Octave-Tunable Constant Absolute Bandwidth Bandstop Filter Utilizing a Novel Passively-Compensated Coupling Method

Mark D. Hickle and Dimitrios Peroulis

Birck Nanotechnology Center, School of Electrical and Computer Engineering,

Purdue University, West Lafayette, IN 47907 USA

Abstract — A new passively-compensated coupling structure, compatible with evanescent-mode cavity resonators and capable of producing constant absolute bandwidth over wide tuning ranges, is presented for the first time. It is used to realize a constant absolute bandwidth 2.0 to 4.2 GHz tunable bandstop filter which utilizes evanescent-mode cavity resonators. The filter has high levels of stopband rejection (> 50 dB) across its entire tuning range, and has a 54.5 ± 6.5 MHz 3-dB fractional bandwidth. When compared to the coupling method traditionally used for evanescent-mode resonators, the proposed method reduces the bandwidth variation of this filter from 295% (21 to 83 MHz) to 27% (48 to 61 MHz).

Index Terms — Filters, microwave filters, passive filters, tunable filters, tunable resonators.

I. Introduction

One of the many challenges associated with frequency-tunable filters is the ability to maintain a constant bandwidth (fractional or absolute) across the filter's tuning range. The bandwidths of microwave filters are determined by the magnitudes of their coupling coefficients, and typical microwave coupling structures produce frequency-dependent coupling values. This phenomenon can be seen in [1], which demonstrates a tunable bandstop filter whose 3-dB fractional bandwidth varies from 1.2% to 3.2% when tuned from 0.65 to 1.65 GHz, and in [2], whose fractional bandwidth changes from 1.6% to 4.2% when tuned over a 0.56 to 1.18 GHz tuning range. Similarly, the filter in [3] experiences a 4.0% to 5.9% 10-dB bandwidth change when tuned from 8.9 to 11.3 GHz. These examples show the difficulty in maintaining constant fractional bandwidth over a wide tuning range, but the task of maintaining a constant absolute bandwidth is even more challenging, as doing so requires the fractional bandwidth to decrease linearly with respect to frequency.

Several methods for reducing bandwidth variation have been proposed in literature. Examples of constant-bandwidth filters utilizing tunable coupling elements have been presented ([4], [5]), but the addition of tunable coupling adds additional loss and tuning complexity, and it is desirable to instead develop a method for maintaining constant bandwidth without additional tuning elements. Guyette demonstrated in [6] that when utilizing edge-coupled microstrip resonators, the length of the coupling section can be optimized to reduce bandwidth variation by mixing electric and magnetic coupling. A similar approach is used in [7], which also optimizes the length of the external coupling section to minimize bandwidth variation. This method is not applicable to all resonators, however, as it relies on the use of mixed electric and magnetic coupling, which is not possible with all resonator technologies. For example, high quality factor tunable evanescent-mode cavity resonators [5] can only utilize magnetic external coupling due to the spatial distribution of the electric and magnetic fields in their resonators, and thus the previous methods of bandwidth compensation cannot be used.

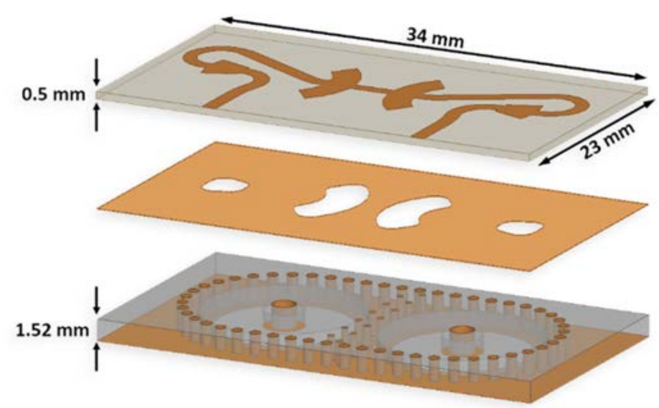

Fig. 1. Exploded view of the proposed constant-bandwidth tunable bandstop filter.

This paper presents, for the first time, a constant-bandwidth coupling scheme which is compatible with tunable bandstop filters utilizing evanescent-mode cavity resonators. This method is passive and does not require additional tuning elements. It is used to realize a constant-absolute-bandwidth tunable quasi-absorptive bandstop filter, which provides high stopband rejection over an octave tuning range while maintaining nearly-constant absolute bandwidth.

II. Constant-Bandwidth Coupling Scheme

To address the issue of bandwidth variation in filters which cannot use mixed electric/magnetic coupling, a bandwidth equalization structure independent of the filter's specific resonator and coupling technology is proposed. It consists of a resonator that is coupled twice to a through-line, with a transmission line of electrical length θ between the coupling elements as shown in Fig. 2(a). It can be shown that this structure has an equivalent circuit consisting of a resonator

978-1-5090-0698-4/16/$31.00 ©2016 IEEE

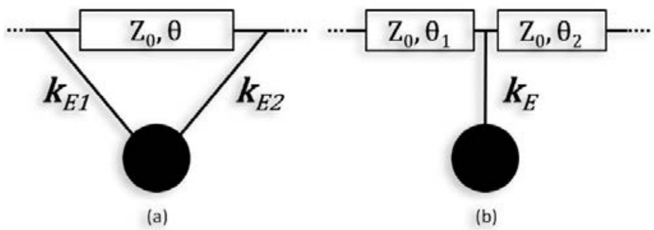

Fig. 2. (a) The proposed coupling structure. (b) Equivalent circuit of (a).

coupled to a through-line with a single coupling k_E, preceded and followed by transmission lines of electrical lengths θ_1 and θ_2. The values k_E, θ_1, and θ_2 are defined as follows [4]:

$$k_E = \sqrt{{k_{E1}}^2 + {k_{E2}}^2 + 2k_{E1}k_{E2}\cos(\theta)} \quad (1)$$

$$\theta_1 = \frac{1}{2}\left(\pi - \arg\left(-\frac{\frac{k_{E1}}{k_{E2}} + e^{-j\theta}}{\frac{k_{E1}}{k_{E2}} + e^{j\theta}}\right)\right) \quad (2)$$

$$\theta_2 = \theta - \theta_1 \quad (3)$$

Since the electrical length of a TEM or quasi-TEM transmission line is directly proportional to frequency, the equivalent coupling value k_E is frequency-dependent even when k_{E1} and k_{E2} are constant. The frequency dependence of k_E is plotted in Fig. 3 for several ratios of k_{E1}/k_{E2}. It can be seen that there are two regions in which the total coupling k_E decreases with increasing frequency: $0^o < \theta < 180^o$, when k_{E1} and k_{E2} have the same sign (—■— —●—), and $180^o < \theta < 360^o$ when k_{E1} and k_{E2} have opposite signs (—▲— —▼—). If the length of through-line is chosen within one of these regions as the filter's center frequency is tuned, then this negative frequency dependence can be used to compensate for the positive frequency dependence inherent to the individual coupling elements.

III. Design of an Octave-Tunable Constant-Bandwidth Bandstop Filter

The proposed concept was used to realize a tunable two-pole quasi-absorptive evanescent-mode cavity-resonator-based bandstop filter which has little bandwidth variation over an octave center-frequency tuning range. An exploded view of the proposed filter is shown in Fig. 1, and details are shown in Fig. 4. The filter utilizes two substrate-integrated evanescent-mode cavity resonators which achieve frequency tuning by means of a movable conductive membrane placed on top of each cavity, which changes a capacitive gap between the cavity's loading post and the cavity's ceiling. The resonators are coupled to a source-to-load transmission line with two coupling elements per resonator, in order to implement the topology of Fig. 2(a). The external coupling elements are realized with apertures in the cavity's ground plane, which is the shared ground plane of the microstrip transmission lines. The filter is designed to be quasi-absorptive in order to provide theoretically-infinite stopband rejection [8], and thus interresonator coupling is added between the two resonators. An iris between the two resonators is used to implement the interresonator coupling, and an array of vias connecting the top and bottom of the coupling iris (similar in

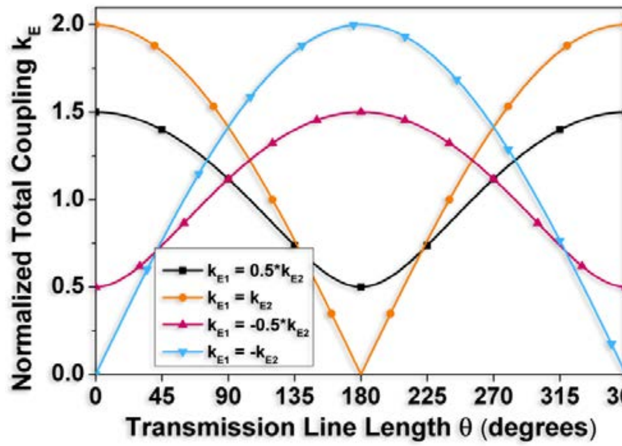

Fig. 3. Dependence of k_E on electrical length θ. k_{E2} = 1.

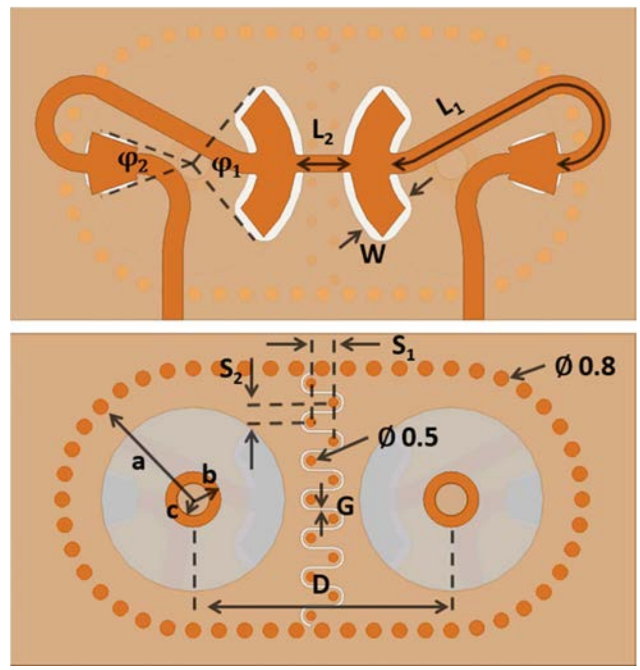

Fig. 4. Dimensions of the designed filter (in millimeters). L_1 = 17.6, L_2 = 2.7, W = 3, $\varphi_1 = 60^o$, $\varphi_2 = 32^o$, a = 6.7, b = 1.5, c = 0.9, S_1 = 1.2, S_2 = 1.05, G = 0.15, D = 14.

concept to [9]) is used to reverse the flow of current in the coupling section in order to reverse the sign of the coupling coefficient as required for the quasi-absorptive design. A meandered section of microstrip transmission line is placed between the coupling apertures to implement the transmission line of length θ from Fig. 2(a).

The frequency variation of the coupling coefficient from a single coupling aperture (the traditional coupling method for tunable cavity resonators, e.g. [2]) is shown in Fig. 5. It is evident that the external coupling coefficient increases as frequency increases, which leads to variation in the bandwidth. However, with the proposed coupling method when both coupling apertures are considered along with the length of transmission line in order to implement the topology of Fig. 2(a), it is seen in Fig. 5(b) that a variety of coupling value frequency dependencies can be realized by choosing different

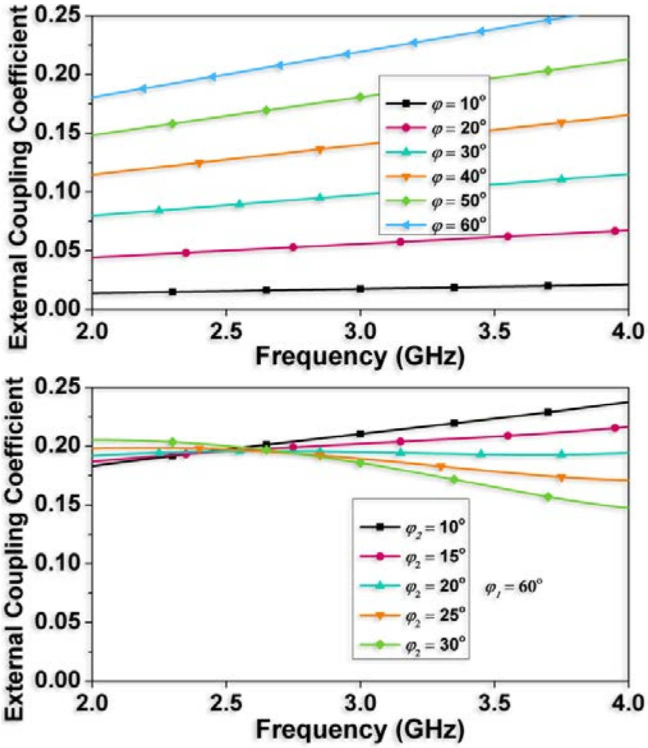

Fig. 5. (top) Variation of the coupling coefficient from a single coupling aperture. (bottom) Variation of the total coupling coefficient from the structure of Fig. 2(a) for a range of values of φ_2 when $\varphi_1 = 60^o$.

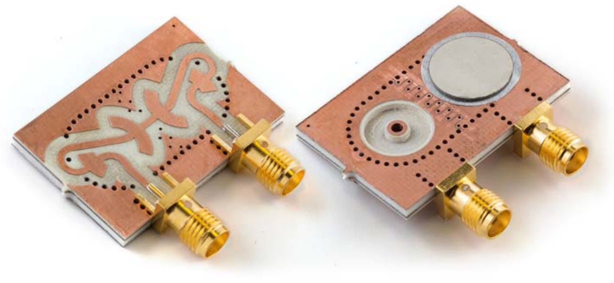

Fig. 6. Photograph of the fabricated constant-bandwidth filter. One piezo disk is removed to show the cavity resonator.

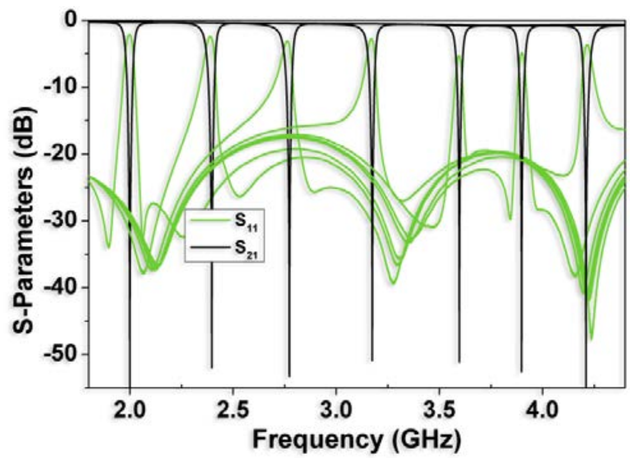

Fig. 7. Measured S-Parameters of the constant absolute bandwidth filter.

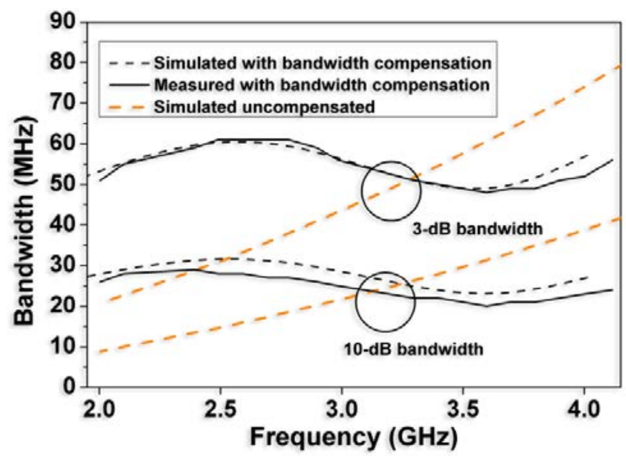

Fig. 8. Measured and simulated 3-dB and 10-dB bandwidths of the constant-bandwidth design compared to the simulated uncompensated case.

ratios of coupling aperture sizes. The coupling structure can realize a constant coupling coefficient (e.g. $\varphi_1 = 60^o$, $\varphi_2 = 20^o$) for a constant fractional bandwidth, or a coupling coefficient with a negative frequency dependence (e.g. $\varphi_1 = 60^o$, $\varphi_2 = 30^o$) for constant absolute bandwidth.

IV. Measured Results

The filter from Section III was fabricated using an in-house multi-layer PCB process, and the final device is shown in Fig. 6. The cavity and signal substrates are made of 1.524 mm and 0.508 mm thick Rogers 4350B material, respectively. Piezoelectric disk actuators are used as the tuning elements. All final dimensions are shown in Fig. 4.

The filter has slightly more than an octave tuning range (2 to 4.2 GHz) with a ±180 V bias voltage as shown in Fig. 7, and has greater than 50 dB of stopband rejection across the entire tuning range. Less than 0.7 dB of passband insertion loss and greater than 17 dB of return loss are achieved up to 4.5 GHz. The unloaded quality factor of the resonators was extracted from the measurement of a single resonator to be 350 at 3.5 GHz. The 3-dB and 10-dB bandwidths are 54.5 ± 6.5 MHz and 24.5 ± 4.5 MHz, respectively, with good agreement between simulation and measurement. The simulated bandwidth of a filter utilizing only a single coupling aperture per resonator (identical to Fig. 4 with $\varphi_1 = 47^o$ and $\varphi_2 = 0^o$) is plotted alongside the measured bandwidth of the demonstrated filter for comparison, and it can be seen that the new coupling method reduces the 3-dB bandwidth variation from 295% (21 to 83 MHz) to 27% (48 to 61 MHz).

V. Conclusion

A coupling structure capable of producing constant bandwidth over wide tuning ranges amenable to use in evanescent-mode cavity resonators is presented for the first time, and is used to realize a constant absolute bandwidth 2.0-4.2 GHz tunable bandstop filter. The filter has high levels of stopband rejection (> 50 dB) and has little absolute bandwidth variation over its octave tuning range. To the best of the authors' knowledge this is the first time that a constant-bandwidth scheme applicable to tunable bandstop filters utilizing evanescent-mode cavity resonators has been presented.

ACKNOWLEDGEMENT

Mark D. Hickle was supported by the Department of Defense (DoD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) program.

REFERENCES

[1] E. J. Naglich, J. Lee, and D. Peroulis, "Tunable bandstop filter with a 17-to-1 upper passband," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, 2012, pp. 1–3.

[2] A. Anand, Y. Liu, and X. Liu, "Substrate-integrated octave-tunable combline bandstop filter with surface mount varactors," in *Wireless Symposium (IWS), 2014 IEEE International*, 2014, pp. 1–4.

[3] I. Reines, S.-J. Park, and G. M. Rebeiz, "Compact Low-Loss Tunable -Band Bandstop Filter With Miniature RF-MEMS Switches," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 7, pp. 1887–1895, Jul. 2010.

[4] A. C. Guyette, "Intrinsically Switched Varactor-Tuned Filters and Filter Banks," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 4, pp. 1044–1056, Apr. 2012.

[5] H. Joshi, H. H. Sigmarsson, S. Moon, D. Peroulis, and W. J. Chappell, "High- Fully Reconfigurable Tunable Bandpass Filters," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 12, pp. 3525–3533, Dec. 2009.

[6] A. C. Guyette, "Alternative architectures for narrowband varactor-tuned bandpass filters," in *Microwave Integrated Circuits Conference, 2009. EuMIC 2009. European*, 2009, pp. 475–478.

[7] X.-Y. Zhang, C.-H. Chan, Q. Xue, and B.-J. Hu, "RF Tunable Bandstop Filters With Constant Bandwidth Based on a Doublet Configuration," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 1257–1265, 2012.

[8] D. R. Jachowski, "Compact, frequency-agile, absorptive bandstop filters," in *Microwave Symposium Digest, 2005 IEEE MTT-S International*, 2005, p. 4 pp.–.

[9] E. J. Naglich, D. Peroulis, and W. J. Chappell, "Wide spurious free range positive-to-negative inter-resonator coupling structure for reconfigurable filters," in *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International*, 2013, pp. 1–4.

978-1-5090-0698-4/16/$31.00 ©2016 IEEE