Practical Implementation of Frequency Monitoring for Widely Tunable Bandpass Filters

Hjalti H. Sigmarsson
School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.9065, Fax: 765.494.6951
Email: hsigmars@purdue.edu,
https://engineering.purdue.edu/IDEAS/People/Sigmarsson.html

Evan Binkerd
School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.9065, Fax: 765.494.6951
Email: ebinkerd@purdue.edu.

Jeff Maas
School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.9065, Fax: 765.494.6951
Email: jmaas@purdue.edu,
https://engineering.purdue.edu/IDEAS/People/Maas.html

Juseop Lee
School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.9065, Fax: 765.494.6951
Email: lee808@purdue.edu,
https://engineering.purdue.edu/IDEAS/People/Lee.html

Dimitrios Peroulis
School of Electrical and Computer Engineering
Purdue University
Birck Nanotechnology Center
1205 West State Street
West Lafayette, Indiana, 47907
Phone: 765.494.3491, Fax: 765.494.3371
Email: dperouli@purdue.edu.

William J. Chappell
School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.6225, Fax: 765.494.6951
Email: chappell@purdue.edu,
https://engineering.purdue.edu/IDEAS/Chappell.html

Abstract

In the present work, a practical method to integrate sensing mechanisms into widely tunable evanescent-mode cavity resonators for tracking the center frequency is introduced. This mechanism allows for in-situ monitoring and outputs a signal that can be used to generate a closed loop feedback that can be used to lock in the center frequency of the resonator. The major benefit of this mechanism is that the performance of a resonator is not sacrificed since the higher order differential mode used for monitoring is orthogonal to the fundamental mode of the resonator. The resonator is created inside a standard printed circuit board using 3-dimensional laser patterning to allow the existence of the differential mode. An example resonator is fabricated to demonstrate the concept and tuned from 3.62 to 6.85 GHz. The differential mode was monitored to be at a frequency 1.8 times higher than the common mode. The unloaded quality factor of the resonator is extracted from measurements to verify that the sensing mechanism does not induce any additional losses. Continuous feedback is a crucial step towards a robust fielded widely tunable filter.

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

1.0 Introduction

Widely tunable filters have been receiving increased attention recently towards realizing highly adaptable wireless and radio frequency (RF) communications systems such as software defined radio (SDR) and cognitive radio (CR). The goal of these systems is to monitor the electrical environment, locate an unused, clean portion of the spectrum, and reconfigure the radio, either in software or in hardware, to operate there. With the current licensing policies, a lot of the commercial bands are very crowded due to the excessively large user base. This includes bands such as cellular and wireless internet, where there is a lot of seldom used spectrum in close vicinity. 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]. The wide frequency ranges CR and SDR systems are projected to use can leave 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]-[11]. The filters in [11] were integrated into a substrate using standard printed circuit board (PCB) processing and exhibited a tuning range of 2:1, going from 1.5 to 3 GHz while maintaining a low insertion loss and a limited bandwidth variation across the range. The absolute bandwidth was limited to less than 25 MHz. An in-situ method for tracking the center frequency of the filter was presented in [12]. The method consists of monitoring the frequency of a higher order differential mode and relating it to the fundamental common mode of the filter. By splitting the capacitive loading post into two sections, the differential mode is created.

In this paper, a higher frequency substrate integrated evanescent-mode resonator with differential mode tracking is presented. In order to increase the frequency of the resonator the size of the capacitive post needs to be reduced. This complicates the monitoring method since 3-dimensional patterning is required to split the post into two sections. The patterning is achieved by ablating the copper on the post using a laser. The resonator presented tunes from 3.62 to 6.85 GHz with a quality factor greater than 1,000, showing that the inclusion of the laser patterning does not degrade the resonator performance. The differential mode is measured to be 1.8 times higher in frequency than the common mode.

2.0 Substrate Integrated Evanescent-mode Cavity Resonator 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. The frequency can be lowered by loading the cavity with a capacitive loading post, C_{post}. The new resonant frequency will be [13]

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

Evanescent-mode cavity resonators can therefore be made substantially more compact than unloaded cavity resonators by properly choosing the post capacitance. An example of the volume reduction

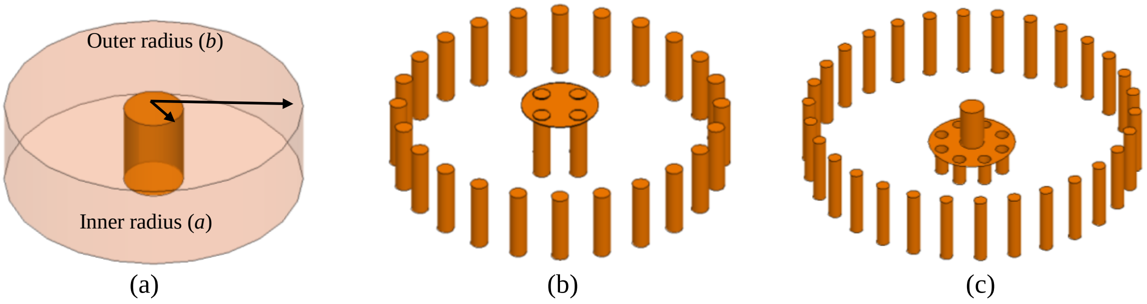

Fig. 1: Substrate integrated evanescent-mode tunable cavity resonators (a) Model of an ideal cylindrical evanescent-mode cavity, (b) an evanescent-mode cavity resonator integrated in a substrate realized using plated thru vias, (c) an evanescent-mode cavity resonator with a stepped post for a higher frequency design.

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 3,000 to 1,200 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 are small enough that they can be realized by using commercially available piezoelectric actuators. In order to increase the operating frequency while still maintaining a wide tuning range, the area of the capacitive loading post has to be reduced. For comparison, the 3 to 6 GHz cavity resonators in [10] had square 40 mil by 40 mil posts as compared to the 115 mil diameter cylindrical posts in [11]. Reducing the post to a diameter of 43.3 mils results in the same area as the post in [10].

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 additional assembly steps. 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 methods. This type of cavity resonator can be easily integrated into any kind of printed circuit board (PCB) substrate. One of the main benefits of this structure is that the majority of the electric field is confined in the air above the capacitive post. Therefore, very high quality factors are possible despite most of the cavity structure being filled with a relatively lossy dielectric. This resonator was demonstrated in [12]. However, in order to create a smaller post inside a substrate the vias would have to be extremely small

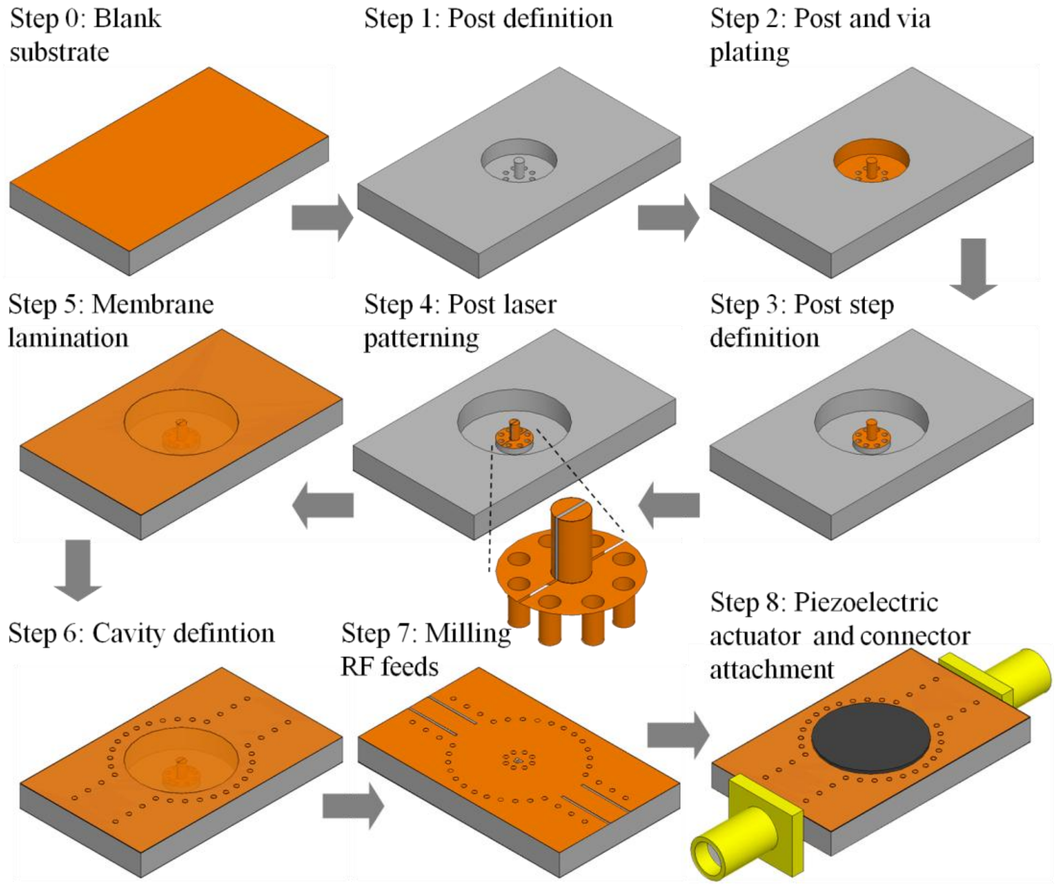

Fig. 2: Substrate integrated resonator step by step fabrication procedure.

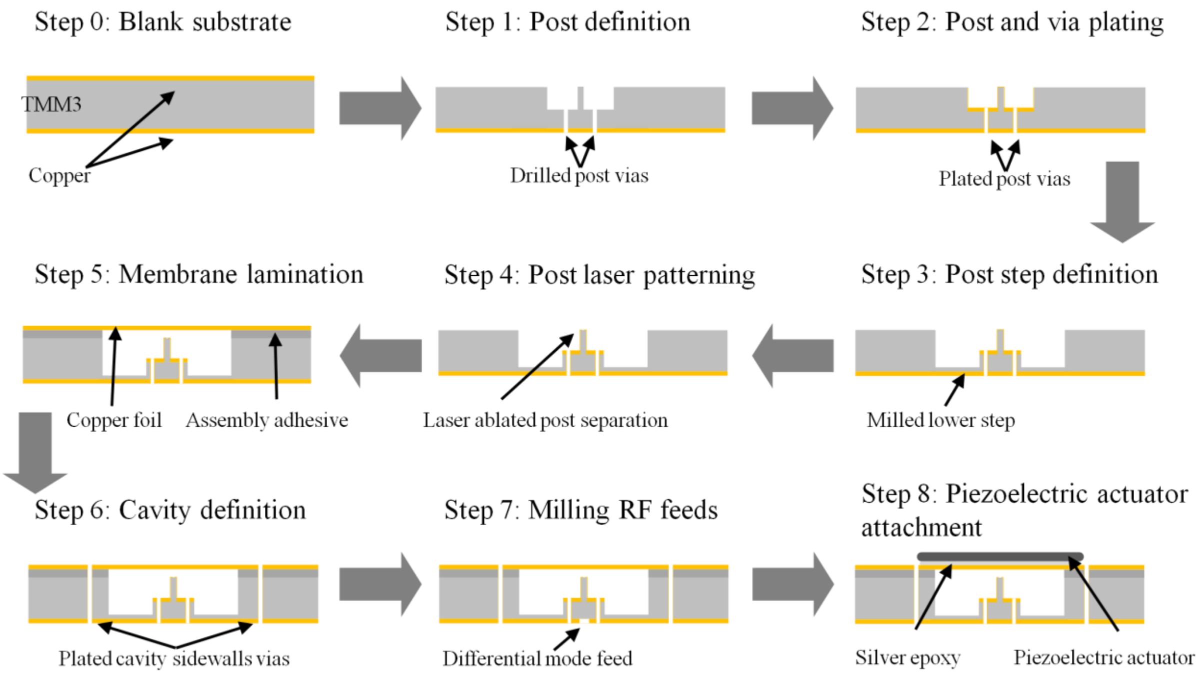

Fig. 3: Cross-section of one of the resonators of the substrate integrated filter with the laser patterned post as it is stepped through the fabrication procedure.

which would make the aspect ratio for the through hole plating very high. Instead of moving to smaller vias the post can be machined into the substrate during the PCB fabrication. This can result in a much smaller post area than possible with vias. A realization of the stepped post can be seen in Fig. 1 (c).

3.0 Substrate Integrated Resonator Fabrication

The substrate integrated evanescent-mode cavity resonators are fabricated inside a standard double-sided copper-clad PCB. For the resonators in this paper a 125 mil thick thermoset microwave material (TMM®) from the Rogers Corporation was used as the host substrate. Fig. 2 shows a step by step overview of the fabrication flow, and Fig. 3 shows a cross-sectional view of the resonators at each step. Prior to any patterning the top copper layer is completely etched off. The first step is to mill out the top portion of the capacitive post and the platform of the lower step. The height of the top post is 80 mils. The via holes are then drilled, forming the side walls of the lower post. The second step is to deposit a 60 µin seed layer of copper using electroless plating. During the third step the lower post area is defined by milling deeper into the substrate, the second depth is 100 mils. The fourth step involves using a frequency-tripled Nd:YVO4 laser at 355 nm from DPSS Lasers

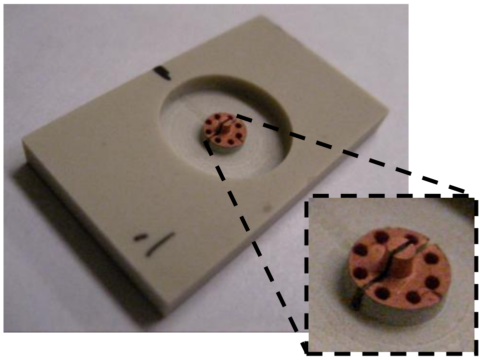

Fig. 4: Top view of the fabricated resonator after the laser patterning in step 4.

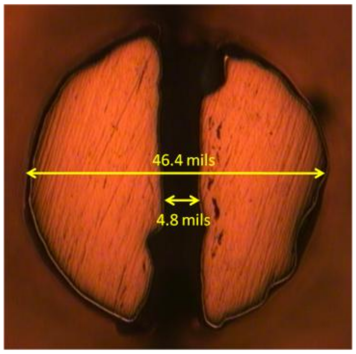

Fig. 5: Optical microscope image of the top of the post in the fabricated resonator.

to ablate the copper on the post to completely isolate it into two sections. The targeted isolation is 4 mils. After the post has been laser patterned a thicker electroplating is performed to build up the copper thickness on the post and in the vias. This plating step is also used to define the initial capacitive gap between the post and the top of the cavity. The roughness of the top plate is reduced by polishing the copper with 1200 grit grinding paper followed by 0.05 µm alumina polishing.

In the fifth step, a 1 oz copper foil is laminated on top of the substrate to create the top of the cavity. The lamination is done using a 1 mil thick patterned Pyralux® assembly adhesive from DuPont. In Fig. 2 the copper foil is semitransparent to show the patterning of the Pyralux® adhesive. The total height of the cavity is defined by the assembly adhesive and therefore the capacitive gap will be the difference between the thickness of the adhesive and the electroplating of the post. The sixth step is to define the cavity outer sidewalls by drilling and copper plating vias through the new stack. During this plating step the backside of the post needs to be covered to prevent contamination of the cavity.

Step seven consists of creating the RF feed lines for both the common and the differential mode in the bottom copper layer using an LPKF C100 HF circuit board plotter. SMA connectors are soldered onto the feeds in step eight and two 0.5 in diameter, 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 top view of the laser patterned post after step 4 is shown in Fig. 4. The actual separation between the two parts of the post in the fabricated resonator was 4.8 mils. Fig. 5 shows a magnified image of the top of the post with dimensions.

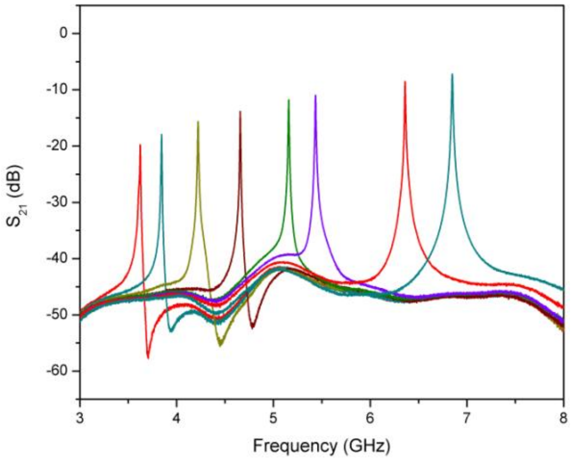

Fig. 6: Measured resonator common mode tuning.

4.0 Experimental Results

The fabricated resonator was measured using a 4 port Agilent N5230C PNA. First the tuning and the unloaded quality factor of the common mode was investigated with a 2 port measurement. The resonator tunes from 3.62 to 6.85 GHz and with an unloaded quality factor of 1,100 at 6.85 GHz. The tuning and the quality factor are shown in Fig. 6 and Fig. 7 respectively. The high quality factor indicates that the presence of the laser pattern does not increase the loss of the device and that there is no undesired debris from the laser processing affecting the performance.

A full wave finite element method simulation using High Frequency Structure Simulator (HFSS) of the structure was used to characterize the ratio between the differential and common mode. The simulated structure with a 1 mil capacitive gap is shown in Fig. 8. The frequency of the common mode turned out to be 6.32 GHz and the differential mode resonates at 11.30 GHz, a 1.789 to 1 ratio. The simulated response is shown in Fig. 8.

To measure the differential mode frequency a 3 port measurement was needed. The connection to the coplanar waveguide feed of the differential mode feed was done with a ground signal ground (GSG) probe from Cascade Microtech, Inc. with a 650 µm

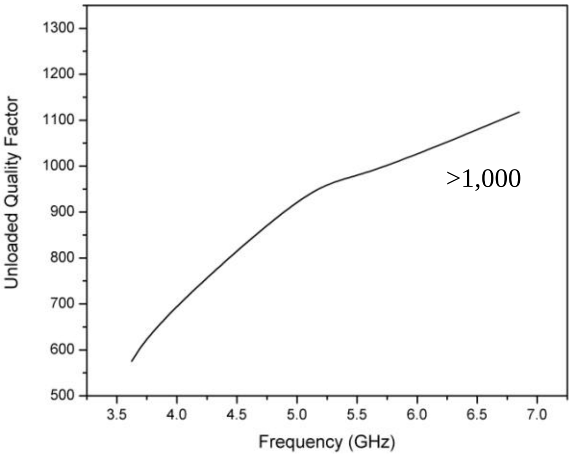

Fig. 7: Measured unloaded quality factor of the fabricated resonator, extracted from the common mode.

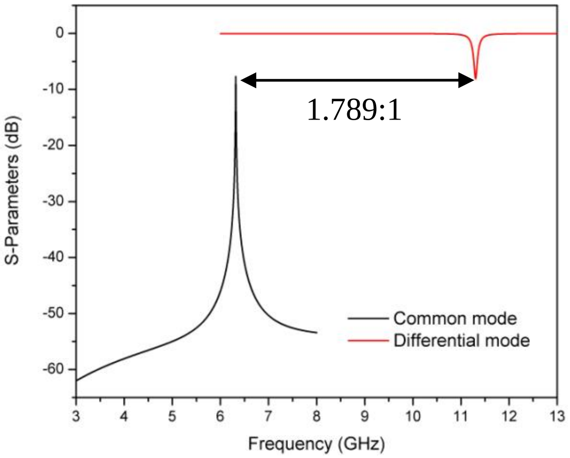

Fig. 8: Simulated resonator common and differential modes.

pitch size. The measured S_{21} and S_{33} representing the common mode transmission and the differential mode reflection, respectively, are shown in Fig. 9. The waviness of S_{33} is from the probe as it was not included in the network analyzer calibration but it does not affect the measure resonant frequency of the differential mode. The measured ratio between the common mode and the higher order differential mode is found to be 1.78:1, which agrees very well to the simulated ratio from HFSS.

5.0 Conclusion

This work presents a novel method of patterning a stepped capacitive loading post in a widely tunable evanescent-mode resonator integrated inside a PCB using a laser. The demonstrated resonator has a wide tuning range from 3.62 to 6.85 GHz with an unloaded quality factor of up to 1,100. The higher order differential mode was simulated and measured. The ratio of the differential to the common mode was found to be 1.78:1 from measurement and 1.789:1 from simulation.

The high quality factor is a clear indicator that the laser patterning does not degrade the performance of the resonator and therefore provides a realistic method for 3-dimensional patterning of the evanescent-mode cavity resonators for active frequency monitoring.

Acknowledgments

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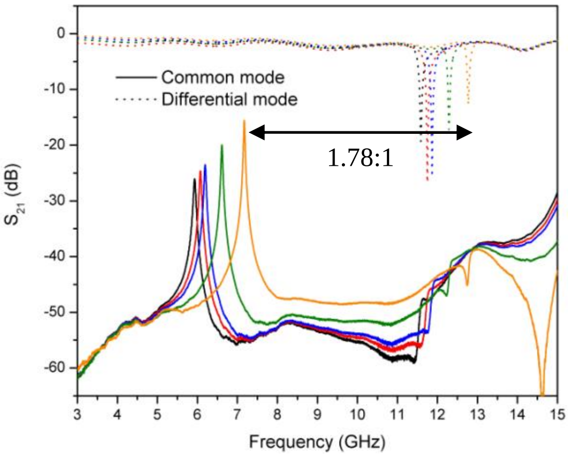

Fig. 9: Measured resonator common mode tuning along with the corresponding higher order differential mode responses.

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