

Substrate Integration of Widely Tunable Bandpass Filters

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Abstract

In the present work, a widely tunable, bandpass filter is integrated into a commercially available printed circuit board using standard PCB processing. The filter consists of two cylindrical evanescent-mode cavity resonators formed by metallized thru vias in a double sided circuit board with an additional copper layer laminated on top. The copper layer forms a thin, flexible membrane that allows variable frequency loading of each of the resonators. The membrane is displaced using two piezoelectric bending disc actuators for precise electrical tuning of the filter center frequency. The concept is demonstrated by creating a tunable filter in a 125 mil thick Rogers TMM® thermoset microwave laminate. The filter can be continuously tuned from 1.5 to 3 GHz with a narrow 3 dB bandwidth of less than 25 MHz while having a low insertion loss of less than 3.1 dB. This type of filter can provide quality pre-select filtering for a reconfigurable front-end receiver while being embedded inside a multilayer circuit board which has the rest of the system components.

Key words: software defined radio, high quality factor, tunable filters, front-end receiver, and microwave packaging.

1.0 Introduction

The recent trend in wireless and radio frequency (RF) components and systems has been towards higher levels of integration and increased functionality without sacrificing quality or raising the cost. Important components for the front-end of such systems include: antennas, low-noise amplifiers (LNAs), and filters. A large portion of the additional

functionality of these components and systems is tunability. With the current licensing policies, a lot of the commercial bands are very crowded because of the large user base. This includes bands such as cellular and wireless internet, where there are a lot of seldom used spectrum close by. This has lead to a lot of research on more adaptable systems which can use the spectrum more efficiently by finding these nearby bands and adjusting all components to operate at that

frequency. These systems are generally known as cognitive radio (CR) and software defined radio (SDR). Currently the digital implementation of the back-end of wireless transceivers allows for dynamic reconfiguration [1]. The future roadmap of military communication networks, going from current date to and beyond the year 2015, projects that the current non-adaptive communication systems will make way for more adaptive systems that can communicate via beyond line-of-sight relays such as unmanned aerial vehicles and satellites. These systems will be able to self-configure themselves to use the spectrum more efficiently [2]. However, tunable band pre-selection still remains a challenge for microwave and millimeter wave operations. CR and SDR architectures often project the use of wide ranges of spectrum, however this leaves the front-end of the system open for saturation from co-site or intentional interference, unless a switched bank of filters or a tunable filter is utilized.

There are several methods available for realizing tunable filters including the use of planar microelectromechanical systems (MEMS) technology [3], ferroelectric thin films [4], and coupled microstrip line bandpass filters with piezoelectric transducers for tuning [5], [6]. Another method is to use evanescent-mode cavities to create tunable filters. Static non-tunable evanescent-mode bandpass filters have been demonstrated previously [7], [8], and tunable evanescent-mode cavity filters were demonstrated with wide tuning ranges while maintaining good loss performance for narrow bandwidths [9], [10].

This work aims to address the need for a compact, integrated, and widely tunable filter for CR and SDR applications. The filter consists of two evanescent-mode cavities integrated into a substrate. The substrate can also be used as a host board for the remainder of the system. The filter presented in this

paper tunes from 1.5 to 3 GHz and has an absolute bandwidth of less than 25 MHz across the entire tuning range while maintaining an insertion loss of less than 3.1 dB.

2.0 Substrate Integrated Evanescent-mode Cavity Filter Realization

The resonant frequency, f_0 , of a waveguide resonant cavity can be written as a function of the cavity inductance, L , and capacitance, C , as

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \quad (1)$$

The frequency can be lowered by loading the cavity with a capacitive loading post, C_{post} , the new resonant frequency will be [11]

$$f_0 = \frac{1}{2\pi\sqrt{L(C + C_{post})}}. \quad (2)$$

Evanescent-mode cavity filters can therefore be made substantially more compact than unloaded cavity filters by properly choosing the post capacitance. An example of the volume reduction possible by loading a cavity can be found in [10], where a rectangular resonant cavity is loaded by a capacitive post to reduce the frequency from 21.21 GHz to 6 GHz. The volume savings, compared to creating an unloaded cavity at 6 GHz, is greater than 90% while the reduction in quality factor is only from 3000 to 1200 or 60%. An additional advantage of the capacitive loading is increased frequency sensitivity with respect to changes in post capacitance. This is a key attribute to achieving very wide tuning ranges while introducing small geometrical changes to the cavity itself. These changes can be realized using commercially available piezoelectric actuators. Such actua-

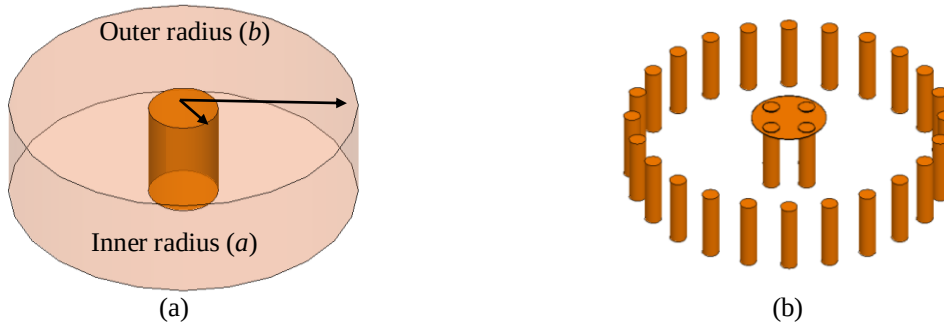


Fig. 1: Substrate integrated evanescent-mode tunable cavity filter (a) Model of an ideal cylindrical evanescent-mode cavity, (b) an evanescent-mode cavity resonator integrated in a substrate realized using plated thru vias.

tors are commonly used for ultra precise positioning, such as nano-imprinting, scanning microscopy, microlithography, and automated alignment [12].

A typical cylindrical evanescent-mode cavity resonator is shown in Fig. 1 (a). This type of a cavity can be created using typical machining as well as some advanced manufacturing methods such as solid free form fabrication, but all of those methods require some assembly. An alternative is to create the cavity within a substrate using plated thru vias to define both the cavity and the post sidewalls, as shown in Fig. 1 (b). The top of the post can be created by traditional board manufacturing. This type of cavity resonator can be easily integrated into any kind of printed circuit board (PCB) substrate. One of the benefits of this structure is that the majority of the electric field is confined in the air above the capacitive post. Therefore, high quality factors are possible despite most of the cavity structure being filled with a relatively lossy dielectric.

A two pole response is generated by placing two of these integrated resonators in close vicinity of each other and removing three vias from each resonator to form an inductive coupling iris. The bandwidth of the filter depends on the amount of coupling through the iris. Therefore, the desired bandwidth can be designed by changing the spacing of the vias in the iris section. An inductive iris will have increased coupling as the frequency is increased and therefore the absolute bandwidth will become wider as the filter is tuned. In order to counter this behavior a parallel transmission line coupling mechanism is placed in parallel with the iris. The transmission line section can be used to reduce the bandwidth variation as a function of frequency as well as cause bandwidth reduction. By terminating the transmission line in a high Q ceramic surface mount capacitor the bandwidth variation can be tailored. A shorted coplanar waveguide (CPW) ending in a slot aperture is used to into couple the filter.

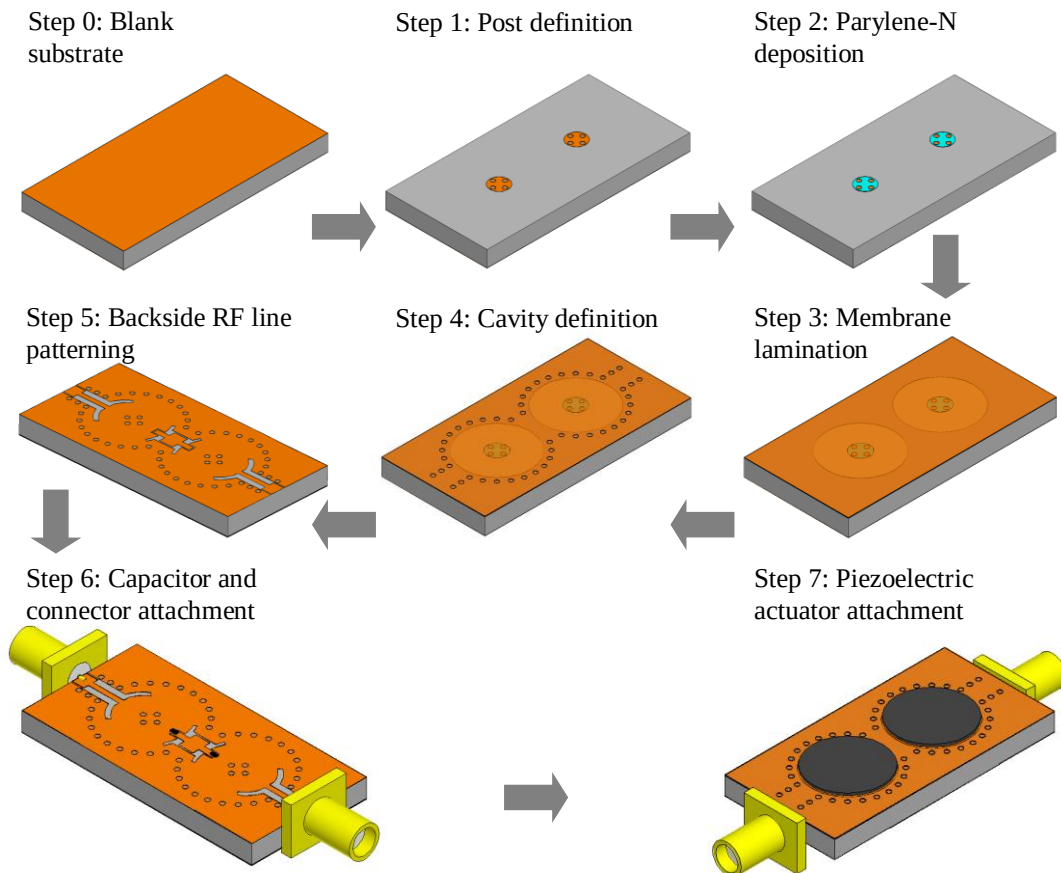


Fig. 2: Substrate integrated filter step by step fabrication procedure.

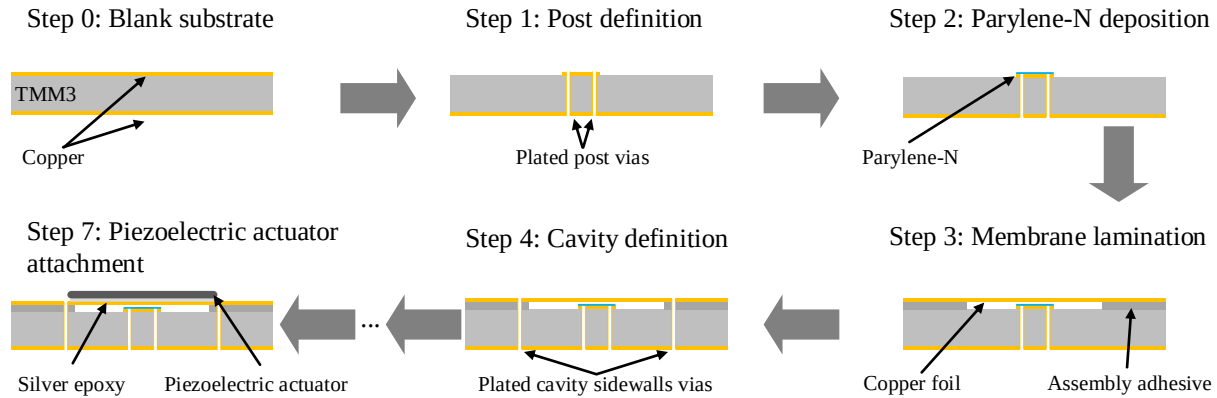


Fig. 3: Cross-section of one of the resonators of the substrate integrated filter as it is stepped through the fabrication procedure. The resonator cross-section of the remains unchanged during steps 5 and 6.

3.0 Substrate Integrated Filter Fabrication

The substrate integrated evanescent-mode cavity filters are fabricated inside a standard double-sided copper-clad PCB. In this paper a 125 mil thermoset microwave material (TMM®) from the Rogers Corporation was used as the host substrate. Fig. 2 shows an overview of the fabrication flow and Fig. 3 shows a cross-sectional view of one of the resonators at each step that that affects the cross-section. The first step is to drill the via holes forming the side walls of the post. Electroless copper plating is used to form a 60 μm seed layer followed by thick copper electroplating. The copper on the top of the PCB is then selectively etched, leaving the top plate of the capacitive post as shown in step 1 in Fig. 2. Roughness of the top plate is reduced by polishing the copper with 600 and 1200 grit grinding paper followed by 0.05 μm alumina polishing. This reduces the roughness from approximately 3-5 μm to less than 1 μm . Chemical vapor deposition (CVD) is used to deposit a 1 μm layer of Parylene-N on top of the post plate. The Parylene-N is used as a dielectric barrier to prevent electrical shorting of the post capacitor at small gaps.

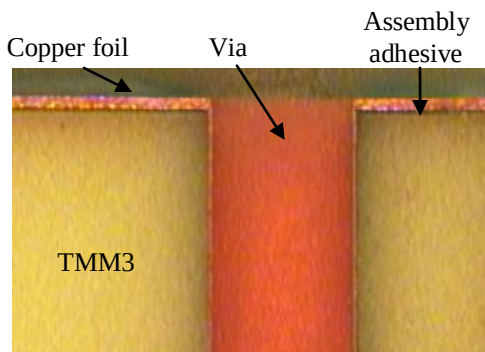


Fig. 4: Cross-section of the interface between a metallized via and the copper foil.

To create the top of the cavity a 1 oz copper foil is laminated on top of the substrate using a 1 mil thick patterned R/flex® 1500 assembly adhesive. Fig. 2 step 3 shows the copper foil being semitransparent so the patterning of the adhesive can be seen. The initial capacitive gap is defined by the assembly adhesive. Vias are drilled through the new stack and copper plated to form the cavity sidewalls as shown in step 4.

In step 5, both the CPW feed lines, coupling apertures, and transmission line bandwidth section are created in the bottom copper layer using an LKPC C100 HF circuit board plotter. SMA connectors are soldered onto the feeds and the surface mount capacitors on the transmission line bandwidth section. Finally, two 0.5 in commercially available 2-layer piezoelectric disc actuators from Piezo Systems, Inc. are attached using a highly flexible conductive silver ink from Shiva Consulting, Inc.

A cross-section of the interface between a via and the copper foil in a fabricated filter is shown in fig. 4. The plating covers the assembly adhesive and forms a good connection from the via to the copper foil. Fig. 5 shows a top view of a fabricated 2-pole evanescent-mode cavity filter.

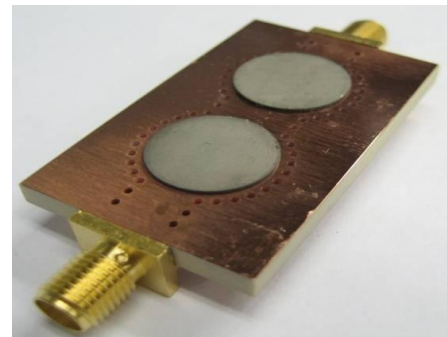


Fig. 5: Top view of a fabricated substrate integrated evanescent-mode cavity filter.

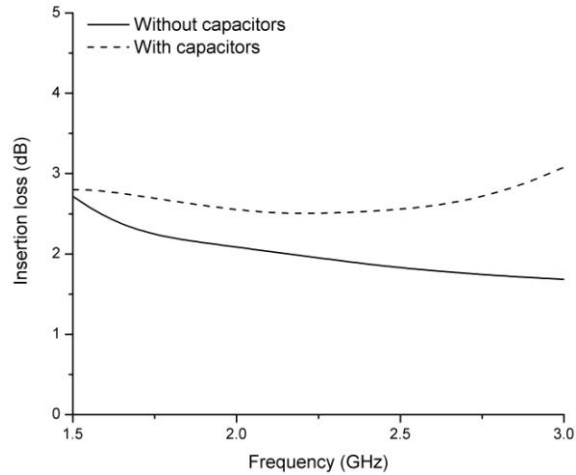


Fig. 6: Measured filter insertion loss with and without the bandwidth limiting capacitors.

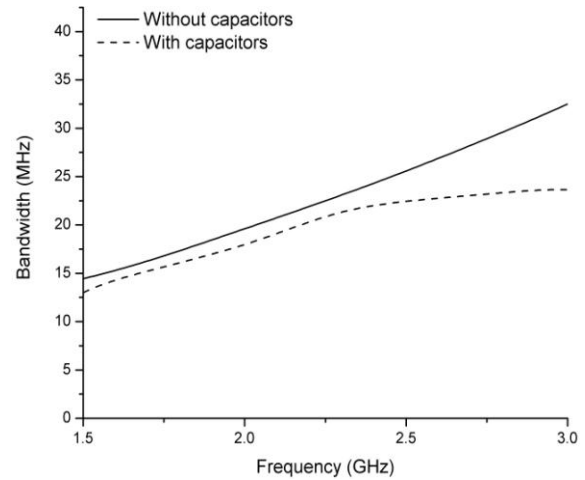


Fig. 7: Measured filter bandwidth with and without the bandwidth limiting capacitors.

4.0 Experimental Results

The filter is fabricated according to the above described method and tested. The filter is first measured prior to attaching the surface mount capacitors on the transmission line bandwidth section. The filter has a very wide continuous tuning range from 1.5 to 3 GHz. The measured insertion loss is shown as the solid line in Fig. 6 and the measured bandwidth is shown as the solid line in Fig. 7. The insertion loss is less than 2.65 dB across the entire range and the bandwidth varies from 14 to 31.6 MHz.

Soldering the surface mount capacitors on the transmission line bandwidth section reduces the bandwidth. The new insertion loss is shown as the

dashed line in Fig. 6. The new bandwidth is limited to less than 25 MHz varying from 13 to 24 MHz across the entire tuning range. The change in bandwidth variation is therefore reduced from 2.26:1 to 1.85:1. The cost of limiting the bandwidth is an increase in loss. The new insertion loss is shown as the dashed line in Fig. 6 and has degraded by 0.1 dB at 3 GHz and 1.3 dB at 1.5 GHz, however, the loss is still less than 3.1 dB across the entire tuning range. This is to be expected since the bandwidth is reduced by 7.6 MHz at the high end and only by 1 MHz at the low end. Fig. 8 shows the measured scattering parameters at four evenly distributed frequencies.

5.0 Conclusion

This work presents a widely tunable evanescent-mode filter integrated in a PCB. The demonstrated filter has a tuning range of 2:1, going from 1.5 to 3 GHz while maintaining a low insertion loss for a limited bandwidth variation across the range. The absolute bandwidth is limited to less than 25 MHz.

The PCB with the integrated filter can also be used as a host for the remainder of the system components forming a complete receiver. This fabrication technique advances the existing evanescent-mode cavity filters and brings them one step closer to enabling the next generation of CR and SDR architectures.

Acknowledgments

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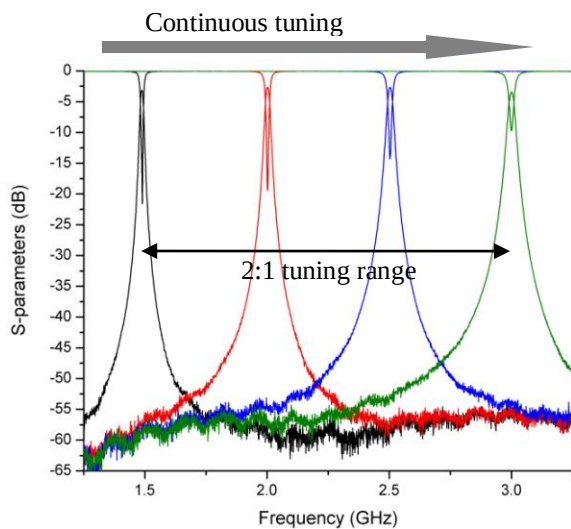


Fig. 8: Measured scattering parameters of the filter being tuned continuously from 1.5 to 3 GHz.

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