

3-6 GHz Tunable Bandpass Filter using Heavily Loaded Evanescent-mode Cavity Resonators and Piezoelectric Actuators

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Abstract

In the present work, a widely tunable, high quality factor (Q), narrow bandpass filter is demonstrated using evanescent-mode cavity resonators as building blocks. The frequency and Q variation of the evanescent-mode cavity are predicted using analytical expressions, which give design variables for the building blocks. A widely tunable evanescent-mode cavity resonator is fabricated to verify the theoretical analysis. A tunable filter can be tuned continuously from 3 to 6 GHz with a very narrow bandwidth (~0.58% is demonstrated). The filter is fabricated in low temperature co-fired ceramics with a low loss Rogers Duroid® flexible substrate forming the top of the filter and hosts the feed lines for the filter. The flexible substrate acts as a deformable membrane that allows variable frequency loading of each of the resonators. A commercially available piezoelectric actuator is mounted on the Duroid® substrate for precise electrical tuning of the filter center frequency. The narrow band filter demonstrates the potential of the tuning mechanism to compensate for fabrication tolerances, which are especially important for such a narrow bandwidth filter. The high-Q and the sensitive tuning combine to allow for high quality pre-select filtering for a front-end receiver.

Key words: software defined radio, high quality factor, tunable filters, front-end receiver, and low temperature co-fired ceramics.

1.0 Introduction

Power-efficient implementations of future handheld adaptable communications and radar systems require a considerable level of pre-processing of different waveforms at the front-end level. This has resulted in significantly increased demand for a new class of tunable systems, particularly tunable filters that can be utilized for front-end receiver pre-selection. With digital implementation of the back-end, wireless receivers are becoming highly flexible and dynamically reconfigurable, e.g. in software defined radio schemes [1]. However, tunable band

pre-selection still remains a challenge for microwave and millimeter wave operations. Dynamic or cognitive receiving architectures often project the use of wide ranges of spectrum, but this leaves the front end of the system open for saturation from co-site or intentional interference, unless a switched bank of filters or tunable filter is utilized. Pre-low noise amplifier (LNA) filtering is required in order to protect the system from saturation from high power signals. Band selection prior to an LNA requires high-Q filters ($Q > 1000$) in order to maintain the sensitivity of the system. High-Q components are essential to sustain narrow bandwidths with a low

insertion loss. Therefore, the challenge is to create high-Q filters (unloaded Q of 1000) with tunabilities on the order of 2:1.

A considerable amount of research has been conducted on tunable components recently, in particular using planar microelectromechanical systems (MEMS) technology to realize varactors [2] and tunable filters [3]. Other technologies include ferroelectric thin films, which have been used to create tunable filters [4]. Evanescent-mode cavity filter theory has been investigated previously [5], [6]. However, Q 's approaching 1000 that are still tunable have remained elusive, so high quality band selection has not yet been achieved. This work aims to address the remaining bottleneck for fully tunable wireless systems by creating widely tunable, high-Q, evanescent cavity filters, piezoelectrically actuated, intended for pre-selection. Waveguide resonant cavities have a very high-Q at the cost of very large sizes (on the order of half of a wavelength). By loading a cavity with a capacitive post, the frequency can be brought down by an order of magnitude, while still maintaining a high-Q [7], thus enabling the design and fabrication of compact high-Q filters [8], [9]. Previously, high-Q tunable resonators have been created using polymer cavities with metallized fingers, forming a parallel plate capacitor to evanescently load the resonator [10]. Piezoelectric transducers have been used to tune coupled microstrip line bandpass filters [11], [12]. A tunable evanescent-mode cavity filter has been demonstrated to tune from 2.7 to 4 GHz with a 2.5% bandwidth [13].

In this paper, a widely tunable evanescent-mode cavity filter is presented. The filter tunes from 3 to 6 GHz and has a very narrow bandwidth of 0.58% across the tuning range. The frequency variation is predicted by using a theoretical analysis of highly loaded evanescent-mode cavities derived from per-

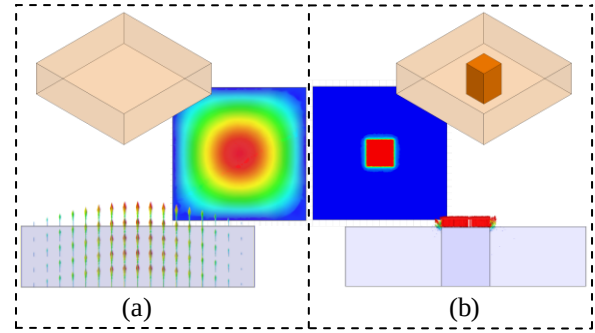


Fig. 1: Comparison between a regular and an evanescent-mode cavity (a) A regular cavity resonator with a cross-sectional and top view of the electric field distribution, (b) a capacitively loaded cavity resonator, showing the confinement of the electric field above the post.

turbation theory. The relationship between the unloaded quality factor and geometry of the cavity resonator is shown. The combination of the frequency prediction and the quality factor provides means of designing the tunable cavity resonator for filter applications.

2.0 Evanescent-mode Cavity Filter Concept

An evanescent-mode cavity resonator consists of a waveguide resonant cavity that has a capacitive loading post at a strategic location. The ideal location is where the electric field is at a maximum. Placing a post in the maximum electric field causes the fields to confine above the post itself, thus disturbing the traditionally sinusoidal field distribution. This brings down the resonant frequency and allows for increased compactness compared to an unloaded cavity resonator without causing a substantial drop in quality factor. Fig. 1 shows both an unloaded and a loaded resonator and the change in electric field caused by the loading post. The two resonators are the same

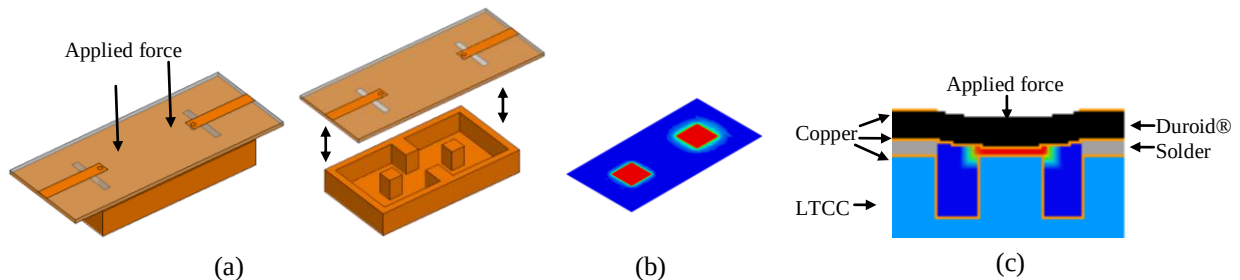


Fig. 2: Evanescent-mode tunable cavity filter (a) Model of the designed two-pole evanescent-mode cavity filter along with an exploded view to show the posts, (b) a top view of the electric field distribution around the posts, (c) cross-sectional view of the filter, showing the concentrated electric field (not to scale).

size, 10 mm x 10 mm 3 mm, and the regular cavity has a resonant frequency of 21.21 GHz and an unloaded quality factor of 3000, whereas the loaded resonator has a resonant frequency of 6 GHz and an unloaded quality factor of 1200. For comparison a regular waveguide cavity resonator at 6 GHz would need to be 35 mm x 35 mm. Fig. 2 (a) shows two evanescent-mode cavity resonators combined for form a two pole filter and the electric field above the posts is shown in Fig. 2 (b).

Another advantage of the field confinement is that the resonant frequency becomes very sensitive with respect to changes in the gap between the post and the top of the cavity. This enables a very wide range tuning with realizable geometrical changes to the cavity itself which can be induced by applying force to the top of the cavity itself using an actuator. Piezoelectric actuators are routinely used for ultra precise positioning, such as nano-imprinting, scanning microscopy, microlithography, and automated alignment [14], 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 need to be very heavily loaded with a post that is approximately 98% of the height of the cavity. A cross-sectional view of the post region is shown in Fig. 2 (c), which shows the confined electric field and the bending of the top of the cavity to demonstrate the tuning concept.

2.1 Frequency Variation Estimation

The resonant frequency of the resonator is changed by modifying the gap between the top of the post and the top of the cavity itself. If the incremental change in gap is small compared to the initial gap so as not disturb the field distribution, the frequency change can be predicted using perturbation theory [15]:

$$\frac{\omega - \omega_o}{\omega_o} \approx \frac{\Delta W_m - \Delta W_e}{W_m + W_e} \quad (1)$$

where ω_o is the initial resonant frequency without any perturbation and ω is the resonant frequency after an incremental change in gap. W_m and W_e represent the energy stored in the magnetic and electric field respectively. ΔW_m and ΔW_e denote the change in the time averaged energy stored in the magnetic and electric field due to the perturbation. For this evanescent cavity, the frequency is changed

by only changing the electric field on top of the post, and hence $\Delta W_m = 0$. At resonance W_m and W_e are the same and hence the expression in (1) reduces to:

$$\frac{\omega - \omega_o}{\omega_o} \approx \frac{-\Delta W_e}{2W_e} = \frac{\int_{\Delta V} \epsilon_o |E_o|^2 dV}{\int_V \epsilon_o |E_o|^2 dV} \quad (2)$$

where E_o is the peak value of the electric field above the post, ΔV is the incremental volume change and V is the initial volume. By ignoring fringing fields, which is a good approximation for high loading percentages, the expression can be further simplified because the volume change is then independent of the area, (2) can therefore be rewritten as:

$$\frac{\omega - \omega_o}{\omega_o} \approx \frac{-\Delta g}{2g} \quad (3)$$

The above expression is verified by comparing to eigenmode simulations using Ansoft's High Frequency Structure Simulator (HFSS) for a 10 mm x 10 mm x 3 mm size cavity with three different square posts of sizes: 1 mm, 3 mm and 5 mm. The results are shown in Fig. 3 and indicate a good agreement between theory and the full-wave simulations. The smaller the post is the greater the effect from the fringing fields. This can be seen from the figure since the frequency difference reduces as the post size increases. However reasonable results are seen for all three sizes shown. As can be seen from the curves, by reducing the post size the sensitivity increases and the frequency change can be achieved with a much smaller change in gap. The sensitive range is exploited in demonstrating the tunable filters. The initial resonant frequency needs to be extracted from

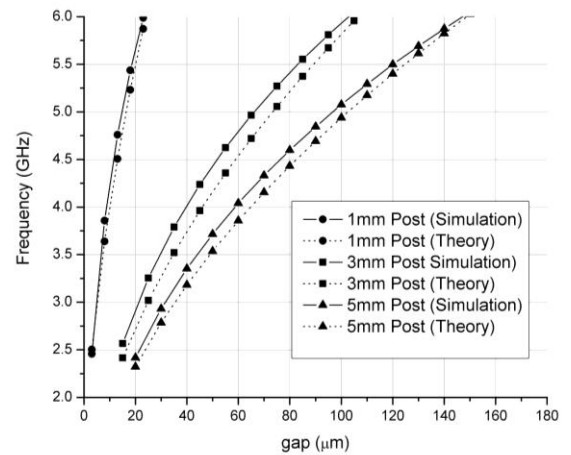


Fig. 3: Simulated change in resonant frequency as a function of the changing gap for three different post sizes compared to the expressions derived from perturbation theory.

an eigenmode simulation and after that the tuning can be calculated iteratively using this simple expression. Equation (3) can thus be used to accurately predict the frequency tuning with changing gap and can be used as a guideline for designing a cavity resonator with the desired frequency sensitivity. Most importantly the small gap needed to change the resonance by a 2:1 ratio is illustrated.

2.2 Quality Factor Estimation

The magnetic field distribution inside an evanescent cavity resonator is similar to a coax transmission line, and the electric field is primarily concentrated on the top of the post. This is particularly true for a cylindrical cavity with a cylindrical post as shown in Fig. 4. The Q of an air-filled evanescent cavity filter can therefore be estimated by looking at the sidewall and top/bottom plate losses on the resonator. The sidewall losses can be estimated using the expression for a coaxial line shown in equation (4). Additional losses are accounted for using a parallel plate mode for the top and bottom regions (5).

$$Q_{side} = \frac{\omega L}{R} = \frac{\beta}{2\alpha} = \frac{2\eta \ln\left(\frac{b}{a}\right) \omega \sqrt{\mu\epsilon}}{R_s \left(\frac{1}{a} + \frac{1}{b}\right)} \quad (4)$$

$$Q_{ends} = \frac{\omega \mu h}{2R_s} \quad (5)$$

The total $Q_{unloaded}$ therefore is the parallel combination of these two loss mechanisms

$$\frac{1}{Q_{unloaded}} = \frac{R_s}{\omega \mu} \left[\left(\frac{\frac{1}{a} + \frac{1}{b}}{\ln\left(\frac{b}{a}\right)} + \frac{2}{h} \right) \right] \quad (6)$$

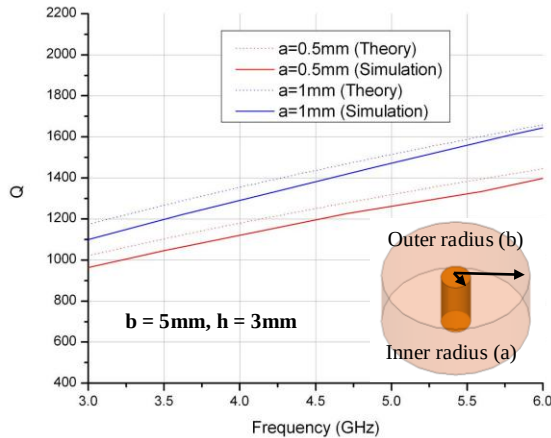


Fig. 4: Comparison between the modeled quality factors and the full wave simulations.

This expression for Q is compared to eigenmode simulations in Ansoft HFSS and the results are shown in Fig. 3 and indicate a good agreement. The theoretical expression can therefore be used as a guideline to get an initial estimate of the Q of an evanescent-mode cavity filter that is accurate to within 5%. For the square implementation, the currents are highly concentrated on the edges of the post because of which the attenuation term in the sidewall Q is worsened by the non ideal geometrical arrangement. This can be related to the circular case by adding a constant, C , to the circular cavity loss.

$$\alpha_{Square} = C \alpha_{Circular} \quad (7)$$

Equation (6) is thus modified for the square cavity:

$$\frac{1}{Q_{unloaded}} = \frac{R_s}{\omega \mu} \left[\frac{C \left(\frac{1}{a} + \frac{1}{b} \right)}{\ln\left(\frac{b}{a}\right)} + \frac{2}{h} \right] \quad (8)$$

The quality factors of both cavity types are simulated and shown in Fig. 5. The cylindrical cavity resonator has approximately 10% higher quality factor than the square resonator.

The cavity dimensions of a resonator can be chosen using equations (6) and (8), for a cylindrical and square resonator respectively, to achieve a desired quality factor, which is determined by the targeted insertion loss of the filter.

3.0 Filter Fabrication

The entire fabrication flow is shown on Fig. 6. The cavity filters are fabricated using 10 mil thick, 6" x 6" DuPont® 951 LTCC tape. 15 layers of tape are stacked up and laminated to form a tall green substrate. This substrate is relatively soft and the filters

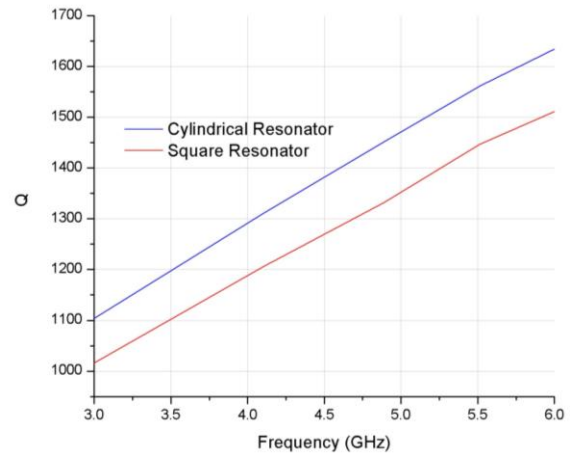


Fig. 5: Comparison between the simulated quality factors of both a cylindrical and a square cavity.

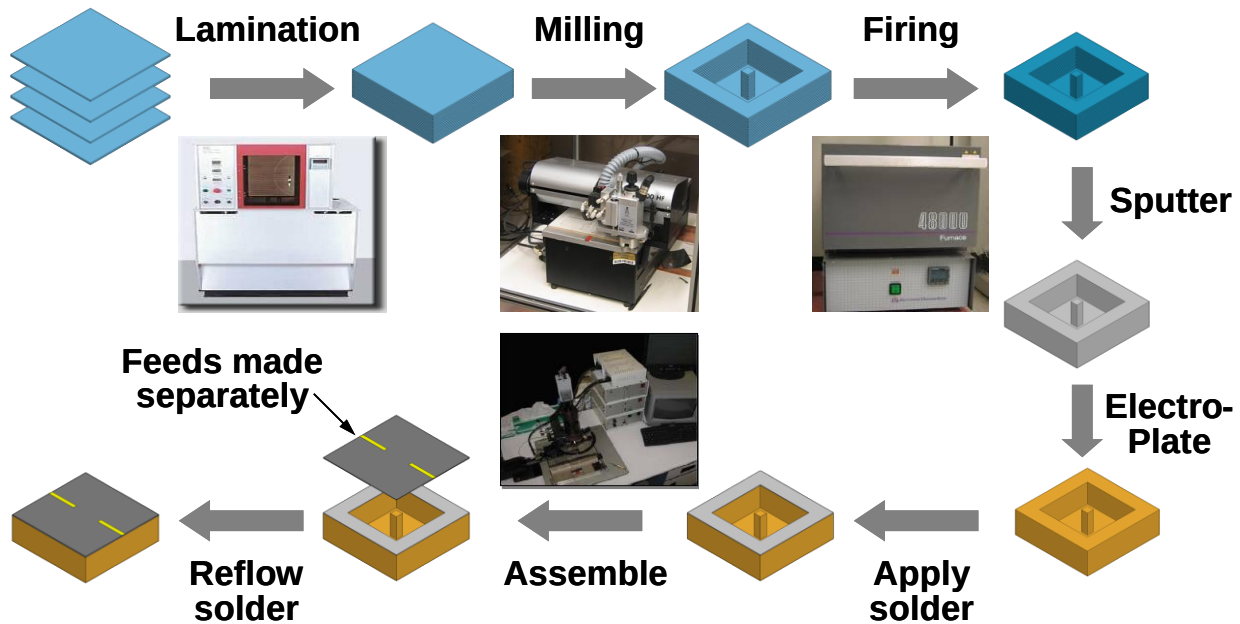


Fig. 6: Cavity fabrication procedure. A stack of 10 mil Dupont® 951 LTCC green tape is laminated to form a thick substrate out of green tape. This substrate is then milled to form a rectangular, evanescent-mode cavity. After firing the machined substrate, the cavity is metallized by first sputtering on a seed layer and then it is copper electroplated. Finally the flexible substrate with the feeds is soldered on.

are machined using a traditional milling machine. The parts are then fired using a standard firing profile for the 951 tape. Au/Pd is sputtered onto the parts to form a seed layer for thick copper electroplating. A sheet of 20 mil thick copper clad Rogers Duroid® 5880 is used to form the top of the filters as well as the feed lines and coupling slots. The substrate is then soldered to the copper plated LTCC parts. During that process the solder adds 1-2 mils to the height of the cavity, depending on amount of solder dispensed during the attachment process. Finally SMA connectors are soldered onto the feeds.

The fabricated filter is formed from two square cavities, each with a side length of 10 mm and a depth of 2.6 mm. The cavities are connected by an iris that determines the bandwidth of the filter. The post height is set equal to the depth of the filter, and the gap from the soldering process is used to determine the initial capacitive gap.

4.0 Experimental Results

A very widely tunable narrow band filter was fabricated to verify the effectiveness of this technology. In order to measure the fabricated filter it is mounted in a sturdy measurement fixture that has two APA120S piezoelectric actuators from Cedrat [16] mounted, one above each post. The piezoelectric

actuators can provide almost 5 mil of free-free displacement. The bias voltage of the actuator is from -20 to 150 V. The actual displacement is limited slightly by the stiffness of the Duroid® substrate. The measurement setup and a picture of the actuator can be seen in Fig. 7 (a).

The filter is tuned from 3 to 6 GHz while having loss around 4 dB across the tuning range with a bandwidth of 0.58% (17.5 to 35 MHz). The low loss is possible due to the high quality factors that can be achieved with this type of filters while keeping a small form factor. Also, because of the heavy loading, the tuning sensitivity is at a level where only 2 mil of total deflection is enough to tune across the entire range. The measured S-parameters are shown in Fig. 7 (b) and the measured S_{21} and bandwidth can be seen in Fig. 7 (c).

5.0 Conclusion

This work presents a very narrow band, widely tunable, high-Q, evanescent-mode filter with a tuning range of 2:1, going from 3 to 6 GHz while maintaining a low insertion loss. This is achieved by highly loading the evanescent-mode cavities, reducing the size and increasing the sensitivity with respect to deflection. Analytical derivations are introduced for both the frequency tuning sensitivity and the resona-

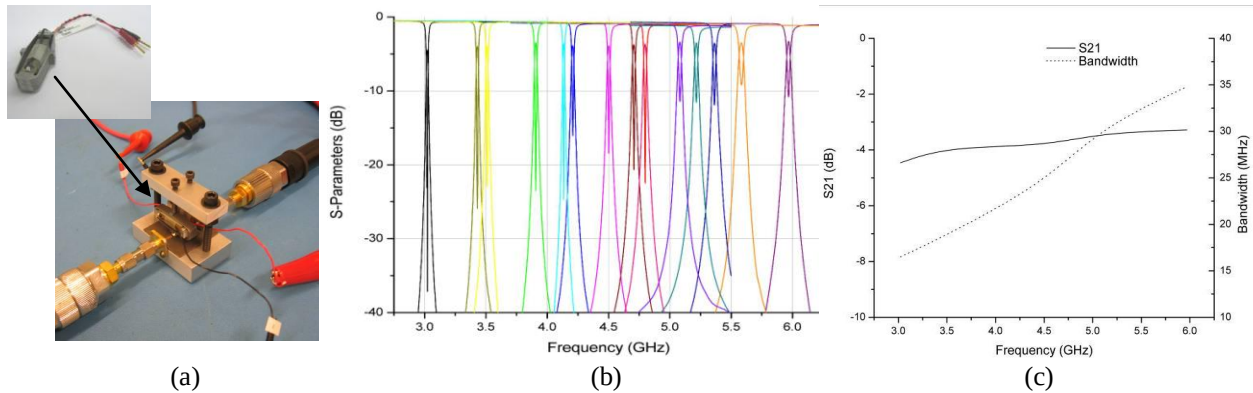


Fig. 7: Filter measurement summary, (a) The measurement setup and the APA120S piezoelectric actuator, (b) the measured S-parameters showing the tuning from 3 to 6 GHz, and (c) the measured S_{21} and bandwidth as a function of frequency.

tor quality factor as a function of the cavity geometry, which are shown to accurately predict the frequency and Q of operation. The performance of the filter suggests that dynamic pre-selection can be achieved using this technique. This class of filters may be an enabler for the next generation of software defined radio architectures.

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