Analytical Modeling of Highly Loaded Evanescent-mode Cavity Resonators for Widely Tunable High-Q Filter Applications

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Abstract

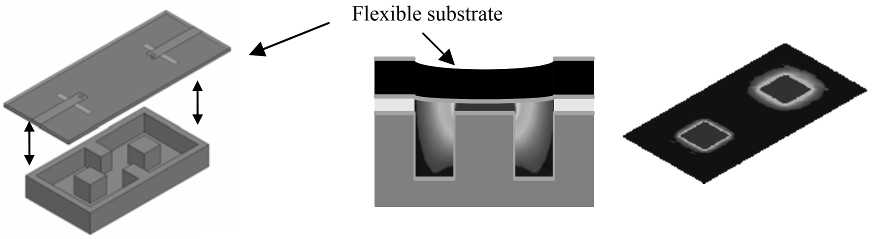
In the present work, the frequency and quality factor (*Q*) variation of an evanescent-mode cavity resonator are predicted using analytical expressions, which give design variables for these structures. Two widely tunable narrowband evanescent-mode bandpass filters having 2.5% and 0.58% bandwidths are demonstrated, tuning from 2.7 to 4 GHz and 3 to 6 GHz respectively. A low loss Rogers Duroid® flexible substrate forms the top of the filter, acting as a deformable membrane that allows variable frequency loading. A commercially available piezoelectric actuator is mounted on the 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 preselect filtering for a front-end receiver.

1. 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 the digital implementation of the back-end, wireless receivers are becoming highly flexible and dynamically reconfigurable, for example 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 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 evanescently loading a cavity 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].

In this paper, a theoretical analysis of highly loaded evanescent cavities is derived from existing perturbation theory in order to obtain analytical expressions for predicting the frequency variation. The geometry is also related to the quality factor of the cavity. The combination of the frequency prediction and the quality factor provides means of designing the tunable cavity resonator for filter applications. Furthermore, two filters are demonstrated with wide tuning ranges, a 2.5% filter from 2.7 to 4 GHz and a 0.58% filter from 3 to 6 GHz.



(a) (b) (c)

Fig. 1. Tunable evanescent cavity filter (a) Exploded view of the designed two-pole evanescent cavity filter, (b) Cross-sectional view showing the bending of the substrate causing the change in capacitance, along with the logarithmic electric field distribution inside the cavity showing the confinement above the post (not to scale), (c) Top view of the electric field distribution.

2. Theory

2.1 Estimating frequency Variation

For an evanescent cavity, the electric field is concentrated on the top of the post creating an effective capacitance (Fig. 1). The resonator can therefore be tuned by changing the gap between the top of the post and the top of the cavity as shown in(1). 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 [13]:

$$\frac{\omega-\omega_o}{\omega_o} \approx \frac{\Delta W_m - \Delta W_e}{W_m + W_e} \tag{1}$$

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:

$$\frac{\omega-\omega_o}{\omega_o} \approx \frac{-\Delta \overline{W_e}}{2W_e} = \frac{\int_{\Delta V} \varepsilon_o \left|E_o\right|^2 dV}{\int_V \varepsilon_o \left|E_o\right|^2 dV} \tag{2}$$

where E_0 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:

$$\frac{\omega-\omega_o}{\omega_o} \approx \frac{-\Delta g}{2g} \tag{3}$$

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. 2 and indicate a good agreement between theory and the full-wave simulations. The contribution of the fringing fields has a greater effect on the smaller post. 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 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. Most importantly the small gap needed to change the resonance by a 2:1 ratio is illustrated.

2.2 Estimating Quality Factor

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. 3. 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).

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

$$Q_{ends} = \frac{\omega\mu h}{2R_s} \tag{5}$$

The total *Q* therefore is the parallel combination of these two loss mechanisms (6)

$$\frac{1}{Q_{Unloaded}} = \frac{R_s}{\omega\mu}\left(\frac{\left(\frac{1}{a}+\frac{1}{b}\right)}{\log\left(\frac{b}{a}\right)}+\frac{2}{h}\right) \tag{6}$$

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.

3. Measurements

Widely tunable narrow band filters were fabricated to verify the effectiveness of this technology. The measurement results are shown in Fig. 4 for a 2.5% and 0.58% filter respectively. The 2.5% filter is tuned from 2.7 to 4 GHz while maintaining a low loss (around 1.3 dB) while the 0.58% filter is tuned from 3 to 6 GHz with a relatively low loss (around 4 dB). The low-loss is possible due to the high quality factors that can be achieved with these filters in small form factor. Also, because of the heavy loading, the tuning sensitivity is at a level where a commercially available piezoelectric actuator can be used to get the desired tuning using only 20 and 50 μm total deflection for the 2.5% and 0.58% filters respectively.

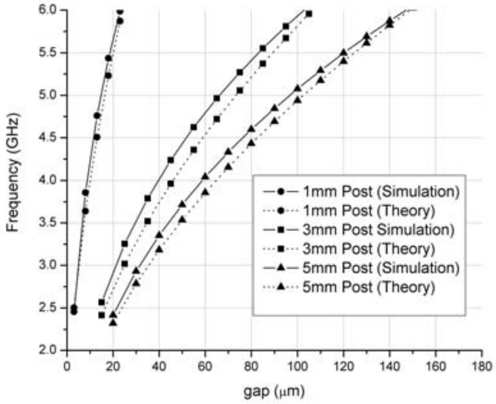


Fig. 2. Simulated change in resonant frequency as a function of the changing gap for three different post sizes.

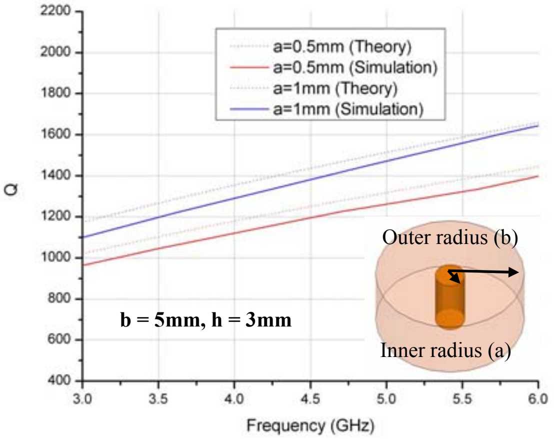


Fig. 3. Comparison between the modeled quality factors and the full wave simulations.

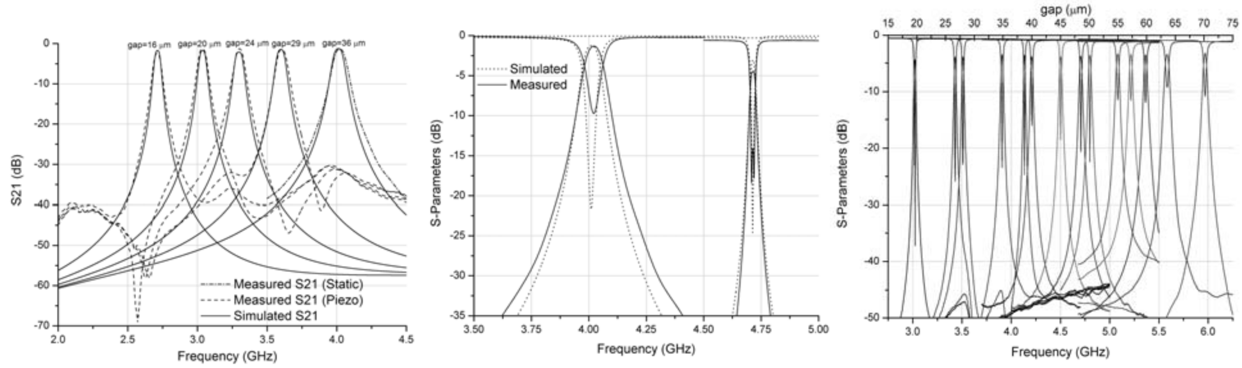


Fig. 4. S-Parameter results for widely tunable second order filters with different bandwidths, the leftmost figure shows a 2.5% filter tuned from 2.7 to 4 GHz, the center figure show the comparison between the 2.5% and 0.58% filters, and the rightmost figure shows the tuning of the 0.58% filter from 3 to 6 GHz.

4. Conclusion

This work presents analytical derivations for both the frequency tuning and the resonator quality factor as a function of the cavity geometry, which are shown to accurately predict the frequency and Q of operation. Very narrow band, widely tunable, high-Q evanescent-mode filters are demonstrated with tuning ranges up to 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. The performance of the filters suggests that dynamic pre-selection can be achieved using this technique. This class of filter may be an enabler for the next generation of tunable radio architectures.

5. References

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