Highly Loaded Evanescent Cavities for Widely Tunable High-Q Filters

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***Abstract* — In the present work, a widely tunable high-*Q* air filled evanescent cavity bandpass filter is created in an LTCC substrate. A low loss Rogers Duroid® flexible substrate forms the top of the filter, acting as a membrane for a tunable parasitic capacitor that allows variable frequency loading. A commercially available piezoelectric actuator is mounted on the Duroid® substrate for precise electrical tuning of the filter center frequency. The filter is tuned from 2.71 to 4.03 GHz, with insertion losses ranging from 1.3 to 2.4 dB across the range for a 2.5% bandwidth filter. Secondarily, an exceptionally narrow band filter is fabricated to show the potential for using the actuators to fine tune the response to compensate for fabrication tolerances. While most traditional machining techniques would not allow for such narrow band filtering, the high-*Q* and the sensitive tuning combine to allow for near channel selection for a front-end receiver. For further analysis, a widely tunable resonator is also created with a 100% tunable frequency range, from 2.3 to 4.6 GHz. The resonator analysis gives unloaded quality factors ranging from 360 to 700 with a maximum frequency loading of 89%. This technique shows a lot of promise for tunable RF filtering applications.**

***Index Terms* —Cavity resonators, evanescent-mode filters, tunable filters, piezoelectric transducers, LTCC.**

I. Introduction

There has been a significant increase in demand for tunable systems, particularly tunable filters that can be utilized for front-end receiver pre-selection. While the digital implementation of the back-end of a wireless receiver allows for dynamic reconfiguration, for example in software defined radios and similar schemes [1], tunable pre-selection is still a difficult task. Band selection, and furthermore potential RF channel selection, prior to an LNA requires very high-Q filters in order to maintain the sensitivity of the system. High-Q components are essential to sustain narrow bandwidths with a low insertion loss. A considerable amount of research has been conducted on tunable components recently, in particular using MEMS technology, tunable varactors [2] and filters [3] have been realized. Other technologies include ferroelectric thin films, which have been used to create tunable filters [4]. However, Q's approaching 1000 that are still tunable have remained elusive, therefore high quality band selection has not been achieved. This work aims to fill the void in tunable filters by the creation of high-Q evanescent cavity filters that are piezoelectrically actuated.

Previously, high-Q tunable resonators have been created using polymer cavities with metallized fingers; forming a parallel plate capacitor to evanescently load the resonator [5]; the maximum frequency loading achieved was 73%. Piezoelectric transducers have been used to tune coupled microstrip line bandpass filters [6]-[7].

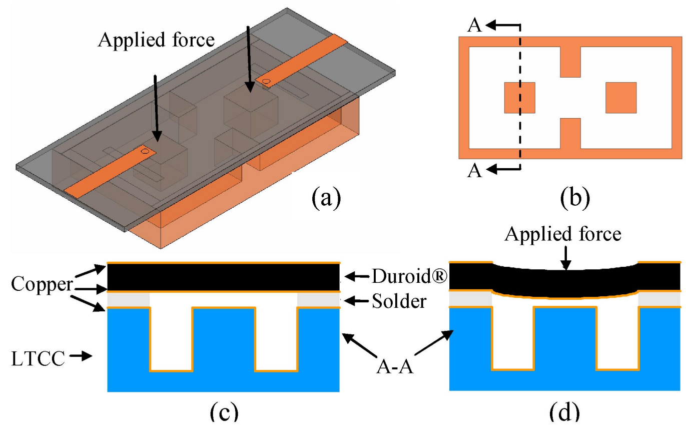

Fig. 1. Evanescent tunable cavity filter (a) Model of the designed two-pole evanescent cavity filter, (b) Top view of the evanescent filter formed by two evanescent cavity resonators, (c) Cross-sectional view of the filter, showing the capacitive post, without any applied force (static case), (d) Cross-sectional view showing the bending of the substrate causing the change in capacitance.

Waveguide resonant cavities have a very high-Q at the cost of very large sizes: on the order of half of a wavelength. By evanescently loading a cavity the frequency can be brought down by an order of magnitude, while still maintaining a high-Q [8], thus enabling the design and fabrication of compact high-Q filters [9]. An additional benefit of evanescently loading a cavity is that the spurious free range is improved [9].

This paper presents a two pole filter utilizing an extremely high-capacitive loading to gain compactness and increased sensitivity for wide range tuning; using a commercially available piezoelectric actuator. Metallized cavities are formed in a multilayer packaging material (LTCC) and bonded to a flexible substrate that is flexed by a piezoelectric actuator. Piezoelectric actuators are routinely used for ultra-precise positioning, such as nano-imprinting, scanning microscopy, microlithography, and automated alignment [10], and allow for extreme control of the capacitive loading of the cavity. This control leads to relatively small cavity filters that are easily tuned over a very wide operating range. In order to utilize the precise control of the piezoelectric actuator, the cavities are very heavily loaded with a post that is approximately 98% of the height of the cavity.

Fig. 1 shows the filter model with a top view of the filter layout along with the tuning mechanism used to get the wide tuning range.

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Furthermore, an extremely narrowband filter with a relative bandwidth of around 0.5% is presented, which is electrically fine tuned using the piezoelectric actuators to obtain the desired response, as a static filter fabricated using traditional machining would be very sensitive to the fabrication tolerances. Lastly a single resonator is also created to determine the quality factor and tuning capabilities of this technique.

II. Tunable Evanescent Filter Fabrication and Design

The filter is fabricated using 250 μm thick 150 mm x 150 mm DuPont 951 LTCC tape. Fifteen layers of tape are stacked up and laminated to form a tall green substrate. The cavity filter is then milled into the substrate and the part is fired using a standard firing profile for the 951 tape. The filter is then coated with a conductive silver paint to form a seed layer for thick copper electroplating. A 0.5 mm thick copper cladded Rogers Duroid® 5880 is used to form the top of the filter as well as the feed lines and coupling slot. The substrate is then soldered to the copper plated LTCC part. During that process the solder adds 25-50 μm to the height of the cavity, depending on amount of solder used during the attachment process.

The filter is formed from two square cavities, each with a side length of 10 mm and a depth of 2.6 mm. The post height is set equal to the depth of the filter, and the gap from the soldering process determines the initial capacitive gap.

The design is done with the aid of Ansoft's HFSS. The initial design begins with a simulation of the empty cavity resonator, and it is then loaded with an evanescent post. The size of the post is chosen to be 3 mm x 3 mm and the gap is estimated as the middle value of the stated range, 37.5 μm. This forms a 2.12 pF parallel plate capacitor, ignoring fringing fields. This capacitive loading reduces the resonance frequency from 21.21 GHz to 4.16 GHz. Two identical evanescent cavities are coupled using an iris to create the second order filter response; the size of the iris determines the inter-resonator coupling coefficient that directly relates to bandwidth. For a 4 mm wide and 2 mm long iris, an 88 MHz bandwidth is achieved at the initial design frequency of 4.2 GHz. The external coupling consists of a shorted microstrip line coupling through the substrate to a slot in the top of the cavity. A plated via is used to create the short to the ground plane; this allows a significant reduction in the length of the feed line. The schematic of the designed filter is shown in Fig. 1 (a), a top view showing the two coupled cavities and the coupling iris in Fig. 1 (b), and a cross-section of the post region in Fig. 1 (c). The thin substrate allows tuning of the filter response by physically bending the substrate, Fig. 1 (d) shows a cross-sectional view of the bending above the post. For this filter, two APA120S actuators from Cedrat Technologies [11] are used for the bending, with one above each post. The actuator has a maximum unloaded deflection range of 120 μm for a voltage range of -20 to 150 V; for this filter, an approximate 40 V range with about 20 μm deflection is utilized to obtain the reported results. An additional benefit of the shorted feed lines is that it prevents the actuators from contacting them and perturbing the coupling. To anchor the actuators, a polymer test fixture was designed and fabricated using stereolithography. The fabricated filter dimension is 19.97 mm x 9.92 mm with 3.12 mm x 3.07 mm posts, and a cavity depth of 2.6 mm.

A secondary use of the tunable filters is to provide very narrow bandwidths that would be impossible to achieve with normal fabrication tolerances. The tuning allows for a fractional bandwidth as low as 0.5%, while maintaining a reasonable insertion loss because of the high-Q of the resonator. This effect is demonstrated in a second filter. The filter is fabricated using two 2 mm deep 10 mm x 10 mm resonators with a 2.5 mm x 2.5 mm posts and a smaller coupling iris than the previous filter, 3 mm wide and 2 mm long. The iris length is designed to give an approximately 0.5% fractional bandwidth, given the variability of the solder height.

To further analyze the achievable unloaded quality factors and the tunable range reasonably accomplishable using this technique, a weakly coupled single resonator is also fabricated and tested. The resonator is a 10 mm x 10 mm cavity, 2 mm deep, with a 4 mm x 4 mm post.

III. Measurement and Analysis

The measured results for the fabricated filter are shown in Fig. 2 (a). The highest frequency curve shows the static measurement, meaning that there is no force applied by the piezo-

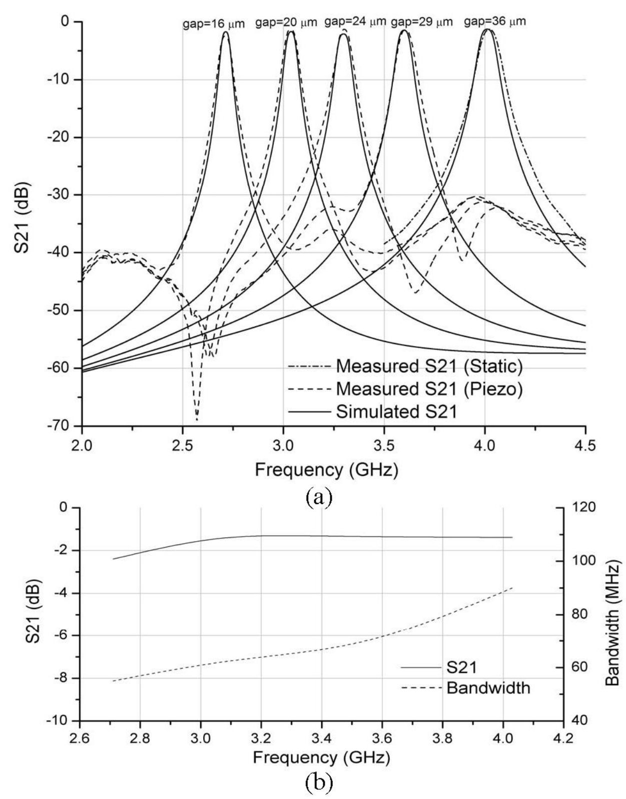

Fig. 2. Filter tuning performance (a) Measured and simulated insertion loss, as a function of the capacitive gap, (b) Measured insertion loss and bandwidth across the tuning range.

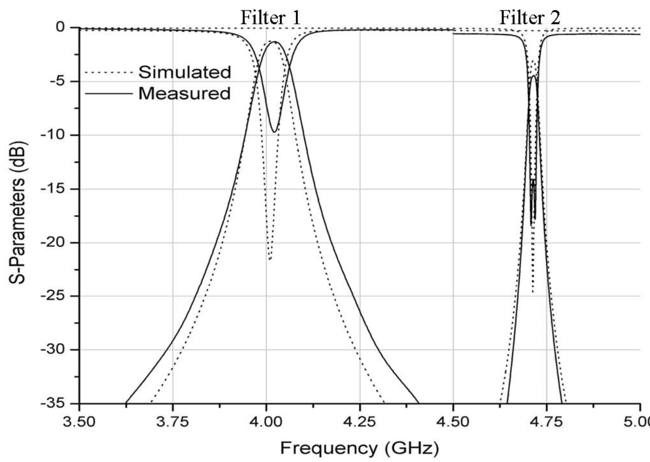

Fig. 3. The S-parameters of both the fabricated filters. Filter 2 has a 0.5% bandwidth; each pole fine tuned using a piezoelectric actuator to compensate for fabrication tolerances.

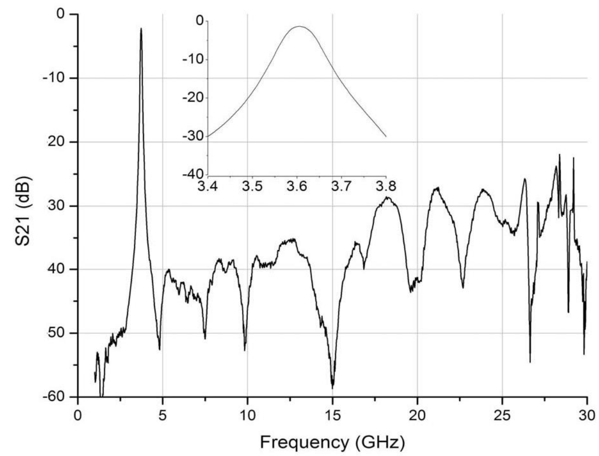

Fig. 4. Measured spurious free range of the fabricated filter.

electric actuator; this measurement gives a center frequency of 4.03 GHz with a 90 MHz bandwidth and a 1.3 dB insertion loss. The center frequency is 4% lower than the design; this difference is due to the solder height. The actual solder height is estimated to be 36 μm from a full wave simulation, assuming a flat surface. The simulated result with the modified solder thickness is shown on Fig. 2. This filter is extremely compact compared to a traditional empty air filled cavity filter at 4 GHz, which would occupy an area of 106 mm x 53 mm for the same mode, so the total reduction in area is 96.4%, which is higher than has been demonstrated previously for evanescent cavity filters [9].

The filter is then tuned using the piezoelectric actuator [11] and the measurements are shown in Fig. 2 (a). The piezoelectric actuator contracts with voltage, therefore the actuator needs to be pressing the substrate prior to actuation. The measured bandwidth of the filter varies from 70 MHz at 3.6 GHz to 55 MHz at 2.7 GHz, as shown in Fig. 2 (b). The insertion loss is consistently 1.3 dB over most of the tuning range.

A full wave simulation is performed in order to obtain the estimated gaps between the capacitive post and the bending substrate. This is necessary since the mechanical loading on the actuators reduces the available deflection. Therefore, the voltage-deflection relation given by the manufacturer no longer applies. The simulated and measured results are in good agreement, indicating that the gap estimation is accurate and that the simulations are clearly tracking the behavior of the tuning experiment.

These results indicate that the filter can be tuned over a large range of frequencies with small deflections of the Duroid® substrate. By utilizing the fine tuning possible with the piezoelectric actuators, extremely narrow band filters (~ 0.5 % bandwidth) can also be achieved. Measured results for the filter are shown in Fig. 3 along with the static filter result from Fig. 2 to further emphasize selectivity of a 0.5% filter. The filter has a 25.3 MHz bandwidth at 4.72 GHz with an insertion loss of 4.46 dB. The corresponding gap extracted from simulations is estimated to be 50 μm. The simulated results indicate a bandwidth of 23 MHz with an insertion loss of 3.1 dB.

Another advantage of the evanescent cavity filter is an extremely large spurious free range, greater than 26 GHz, with no additional modes excited up to 30 GHz. The measured spurious free range of the filter is shown in Fig. 4. It should be noted that the isolation beyond 18 GHz is compromised due to overmoding of the SMA connectors. Since the resonant element is a highly loaded cavity that is a hybrid between a lumped and a distributed component, the fundamental mode is well below modes based on distributed effects.

To further analyze the underlying fundamental properties affecting the filter performance, such as the quality factor and tuning ratio of each cavity, a weakly coupled single resonator is also fabricated and tested using the same piezoelectric actuator to bend the substrate. The resonator can itself be tuned from 2.3 to 4.6 GHz (100% tuning range) by changing the actuation voltage from -10 to 90 V, and the measured response is shown in Fig. 5. The cavity resonator is relatively insensitive to tuning after 90 V as the substrate is almost at the initial position and minimal additional increase in frequency

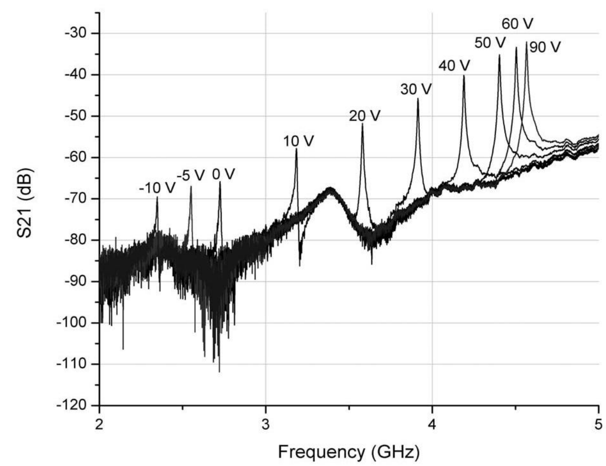

Fig. 5. Single resonator tuning measurements showing the voltage applied to the piezoelectric actuator.

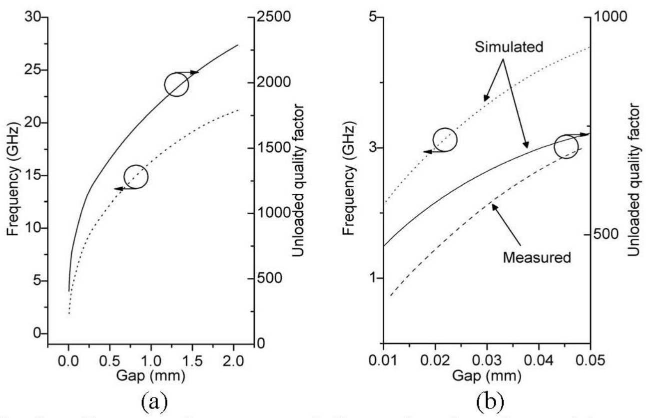

Fig. 6. Resonant frequency and Q as a function of capacitive gap between the post and top of the cavity (a) The simulated broad loading range, (b) A blow-up of the highly sensitive region of the curve.

can be achieved. The measured unloaded Q varies from 360 at 2.3 GHz to 702 at 4.6 GHz. This corresponds to a total displacement of about 40 μm, as determined from full wave simulations. Full wave simulations are performed to better characterize the relationship between the resonant frequency and unloaded Q versus the capacitive gap, the results are shown in Fig. 6 (a). Fig. 6 (b) shows the resonator is being operated in a highly sensitive region where the gap ranges from 10 to 50 μm. Also in Fig. 6 (b) the measured Q values are compared to the simulation. The shape of the resonance curve indicates a sharp slope in the heavily loaded region, where the sensitivity of the tuning is approximately 65 MHz/μm from a linear approximation. While Q decreases accordingly, it is still large enough to give good performance within this region.

IV. Conclusion

This work presents a new technique for widely tunable, highly loaded high-Q evanescent filters suitable for dynamic pre-selection. By loading the resonant cavity embedded with micron size gaps between a center located post and the cavity top, the cavity operates in a sensitive yet high-Q region. This region of operation for the cavity is suitable for tunable band select filters, potentially useful for the next generation of tunable radio architectures. The evanescent cavities integrated a traditional packaging material, allow for a very large tuning range using a small physical displacement, accomplished by using a piezoelectric actuator. A tuning range from 2.7 to 4.03 GHz with only a 20 μm deflection was demonstrated. As an additional application of the high-Q tunable cavities, very narrow band filters approaching channel select bandwidths can be implemented. The concept was demonstrated by a 0.5% filter at 4.72 GHz. This would not be feasible in static designs due to fabrication tolerances. The fundamentals of the filter performance were explained by analyzing single cavity resonators, with performance consistent with the filter measurements. The full cavity resonator tuning range was 2.3 to 4.6 GHz, demonstrating 100% frequency tuning. The results indicate the possibility of tunable pre-select filtering that does not degrade the sensitivity of front-end receivers.

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