RF MEMS Based Tunable Bandpass Filter For X-Band Applications

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Abstract. In this paper, we present the design and simulation of RF MEMS based Tunable combline band pass filters for X-band applications at different substrate thicknesses and studied the effect of thickness on tuning. The proposed filters are designed on high resistive silicon substrate of 500µm and 300 thicknesses. The tunability is achieved by using MEMS based varactor replaced with fix capacitor in conventional combline filter. First, the microstrip combline filter is designed at the centre frequency of 9.5 GHz and then tuning is achieved by varying the capacitance in the designed combline filters. The electromagnetic simulation has been carried out using HFSS v15 software based on finite element method (FEM). The tuning of the filter on silicon substrate of 500 µm is achieved by changing the capacitance value from 0.2035 pF to 0.4035 pF in the model in HFSS, which resulted the tuning in the frequency range of 7.85 to 10.35GHz. Insertion loss of design filter is in the range of 1dB within the tuning range. In case of substrate thickness 300 µm the tuning of the filter is achieved by changing the capacitance value from 0.293 pF to 0.403 pF in the model in HFSS, which resulted the tuning in the frequency range of 8.80 to 9.9 0 GHz. Insertion loss of design filter is in the range of ~1.2dB within the tuning range.

1. INTRODUCTION

Tunable or reconfigurable RF filters make microwave systems adaptable to multiple frequency bands of operation using a single filter, which has tremendous applications in modern communications systems like satellite communication, radar, medical electronics and software defined radio and cognitive radios. Tunable filters can meet the requirement of several filters to have more than one filter response by introducing tuning elements introducing into a filter topology [1]. These tunable filters can be divided into two groups (i) filters with discrete tuning and (ii) filters with continuous tuning. Filter topologies for a discrete tuning can be realized by using PIN diodes or MEMS switches. While the continuous tuning can be achieved by using varactor diodes, MEMS capacitors, ferroelectric materials or ferromagnetic materials are frequently used to obtain a continuous tuning device. Center frequency is the most common filter parameter to reconfigure. Fewer designs reconfigure other parameters, such as the bandwidth or selectivity. When deciding which technology is adequate for a given application, the designer must consider the following issues: cost, power consumption, size, performance and operating frequency.

This paper present and discusses the use of Micro Electro Mechanical Systems (MEMS) varactors as tuning elements on combline filter topology for x-band applications [2,3]. X-band tunable band pass
filter is widely used by the military applications for beyond line of sight communication. These systems are less prone to interference, rain resilience, and terminal size. X-band has several applications in various radars with continuous wave, pulsed wave, single polarization, dual-polarization, synthetic aperture radar, and phased arrays.

The proposed filters are designed on high resistive silicon substrate of 500µm and 300µm thicknesses. First, the microstrip combline filters are designed at the center frequency of 9.5 GHz and then tuning is achieved by varying the capacitance in the designed combline filter. To study the performance of the filters the simulations are carried out using HFSS v15 software based on finite element method (FEM). For the filter designed on substrate thickness 500µm, the tuning of the filter is achieved by changing the capacitance value from 0.2035 pF to 0.4035 pF, resulted the tuning in the frequency range of 7.85 to 10.35GHz with the insertion loss in the range of 1dB within the tuning range. Similarly, the filter designed on substrate thickness 300µm, the tuning of the filter is achieved by changing the capacitance value from 0.2930 pF to 0.4030 pF, resulted the tuning in the frequency range of 8.80 to 9.90 GHz with the insertion loss in the range of ~1.2 dB within the tuning range. The First to realize tunable filter the combline filter topology is used to realize and designed at center frequency of 9.5 GHz. The tuning is achieved by varying the capacitances in the designed combline filter.

The typical combline filter is shown in Figure 1. The microstrip resonators in this type of filter based on quasi transverse electromagnetic (TEM)-mode transmission lines that are shorted at ground through via holes at one end and terminated to the ground by a lumped capacitor at the another end of each resonator line [4]. Coupling between microstrip resonator lines is achieved in by fringing fields between the resonator lines. The resonator lines have length, \( \lambda_o/8 \) long at the designed center frequency (\( f_o \)). The combline filters topology has been chosen due to following attractive features:

(a) They are compact.
(b) They have strong stop-bands, and the stop-bands above the primary pass-band can be made to be strong.
(c) If desired, they can be designed to have an unusually steep rate of cut-off on the high side of the passband.
(d) Adequate coupling can be maintained between resonator elements with sizeable spacing between resonator lines. (This feature means that the proper coupling can be maintained in manufactured filters without unreasonable production tolerance requirements.)
(e) Filters of this type can usually be fabricated without dielectric support materials so that, if desired, dielectric losses can be eliminated.

A five pole comb-line filter topology has been chosen for our study and schematics have been shown in figure 1(a) and (b). The input is feed through the resonator line of length \( L_1 \) and output is taken from resonator line length \( L_7 \). Filters are designed on a 500 µm and 300µm thick silicon substrate with thick high resistivity.

![Figure 1. Combline BPF (a) Top view (b) Side view](image)

The typical MEMS varactor is shown in Figure 2. The capacitance is controlled by varying the gap between the two parallel plates of the capacitor using electrostatic actuation, Where one plate is fixed and another kept suspended for movement under electrostatic actuation due to force of attraction be
applied electric field [5]. When a dc potential is applied to between these two electrodes, due to electrostatic actuation, the gap between electrodes reduces; resulting in an increase in the parallel plate capacitance. Thus, by changing the applied potential, the structure can be made to operate as a variable capacitor [6].

![Figure 2. Schematic of MEMS varactor (a) without bias (b) with bias](image)

2. DESIGN AND SIMULATION

(i) Design Methodology

The combline bandpass filter is comprised of an array of coupled resonators as shown in Figure 3. The resonators consist of line elements 1 to n, which are short-circuited at one end, with a lumped capacitance $C_{Li}$ loaded between the other end of each resonator line element and ground. The input and output of the filter are through coupled-line elements 0 and n + 1, which are not resonators. With the lumped capacitors present, the resonator lines will be less than $\lambda_{go}/4$ long at resonance, where $\lambda_{go}$ is the guided wavelength in the medium of propagation at the midband frequency of filter [7]. It is interesting that if the capacitors were not present, the resonator lines would be a full $\lambda_{go}/4$ long at resonance, and the filter structure in Figure 1, would have no passband at all when the line elements are constructed from a pure TEM-mode transmission line such as stripline [8]. This is because the magnetic and electric couplings totally cancel each other out in this case. The larger the loading capacitances $C_{Li}$, the shorter the resonator lines, which results in a more compact filter structure with a wider stopband between the first passband (desired) and the second passband (unwanted). The lumped capacitors may offer a convenient means for filter tuning, which may be required particularly for narrow-band filters.

![Figure 3. Schematic of n-pole combline filter](image)

Filter can be designed from a chosen ladder type of lowpass prototype with the lowpass parameters $g_i$ for $i = 0$ to $n + 1$. A design procedure as described in [9] starts with choosing the resonator susceptance slope parameters $b_i$

$$\frac{b_i}{Y_A} = \frac{Y_{sl}}{Y_A} \left( \cot \theta_i + \theta_i \csc^2 \theta_i \right) \frac{2}{2} \quad \text{for } i = 0 \text{ to } n$$ (1)
where $Y_A$ is the terminating line admittance, $\theta_o$ is the midband electrical length of the resonators, and $Y_{ai}$ is interpreted physically as the admittance of line with the adjacent lines $i-1$ and $i+1$ grounded. The choice of $Y_{ai}$ fixes the admittance level within the filter and can influence the unloaded quality factors of the resonators. For a specified fractional bandwidth $FBW$, calculate

$$J_{n+1} = \frac{FBW \frac{b_{n+1}}{Y_A}}{g_{n}g_{n+1}}$$
$$J_{n, n+1} = \sqrt{FBW b_{n}}$$
$$J_{i, i+1} = FBW \sqrt{b_i Y_A (b_{i+1} Y_A - 1 + (J_{i, i+1} Y_A \cot \theta_o - J_{i-1, i} Y_A \tan \theta_o)) + \frac{C_{n+1}}{\varepsilon_o \sqrt{\varepsilon_{re}}}}$$

where, the lowpass element values $g_i$ are given for a normalized cut-off frequency $\Omega_c = 1$. The design procedure leads to the determination of the lumped capacitances as well as the self- and mutual capacitances per unit length of the distributed line elements.

The lumped capacitances $C_{Li}$ are:

$$C_{Li} = Y_A \left( \frac{Y_{ai}}{Y_A} \right) \cot \theta_o \omega_o$$

where, $\omega_o$ is the angular frequency at the midband.

The self-capacitances $C_i$ are given by

$$C_{0} = \frac{\eta_A Y_A (1 - \frac{\omega_0}{Y_A})}{\epsilon_o \sqrt{\varepsilon_{re}}}$$
$$C_{n+1} = \frac{\eta_A Y_A (1 - \frac{\omega_0}{Y_A})}{\epsilon_o \sqrt{\varepsilon_{re}}}$$
$$C_{n} = \frac{\eta_A Y_A (Y_{ai} - 1 + (J_{n+1} Y_A - J_{n} Y_A \tan \theta_o)) + \frac{C_{n+1}}{\epsilon_o \sqrt{\varepsilon_{re}}}}{\epsilon_o \sqrt{\varepsilon_{re}}}$$

And the mutual capacitances $C_{Li+1}$ are

$$C_{0,1} = \frac{\eta_A Y_A - \frac{C_o}{\epsilon_o \sqrt{\varepsilon_{re}}}}{\epsilon_o \sqrt{\varepsilon_{re}}}$$
$$C_{n, n+1} = \frac{\eta_A Y_A - \frac{C_{n+1}}{\epsilon_o \sqrt{\varepsilon_{re}}}}{\epsilon_o \sqrt{\varepsilon_{re}}}$$
$$C_{0,1} = \frac{\eta_A Y_A J_{Li+1} Y_A \tan \theta_o}{\epsilon_o \sqrt{\varepsilon_{re}}}$$

Note that in (5 to 8) and (9 to 10) the self- and mutual capacitances are normalized with the free space permittivity $\epsilon_o$ and scaled by $\sqrt{\varepsilon_{re}}$ with $\varepsilon_{re}$ denoting the relative effective dielectric constant constant of the line element and $\eta_o = 120\pi$ ohm the wave impedance in the free space.

Using the above steps, we have designed the 5 pole microstrip combline filter at the center frequency of 9.5GHz, using high resistivity silicon substrates of 500µm and 300µm thickness. We have used
To design the filter we have chosen the dielectric constant of the silicon metal of bulk conductivity $\varepsilon_r = 11.9$, the aluminium metal of bulk conductivity $3 \times 10^7$ S/m is used for resonator lines and ground plane. The microstrip is shorted to ground by via holes of radius of 0.1mm for 500µm and 300µm thick high resistivity silicon substrate. These via holes are filled with copper metal. To carry out simulation in HFSS, we have used driven modal solution type. The wave ports were assigned for port excitation. An air box is created to cover the device and to provide the appropriate boundary conditions. The length of input lines and

Chebyshev low pass prototype element having pass band ripple of 0.1dB. the low pass prototype parameter are:

| $g_0$ | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ |
|------|------|------|------|------|------|------|
| 1.0  | 1.1468 | 1.3712 | 1.9750 | 1.3712 | 1.1468 | 1.0  |

Using above parameters, the microstrip resonators are calculated on different substrates and further optimized which are shown given in following tables.

### Table 1. Low pass prototype parameter

| $g_0$ | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ |
|------|------|------|------|------|------|------|
| 1.0  | 1.1468 | 1.3712 | 1.9750 | 1.3712 | 1.1468 | 1.0  |

### Table 2. Design Parameter of Combline Filter on silicon substrates of 500µm thickness

| Initial design Parameter | Optimized Parameter |
|--------------------------|---------------------|
| Length (mm) | Width (mm) | Spacing (mm) | Length (mm) | Width (mm) | Spacing (mm) |
| $L_1 = 2.8273$ | $W_1 = 0.39492$ | $S_1 = 0.0523$ | $L_1 = 2.58938$ | $W_1 = 0.39492$ | $S_1 = 0.055$ |
| $L_2 = 1.4186$ | $W_2 = 0.39492$ | $S_{2,3} = 0.40494$ | $L_2 = 1.27969$ | $W_2 = 0.39492$ | $S_{2,3} = 0.53$ |
| $L_3 = 1.4186$ | $W_3 = 0.39492$ | $S_{3,4} = 0.53503$ | $L_3 = 1.34969$ | $W_3 = 0.39492$ | $S_{3,4} = 0.73$ |
| $L_4 = 1.4186$ | $W_4 = 0.39492$ | $L_4 = 1.34969$ | $W_4 = 0.39492$ |
| $L_5 = 1.4186$ | $W_5 = 0.39492$ | $L_5 = 1.34969$ | $W_5 = 0.39492$ |
| $L_6 = 1.4186$ | $W_6 = 0.39492$ | $L_6 = 1.27969$ | $W_6 = 0.39492$ |
| $L_7 = 2.8273$ | $W_7 = 0.39492$ | $L_7 = 2.58938$ | $W_7 = 0.39492$ |

### Table 3. Design Parameter of Combline Filter on silicon substrates of 300µm thickness

| Initial design Parameter | Optimized Parameter |
|--------------------------|---------------------|
| Length (mm) | Width (mm) | Spacing (mm) | Length (mm) | Width (mm) | Spacing (mm) |
| $L_1 = 2.8277$ | $W_1 = 0.395$ | $S_1 = 0.0273$ | $L_1 = 3.0555$ | $W_1 = 0.395$ | $S_1 = 0.0346$ |
| $L_2 = 1.434$ | $W_2 = 0.395$ | $S_{2,3} = 0.233$ | $L_2 = 1.4456$ | $W_2 = 0.395$ | $S_{2,3} = 0.412$ |
| $L_3 = 1.434$ | $W_3 = 0.395$ | $S_{3,4} = 0.3066$ | $L_3 = 1.5056$ | $W_3 = 0.395$ | $S_{3,4} = 0.603$ |
| $L_4 = 1.434$ | $W_4 = 0.395$ | $L_4 = 1.5056$ | $W_4 = 0.395$ |
| $L_5 = 1.434$ | $W_5 = 0.395$ | $L_5 = 1.5056$ | $W_5 = 0.395$ |
| $L_6 = 1.434$ | $W_6 = 0.395$ | $L_6 = 1.4456$ | $W_6 = 0.395$ |
| $L_7 = 2.8677$ | $W_7 = 0.395$ | $L_7 = 3.0555$ | $W_7 = 0.395$ |

The terminating capacitance value has been chosen uniform and the capacitance value for each resonators is $C = 0.335063\text{pF}$. The spacing between the input feed line and first resonator is $S_{o}$, while resonator 2-3 and 3-4 are $S_{2,3}$ and $S_{3,4}$ respectively. Similarly for 300µm Using microstrip design formula calculated value and optimized value of the filter are given in tabular form. The capacitance value the resonators are $C = 0.333\text{pF}$.

(ii) Electromagnetic Simulation

To study the transmission behaviour of proposed filters, we have carried out finite element method (FEM) based simulations on a proposed structure using commercial software ANSOFT HFSS v15. In FEM the unknown fields are discretized using a finite element mesh; typically triangular elements are for surface meshes and tetrahedrons for volumetric meshes [10]. Both these geometries are chosen as with these geometries two dimensional and three dimensional regions respectively can be meshed [11]. To design the filter we have chosen the dielectric constant of the silicon $\varepsilon_r = 11.9$, the aluminium metal of bulk conductivity $3 \times 10^7$ S/m is used for resonator lines and ground plane. The microstrip is shorted to ground by via holes of radius of 0.1mm for 500µm and 300µm thick high resistivity silicon substrate. These via holes are filled with copper metal. To carry out simulation in HFSS, we have used driven modal solution type. The wave ports were assigned for port excitation. An air box is created to cover the device and to provide the appropriate boundary conditions. The length of input lines and
output lines are larger than the remaining resonator lines. In our simulation the capacitance are connected through the lumped ports.

We have tuned the pass band of combline band pass filter by changing the capacitance values. We have also studied the group delay of the filter with different capacitance. The group delay can be defined as the rate of change of transmission phase angle with respect to frequency. Mathematically group delay can be expressed as

$$\tau_g = \frac{\Delta \phi}{\Delta \omega}$$  \hspace{1cm} (11)$$

where $\Delta \phi$ is the change in phase of $|S_{21}|$ in radians and $\Delta \omega$ is the change in frequency.

![Figure 4](image-url)  

(a) (b) (c) 

Figure 4.  Combline band pass filter model in HFSS (a) Top view (b) Side view (c) Simple view

3. RESULTS AND DISCUSSION

The simulated transmission behavior of proposed filters are shown in Figures 5, 6, and 7. Figure 5 shows the band pass behavior $|S_{11}|$ and $|S_{21}|$ of combline filters designed at 9.5 GHz at different substrates thicknesses. In the Figure 5, at center frequency 9.5GHz the insertion loss is 0.9579dB for the substrate thickness of 500μm while 1.2dB for substrate thickness of 300μm.

![Figure 5](image-url)  

(a) (b) 

Figure 5. Simulated S-parameters of combline filter at center frequency of 9.5 GHz  
(a) For 500μm (b)For 300μm
Figures 6(a) and 7(a) show the $|S_{21}|$ of the combline band pass filter by changing the value of lumped capacitance. The simulation results show that frequency band can be tuned by varying the capacitance of MEMS varactor with keeping bandwidth constant. Figure 6(b) and 7(b) show the group delays in during tuning by varying the capacitance.

![Figure 6](image)

**Figure 6.** Plots (a) $|S_{21}|$ and (b) Group Delay of MEMS Tunable filter on substrate thickness 500μm

![Figure 7](image)

**Figure 7.** Plots (a) $|S_{21}|$ and (b) Group Delay of MEMS Tunable filter on substrate thickness 300μm

### 4. CONCLUSION

We have designed and simulated the tunable band pass filter using microstrip combline filter topology. The proposed filters were designed and its transmission behaviour studied on two different substrate thicknesses of high resistivity silicon. The five-pole combline filter with insertion loss 0.9579dB and 1.2dB have been designed at the center frequency of 9.5GHz on 500μm and 300μm thick silicon substrates respectively. It has been seen that insertion loss is better and tuning range is wider for filter designed on 500μm thick silicon substrate while in case of 300μm thick silicon substrates we have obtained lesser tuning range and higher insertion loss. RF MEMS filter show great potential for weight, power consumption, and size reduction. The group delay is lesser in case of 300μm thick silicon substrates as compared to 500μm thick silicon substrates. Therefore, to design a tunable filter the substrate thickness also plays an important role.
ACKNOWLEDGEMENT

Authors are grateful for the Director, CSIR CEERI Pilani for his support and encouragement.

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