Substrate Integrated Evanescent-Mode Cavity Filter With a 3.5 to 1 Tuning Ratio

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***Abstract*—In this letter, the design and RF packaging of substrate integrated widely tunable filter is presented. The filter consists of two heavily loaded evanescent-mode cavities embedded into the substrate. The filter is actuated using two piezoelectric discs, which move thin, flexible membranes that form the top of the cavities. To demonstrate the wide tuning a filter is fabricated and measured to cover a very wide frequency range from 0.98 to 3.48 GHz (tuning ratio-3.55:1). The measured insertion loss is less than 3.57 dB for a 1.1% fractional bandwidth filter.**

***Index Terms*—Evanescent-mode cavity, RF packaging, tunable filter, wireless communication.**

I. Introduction

TODAY, wireless communication is rapidly evolving from voice to multimedia services and the new trend is driven by ever-increasing user demands. A reconfigurable network is required to increase capacity and Quality of Service (QoS) [1]. For realizing a compact and reconfigurable wireless system, an integration technology to combine distributed components using tunable devices in a compact package is necessary. One device would be a high-Q pre-select filter with a wide tuning range. This device is a key component for implementing a reconfigurable front-end for wireless networks [2]. Up till now, various technologies have been used to implement tunable filters including MEMS [3], ferroelectric thin films [4], and evanescent-mode cavities [5]. However, there have not yet been any tunable filters with tuning ratios greater than 2.4:1 reported [6].

Until now, we have demonstrated an evanescent-mode cavity filter with a tuning range of less than an octave, and have focused mainly on specific design issues such as inter-resonator and external coupling control for the evanescent-mode cavity based tunable filters [7]–[9]. In this letter, we focus more on the design and packaging concept for a compact evanescent-mode cavity filter with an extremely wide tuning ratio (3.55:1). The tunable filter is implemented inside a ceramic filled polymer board and its total packaging volume including feed line is approximately 3.3 cm^3. This filter is tuned by thin 380 μm piezoelectric discs that are surface mounted on the top of the substrate with the integrated cavities.

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II. Evanescent-Mode Cavity Filter

A. Design and Packaging

The filter is a second order Butterworth design consisting of two resonators coupled together through a coupling iris. The input and output impedance matching is achieved through identical coupling slots to enable a maximally flat response. The layout of a high Q evanescent mode cavity filter design is shown in Fig. 1(a). The filter, simulated by Ansoft HFSS, is made on a 3.17 mm thick Rogers TMM substrate. A coupling iris connects the two resonators formed by conductive vias. Each resonator has a capacitive post in the center created by four vias and a cylindrical copper plate. The radius of the capacitive post is chosen to be 1.45 mm based on single resonator simulations. This allows the resonator to cover the tuning range from 1 to 3.4 GHz in about 38 μm deflection, which is within the deflection specification of the piezo electric actuator. Its resonant volume is approximately 0.6 cm^3. A thin copper membrane is laminated on top of the substrate forming a gap between the post and top of the cavity, which creates the tank capacitance (C_{res}) in Fig. 1(c). The membrane is deflected using a commercially available piezoelectric disc actuator with a 12.7 mm diameter from Piezo Systems Inc. The actuator can provide up to 38 μm of free-free displacement. The filter in this letter is implemented using a double sided, copper cladding, Rogers' TMM3 substrate. It is chosen because the coefficient of thermal expansion (CTE) matches the CTE of copper. A mismatch can cause the deformation of the copper foil during a lamination process. Fig. 2(a) shows the fabrication process. In step 1, the top-side copper layer on a TMM substrate is etched off, and vias defining the loading post drilled. Next, the RF feed lines are patterned on the bottom side of the board. Electroless copper plating is used to create a thin conductive seed layer followed by a 20 μm thick copper electroplating on the inside the vias and on the post top surface. The top area of the post is polished to reduce the surface roughness. The presence of roughness on the surface can reduce the achievable tuning ratio because rough features on the post can come into contact with the top membrane prior to the lowest frequency position is reached. Additionally, an insulating barrier is required to prevent electrical shorts. In step 2, a thin dielectric layer is coated on the top surface of the post. The dielectric used in this work is Parylene-N, which has been widely used for RF and biomedical applications thanks to superior RF properties and biocompatibility [10], and the deposited thickness is less than 1 μm. The low loss insulator is ideal for isolating the metals while not compromising the high Q of the cavity. In step 3, to attach the copper membrane above the cavities, a prepreg layer (R/Flex 1500, Rogers

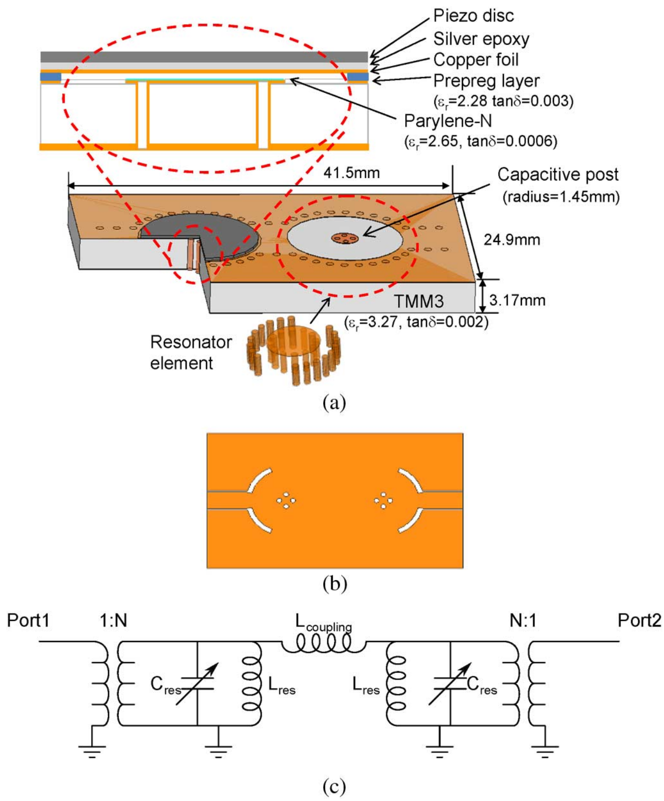

Fig. 1. (a) 3-D view of the 3.5 to 1 tunable evanescent-cavity mode filter, (b) bottom-side pattern for impedance matching, and (c) an equivalent circuit model of the tunable filter ($L_{coupling} = 77$ nH, $L_{res} = 0.8$ nH, $C_{res} =$ 0.3 pF–2.2 pF).

Inc.) is used as a bonding layer. The prepreg layer is approximately 25 μm thick and the copper membrane is 35 μm thick. In step 4, plated copper thru vias form the walls of the evanescent-mode cavity. During this process, the vias through the top post and feed line patterns on the bottom side of the TMM board are covered by a silicone sealant to prevent chemical contamination inside the cavity and plating of the RF feed lines. In order to maximize the available deflection of the piezoelectric actuators, the top of the membrane is also masked by the silicone sealant. This is important because the spring constant of a circular membrane increases triply with the thickness of membrane while in a quadratic fashion with the radius of membrane [11]. Finally, the piezoelectric disc actuators are mounted on top of the finished substrate above the membrane using silver epoxy as shown in step 5.

B. Measurement

The Parylene serves multiple purposes. Since it is a very thin insulator, it allows for close proximity of the metal plates defining the capacitive gap. Since it is a dielectric it also increases the total capacitance range as well. Therefore, it is useful in creating a wideband tuning range. A resonator shown in Fig. 3 is fabricated. Its size is 22.7 mm × 32.7 mm × 3.17 mm (2.3 cm^3). The measured result of unloaded Q is shown in Fig. 3. The measured Q curve is observed to increase a quadratic fashion as the tuned frequency increases. In comparison, there is the Q difference of an approximately 30

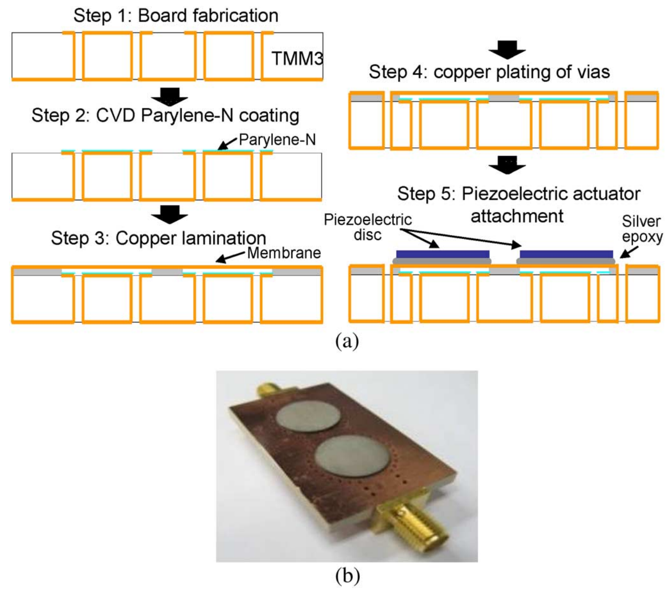

Fig. 2. (a) Fabrication flow of a substrate integrated evanescent-mode cavity filter and (b) fabricated tunable filter.

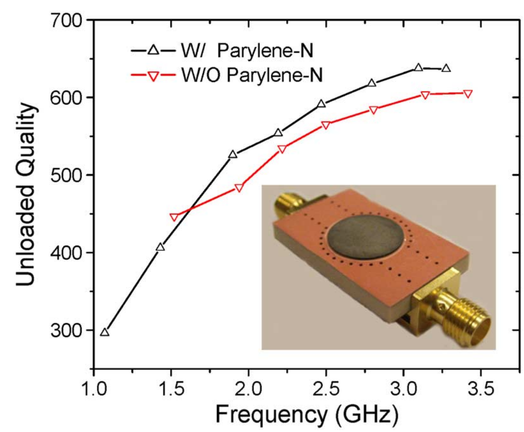

Fig. 3. Measured Q factor in an evanescent-cavity mode resonator with and without Parylene-N coating layer.

between with and without Parylene-N layer, which results from the fabrication repeatability between samples. While it is not expected that Parylene increases the Q, the result demonstrates that the low loss Parylene is secondary to other variables in the manufacturing process. In the sample without Parylene-N layer, its Q below 1.5 GHz cannot be measured due to electric shorts between the top metal on the post and the membrane. This result indicates the importance of thin insulating layer with low loss property in RF applications tuned in a micro-order scale.

A filter with two evanescent-mode cavity resonators was fabricated and its size is 25 mm × 41.5 mm × 3.17 mm (3.3 cm^3). The filter was measured by using Agilent 8720ES VNA. Applying voltage to the attached piezoelectric disc actuators, the membrane is physically displaced and the center frequency of the filter can be swept across a very wide frequency range. To achieve a wide tuning ratio, the initial gap between the top post and the membrane should be as small as possible. This will achieve the lowest tuned frequency and will be largely affected by the thickness of the Parylene-N coating. The highest tuned

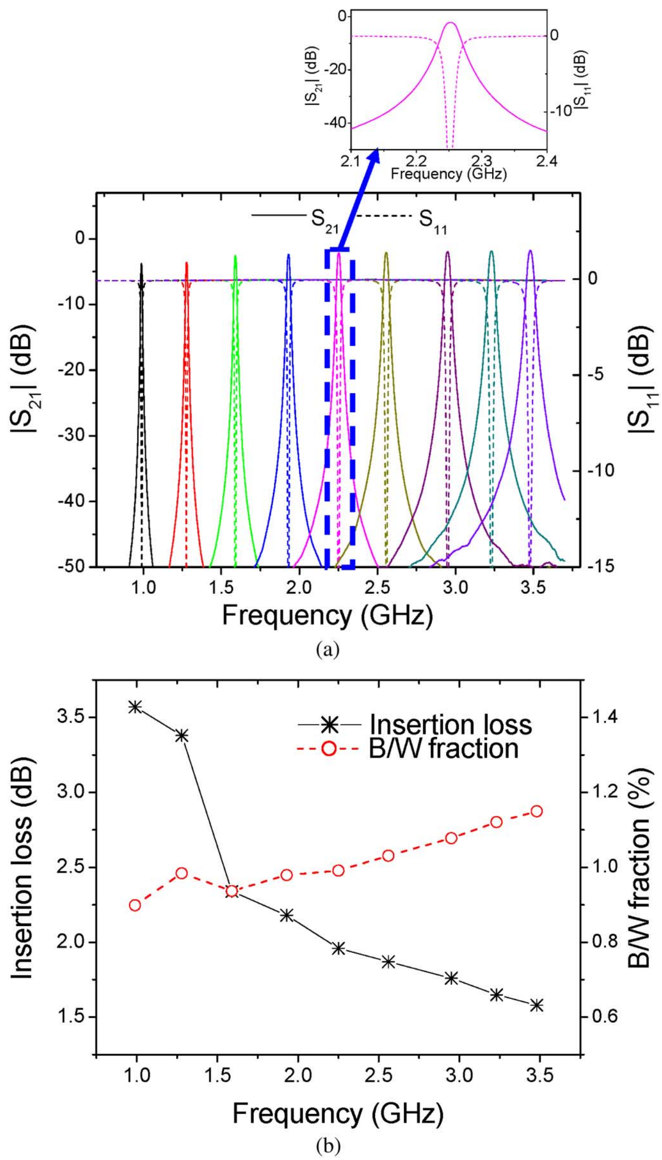

Fig. 4. Measurement result of the evanescent-cavity mode filter: (a) |S11| and |S21| in dB and (b) insertion loss and fractional bandwidth.

frequency is decided by the piezo deflection, whose displacement range is 38 μm.

In terms of tuning ratio, the gap is dominated by the roughness of top surface in the post. To achieve at least 3.5:1 tuning ratio, the gap at the lowest tuned frequency is calculated to be less than approximately 3 μm, taking into consideration the deflection limit of piezoelectric discs. After polishing the surface using alumina grain with 50 μm diameter, the difference between the highest and lowest point of the Parylene-N coated copper on the post is measured to be less than 2.5 μm. Thus, the roughness of the polished top surface is small enough to allow for more than 3.5:1 tuning ratio when the membrane approaches at the lowest point. Fig. 4(a) shows the measured S-parameters of the filter and it tunes from 0.98 GHz to 3.48 GHz (tuning ratio of 3.55:1). The applied voltage to deflect the piezoelectric discs ranges from -210 V and 210 V, and the corresponding gap between top surface and membrane is estimated to be changed from 2.8 μm to 40 μm. The reflection coefficient is better than 15 dB across the entire tuning range. A major challenge involved in the design of such a wide tuning filter is to achieve good return loss performance over the tuning range. The filter is designed to have Butterworth response with 1% fractional bandwidth and design parameters given by [12].

In order to achieve a constant fractional bandwidth with good return loss, we used an iris between two resonators for inter-resonator coupling and CPW feed line with rounded slots for external coupling. The insertion loss of the filter varies from 3.57 dB at 0.98 GHz to 1.56 dB at 3.5 GHz. This is because the resonator Q increases from about 300 to 650 over this tuning range as the electrical volume is increased. Finally, in this work it was successfully demonstrated that the evanescent-mode cavity filter can be very widely tuned by piezoelectric discs.

III. Conclusion

This letter reports the packaging process of an evanescent-cavity mode filter, including milling, lamination, copper plating, and insulating layer coating taking into accounts both RF and mechanical material properties. The fabricated filter is validated to have an ultra-wide tuning ratio (3.55:1) with low loss (<3.57 dB). Specifically, this fabricated filter, to authors' knowledge, has the widest tuning ratio of all reported tunable filters known to date. Overall, the substrate integrated tunable filter is a very promising technique for realizing a compact and tunable bandpass filter of nearly two octaves tuning range.

References

[1] J. M. Garcia and A. Flores, "A novel approach to improve the performance of interconnection networks with hot-spots," in *Proc. 22nd Euromicro Conf.*, Prague, Czech Republic, Sep. 2–5, 1996, pp. 215–222.

[2] R. Berezdivin, R. Breinig, and R. Topp, "Next-generation wireless communications concepts and technologies," *IEEE Commun. Mag.*, vol. 40, pp. 108–116, 2002.

[3] A. Abbaspour-Tamijani, L. Dussopt, and G. M. Rebeiz, "Miniature and tunable filters using MEMS capacitors," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 7, pp. 1878–1885, Jul. 2003.

[4] J. Nath, D. Ghosh, J.-P. Maria, A. I. Kingon, W. Fathelbab, P. D. Franzon, and M. B. Steer, "An electronically tunable microstrip bandpass filter using thin-film barium-strontium-titanate (BST) varactors," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 9, pp. 2707–2712, Sep. 2005.

[5] H. Joshi, H. H. Sigmarsson, D. Peroulis, and W. J. Chappell, "Highly loaded evanescent cavities for widely tunable high-Q filters," in *Proc. IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 3–8, 2007, pp. 2133–2136.

[6] M. Al-Ahmad, R. Maenner, R. Matz, and P. Russer, "Wide piezoelectric tuning of LTCC bandpass filters," in *Proc. IEEE MTT-S Int. Dig.*, Jun. 12–17, 2005, pp. 1275–1278.

[7] H. Joshi, H. H. Sigmarsson, D. Peroulis, and W. J. Chappell, "Highly loaded evanescent cavities for widely tunable high-Q filters," in *Proc. IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 3–8, 2007, pp. 2133–2136.

[8] H. Joshi, H. H. Sigmarsson, S. Moon, D. Peroulis, and W. J. Chappell, "High Q narrowband tunable filters with controllable bandwidth," in *Proc. IEEE/MTT-S Int. Microw. Symp. Dig.*, Jun. 7–12, 2009, pp. 629–632.

[9] H. Joshi, H. H. Sigmarsson, S. Moon, D. Peroulis, and W. J. Chappell, "High Q fully reconfigurable tunable band pass filters," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 12, pp. 3525–3533, Dec. 2009.

[10] B. Humphrey, "Using Parylene for medical substrate coating," *Med. Plastics Biomater. Mag.*, vol. 3, no. 1, pp. 28–33, 1996.

[11] G. M. Rebeiz, *RF MEMS Theory, Design and Technology*. New York: Wiley, 2003.

[12] G. L. Matthaei and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*. New York: McGraw-Hill, 1980.