GHz filter with and without MEMS in a measurement fixture.

cavities were made in 0.762 mm thick Rogers TMM3 material, and the microstrip line was made on 0.254 mm thick Rogers 5880 material. The cavity surfaces were accurately polished in order to obtain small initial air gaps (approximately 5 μm) between the cavities' loading posts and the MEMS tuners. The MEMS tuners were designed to provide a maximum of 25 μm of deflection, making the tunable range of the air gap 5 μm to 30 μm. In order to achieve that tuning range, up to 600 Volts DC bias needed to be applied at very low current. Subsequent tuner designs that include corrugations or perforations in the membrane have reduced the required voltage for the same tuning range to below 100 Volts.

A model and images of the 6 GHz to 12 GHz tuning filters can be seen in Figure 5. The cavities for these designs were made in 3.175 mm thick Rogers TMM3 material, and the microstrip lines were made on 0.254 mm thick Rogers 5880 material. Figure 5 a) shows a simulation model of the 2-pole 6 GHz to 12 GHz tuning filter with relevant dimensions labeled. All of the resonators in the 6 GHz to 12 GHz tuning designs are the same. The loading post is not straight or cylindrically symmetric as in most past highly-loaded coaxial cavity designs to increase external coupling for a given coupling aperture size at a slight cost to quality factor [8]. Figure 5 b) shows the 2-pole filter with SMA connectors and MEMS tuners, and Figure 5 c) shows the 4-pole filter before the addition of these components with a U.S. quarter for size reference.

Measured Results

The measured transmission response of the 12 GHz to 21 GHz tunable 2-pole filter shown in Figure 4 can be seen in Figure 6. The actual measured tuning range was 12.1 GHz to 20.6 GHz. The filter provided 15 dB to 39 dB attenuation over the tuning range. Passband insertion loss over the tuning range varied from 1.5 dB at 12 GHz to a maximum of 3.7 dB at 15 GHz. By comparison to simulation and testing with various types of connectors, the cause of the ripples in the passband was the connector-to-

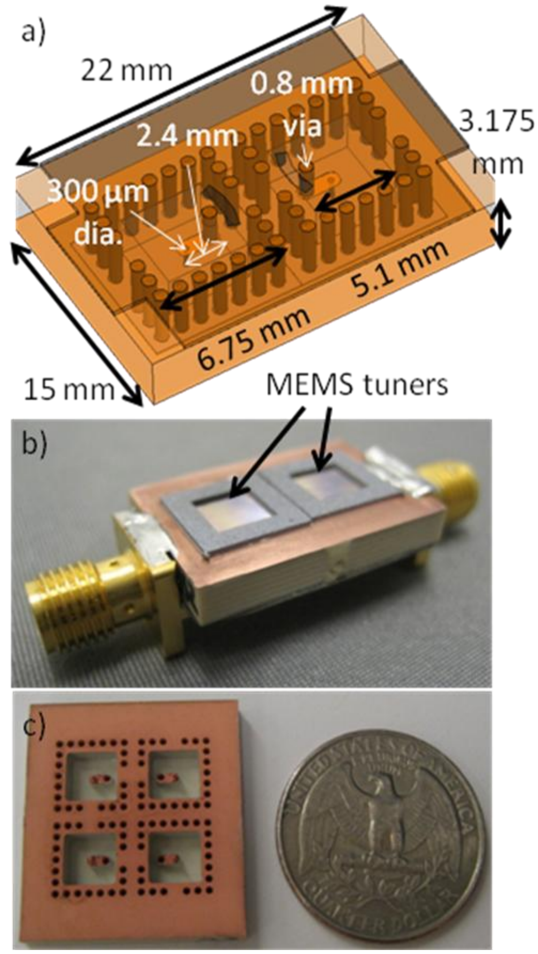

Figure 5. 6 GHz to 12 GHz tuning filters. a) Simulation model of 2-pole filter. b) Fabricated 2-pole filter. c) Fabricated 4-pole filter

microstrip transition. The microstrip line was made on a 0.254 mm thick substrate, which is much thinner than the dielectric inside of SMA and 2.92 mm connectors. Smaller connectors, a thicker microstrip substrate, or probe measurements would help to mitigate this effect. Figure 7 shows the measured results of the 6 GHz to 12 GHz tuning 2-pole bandstop filter design shown in Figure 5 b). The measured tuning range was 5.9 GHz to 11.4 GHz. Isolation ranged from 15 dB to 36 dB across the tuning range, while the passband insertion loss ranged from 0.4 dB to 3.8 dB. Above 12 GHz, the passband deteriorates rapidly. This is an effect of the inductance added to the microstrip line ground plane by the coupling apertures [7].

Figure 8 shows the measured results of the 4-pole 6 GHz to 12 GHz tuning bandstop design shown in Figure 5 c). The measured 4-pole tuning range was 6.2 GHz to 10.8 GHz. 32 dB to 64 dB isolation was achieved. Passband insertion loss varied from 0.5 dB to 4.0 dB over the tuning range.

The quality factor of similarly constructed resonators was determined to be between 300 and 1000 in the range of 6 GHz to 21 GHz. The limiting factor of Q is the silver epoxy

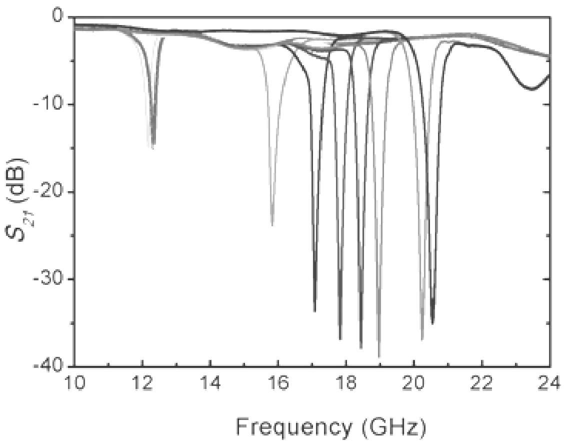

Figure 6. Measured S_{21} results of 12 GHz to 21 GHz tuning 2-pole bandstop filter.

attachment method that was used, and lower-loss attachment methods are currently being developed. The tuning speed of the MEMS diaphragms allows for tuning across the total frequency range in 100's of μs, and it is dependent on the size and thickness of the diaphragms [6]. Corrugations or perforations in the diaphragms can increase tuning speed at the cost of quality factor.

Conclusion

The extension of SOI MEMS diaphragm tuned bandstop filters to the 6 GHz to 21 GHz frequency range was shown in this paper. The ability to retain high Q performance at X band and above sets such filters apart from solid state varactor and tunable dielectric filters, while their low-power operation distinguishes them from YIG filters. Combined with the hysteresis-free and low-creep operation of SOI diaphragm tuners that enable simplified control schemes, these filters offer important capabilities to high frequency systems of the future.

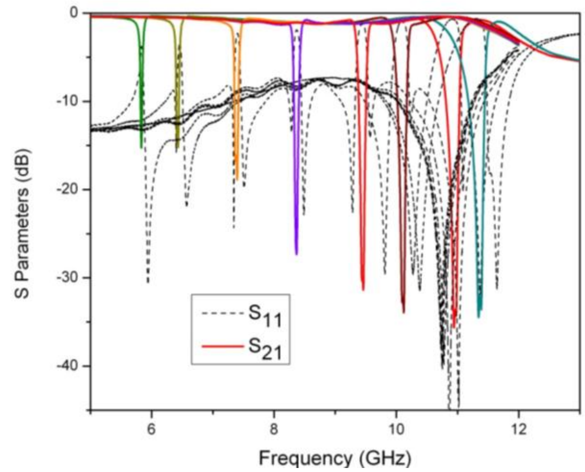

Figure 7. Measured results of the 6 GHz to 12 GHz tuning 2-pole filter across the tuning range.

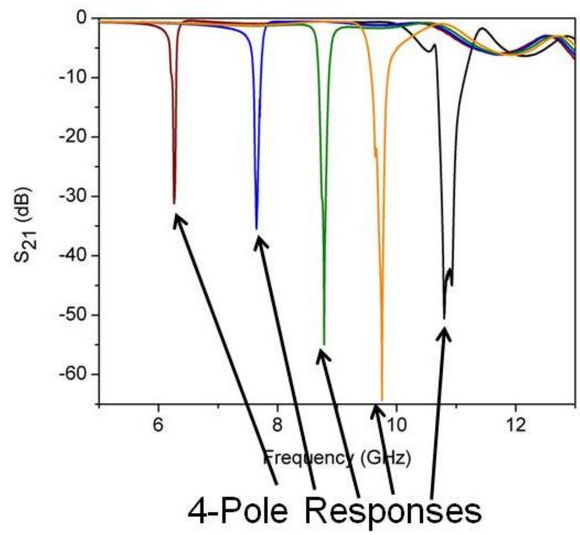

Figure 8. Measured results of the 6 GHz to 12 GHz tuning 4-pole filter across the tuning range.

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