SMALL-BANDWIDTH INTEGRATED TUNABLE BANDPASS FILTERS FOR GSM APPLICATIONS

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ABSTRACT

This paper presents an integrated tunable lumped-element filter at 831 MHz with a 3dB-bandwidth of 77 MHz (9% bandwidth) and an embedded insertion loss of 4.0 dB. The filter is fabricated using a combination of thick high aspect-ratio silver plating and bulk micromachining that enables the implementation of high-quality factor inductors as well as high-performance fixed and tunable two-port capacitors. The third-order filter shows good thermal stability and is continuously tuned using voltage-tunable capacitors.

1. INTRODUCTION

Low insertion loss (*IL*) tunable bandpass filters are needed in various RF applications including multi-band radios. To date, lumped-element filters have failed to show tunable integrated solutions with low *IL* in the UHF range (300 MHz-3 GHz) due to the fact that the loaded quality factors (*Q*) of on-chip inductors and capacitors (fixed and/or tunable) have not been adequately high. The required component *Q* to achieve small-bandwidth UHF filters with low insertion loss is greater than 100.

Although distributed filters have been shown at frequencies > 5 GHz [1], the size of such filters in the UHF range would be much larger (> 10×) than the alternative lumped element filters. Also, the majority of reported tunable filters use an array of switched capacitors [1] or other discrete tuning methods [2] to achieve frequency tuning. Continuous tuning, on the other hand, offers the additional benefit of adjusting the frequency response to account for any fabrication inaccuracies.

In this paper, we present a continuously tuned filter at 831 MHz with 3dB-bandwidth of 77 MHz using a novel fabrication technique. We have previously shown a post CMOS-compatible fabrication process for implementation of high-performance one-port tunable capacitors and inductors at radio frequencies [3, 4]. In this paper, we modified this process and developed a low-temperature fabrication method to add the possibility of realizing two-port isolated tunable capacitors that are required in most high-order bandpass filters.

2. DESIGN

The bandpass filter is designed for a 3dB-bandwidth of 50 MHz at 834 MHz with a termination of 200 Ω in a third-order pseudo- elliptic configuration (Figure 1). The termination impedance determines the inductance over capacitance ratio of the parallel LC tanks shown in Figure 1(a). Assuming a matched condition, capacitance of the parallel LC tank decreases as the termination impedance increases. Smaller tunable capacitors (a few pF) are preferred as they occupy smaller area and exhibit higher *Q* at UHF. As a result, a 200-Ω termination design offers more suitable component values compared to a 50-Ω termination design.

To achieve *IL* < 3dB, the *Q* of each LC tank must be greater than 100. Such high-*Q* passive components have been demonstrated on silicon substrate using micromachining techniques [3-6]. However, several challenges have impeded the realization of low-loss tunable filters. The main challenge has been to devise a process flow that would enable *simultaneous* fabrication of high-*Q* inductors and tunable capacitors. Using a suitable fabrication process, the subsequent challenge is to design the physical layout of the inductors and tunable capacitors such that their peak *Q* occurs at the center frequency of the filter, while having realizable values for on-chip integration. Last but not least is to design a tunable component that maintains its high *Q* over a large tuning range. To tackle this task, we have developed a high-yield low-temperature fabrication process that meets these specifications.

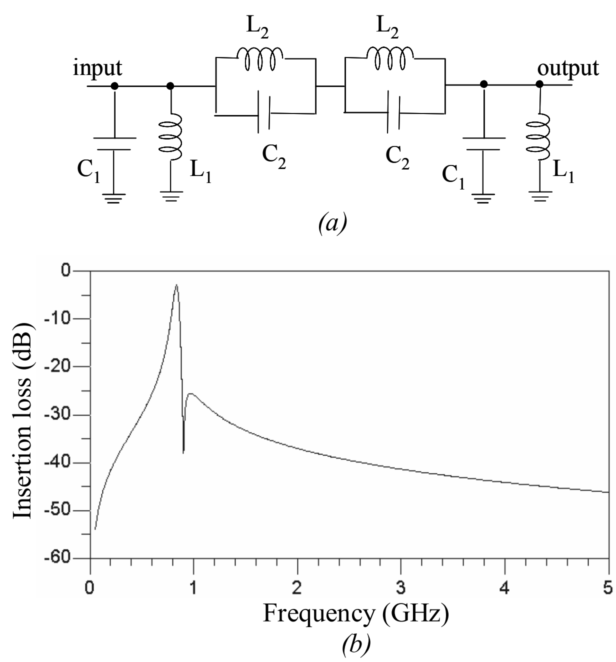

Figure 1: (a) Schematic circuit diagram and (b) simulated frequency response of the lumped-element third-order pseudo-elliptic filter, showing an IL of 3dB assuming a Q of 100 for each individual LC tank.

3. FABRICATION

Figure 2 shows the cross-sectional view of the fabrication process flow. The process requires four lithography steps, and enables the co-fabrication of high-Q inductors and tunable capacitors. The fabrication process starts with the deposition of a 3 μm thick PECVD silicon dioxide isolation layer. The first metal layer is evaporated on top and patterned, followed by the deposition of a 1 µm thick interlayer PECVD silicon dioxide. A 20 µm thick silver layer is then electroplated into a photoresist mold to define the inductors and the tunable capacitors. The mold and the seedlayer are subsequently removed. Finally, the devices are dry-released by selective etching of the silicon substrate from the backside in an inductively coupled plasma system (ICP). A SEM view of a fabricated filter is shown in Figure 3.

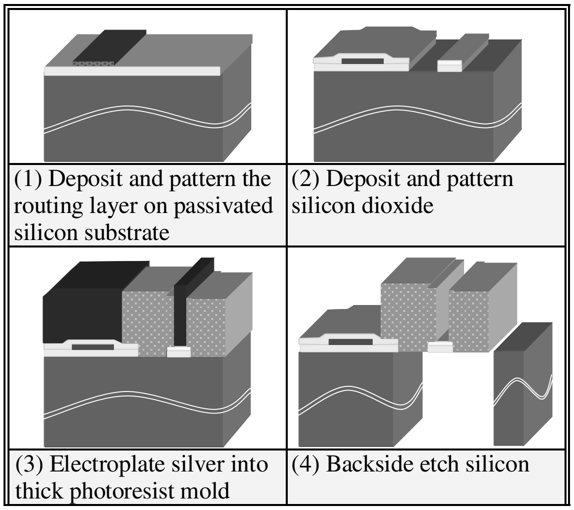

Figure 2: Fabrication process flow of the tunable filters.

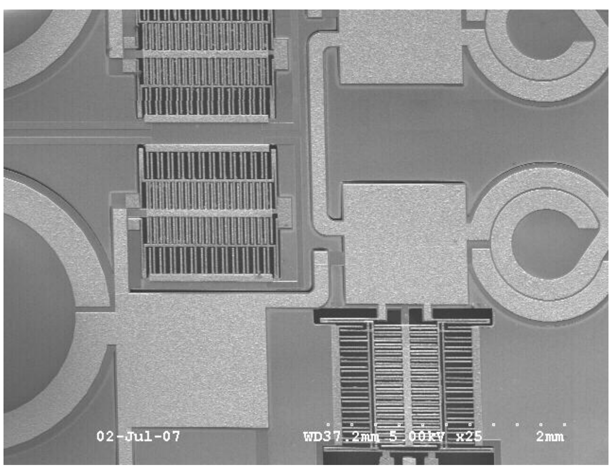

Figure 3: SEM view of the tunable silver filter fabricated on a CMOS-grade silicon substrate.

Figure 4 shows a SEM view of a dual-gap one-port tunable capacitor [3], identifying the actuator and the parallel-plate capacitor. The main challenge in realizing a two-port tunable capacitor is to electrically isolate the movable plates of the tunable capacitor from the actuator while maintaining a mechanical connection [7]. Here, such a connection is provided by silicon dioxide. Figure 5 shows a SEM view of a two-port tunable capacitor with a close-up view of the isolation area. As shown, the tunable capacitors are suspended in air and thus exhibit very low loss at high frequencies.

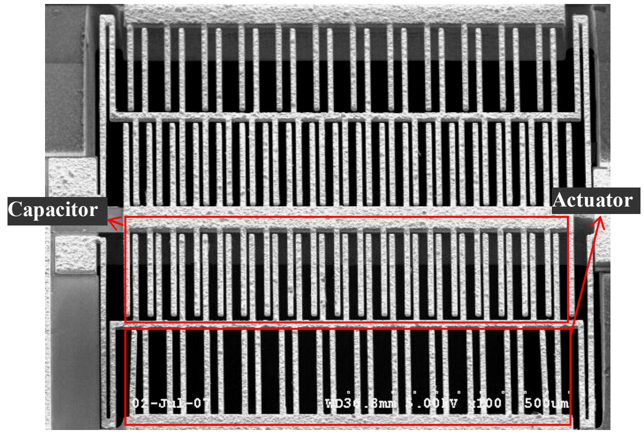

Figure 4: SEM view of a one-port tunable capacitor.

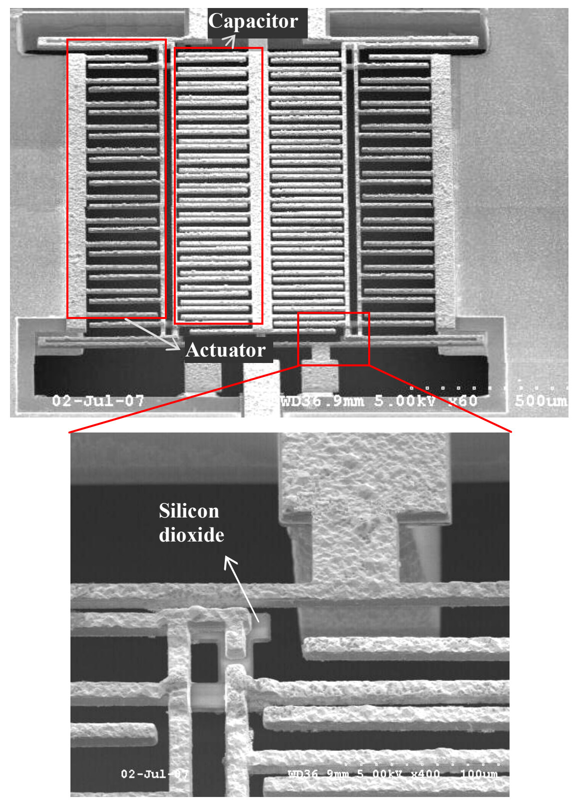

Figure 5: SEM view of the two-port tunable capacitor together with the close-up view of the isolation area. Silicon dioxide is used to isolate the actuator from the tunable capacitor.

4. RESULTS

We have previously shown fixed-frequency lumped-element silver bandpass filters with low insertion loss [8]. The two-port tunable capacitor is the critical component for the realization of high-order tunable filters and is reported in this paper. On-wafer S-parameter measurements are carried out using an Agilent E8364B PNA and Cascade GSG infinity microprobes. The pads parasitics are not de-embedded from the measured S-parameters.

Two-Port Tunable Capacitor

Figure 6 shows the measured S_{11} of the actuator and the two-port capacitor. Due to the excessive reduction of both metal loss and substrate loss, the two-port capacitor shows a very high Q in excess of 500 up to 2 GHz (Marker 1 in Figure 6). However, the fixed port of the actuator is supported by the CMOS-grade silicon substrate and thus the actuator exhibits a lower Q (Marker 2 in Figure 6). Figure 7 shows the C-V tuning curve of this capacitor. The capacitor is changed by 1 pF with the application of 61 V.

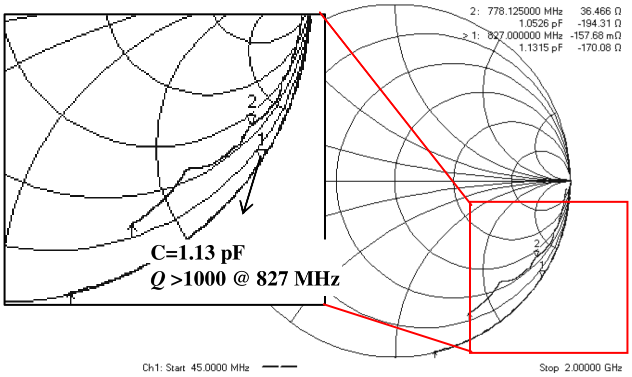

Figure 6: Measured S_{11} of the actuator (Marker 2) and the two-port capacitor (Marker 1), showing Q in excess of 500 up to 2 GHz for the tunable capacitor.

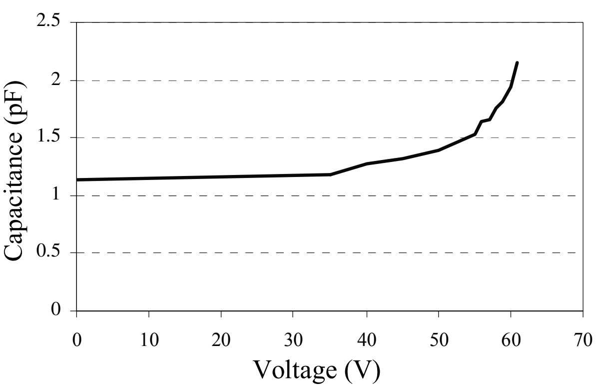

Figure 7: C-V tuning curve of the two-port tunable capacitor. The DC bias is applied to the isolated actuator.

Tunable Filter

Figure 8 shows the measured S-parameter of the filter when terminated to 200 Ω. The measured embedded-*IL* of the filter is 4.0 dB, indicating an individual component Q of more than 150 and tank Q in excess of 75 at the passband (as demonstrated in Figure 6). The measured response of the filter is in good agreement with the simulated response shown in Figure 1. In this filter, tunable capacitors of 1 pF are laid in parallel with fixed capacitors to obtain the desired capacitance value. Due to the large value of the fixed capacitors, the total capacitance change is not as pronounced, and hence the frequency shift obtained by electrostatic tuning of the capacitors is not more than 17 MHz (Figure 9). Figure 10 shows the measured frequency response of the filter at the initial state together with the measured response when each capacitor is changed by 2× (by depositing a thinner interlayer silicon dioxide dielectric), demonstrating that the filter can be potentially tuned by 150 MHz if a larger portion of the capacitors is made tunable. As shown in Figure 10, by increasing the capacitor values, the Q of each parallel LC tank increases, resulting in a lower bandwidth as the filter is tuned. This filter could be a potential candidate for GSM 850 band. The frequency shift of 150 MHz shown in Figure 10 is more than the maximum tuning required to cover both GSM 900 and GSM 850.

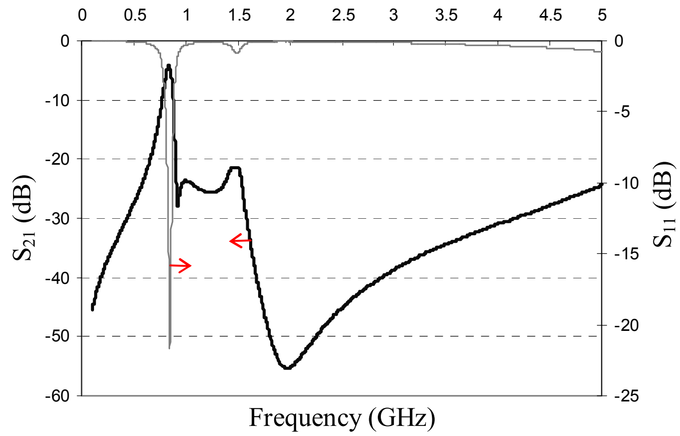

Figure 8: Measured S-parameter of the filter at 831 MHz, showing an IL of 4 dB when terminated to 200 Ω.

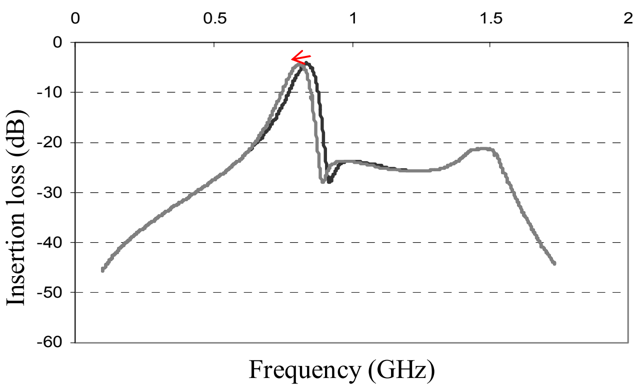

Figure 9: Measured electrostatic tuning of the filter. A DC voltage of 61V is applied to the tunable capacitors.

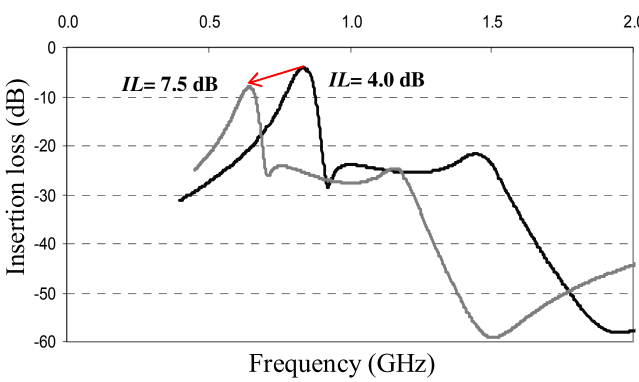

Figure 10: Measured response of the filter. Each capacitor is increased by 2×, resulting in 150 MHz frequency shift.

To examine the temperature stability, the filter is tested at elevated temperatures in a temperature-controlled RF probe station from Desert Cryogenics. Over the range of 23 °C to 85

°C, the filter exhibits a temperature drift of < 0.19% in center frequency and < 0.5% in 3dB-bandwidth, as shown in Figure 11. The *IL* of the filter is very stable with temperature (Figure 12). The temperature test took several hours resulting in a slight degradation in the calibration that is a contributing factor for the higher *IL* at high temperatures.

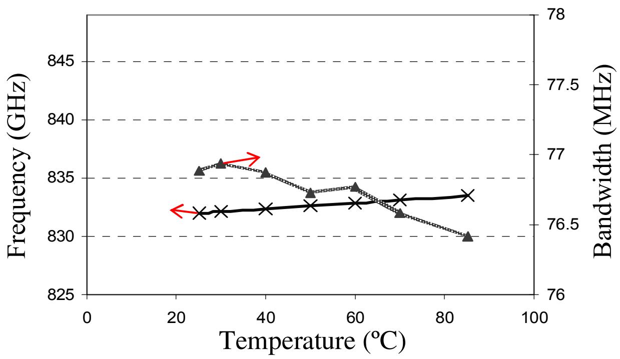

Figure 11: *(Left) frequency and (right) bandwidth behavior of the filter in 23 °C to 85 °C temperature range.*

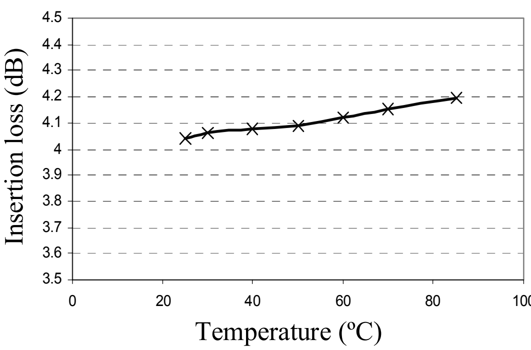

Figure 12: IL vs. temperature, showing a stable performance over 23°C -85°C range.

Although this filter shows promising performance for GSM applications, the bandwidth of the filter has to be further reduced to 25 MHz. With the current *Q* obtained for the integrated passives ($Q > 150$), a filter has been designed using the elliptic configuration to meet the rejection mask of the GSM band. The simulated response of the filter is compared to the rejection mask of a GSM 850 SAW filter from Epcos (B4180) [9], and is shown in Figure 13. Once implemented, this filter can replace several SAW filters that are required to cover its tunable range while offering a comparable performance.

5. CONCLUSION

A new low-temperature fabrication process was presented that enables the co-fabrication of high-*Q* inductors and two-port tunable capacitors. Using this technique, a tunable filter was demonstrated and exhibited a low insertion loss of 4 dB at 831 MHz with a 3dB-bandwidth of 77 MHz. The filter shows good thermal stability and could be a potential candidate for use in multi-band radios.

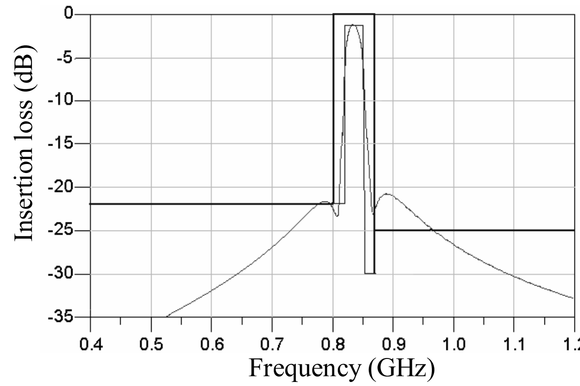

Figure 13: Comparison of the designed tunable filter with the rejection mask of a GSM SAW filter from Epcos (B4180). The inner box determines the bandwidth and the outer box determines the out-of-band rejection.

6. ACKNOWLEDGEMENT

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