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Mafinejad, Yasser, Mafinezhad, Khalil and Kouzani, Abbas Z. 2009, Design and simulation of a tunable MEMS filter for wireless biomedical signal transceivers, *in ISBB 2009: Proceedings of the 2009 International Symposium on Bioelectronics and Bioinformatics*, ISBB, Melbourne, Vic., pp. 140-143.

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Design and Simulation of a Tunable MEMS Filter for Wireless Biomedical Signal Transceivers

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Abstract—**This paper presents a new architecture for a high quality tunable MEMS filter that can be used in wireless biomedical signal transceivers. It consists of a π match circuit with two shunt capacitive coupling switches separated by a piece of high impedance short transmission line, and also a series switch placed at the quarter wavelength distance away from the π match circuit. The low actuation voltage and also tunability are important features of the design objective. All portions of the filter can be realized simultaneously. Thus, the filter does not require any extra steps during its fabrication, and is not costly. The simulation results confirm the good performance of the filter.**

I. Introduction

In wireless biomedical signal transceivers, filters play an important role in the quality of the received signals. The performance of the filters are specified by several parameters including loss, quality factor, beam width, noise, nonlinearity, power consumption, and the ability of tuning. In addition, another fundamental basic element in transceiver circuits is a switch. In the last two decade, many researchers have investigated on this element [1-3].

Micro electromechanical systems (MEMS) offer exceptional features such as low noise, low power consumption, and high linearity. Particularly, MEMS devices can be integrated with conventional integrated circuit at a low cost. MEMS technology can be used to realize devices such as switches, filters, oscillators, and phase shifters. MEMS components have demonstrated outstanding performance not only as tunable analogue [4-5] and digital [6-7] filters, but also as broad band tuning range filters [8], and switches [3] in transceiver systems.

This paper presents a tunable filter based on MEMS switches. The filter could be easily tuned by varying the height of the gap via the actuation voltage of an electrostatic MEMS capacitor coupling switch.

Noise reduction is one of the important goals of any design. The conventional elements inherently are lossy and noisy. A lossy filter is not only itself a source of noise, but also increases the effect on the noise of the other stages in the circuit. A MEMS capacitor or filter is nearly noise less [9]. Utilization of a noiseless MEMS filter decreases the input noise and suppresses the unwanted signals.

II. Filter Topology and Design Principle

Noise reduction is an important feature of all tuning filters. Three important criteria should be considered for noise reduction. Firstly, the filter itself must be noiseless or have the lowest possible noise. Secondly, the bandwidth of the filter should be equal to the desired frequency band. If the filter bandwidth is smaller than the receiver frequency band, the quality of the received signal is affected or some data may be lost. If the filter bandwidth is greater than the receiver frequency band, the noise figure may increase. Thirdly, the losses of the filter should be as low as possible.

MEMS filters that are based on a single capacitive coupling switch satisfy the first and the third design criteria because they are noiseless, and also their capacitive coupling switch has negligible insertion loss. The cut-off frequency of the switch can be much larger than the millimeter waves frequency [10-11]. Many different designs are proposed for the MEMS filter [4-12]. The main features of our filter are its simplicity, integrateability with the conventional microwave integrated circuits, and high performance as confirmed by simulation results.

Fig. 1(a) shows the topology of the proposed filter. As can be seen, the circuit consists of a combination of a series switch and two shunt switches that form a π match circuit. All three switches are capacitive coupling switches because they offer higher life cycle than contact switches.

While all switches are on (S1 in down-state, and S2 and S3 in up-state), the desired signal propagates from the input to the output. In this state, all switches should provide a low insertion loss. To achieve a low insertion loss, the gap height of the switch should be increased. However, this increases the actuation voltage that is not desirable for most applications. The authors [11] tried to solve this problem by using a T match circuit, but this design needed a larger area especially in lower frequencies due to the use of two pieces of transmission lines. However, a π match circuit needs only one short transmission line and thus lower area is utilized.

The basic equivalent electrical circuit of the filter is shown in Fig. 1(b). The two shunt capacitive switches with the high impedance short transmission line (HISTL) in between them are calculated for the centre frequency of the desired band. Therefore, the value of the characteristic impedance and the length of the short transmission line are optimized for the total desired frequency band of the receiver.

Manuscript received August 31, 2009.

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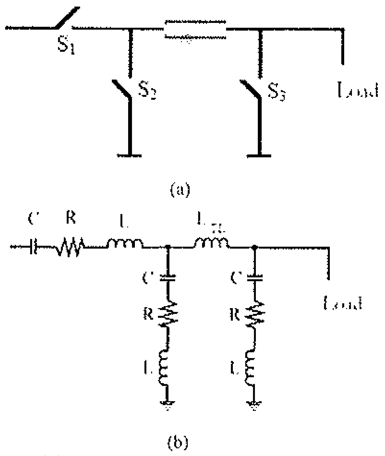

Fig. 1. Proposed filter. (a) Topology. (b) Equivalent electrical circuit

As shown in Fig. 1(a), three switches are placed in the line of signal, therefore, excessive isolation in off position is expected. To achieve high life cycle and low actuation voltage, the flexure membrane [12] is chosen and gap height is fixed at 2 μm for the pull-down voltage of 9 volts. The area and the up-state capacitance of the membrane are calculated as follows:

$$C_u = k\frac{\varepsilon A}{g+\frac{t_d}{\varepsilon_r}} \quad (1)$$

Therefore, $A = 13954\ \mu m^2$ and $C_u = 61.75$ fF. C_u of the low actuation voltage switches are typically between 20 to 100 fF. For a 50 Ω characteristic impedance, the length of the membrane is chosen 120 μm. This leads to a short circuit in down-state position. Therefore, the width of the membrane is 116.3 μm.

In the case of an ideal matching, the input impedance of the π circuit should be equal to the characteristic impedance (50 Ω). The equivalent circuits of the two switches are identical. As the switches are coupling capacitance switches, their resistances are negligible and thus not considered in the design calculation. Regarding the length of the contact, the equivalent inductances of switches are not significant and could be therefore ignored in the calculation. The required inductance to match the switch is calculated as follows:

$$Z_i = Z_o = \frac{1}{jC_u\omega_0} \,||\, [\left(Z_0 \,||\, \frac{1}{jC_u\omega_0}\right) + j\omega_0 L] \quad (2)$$

$$L = \frac{2{Z_0}^2 \mathrm{Cu}}{1+(Z_0 C_u \omega_0)^2} \quad (3)$$

Therefore, L=0.23 nH. Then, the equivalent high impedance short transmission line can be obtained by solving the simplified wave equation as follows:

$$\tan(\beta l) \approx \frac{L\omega_0}{Z_h} \quad (4)$$

For small value of βl, the length of the short transmission line could be calculated as follows:

$$l = \frac{L v_0}{Z_h\sqrt{\varepsilon_{eff}}} \quad (5)$$

where v_0 is the speed of the light in free space, and ε_{eff} is the dielectric constant of the substrate. By using Eq. (4-5) the optimum length for HISTL is l = 278 μm.

III. Simulation Results

The proposed filter is implemented in EM3DS software. Fig. 2 shows the topology and co-planar waveguide of the implemented filter.

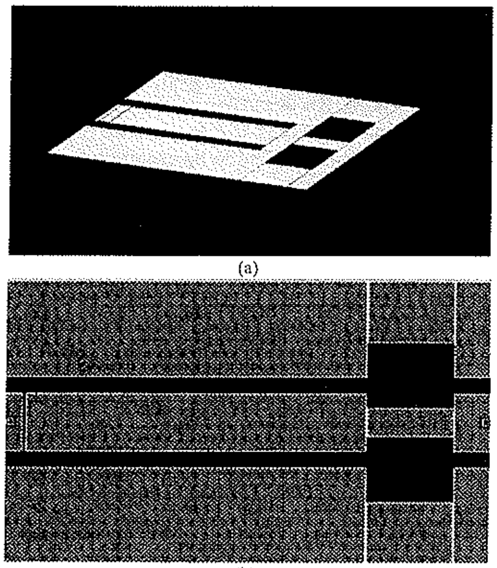

Fig. 2. Proposed filter. (a) Architecture. (b) Co-planar waveguide.

Next, the π section of the filter is simulated. Fig. 3 compares the scattering parameters of the π circuit and a single traditional switch. As can be seen, the reflection coefficient of the proposed switch around the middle of the frequency band is much lower than that of the single switch. An excellent match exists between the proposed π circuit and the input and output ports.

Next, the entire filter is simulated. Fig. 4 presents the scattering parameters of the filter. When the shunt switches are in up-state and series switch is in down-state positions, a narrow band filter with excellent performance is observed. For frequencies outside the desired frequency, the input impedance of the π circuit rapidly approaches zero. Therefore, the input of the π circuit acts as a short circuit and then an open circuit is observed at the series switch. This situation creates a mismatch and causes for the signal to get reflected. Therefore, a narrow band filter is resulted.

Filter tunning is obtained by varying the voltage applied to switches. It should be noted that the applied voltage should be less than a critical value [12] to prevent the instability and the snap down of the membrane.

$$F_e = \frac{1}{2}V^2\frac{dC}{dg} = -\frac{1}{2}\frac{\varepsilon W w V^2}{g^2} \quad (6)$$

where, V is the voltage applied between the beam and the electrode. The spring constant creates the electrostatic forces:

$$F = k(g_0 - g) \quad (7)$$

$$\sum F = 0 \rightarrow \frac{1}{2}\frac{\varepsilon W w V^2}{g^2} = K(g_0 - g) \quad (8)$$

$$V = \sqrt{\frac{2Kg^2(g_0-g)}{\varepsilon w W}} \quad (9)$$

The plot of the beam height versus applied voltage shows two possible beam positions for every applied voltage (see Fig. 5). By taking the derivative of Eq. (9) with respect to the beam height and setting that to zero, the height at which the instability occurs is found to be exactly two-thirds of the zero-biased beam height.

$$\frac{dV}{dg} = 0 \rightarrow \frac{d\left(\sqrt{\frac{2Kg^2(g_0-g)}{\varepsilon w W}}\right)}{dg} = 0 \rightarrow 2gg_0-3g^2=0 \rightarrow g=0,\ g=\frac{2}{3}g_0 \quad (10)$$

Therefore, the gap should be varied between 2 to 1.4 μm. By applying the voltage, the height of the gap between the membrane and transmission lines is varied changing the resonant frequency of the filter. Fig. 6 shows the relation between the resonant frequency and the gap height.

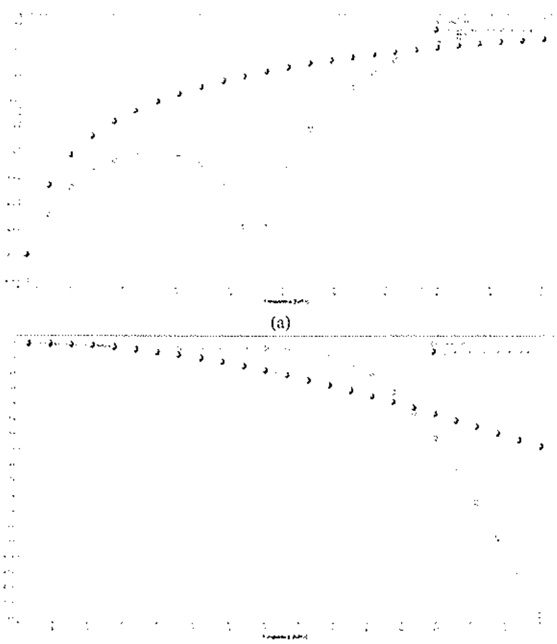

Fig. 3. Scattering parameters of the π section for up-state position. (a) S_{11}. (b) S_{21}. Rectangle: Proposed switch. Circle: Switch without modification.

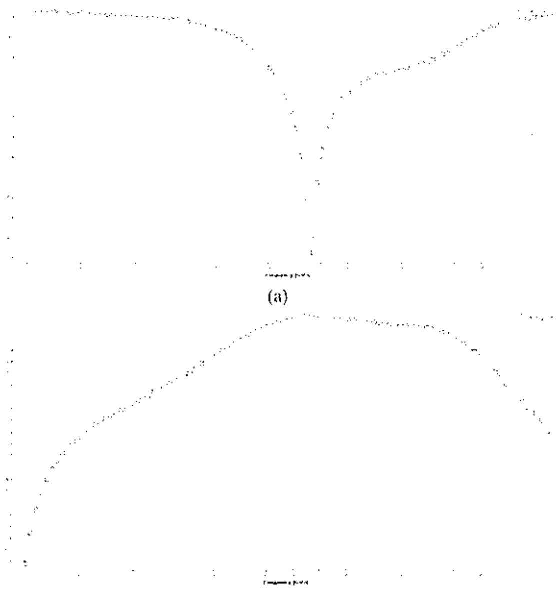

Fig. 4. Scattering parameters for the proposed filter with the gap height of 1.5 μm. (a) S_{11}. b) S_{21}.

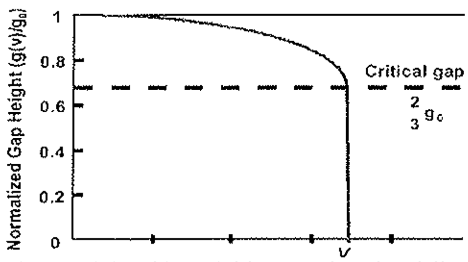

Fig. 5. Variation of the gap height to actuation voltage [12].

IV. CONCLUSIONS

A high quality filter that has a new architecture is proposed. It is based on a π match circuit and a series switch that are joined through a quarter wavelength transmission line. The π circuit is calculated for matching condition for the desired frequency band through selection of proper values for the characteristic impedance and length of the short transmission line. For the desired frequencies, because the π circuit is matched, at any location on the transmission line including the input of the series switch matching is established. For unwanted frequencies, the input of the π match circuit is shorted to ground. Therefore, at the quarter wavelength away from this short circuit where series switch is placed, an open circuit is observed by the input signal. If the series switch is in up-state position, two consecutive open circuits are seen by the input signal and excellent isolation is created.

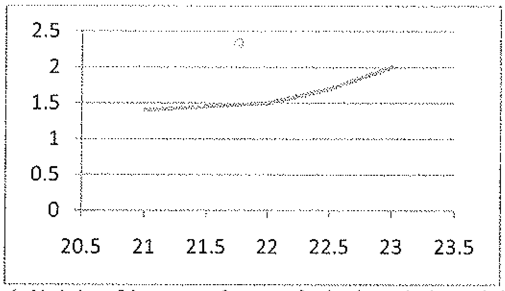

Fig. 6. Variation of the resonant frequency for the change in the gap height of the switches.

ACKNOWLEDGMENT

The authors wish to acknowledge the support of Dr. Marco Farina, MEM Research, through the EM3DS software.

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