Design and Simulation of a Miniaturized RF-MEMS Reconfigurable Microstrip Combline Band Pass Filter

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Abstract- Reconfigurable bandpass filter (RBPF) is crucial in various radio frequency (RF) applications. However, the use of lumped element filters have failed to show tuneable integrated solutions with low insertion loss in the high frequency range. Most reconfigurable filter designs are faced with the challenges of narrow bandwidth, high losses, bulkiness, high voltage and high power consumption. To overcome these issues, this research undertakes to develop a miniaturized reconfigurable radio frequency micro-electro-mechanical system (RF MEMS) band-pass filter designed for wireless communication at the center frequency of 30 GHz. The filter is optimized for low insertion loss, broad bandwidth, low applied voltage, lower power consumption and high linearity. The design consists of 3rd order tapped input microstrip combline transmission lines structure integrated with in-plane tunable parallel capacitors and electrothermal actuator. The transmission lines are patterned on a silicon dioxide (SiO₂) of thickness 1µm placed on a silicon (Si) substrate with the dielectric constant of εr = 11.9. The filter occupies chip area of 1.1 mm x 0.9 mm without the dummy substrate. The 3D structure is designed and simulated in Computer Simulator Technology (CST). The result shows the achieved inband insertion loss of less than 1 dB and the return loss better than 8 dB. The proposed reconfigurable bandpass filter can tune its center frequency with relatively constant absolute bandwidth.

1. Introduction
Microwave/RF filters are essential components of modern communication systems [1]. They are the basic components of all signal processing and communication systems. One of the most important applications for Micro-Electro-Mechanical-Systems (MEMS) is filter design. The filtering idea comes from the need to transmit or receive certain frequency band of interest and reject others. Typical filters are bulky, requiring high operational voltage (40-100V), and costly. Therefore, miniaturized and inexpensive reconfigurable filter can significantly enhance performance and compact size. The implementation of a MEMS provides new possibilities for achieving the desired reconfiguration characteristics of a filter by tuning the frequency based on application requirement. Reconfigurable RF/Microwave filters are designed using a large array of technologies (Microstrip, Coplanar Waveguide, Stripline, Slot line). Reconfigurable filters are aimed at addressing the multiband problem by permitting a single component to operate in multiple bands. Reconfigurable filters promise to enable frequency agile receivers and have been implemented using a variety of tuning elements.
including varactor diodes, MEMS, piezoelectric elements and Para electric elements. The initial technical challenge is in achieving low-loss and high-quality factor $Q$ from the filter structures [2]. The electrical performances of the filter are described in terms of insertion loss, return loss, frequency-selectivity (or attenuation at rejection band), group-delay variation in the passband etc. Filters are required to have low insertion loss, large return loss for good impedance matching with interconnecting components, and high frequency-selectivity; however, bandwidth-insertion loss trade-off in every filter causes Insertion Loss increase as quality factor of the filter increases [3].

2. Microstrip combline filter
A microstrip combline filter, as depicted in Figure 1, is one of the favourite structures for tunable or reconfigurable bandpass filters design [4-6]. The structure consists of conducting strips of width $W$, thickness $t$ of a transmission lines shorted at one end and loaded capacitors on the other end mounted of the surface of the dielectric substrate of height $H$, relative pemittivity $\varepsilon_r$ and a conducting ground plane on the reverse side of the substrate [7]. Figure 1b shows the schematic of a tapped combline transmission lines with the loaded capacitors. It is preferred that the loading capacitors have equal capacitance values, denoted by $C_L$. Therefore, the resonators have the identical electrical length of $\theta_0$ as well as characteristic admittance of $Y_A$. The coupling between the resonators is controlled by the spacing or gap between the resonators.

![Figure 1](image1.png)

**Figure 1.** General coupled microstrip combline bandpass filter (a) Layout structure (b) Tapped combline filter

3. Design of bandpass filter

3.1 Lowpass prototype
Filter design is usually preceded by selection of lowpass prototype, determination of the lowpass element values, element transformation (lowpass to bandpass transformation) and choosing the filter specifications based on the application and performance requirement of the filter. These specifications include the filter response, passband ripple level, insertion loss (IL), upper and lower band frequencies, bandwidth (BW), resonant frequency ($f_0$), $Q$ factor, selectivity, and switching time [8]. The complete description of the filter synthesis method for a desired filter specification can be found in [7,9]. Figure 2 shows the realization of lowpass prototype (LPP) using LC components. These normalized element values $g_1, g_2, \ldots g_n$ can be determined from the $n^{th}$ order Chebyshev LPF element as listed in Table 1.
Figure 2. General realisation of Lowpass prototype (LPP) using LC components.

Table 1. Elements values for Equal-Ripple Low pass Filter prototypes ($g_o=1$, $\omega_c=1$, $N=1–10$, 0.5 dB and ripple).

| Filter order (N) | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ | $g_7$ | $g_8$ | $g_9$ | $g_{10}$ | $g_{11}$ |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|---------|
| 1                | 1.0000|       |       |       |       |       |       |       |       |         |         |
| 2                | 0.7071| 1.9841|       |       |       |       |       |       |       |         |         |
| 3                | 1.5963| 1.0967| 1.5963| 1.0000|       |       |       |       |       |         |         |
| 4                | 1.6703| 1.1926| 2.3661| 0.8419| 1.9841|       |       |       |       |         |         |
| 5                | 1.7058| 1.2296| 2.5408| 1.2296| 1.7058| 1.0000|       |       |       |         |         |
| 6                | 1.7254| 1.2583| 2.6064| 1.3137| 2.4758| 0.8696| 1.9841|       |       |         |         |
| 7                | 1.7372| 1.2647| 2.6381| 1.3444| 2.6381| 1.2583| 1.7372| 1.0000|       |         |         |
| 8                | 1.7451| 1.2647| 2.6564| 1.3590| 2.6964| 1.3389| 2.5093| 0.8796| 1.9841|         |         |
| 9                | 1.7504| 1.2690| 2.6678| 1.3673| 2.7239| 1.3673| 2.6678| 1.2690| 1.7504| 1.0000  |         |
| 10               | 1.7543| 1.2721| 2.6754| 1.3725| 2.7392| 1.3806| 2.7231| 1.3485| 2.5239| 0.8842  | 1.9841  |

The selectivity ($S$) of the filter is determined by (1) [9]

$$S = \frac{\omega_s}{\omega_p}$$

where $\omega_s$ and $\omega_p$ are the angular frequencies of the stopband and passband respectively.

The filter order is calculated using the formula given in equation (2) [9]

$$N \geq \frac{L_A + L_B + 6}{20 \log \left| \frac{1}{S + \sqrt{(S^2 - 1)}} \right|}$$

where $L_A$ is the stopband insertion loss, and $L_B$ is the passband return loss in dB.

The ripple allowance of the signal is determined by (3) [9]

$$\varepsilon = \frac{1}{\sqrt{10} \left( \frac{L_B}{L_A} \right)^{1/10} - 1}$$

3.2 Lowpass to bandpass transformation

The lowpass filter can be transformed to a bandpass filter of series and parallel resonators of element L and C as shown in figure 3[10-11]. The series resonators which is transformed from inductor L consist of elements $L_s$ and $C_s$, while the parallel resonator which is transformed from capacitor C consist of elements $L_p$ and $C_p$. 
Figure 3. Bandpass transformation of the LPP.

Figure 3 is the bandpass transformation of the LPF. The frequency transformation is given by (4) [7]

$$\Omega = \frac{\Omega_c}{FBW} \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)$$

with

$$FBW = \frac{\omega_2 - \omega_1}{\omega_0}, \quad \omega_0 = \sqrt{\omega_1 \omega_2}$$

where, $\omega_0$ is the centre angular frequency and FBW is the fractional bandwidth. The resulting element values of the series LC resonators in the BPF with the impedance scaling taking into consideration are given by (6a) and (6b) [7].

$$L_s = \left( \frac{1}{\omega_0 \Omega_c \omega_z} \right) \frac{Y_0}{g_k}$$  \hspace{1cm} (6a)

$$C_s = \left( \frac{\Omega_c FBW}{\omega_0} \right) \frac{g_k}{Y_0}$$  \hspace{1cm} (6b)

The resulting element values of the parallel LC resonators in the BPF with the impedance scaling taking into consideration are given by (7a) and (7b) [7].

$$C_p = \left( \frac{1}{\Omega_c FBW \omega_0} \right) \frac{1}{Y_0 g_k}$$  \hspace{1cm} (7a)

$$L_p = \left( \frac{\Omega_c FBW}{\omega_0} \right) Y_0 g_k$$  \hspace{1cm} (7b)

Here, $Y_0$ is the scaling factor and $g_k$ is the $k^{th}$ capacitance value.

4. **Geometry and design of microstrip band pass filter**

Computer simulator technology (CST) 3D electromagnetic (EM) simulation design and analysis work flow was adopted in the geometry design and Simulation of the miniaturized RF-MEMS reconfigurable microstrip combline band pass filter as illustrated in figure 4.
The filter parameters were determined using the built in tool in CST for microstrip structure. The optimized dimensions of different parameters of the design are given in Table 2.

| Parameters                      | Values (μm) |
|---------------------------------|-------------|
| Substrate Height (H)           | 30          |
| Conductor Thickness (t)        | 3           |
| Feed width (Wf)                | 80          |
| Transmission lines of width (W)| T₁ = 60, T₃ = 80, T₃ = 60 |
| Ground plane Thickness (tg)    | 3           |
| Resonator Gap (G)              | 60          |

The reconfigurable bandpass filter has been designed based on the microstrip structure. The conducting strips are made of Aluminium of thickness (t) on a silicon substrate of height (H) and relative permittivity $\varepsilon_r = 11.9$ with the ground plane on the opposite side of the substrate. The conducting strips are connected to the ground using the via holes. The filter is a 3rd order Chebyshev filter with tapped input. The loading capacitors for tuning the filter are represented by a gap between the resonators end and the opposite face. The thickness of the end of the resonator and opposite face are twice the thickness of the conducting line to increase the overlapping area for increase capacitance value. The input feeding and output feeding of the filter are achieved using waveguide port excitation. The filter is reconfigured to different operating frequencies by tuning the gap between the open end of the conductor resonators and the opposite face by the movement of the actuator. The actuator is anchored on one end and connected to a beam of 270 x 30 um on the other end to cause an equal displacement of the capacitor plate in order to have a simple dc bias circuit. The actuator is based on the pinciple of thermal actuation or joule heating which requires very low voltage ($0 - 5V$) as compared to other forms of actuations with realltively high voltage (40 -100V). This high voltage is not readily available in wireless mobile application devices. This actuation technique also has the advantage of low power consumption and fast switching time. Electrothermal actuation requires that
when current or heat is applied to the terminals of the actuator, it causes it to expand, resulting in a force of displacement or movement. The beam is also anchored on both sides to keep the beam in place after displacement. The substrate beneath the capacitor is etched which allows the capacitors to be hanging and move freely by slight movement by the actuator. Figures 6 and 7 show the schematic top view and the 3D structure of the proposed miniaturised microstrip reconfigurable bandpass filter.

5. Results and Analysis
The simulation responses using CST for tuning gaps of 5 µm, 10 µm and 20 µm of the microstrip reconfigurable bandpass filter are shown in figures 7, 8 and 9. The S-parameter results indicate the filter is tuneable to different operating centre frequencies of 29 GHz, 30 GHz and 32 GHz by varying the gap at the resonator end. The filter maintains a relatively constant bandwidth in the operating frequency band of 25 – 35 GHz. This indicates a good filter characteristics with the insertion loss of less than 1 dB and return loss better than 8 dB, 9 dB and 10 dB respectively. The total filter area is 1.1 mm x 0.9 mm. The surface of the silicon substrate is oxidized due to surface effects and to reduce the relatively high loss. The silicon dioxized (SiO2) serves as an intervening layer and it has a relative permittivity of 3.9.

6. Conclusion
This manuscript presented a miniaturized RF-MEMS reconfigurable bandpass filter for application in mobile and wireless communications using the microstrip combline structure. Reconfiguration is achieved through the actuator by varying the gap between the combline transmission lines and the opposite overlapping face which serves as the parallel plate capacitor. The filter was found to have a
good response within the frequency range of 25-35 GHz with less than 1 dB insertion loss and a relatively constant bandwidth. The filter is very compact with a size of 1.1 mm x 0.9 mm. Potential future work is to improve the filter performance, integrate interdigital capacitors instead of parallel plate capacitor and fabrication using the CMOS-MEMS technology.

Acknowledgement
The authors acknowledge Universiti Teknologi PETRONAS for providing the research facilities and environment for this research.

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