A Micromachined Two-state Bandpass Filter using Series Inductors and MEMS Switches for WLAN Applications

Jong-Man Kim*, Sanghyo Lee*, Jae-Hyoung Park, Jung-Mu Kim*, Chang-Wook Baek*, Youngwoo Kwon*, and Yong-Kweon Kim***

Abstract—**This paper reports a novel tunable bandpass filter using two-state switched inductor with direct-contact MEMS switches for wireless LAN applications. In our filter configuration, the switched inductor is implemented to obtain more stable and much larger frequency tuning ratio compared with variable capacitor-based tunable filter. The proposed tunable filter was fabricated using a micromachining technology and electrical performances of the fabricated filter were measured. The filter consists of spiral inductors, MIM capacitors and direct-contact type MEMS switches, and its frequency tunability is achieved by changing the inductance that is induced by ON/OFF actuations of the MEMS switches. The actuation voltage of the MEMS switches was measured of 58 V, and they showed the insertion loss of 0.1 dB and isolation of 26.3 dB at 2 GHz, respectively. The measured center frequencies of the fabricated filter were 2.55 GHz and 5.1 GHz, respectively. The passband insertion loss and 3-dB bandwidth were 4.2 dB and 22.5 % at 2.55 GHz, and 5.2 dB and 23.5 % at 5.1 GHz, respectively.**

Index Terms—**tunable filter, switched inductor, direct-contact type MEMS switch, WLAN application.**

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I. INTRODUCTION

Tunable filters are the basic components of radar and multi-band communication systems. Developments of micromachining technology have made it possible to replace conventional electrical tuning elements, such as active resonators and semiconductor-based varactor diodes, with micromachined tuning devices. MEMS-based devices offer superior advantages compared with solid-state elements because they show lower insertion loss and power consumption, smaller size and higher linearity [1-3].

As the demands for MEMS tunable filter is increased, many micromachined tuning elements have been developed. Generally, variable MEMS capacitors have been mainly used as tuning elements in the reconfigurable systems [1, 4-6]. However, the variable MEMS capacitors and MEMS varactors cannot provide a wide tuning range in simple configuration, and they show nonuniform capacitance change ratio due to the structural deformation of the switch membrane during fabrication process [7, 8].

The switched inductor with direct-contact type MEMS switch can be successfully implemented on the tunable filter topology. In case of using the switched inductor, the frequency tunability is controlled by discrete change of an inductance with ON/OFF switching operations of the direct-contact MEMS switch. Because the frequency tunability is determined by the uniplanar metal pattern on the substrate and the switch actuations, both stable frequency tuning ratio and large frequency tuning range can be obtained [9, 10].

This digital-type tuning method is available for obtaining a discrete change of the center frequency for WLAN applications, where two center frequencies of 2.4 and 5.1 GHz are used.

In this paper, tunable filter using switched inductor with direct-contact type MEMS switches for WLAN applications was fabricated by using micromachining technology and its performances were measured.

II. DESIGN

1. Filter design

Tunable filter was designed with consideration both of its electrical and mechanical characteristics. Figure 1 shows the photograph of the fabricated tunable filter. The proposed filter consists of spiral inductors, MIM capacitors, and direct-contact type MEMS switches, and LC-based elements are used as resonators. All the components of the filter were designed with commercially available electromagnetic (EM) simulators, IE3D and ADS. The direct-contact MEMS switch is successfully implemented on the filter configuration for obtaining the tunability of the filter. Total size of the designed filter is 3.53 mm × 1.21 mm. The width of the signal line and the distance between the signal line and the ground plane are 20 and 40 μm, respectively. In this design, only the switched inductor plays a role of tuning the center frequency, and the coupling capacitors are chosen to give a correct bandwidth.

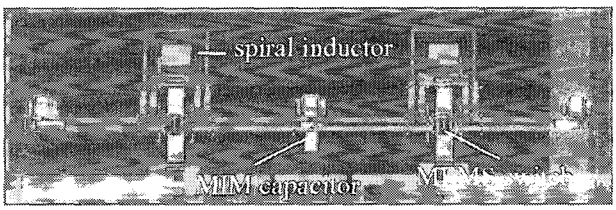


Fig. 1. Photograph of the proposed tunable filter

Figure 2 shows the equivalent circuit of the designed filter. Dashed areas in figure 2 are switched inductors, which are realized by MEMS switch actuations. Tuning of the center frequency is achieved by the total inductance change of the filter due to the switch actuation. In the switch OFF state, the applied RF signal flows along the spiral inductors. On the other hand, the applied signal passes through the straight signal line in the switch ON state. Two MEMS switches are simultaneously actuated when a DC bias is applied. The DC bias is applied through a resistive line to isolate the DC and RF signals.

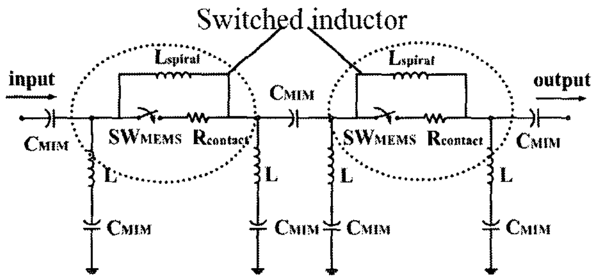


Fig. 2. Equivalent circuit of the designed tunable filter

2. MEMS switch design

Figure 3 shows the schematics of the implemented direct-contact MEMS switch. Figure 3 (a) is the schematic view of the MEMS switch, and figure 3 (b) and (c) are cross-sectional view along the line A-A' on the figure 3 (a) at switch off and on state, respectively. The signal line is initially disconnected, as shown in the figure 3 (a). The applied actuation voltage makes a connection between the disconnected signal lines like the figure 3 (c). This switch has already been reported in [11], and in this work, it is successfully used to tune the center frequency of the filter. All the components of the switch are formed on the coplanar waveguide (CPW). The total length and the width of the switch membrane are 552 and 100 μm, respectively. The contact material is suspended on the separated signal line. The contact bar and the actuation pad are connected through a silicon nitride (Si_3N_4) layer for electrical isolation between the two parts. Holes on the actuation pad make it easy to remove the sacrificial layer during the release process. The support beam is employed to improve the contact force and to decrease the structural deformation. The RF switching operations of the switch are achieved by an electrostatic force generated as the application of the DC bias between the actuation pad and the bottom electrode.

All the components of the filter are fabricated on a 520- μm-thick quartz substrate. A CPW transmission line is formed by electroplating of gold. A NiCr resistive

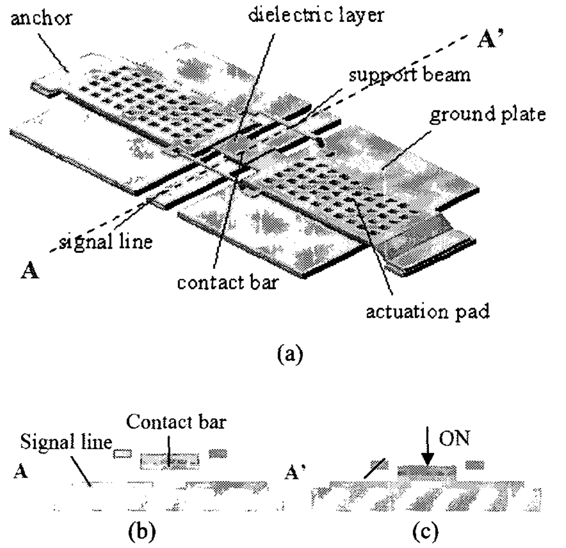


Fig. 3. Schematics of the direct contact MEMS switch; (a) schematic view of the MEMS switch, (b) cross-sectional view along A-A' at switch off state, and (c) cross-sectional view along A-A' at switch on state

3. Fabrication

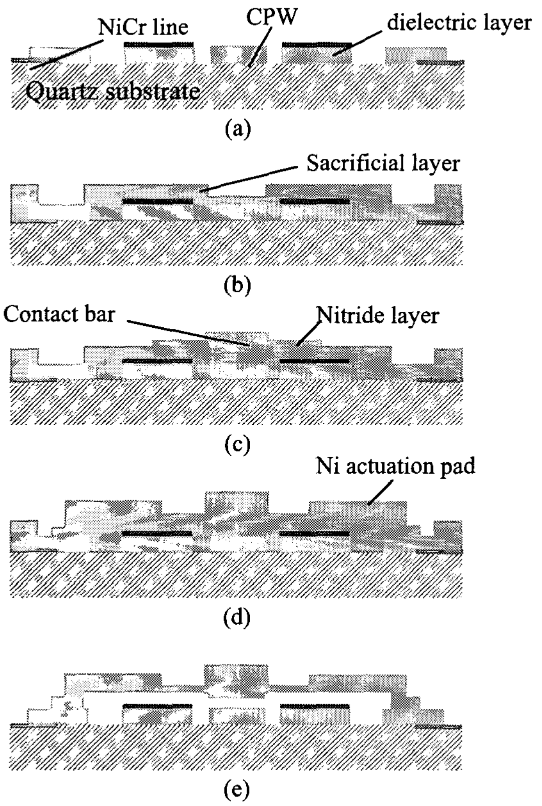


Fig. 4. Fabrication process, (a) CPW line and dielectric layer patterning, (b) sacrificial layer and contact region patterning, (c) contact metal electroplating and dielectric membrane forming, (d) Ni actuation pad electroplating, and (e) structure release with oxygen plasma

line connects the bottom electrode and the DC bias pad to isolate the DC and RF signals. The actuation pad of the MEMS switch is made of the electroplated nickel. Because the nickel structures are insensitive to the thermal effect during the release process compared with gold structure, they are available for the mechanical structure of the switch.

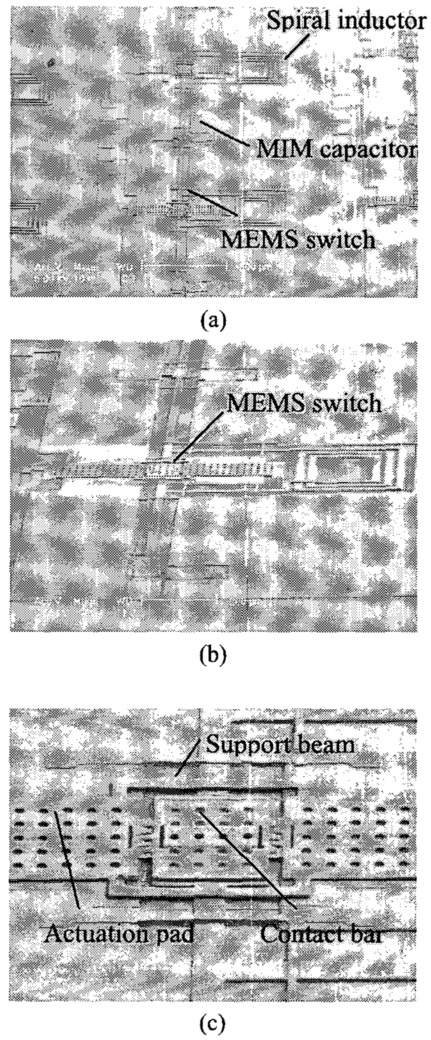


Fig. 5. Fabrication results, (a) full-view of the fabricated filter, (b) enlarged view of the switch and spiral inductor, (c) enlarged view of MEMS switch

Figure 4 shows the fabrication process. The fabrication process starts with a quartz substrate. At first, a 800-Å-thick NiCr resistive line is formed on the quartz substrate by lift-off process. On the NiCr resistive line, a 3-μm-thick transmission line is electroplated. A 0.3-μm-thick silicon nitride layer is deposited and patterned for electrical isolation between the actuation pad and the bottom electrode (figure 4 (a)). After that, gap filling process is followed to obtain a plane surface. Commercial photoresist AZ1512 is used as a sacrificial layer material. The deposited sacrificial layer is patterned and cured at the temperature of 210 °C. The thickness of the cured sacrificial is 1.5 μm. Next, contact bar is defined by anisotropic reactive ion etching (RIE). From this process, the gap between the contact bar and the signal line is determined to be 1 μm (figure 4 (b)). The electroplated gold is used for a contact material. Next, a 0.3-μm-thick silicon nitride layer is deposited and patterned to connect the contact bar with the actuation pad (figure 4 (c)). The actuation pad is formed by electroplating of a 2-μm-thick nickel layer (figure 4 (d)). Finally, the sacrificial layer is removed by oxygen plasma process (figure 4 (e)).

Figure 6 shows scanning electron microscope (SEM) photographs of the fabricated results. Figure 6 (a) is the whole structure of the fabricated filter including spiral inductors, MIM capacitors, and MEMS switches, and enlarged images of the switched inductor and the MEMS switch are shown in figure 6 (b) and (c), respectively.

IV. Measurement

1. RF performances of the MEMS switch

Measured pull-in and actuation voltage of the fabricated switch was 40 and 58 V, respectively. Figure 6 shows the measured RF responses of the switch. Measurement of the fabricated switch was performed using an HP 8510C network analyzer with the frequencies range from 0 to 60 GHz. Isolation of the switch is represented by S_{21} between input and output port at switch OFF state. Insertion loss is defined by S_{21} at switch ON state with the applied actuation voltage. The fabricated switch shows an insertion loss of 0.1 dB and an isolation of 26.3 dB at 2 GHz.

2. RF performances of the fabricated filter

RF performances of the fabricated filter were also measured using the HP 8510 network analyzer with the frequencies range from 0 to 10 GHz. Figure 7 shows the measured RF responses of the fabricated filter. The measured center frequencies were 2.55 GHz with a 3-dB bandwidth of 22.5 %, and 5.1 GHz with a 3-dB bandwidth of 23.5 %, respectively. The total insertion loss was 4.2 dB at a lower frequency band and 5.2 dB at a higher frequency band. The frequency tuning ratio was 50 %, and this large value is adequate for digital mode

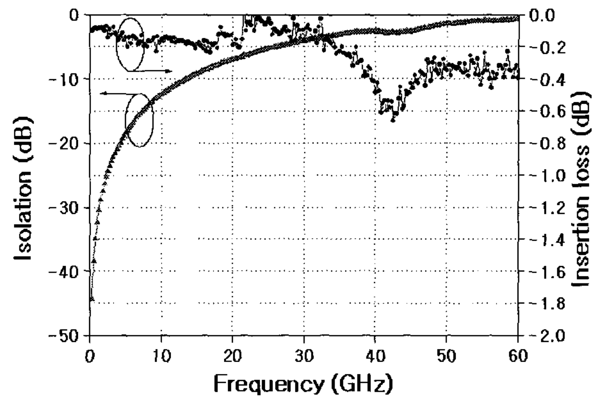
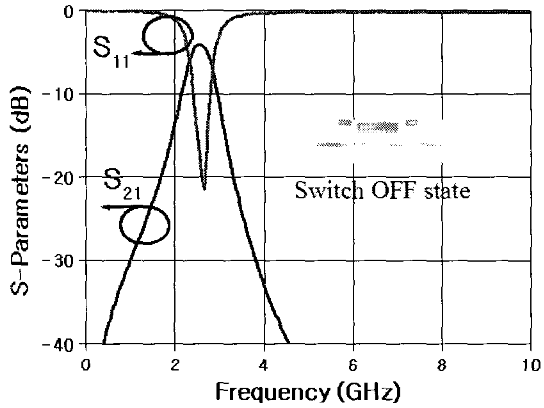
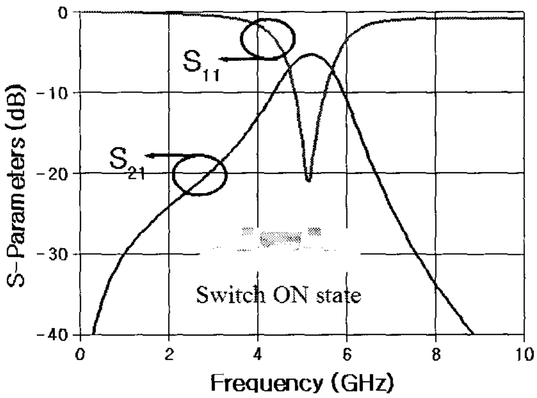


Fig. 6. Measured RF responses of the fabricated switch



(a)



(b)

Fig. 7. Measured RF responses of the fabricated filter, (a) at a lower frequency band (switch OFF state), and (b) at a higher frequency band (switch ON state)

of operation. The insertion loss of the filter mostly depends on the conductor loss in the switch OFF state, and the contact resistance of a MEMS switch in the switch ON state. Therefore, it is expected that the filter performances will be improved by optimizing the dimensions of conductor lines and the switch design.

V. CONCLUSION

A novel micromachined tunable filter for WLAN applications has been designed and fabricated using MEMS technology. The RF responses of the fabricated filter were measured. As a key component of the proposed tunable filter, the direct-contact MEMS switch was successfully implemented for discrete change of inductance. The applied voltage for the switch actuation was 58 V, and the measured isolation and insertion loss of the fabricated switch were 26.3 dB and 0.1 dB at 2 GHz, respectively. The measured center frequencies of the filter were 2.55 GHz with a 3-dB bandwidth of 22.5 %, and 5.1 GHz with a 3-dB bandwidth of 23.5 %. The passband insertion losses were 4.2 dB at 2.55 GHz, and 5.2 dB at 5.1 GHz. From these results, the proposed tunable filter using only inductance change shows feasibility that it can be applied for tuning elements of multi-band communication systems.

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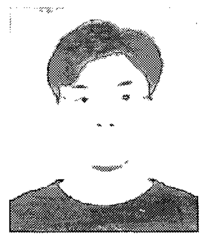

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