High-Q RF-MEMS Tunable Evanescent-Mode Cavity Filter

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Abstract—This paper presents a high-Q tunable evanescent-mode cavity filter using capacitive RF MEMS cantilever switches with a frequency coverage of 5.5-4.3 GHz. The filter results in an insertion loss of 2.6-5.3 dB over the tuning range and a 3-dB bandwidth of 55-40 MHz (fractional bandwidth of %1). The measured Q_u of the filter is 511-273 over the frequency range, which is to our knowledge, the best report Q using RF-MEMS technology.

Index Terms—evanescent-mode, RF MEMS, Capacitive cantilever switch, high-Q tunable filter, waveguide filter.

I. INTRODUCTION

Low-loss tunable filters are essential for multiband radios are essential, and to our knowledge tunable filters with Q > 200 have not yet been reported at 2-10 GHz. To realize a tunable filter with Q_u > 400, both the resonator and tunable device must have a Q_u > 400. The resonator Q using planar technology is 100-250 depending on the substrate. The Q can be increased to ~500 using a suspended strip-line configuration, but this occupies a substantial volume. Standard (full size) cavity resonators can also be used in tunable filters for the high Q (> 5,000), but their large volume at 2-10 GHz and incompatibility with fabricated tuning devices limit their usefulness for wireless systems. The volume can be significantly reduced with evanescent-mode designs which result in Q_u of 2,000-5000 [1]. These have been extensively used in the industry and recently, Joshi et al. showed a 3-6 GHz tunable evanescent-mode filter with external piezoelectric actuators [2], [3], [4].

In this work, a novel high-Q cantilever-switch capacitance network is used as a tuning network inside an evanescent-mode cavity filter. The measured results with RF-MEMS cantilever-switch capacitance network show a Q_u of 511-273 at 5.5-4.3 GHz.

II. DESIGN AND IMPLEMENTATION OF THE FILTER

A. Extracting Filter Design Parameters

The waveguide mode below cutoff creates a localized reactive region. The characteristic impedance of the TE evanescent-mode is inductive and equivalent to either a T- or a II-circuit model. As is well known, these inductances can be utilized as coupling and loading element in a filter design. It is usually easier to realize a shunt capacitance than a series one in a waveguide, and a filter circuit with shunt capacitances is shown in Fig. 1. Using the resonance condition, the required shunt capacitance values can be found by

\[ \omega_0 C_r = B_r = \frac{1}{X_0} \coth \gamma l \]  

where

\[ X_0 = \frac{377}{\sqrt{(\frac{k_e}{k_c})^2 - 1}} \]  

\[ k_c = \sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2} \]  

The shunt capacitances are implemented using capacitive posts in the waveguide, and a substrate with an RF-MEMS tunable switch network is mounted on each side of the posts to tune the resonance frequency. An inductive loop coupling scheme is utilized as the external coupling circuit due to its matching characteristics over a wide frequency range.

A full-wave model of the evanescent-mode cavity resonator is shown in Fig. 2, and HFSS simulation is used to extract \( f_c, f_o, Q_e, Q_L, \) and \( C_L \) (\( C_L \) is the RF-MEMS capacitance network). A lumped-port is placed between the cavity wall and the post to include \( C_L \) in the simulation in addition to a wave-port at the coaxial input. The coupling coefficient of the filter, \( k_c \), is calculated using the pole-splitting method, and is given by

\[ k_c = \frac{f_e^2 - f_o^2}{f_e^2 + f_o^2} \]  

The extracted \( C_L, Q_e, \) and \( k_c \) values are plotted versus resonance frequency in Fig. 3. \( C_L \) values of 640-180 fF result in a resonance frequency of 4.0-6.0 GHz, respectively.
Fig. 2. Full-wave simulation model of the evanescent-mode cavity resonator with loop coupling.

Fig. 3. The extracted $C_L$ (a), $Q_e$, and $k_c$ (b) with the resonance frequency change ($y_e=5$ mm, $x_c=2.5$ mm). The calculations are done at 5 GHz with the cavity in Fig. 2.

and the corresponding $Q_e$ and $k_c$ values are $170 \pm 23$ and $0.0062 \pm 0.0005$, respectively. The frequency dependence in $k_c$ shows a constant fractional-bandwidth behavior (23-40 MHz 3-dB bandwidth at 4-6 GHz), and the filter maintains good impedance matching over the frequency range due to the decrease in $Q_e$.

The external coupling of the resonator is controlled by the area between the cavity wall and the coaxial pin, and can be adjusted by changing $y_e$. The symmetry plane of the filter in the resonator is set to PEC or PMC to obtain the even- or odd-mode resonance frequency. The extracted $Q_e$ and $k_c$ values versus $y_e$ and $x_c$ are plotted in Fig. 4.

**B. High-Q RF-MEMS Cantilever-Switch Capacitance Network and The Filter Implementation**

For a narrow-band tunable filter, it is very important to match the resonance frequencies of each resonator. Simu-

Fig. 4. The extracted $Q_e$ ($x_c=2.5$ mm) (a) and $k_c$ ($y_e=5$ mm) for the cavity resonator in Fig. 2 with different $y_e$ and $x_c$, respectively. The calculations are done at 5 GHz with the cavity in Fig. 2.

Fig. 5. The high-Q RF-MEMS cantilever-switch capacitance network and its installation in the tunable evanescent-mode waveguide cavity.
lations show that at 6.0 GHz, the two loading capacitance values ($C_{L1}$ and $C_{L2}$) need to be controlled within ±1 fF so as not to degrade the filter response. At 4.0 GHz, a 2 fF variation is the maximum allowed. This, as well as the high-$Q$ requirement, put serious limitations on the design of the RF-MEMS capacitance network.

An RF-MEMS cantilever-switch with a digital/analog tuning capability is utilized to fulfill those requirements. The thick plated (3.5-4.0 μm) cantilever and the zipping effect with a hold-down bias voltage, $V_h$, make this switch a good candidate for both high-$Q$ and analog tuning capability. The measured cantilever-switch has an up-state and down-state capacitance of 40 fF ($V_p=30$ V) and 250 fF ($V_p=30$ V, $V_h=0$ V), respectively, and its analog capacitance coverage is 250-320 fF ($V_p=30$ V, $V_h=0$-12 V). The measured $Q$ of this device is > 300 at 6 GHz, even in the down-state position [5].

The loading capacitor, $C_L$, is realized using a 4-bit RF-MEMS cantilever-switch capacitance network and each switch has two bias-lines attached to it (Fig. 5). To minimize the impact on the filter $Q$, the bias-line length is minimized and the connections between the bias-lines and the bias-wires are accomplished with conductive bias-paths. The bias-wires connected at the end of the bias-paths go through a small channel on the cavity wall, and create a link to the external voltage source. For this high-$Q$ resonant cavity, it is very important to minimize radiation loss through this biasing channel. An $RC$ circuit is implemented in the bias-path to prevent the RF energy leakage to the bias wires.

The chip layout of the 4-bit high-$Q$ RF-MEMS cantilever-switch capacitance network is also shown in Fig. 5. Each switch has a metal-air-metal fixed scaling capacitor connected in series, and two bias-lines covered with metal bridges. With the analog tuning capability, the 4-bit $C_L$ network covers the capacitance range of 160-630 fF (Fig. 6), which in turn, results in the 4-6 GHz frequency coverage (Fig. 3).

The complete filter model with the high-$Q$ tunable RF-MEMS chips is shown in Fig. 7. Two separate chips are installed on each posts to create capacitive loading in each resonator. The bias-wires attached to the RF-MEMS chip pass through the small channels in the cavity and are connected to the outside bias source. The input couplings are realized using center pins of the coaxial connectors, and the inter-resonator coupling is controlled by the coupling iris located at the center and sets the filter bandwidth.

### III. FABRICATION AND MEASUREMENTS

High-$Q$ cantilever-switch capacitance network chips were fabricated and installed in the evanescent-mode cavity. A single resonator with different RF-MEMS chip was measured. Two RF-MEMS cantilever-switches were actuated in this measurement and the results are summarized in Table I. A measurement tunable $Q$ of 425-528 was achieved at 4.7-5.5 GHz, which is to our knowledge, the highest tunable $Q$ ever recorded for a tunable RF MEMS network.

The filter is designed to cover a 4-6 GHz range but the measurement was done by actuating only one cantilever-

### TABLE I

**MEASURED RESPONSE OF THE RESONATOR WITH TWO RF-MEMS SWITCHES ACTUATED.**

<table>
<thead>
<tr>
<th>$f_r$ (GHz)</th>
<th>4.69</th>
<th>4.73</th>
<th>5.02</th>
<th>5.05</th>
<th>5.08</th>
<th>5.41</th>
<th>5.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_m$</td>
<td>425</td>
<td>430</td>
<td>447</td>
<td>450</td>
<td>458</td>
<td>536</td>
<td>548</td>
</tr>
</tbody>
</table>

### TABLE II

**THE MEASURED RESPONSES OF THE TUNABLE FILTER.**

<table>
<thead>
<tr>
<th>$f_0$ (GHz)</th>
<th>4.36</th>
<th>4.48</th>
<th>4.64</th>
<th>5.37</th>
<th>5.48</th>
<th>5.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ (dB)</td>
<td>5.36</td>
<td>5.13</td>
<td>4.48</td>
<td>3.26</td>
<td>2.75</td>
<td>2.68</td>
</tr>
<tr>
<td>3-dB BW (%)</td>
<td>0.94</td>
<td>0.97</td>
<td>0.93</td>
<td>1.0</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>3-dB BW (MHz)</td>
<td>40.9</td>
<td>42.1</td>
<td>43.2</td>
<td>56.5</td>
<td>53.7</td>
<td>55.5</td>
</tr>
<tr>
<td>$Q_m$</td>
<td>273</td>
<td>285</td>
<td>332</td>
<td>424</td>
<td>506</td>
<td>511</td>
</tr>
</tbody>
</table>
MEMS switch
Fixed Scaling
Capacitor
Covered Bias Lines
biasing pad
RC network
input loop coupling
MEMS chip

Fig. 8. The fabricated tunable evanescent-mode cavity filter with the RF-MEMS cantilever-switch capacitance network chip.

switch due to mechanical difficulties encountered in attaching 8 thin insulated wires on the chip. The evanescent-mode cavity with the installed RF-MEMS chip is shown in Fig. 8, and the measured results are presented in Fig. 9. A frequency coverage of 4.36-4.65 GHz was measured with the analog tuning coverage in the down-state position (of the switch) and 5.37-5.53 GHz coverage was measured with analog tuning in the up-state position. The measured results are summarized in Table II. The measured frequency response shows a 3-dB bandwidth of 1% and $Q_u$ of 273-511 at 4.3-5.6 GHz with excellent impedance match. To our knowledge, this represents the state-of-the-art in this frequency range.

IV. CONCLUSION

This paper presented the first results of a tunable high-$Q$ tunable resonator based on a 4-bit RF-MEMS capacitance network. Mechanical difficulties prevented the control of all four RF-MEMS switches and limited the tuning range. Both tunable resonator and filter measurements indicate the potential of very high-$Q$ tuning, and a tunable resonator $Q_u$ of 425-550 was achieved at 4.7-5.5 GHz. RF-MEMS chips with a more robust mechanical biasing network are currently being fabricated, and filter tuning results will be presented at the conference.

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