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Broadband Implementation of Tunable, Substrate-Integrated, Evanescent-Mode, Cavity Bandpass Filters

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***Abstract*—A novel structure for implementing broadband external and internal coupling in heavily loaded, substrate integrated, evanescent-mode, cavity filters is presented. The proposed structure is based on adding electric field coupling to the magnetic field iris coupling, which is commonly used for such cavities. It is shown that fractional bandwidth on the order of 40% can be achieved using this new structure. As an illustration, a second order Butterworth filter is designed using the presented coupling method and then fabricated inside a two-layer RF circuit board. The measured and simulated filter results are shown to be in good agreement, with measured insertion loss of around 0.4 dB including connector losses. Finally, the filter is continuously tuned from 2910 MHz to 3795 MHz.**

***Index Terms*—Filters, band-pass filters, microwave filters, tunable filters, wideband filters, evanescent-mode filters.**

I. INTRODUCTION

Spectrum management is becoming increasingly important as more wireless systems emerge each year, further crowding this already scarce resource. Ideally, future systems will possess the ability to cognitively adjust their operation to the spectral occupancy at any given instance. This envisioned development has resulted in an increased interest in multiband/multi-mode radios in recent years. These systems need reconfigurable RF front-ends with the capability of processing wide ranges of wireless signals. Tunable filters are key front-end components; therefore, extensive research has been devoted to tunable bandpass and bandstop filter design. A wide range of technologies for realizing tunable filters has been investigated, such as using varactors, MEMS, ferro-electric thin films, and evanescent-mode cavities [1], [2], [3], [4]. Maintaining high quality factor (Q) while tuning frequency, bandwidth, and/or filter shape is sought after for narrowband applications [4], [5], [6]. However, tunable filters with broad bandwidths have not been investigated as extensively. There are limitations to the achievable bandwidth that commonly used coupling structures can provide. These limitations are often a side-effect of confining either the electric or magnetic field in order to increase the frequency sensitivity of the resonator structure.

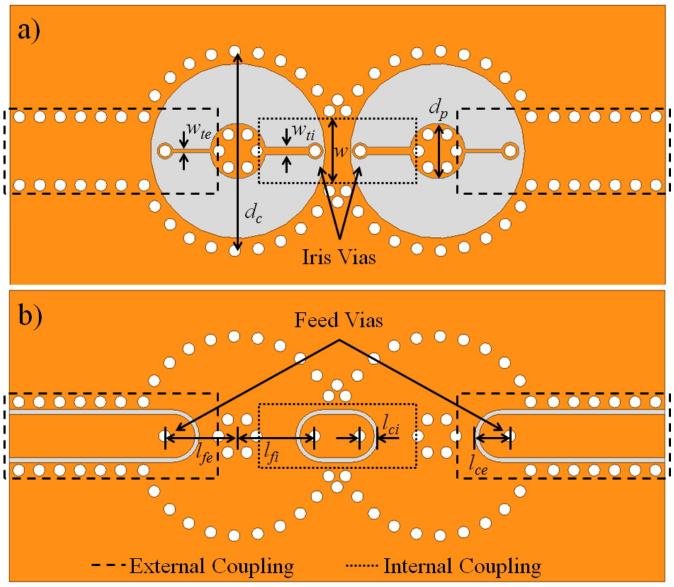

Fig. 1. Layout of the proposed filter structure, a) top layer, b) bottom layer. The emphasized external and internal coupling sections are designed separately and combined to form the complete filter.

In spite of these limitations, a network synthesis method for wideband microwave filter has already been developed [7]. However, achieving the appropriate coupling mechanism for broadband coupling using specific filter technologies still requires investigation. In this paper, a novel structure for broadband coupling in substrate integrated, evanescent-mode cavity filters is presented. In order to increase the external coupling, direct tapping to the center post of the cavity is used in addition to the magnetic field coupling from the feed transmission line. The internal coupling is similarly increased by using the same type of direct tapping in addition to a traditional inductive magnetic iris. An example filter is created to demonstrate that this structure can be used to realize bandpass filters with fractional bandwidths on the order of 40%. By changing the capacitive loading gap using a commercial

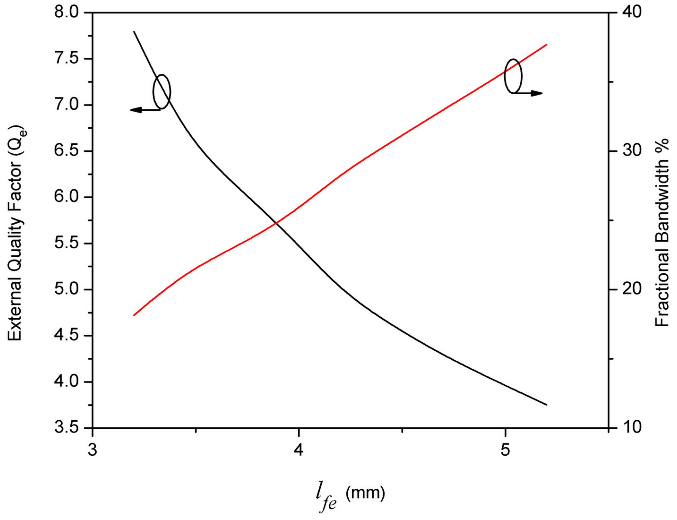

Fig. 2. Simulated external Q of the proposed filter structure at 3300 MHz as a function of the external feed via position. The other design variables are kept fixed as shown in Table I.

piezoelectric transducer, a center frequency tuning range of 30% is achieved while maintaining an insertion loss of less than 0.4 dB.

II. WIDEBAND COUPLING IMPLEMENTATION

Aperture coupling has been widely used for realizing external coupling of substrate-integrated, evanescent-mode, cavity filters both for bandpass and bandstop operation. In bandpass filters, the apertures are usually used in combination with a short circuit termination of a coplanar waveguide to couple the signal into the resonators [4]. In the case of bandstop filters, the apertures are commonly incorporated as defects in the ground plane of a microstrip line acting as the through line between the source and the load [8]. In both cases, the aperture provides a magnetic field coupling between the transmission line and the first mode of the resonator [8]. However, the achievable coupling magnetic field coupling strength using these previously demonstrated aperture coupling methods, is limited since the magnetic field is distributed over the entire cavity. A method for confining the magnetic field was demonstrated in an evanescent-mode cavity bandstop filter [6]. In this method, the lower part of the center post was brought closer to the outer walls of the cavity resulted in increased coupling strength and external Qs on the order of 50. An alternative method for providing high external coupling uses a U-shape transmission line that is routed through the cavity instead of the aperture. This method is capable of providing external Qs down to around 40 [9]. However, for realizing very wide bandpass filters, even stronger external coupling is required. For example, for a second order Butterworth filter with 40% fractional bandwidth the required external Q is 3.53 or an order of magnitude lower than what has previously been reported. Since the electric field is primarily confined between the top of the cavity and the center post, tapping directly into the electric field, using a tap-line technique, will result in coupling levels that are suitable for wideband filters.

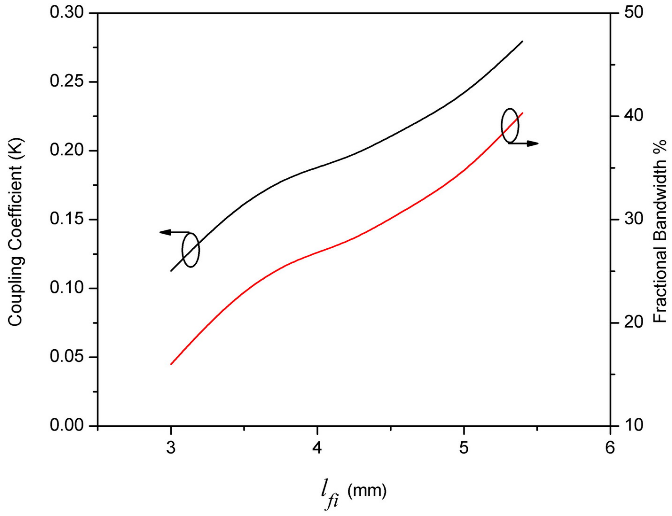

Fig. 3. Simulated coupling coefficient of the proposed filter structure at 3300 MHz as a function of the internal feed via position. The other design variables are kept fixed as shown in Table I.

When designing a tap-line coupling structure, the position of the tap is a critical parameter for providing the required coupling strength. However, in the method presented in this paper, the tap point is considered to be fixed to the top of the post where the maximum electrical field confinement is located. The reason for this design choice is to reduce the number of fabrication steps and limit the structure to two metal layers. However, this reduces the degrees of freedom in the design as the height of the tap can be used to adjust the external coupling. The primary design parameters used in the proposed design are the position and diameter of the feeding via that provides the connection from the coplanar waveguide feeding line to the tap-line. Additional design parameters that can be adjusted are the width of tap-line, the relative position of the coplanar waveguide termination with respect to the feed via position, and the coplanar waveguide spacing and gap size. The proposed external coupling structure is emphasized in Fig. 1 using dashed lines. In Fig. 2, the result of an ANSYS HFSS® full-wave simulation for the external quality factor variation in terms of the external feed via distance, l_{fe}, is shown. Additionally, the achievable fractional bandwidth as a function of l_{fe} is depicted in the same figure. Group delay method was used to extract these values [10].

TABLE I
THE FABRICATED FILTER PRIMARY DIMENSIONS

Substrate Thickness	3.175 mm	
Post Diameter (d_p)	3.8 mm	
Cavity Diameter (d_c)	13.7 mm	
Iris Width (w)	7 mm	
-	Internal (i)	External (e)
Tap-line Width (w_t)	0.5 mm	0.25 mm
Feed Via Diameter (d_f)	0.8 mm	0.8 mm
Feed Via Distance (l_f)	5.3 mm	5 mm
CPWG Term. Length (l_c)	1.15 mm	2.25 mm

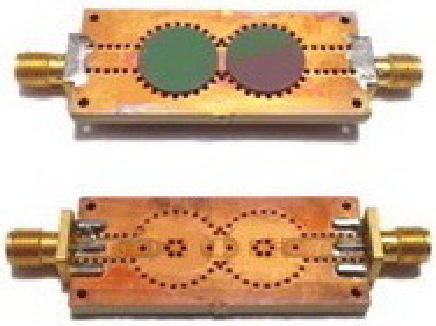

Fig. 4. Fabricated prototype of the proposed bandpass filter a) top view b) bottom view.

Conventionally, magnetic field iris coupling has been used to provide the internal coupling for this type of evanescent-mode cavity filters. However, this is limited to narrow bandwidth designs, typically less than 10% [4], [5]. The iris provides the internal coupling but the coupling strength is limited by the physical geometry of the structure. Because, the width of the iris cannot exceed the resonator width and its length has a lower limit to prevent overlap between the resonators. Therefore, the same design principles are applied in order to realize stronger internal coupling. One significant difference between the external and the internal coupling mechanisms is that the iris provides a greater contribution to the overall coupling than the feed lines in the case of internal coupling. The design parameters in this case are the same as for the external coupling with the addition of the width of the coupling iris and the spacing between the resonators. The same limitations are applied for this design methodology regarding the fixed tap-line height. The internal coupling mechanism is emphasized by the dotted line in Fig. 1. Examples of the achievable coupling coefficient, K, and fractional bandwidth as a function of the internal feed via distance, l_{fi}, are shown in Fig. 3. Similar curves can be generated for the other design parameters for characterizing both the external and the internal coupling.

To demonstrate the wide bandwidth capability of the proposed coupling structure, a second order, Butterworth bandpass filter in Rogers TMM3® substrate ($\epsilon_r = 3.27$, $tan(\delta) = 0.002$ at 10 GHz) with a fractional bandwidth of 38% at 3300 MHz was designed. The desired tuning range of the filter center frequency is from 3000 MHz to 3600 MHz. To achieve 38% fractional bandwidth the required external feed via distance is 5 mm, as can be seen in Fig. 2. From Fig. 3,the corresponding internal feed via distance for this bandwidth needs to be 5.3 mm, if the iris width is kept at 7 mm. The filter primary dimensions are listed in Table I. For this design, the initial capacitive loading gap was chosen to be 62 μm to achieve the desired center resonant frequency of 3300 MHz. In order to tune the filter across the entire tuning range, the capacitive loading gap will need to be changed from 45 μm to 75 μm. A piezoelectric transducer from Piezo Systems, specified to have ±19 μm of movement, was used to physically deflect the top of the cavity by the required displacement.

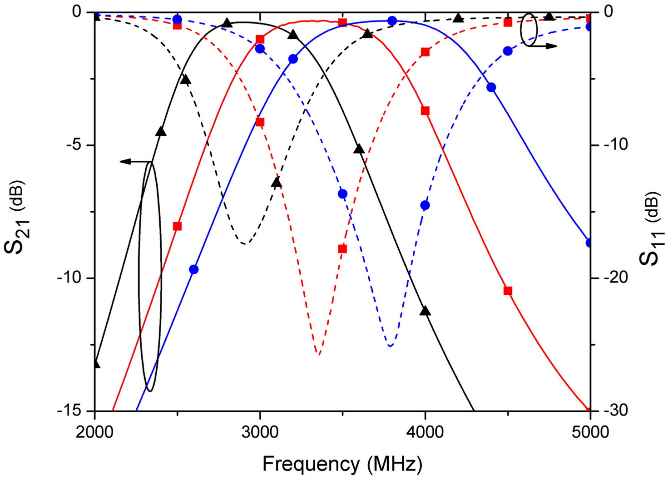

Fig. 5. Measured S-parameters of the proposed filter as it is tuned from 2910 MHz to 3795 MHz.

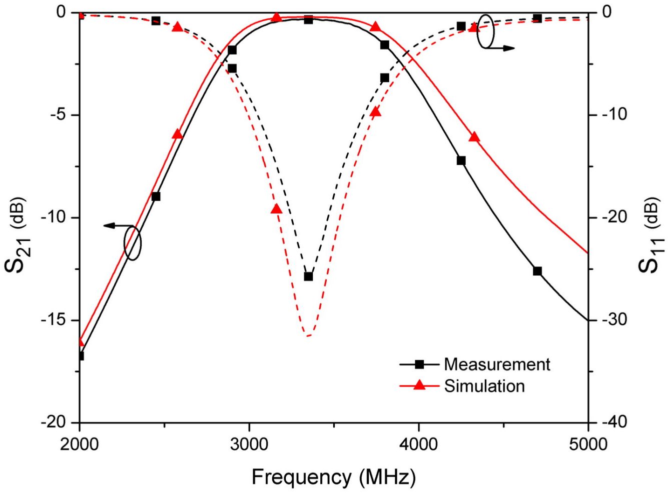

Fig. 6. Comparison between the measured and simulated results.

III. FABRICATION AND MEASUREMENT

The filter was fabricated using the traditional circuit board fabrication processing of a Rogers TMM3® microwave substrate. The processing steps are similar to those reported in [4]. A photo of the fabricated filter is shown in Fig. 4. The filter was measured using an Agilent N5222 PNA calibrated using an electronic calibration kit. Fig. 5 shows the measured response of the filter while it was tuned over the desired frequency range. The measured response exhibits an insertion loss as low as 0.4 dB while tuned across the range from 2910 MHz to 3795 MHz. The 3-dB bandwidth varied from 1018 MHz to 1411 MHz. This is equivalent to a fractional bandwidth of 35% to 37.2%. Also, a comparison of the simulation and the measurement at 3350 MHz has been depicted in Fig. 6. A good agreement is seen between the results. A comparison between the measured and simulated insertion loss and the bandwidth is shown in Fig. 7. The

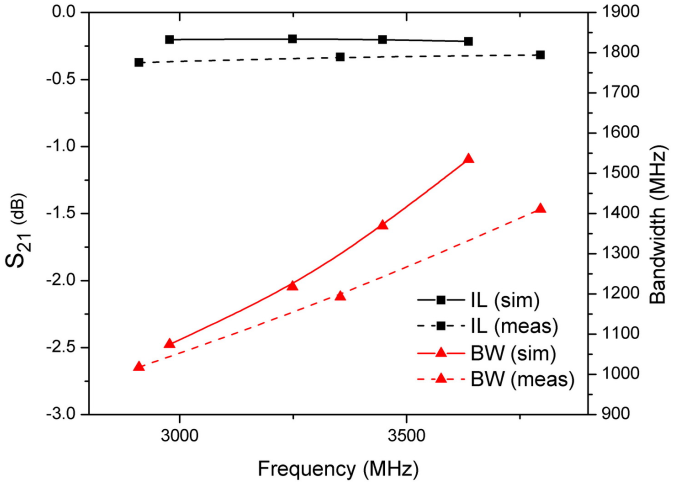

Fig. 7. Simulated and measured insertion loss and bandwidth of the proposed bandpass filter.

insertion loss is slightly higher in the measurement than the simulation but the measurement includes the loss from the SMA edge mounted connectors. Also, the narrower bandwidth contributes to the increase in loss. The difference in bandwidth can be attributed to the non-planar movement of the top copper as the piezoelectric transducers are operated. This design can be extended to higher order designs as both the internal and external coupling can be tailored to a wide range of coupling coefficients.

IV. CONCLUSION

A new wideband implementation of substrate-integrated, evanescentmode, cavity filters was demonstrated. The structure is based on using direct electric field coupling for providing strong external coupling and a combination of electric and magnetic field coupling for the internal coupling. Fractional bandwidths on the order of 40% are demonstrated to be feasible using this methodology. A second order Butterworth filter was designed with a 38% fractional bandwidth at 3300 MHz with an expected insertion loss of 0.21 dB. The desired tuning range of the filter was from 3000 MHz to 3600 MHz. This filter was fabricated using traditional circuit board processing. The fabricated filter exhibited a frequency tuning range from 2910 MHz to 3795 MHz and the bandwidth ranged from 35% to 37.2%. The measured insertion loss was around 0.4 dB, which includes the loss from the connectors. The good agreement between the simulated and measured results confirms the wide bandwidth capability of the proposed structure. To the best knowledge of the authors, the proposed filter has the widest bandwidth reported in a tunable evanescent-mode cavity filter to date.

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