Substrate-Integrated Coaxial-Cavity Filter With Tunable Center Frequency and Reconfigurable Bandwidth

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***Abstract*—This paper presents a substrate-integrated coaxial-cavity bandpass filter with both continuous center frequency tuning and continuous bandwidth (BW) tuning. A surface mount varactor connects the center conductors of the coaxial resonators. Tuning this varactor's capacitance changes the inter-resonator coupling between the resonators and tunes the BW. Another surface mount varactor on the coplanar waveguide feed line adjusts the external coupling at different BWs. Lumped varactors are also used to capacitively load the coaxial transmission line to tune the center frequency. Measured results show a BW range of 20–100 MHz from 0.8 GHz to 1.13 GHz and a BW range of 34–40 MHz from 0.55GHz to 1.13 GHz with return loss better than 10 dB. Peak insertion loss of 1.07 dB is measured at 1.13 GHz with 100 MHz BW. Due to dispersive inter-resonator coupling, a transmission zero occurs above the passband that sharpens skirt selectivity. Fabrication is compatible with standard PCB technology with single-layer surface-mount lumped elements as tuners.**

***Index Terms*—combline filter, combline resonator, evanescent-mode design, tunable bandwidth, tunable filters, tunable resonators, waveguide filters**

I. Introduction

The recent interest in reconfigurable microwave systems requires tunable filters. Challenges arise in tunable filters when trying to achieve wide tuning with a constant bandwidth (BW) or constant fraction bandwidth (FBW) while maintaining an acceptable return loss. A filter with adjustable bandwidth and simultaneous center frequency tuning is an attractive solution to maintain constant BW or FBW. For example, a planer microstrip filter reports frequency tuning from 0.669 GHz to 1.215 GHz with a constant BW of 310 MHz [1]. Another planer microstrip tunable filter reports a frequency range of 0.6–1.4 GHz with a 40 MHz constant BW [2]. 3-D cavity filters, in particular highly loaded evanescent-mode (EVA) cavities, have been considered instead of planar structures for higher unloaded quality factor (Q_u). For example, [3] shows a tunable EVA filter with constant BW of 25 MHz over a frequency range of 0.89–1.47 GHz. This structure however is complex in fabrication compared to planar structures because it requires multiple layers and requires precise assembly to align the piezoelectric-actuator with the cavity post. All of these structures are BW adjustable in at least part of the tuning range.

Fig. 1 shows a proposed substrate-integrated 3-D coaxial cavity two-pole filter as an alternative between low Q planar and high Q air-filled 3-D filters. Previous works show that such filters have the ease of fabrication of 2-D planer structures with lumped elements but achieve higher Q_u [4]–[7]. Whereas [4]–[7] show only tunable center frequency, this work shows tunable center frequency and tunable BW. Fig. 1 shows that the center frequency, BW, and external coupling is reconfigured by various surface mounted varactors. Measured results in section III shows center frequency tuning of 0.55–1.13 GHz with BW ranging from 20 MHz to 100 MHz for the most part, except in the lower frequency range where BW can range from 34 MHz to 40 MHz with 10 dB minimum return loss.

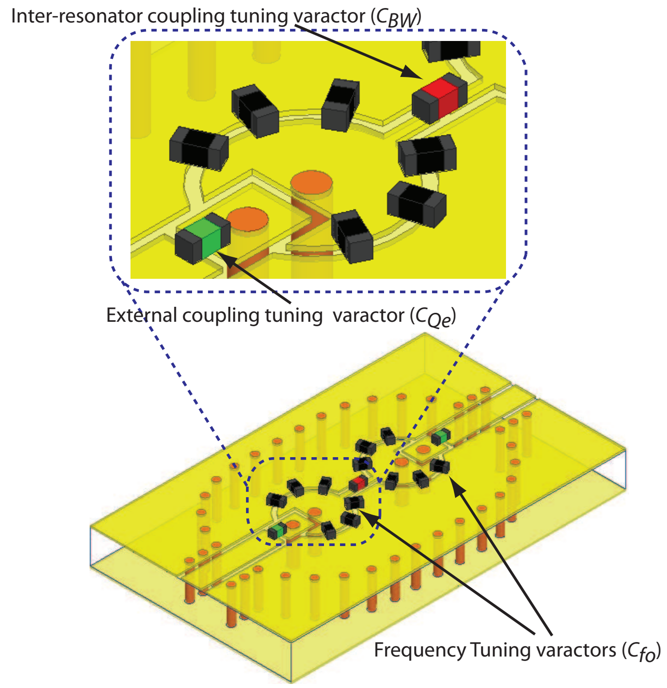

Fig. 1. Proposed substrate-integrated 3-D coaxial cavity two-pole filter and close up of top surface showing the various lumped components

II. Design

In [5] and [6], a ring gap is created on the top surface of a coaxial cavity resonator isolating the cavity's top surface from the center post (Fig. 2(a)). Varactors are then mounted on the ring gap to tune the center frequency of the resonator. This is analogues to capacitively loading microstrip transmission lines in planar combline filters. The shorted coaxial transmission line looks inductive with capacitive loading and resonates with the varactors like a LC tank [8]. The similarity in tuning the center frequency is evident in the previously demonstrated structure in Fig. 2(a) and the proposed structure in Fig. 1 with the frequency tuning varactors (C_{fo}) mounted on the ring gaps.

To maintain the high Q_u of 3-D cavities and achieve

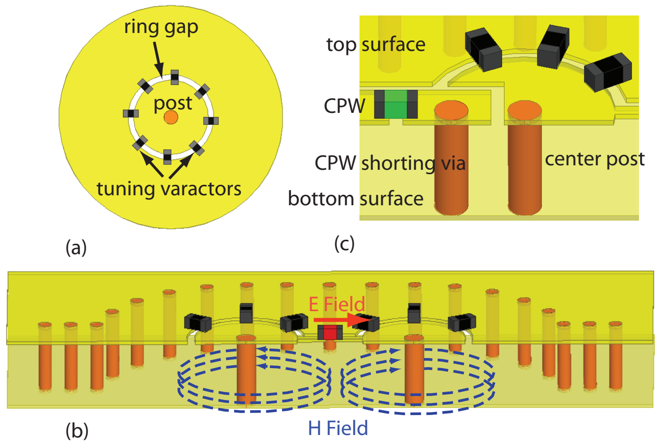

Fig. 2. (a) Previously demonstrated resonator in [5] and [6] and (b) proposed mixed inter-resonator magnetic and electric coupling. (c) Tunable external coupling structure where CPW is shorted from top to bottom surface.

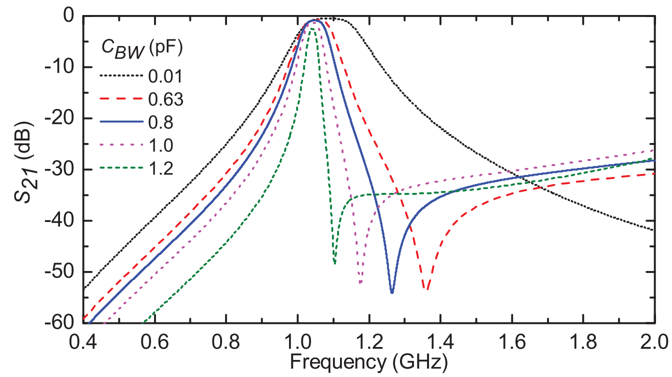

Fig. 3. Ansys HFSS filter simulation shows that as C_{BW} increases and becomes significant, BW decreases and a transmission zero appears above the passband.

bandwidth tuning, [3] showed that two paths for inter-resonator coupling are needed: a primary dominant path with fixed amount of coupling and a weaker secondary path with tunable coupling. Low Q tuners can be used in the secondary path to tune the BW without significantly affecting Q_u. Thus, a secondary inter-resonator coupling path is used to adjust the bandwidth. Fig. 2(b) illustrates this concept more clearly (external coupling not shown): the dominant primary inter-resonator coupling is between the magnetic fields created by the two closely placed posts and the secondary weaker inter-resonator coupling is through the electric fields created by the lumped varactor (C_{BW}). The mixed magnetic and electrical inter-resonator coupling (k) is shown in [9] to be

$$k = \frac{k_M + k_E}{1 + k_M k_E} \approx k_M + k_E \qquad (1)$$

for narrow band filters where k_M is the magnetic inter-resonator coupling and k_E is the electric inter-resonator coupling.

In the presented structure, the signs of magnetic $(+)$ and electric $(-)$ coupling are opposite. Around the center frequency, if the magnetic field is designed to be dominant, then $k \approx k_M - k_E$ and $k > 0$. Thus, BW will decreases as k_E increases. Additionally, if k_M and k_E have opposite signs, it is possible that the magnetic and electric coupling can cancel each other at a particular frequency to produce a transmission zero (TZ). Such TZs are well known for mixed electric and magnetic structures with dispersive coupling in both planar and non-planar structures [10]–[19]. Full Wave Ansys HFSS simulation in Fig. 3 shows that BW does decreases as k_E increases and a TZ occurs above the passband. Initially, $C_{BW} = 0.01$ pF (negligible k_E) and BW is maximum while no TZ is observed up to 2 GHz. As C_{BW} is increased to a significant value (k_E increased), BW decreases and a TZ appears in the frequency range. Thus HFSS validates that k_E and k_M indeed have opposite signs. The two-pole filter dimensions and parameters for HFSS simulation (and fabrication) are discussed in section III. Note that the electrical coupling can become the dominant inter-resonator coupling path ($|k_E| > |k_M|$) if C_{BW} is large enough and in this case, the TZ will occur below the passband.

Fig. 1 shows that a coplanar waveguide (CPW) feed structure on the top surface of the cavity is used to provide external coupling (Q_e) to the filter. The CPW line extends towards the center post where it is then shorted to the cavity's bottom surface through a conductive via [20] (Fig. 2(c)). Thus current flows from the CPW line through the CPW shorting via and to the bottom surface. Magnetic fields generated by the current flowing through the CPW shorting via couples to the center post and into the resonators. Since the BW of the filter will be tuned, the value of Q_e will also need to tuned. To make Q_e adjustable, gaps are created on the surface of the CPW line and varactors C_{Qe} are mounted over these gaps. These varactors can vary the amount of current that flows through the CPW shorting via and change the amount of magnetic field coupling into the resonators. Thus, tuning C_{Qe} tunes Q_e.

III. Experimental Validation

A Rogers TMM3 board is used to fabricate the two-pole substrate-integrated coaxial cavity filter. Vias are drilled in the substrate and plated with copper to form the cavities following the guidelines given in [21]. The center posts and CWP shorting vias are also created with copper plated vias. The top copper surface is milled to make the CPW traces and ring gaps. Then Skyworks SMV1405 varactors with $0.8\ \Omega$ resistance and 0.63–2.67 pF capacitance are placed back-to-back to reconfigure the filter response: 64 varactors for frequency tuning, 2 varactors for BW tuning, and 16 varactors for external coupling tuning. Fig. 4(a) and (b) show close up and full view of the designed filter with dimensions in mm and Fig. 4(c) shows the fabricated filter with back-to-back varactors. Fig. 4(c) also shows the dc bias lines needed to tune the varactors where dc_{Qe} tunes C_{Qe}, dc_{fo1} and dc_{fo2} tunes the two C_{fo} individually (mismatch in dc bias is due to fabrication), and dc_{BW} tunes C_{BW}. Lumped resistors are used in the dc bias lines to reduce RF loss.

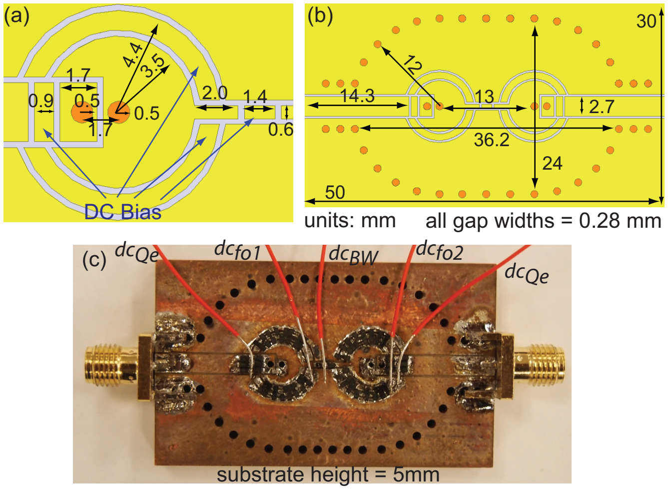

Fig. 4. Designed filter dimensions (units in mm) with (a) close up and (b) full view. (c) Fabricated filter with back-to-back varactors.

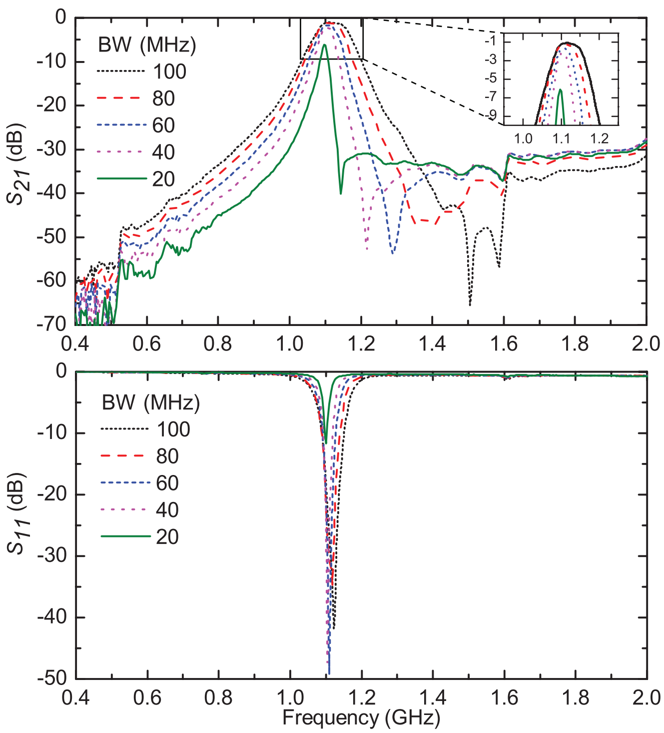

Fig. 5. Measured S_{21} for fabricated two-pole tunable filter. Both BW and TZ frequency decrease as k_E is increases.

Fig. 5 shows measured results around 1.13 GHz as k_E is increased by tuning C_{BW}: BW decreases from 100 MHz to 20 MHz. As expected from section II, the inter-resonator TZ frequency also decreases as k_E increases improving the skirt selectivity. Peak insertion loss of 1.07 dB at 1.13 GHz is measured and $\approx$ 30 dB of out band rejection is maintained up to 2 GHz.

Fig. 6 shows measured S_{21} and S_{11} as both BW and center frequency are tuned. Though the filter can continuously tune center frequency and BW, only the maximum and minimum

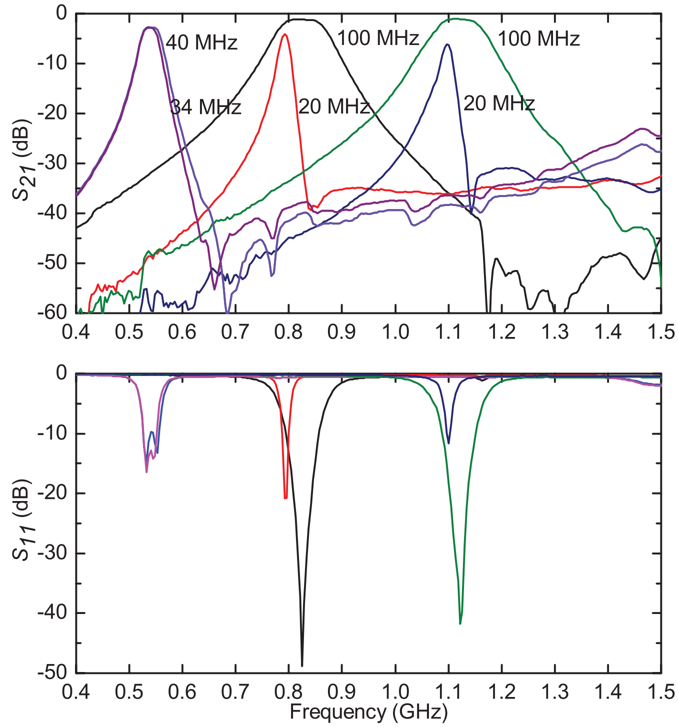

Fig. 6. Measured (a) S_{21} and (b) S_{11} showing the maximum and minimum bandwidths at selected frequencies. The filter can continuously tune center frequency and BW.

BWs at selected frequencies are shown. Octave frequency tuning (0.55–1.13 GHz) is demonstrated with BW ranging between 20–100 MHz (1.77–8.85% FBW) around 1.13 GHz, 20–100 MHz (2.5–12.5% FBW) around 0.80 GHz, and 34–40 MHz (6.2–7.3% FBW) around 0.55 GHz. The BW is limited by external coupling at lower frequencies. A return loss better than 10 dB is maintained at all measured BWs. In summary, this filters achieves a constant BW of 20–100 MHz from 0.8 GHz to 1.13 GHz and 34–40 MHz over the octave tuning range of 0.55–1.13 GHz.

IV. Conclusion

This paper presents a filter with both tunable center frequency and tunable BW while maintaining an acceptable return loss by adjustable the external coupling. BW is tuned by biasing the varactor connecting the center conductors of the coaxial resonators to change the inter-resonator coupling. Similarly, varactors on input/output feed lines adjust the external coupling and varactors on the surface gap tune the center frequency. Measured results show a BW range of 20–100 MHz from 0.8 GHz to 1.13 GHz and a BW range of 34–40 MHz from 0.55GHz to 1.13 GHz. A transmission zero from dispersive coupling is also observed above the passband that sharpens skirt selectivity.

Acknowledgment

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