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Effect of Center Frequency Deviation in Miniaturized CMOS Bandpass Filter

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Abstract : *In this letter, the effect of quality factor on center frequency deviation in miniaturized coupled line bandpass filter (BPF) with diagonally end-shorted at their opposite sides and lumped capacitors is theoretically analyzed. The miniaturized BPF of a two-stage structure with two types of quality factors in standard CMOS process was designed and manufactured at 5.5 GHz. The die area of BPF was 1.44 × 0.41 mm^2. The measured center frequency of BPF with a quality factor of 4.9 was deviated from 5.5 GHz to 4.7 GHz. The one with 14.8 was shifted to 5GHz. The theoretical and measured results validate that quality factor influences the center frequency shift of BPF.*

Key words : *Center frequency shifts, Quality factor, Shunt resonator, Substrate loss, Bandpass filter, CMOS*

1. Introduction

Bandpass filters are essential components in wireless communication circuits. RF transceiver development has been moving toward single-chip implementation, eliminating the discrete elements. Many BPFs have been published by CMOS technology, which has emerged as a viable system-on-a-chip technology that enables the full integration of RF integrated circuits. However, these filters have suffered from inherent losses with silicon substrate and low quality factor [7], [2], [6] (Soorapanth & Wong, 2002 ; Georgescu & Finvers, 2006 ; Mohieldin & Sinencio, 2003). The miniaturized bandpass filter using diagonally end-shorted at their opposite sides and lumped capacitors showed more promise and a relatively higher quality factor than filters with the spiral inductors [5] (Kang & Zhang, 2009). However, the center frequencies of these filters are inclined to shift to the lower frequency. The greater difference in the center frequency of these filters between simulation and measurement in CMOS fabrication has not been analyzed until now.

In this letter, miniaturized coupled line BPF with a two-stage structure by standard silicon integrated circuits was designed and manufactured at 5.5 GHz. One-layer and six-layer BPFs were implemented for the comparison. The center frequency shifts will be theoretically proven to be caused by transmission losses and quality factors in the lossy distributed inductor of the shunt resonator. These approaches will be verified by the measurements of BPFs with two types of quality factors.

2. Technology Description

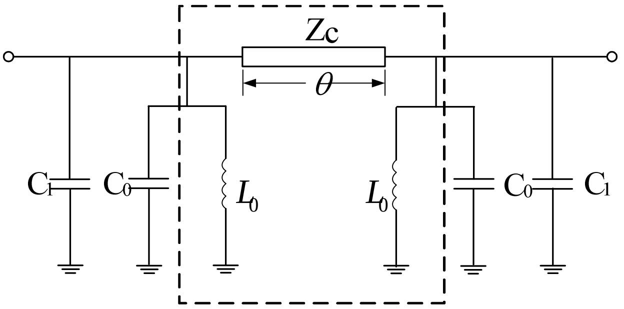

Fig. 1 A highly-miniaturized BPF

A highly-miniaturized BPF can be implemented using a shunt resonator and a section of high- impedance transmission line [4] (Kang & Shan, 2007), and the structure is shown in Fig. 1. For the ideal BPF, we can set the conductivity of the substrate to zero and transmission line to lossless.

Z_C,C_1andΘ in Fig. 1 are the characteristic impedance of the shortened transmission line, the lumped capacitor, and the electrical length of the shortened line defined in Hitota's size reduction method [3] (Hirota & Minakawa, 1990). $C_0$and$L_0$are the capacitor and the inductor for the resonance. The resonator in Fig. 1 has a resonance frequency as follows:

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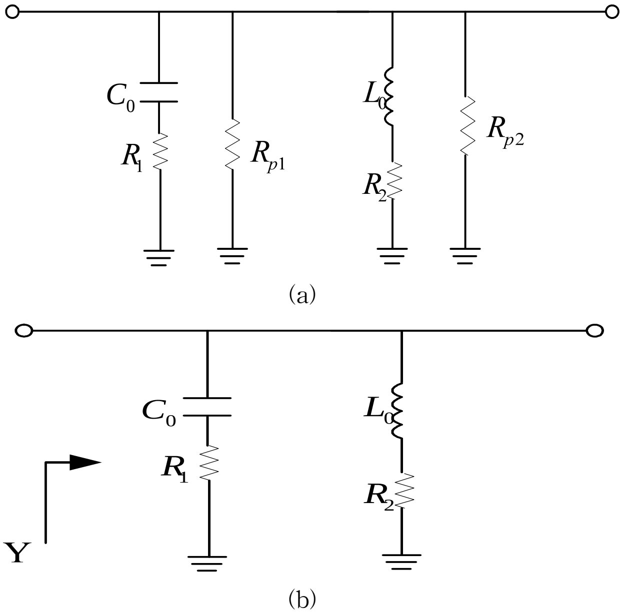
$$w_r = \sqrt{\frac{1}{L_0 C_0}} = w_0 \tag{1}$$

where w_o is the center frequency.

However, the substrate's loss effect is actually too severe to be ignored as the silicon substrate is inherently lossy and the electrical field which exists in the coupled line circuit on the top plates tends to leak into it. Although the exact equivalent circuit of the distributed inductor is complicated, we assume that the distributed inductor loss of coupled line is mainly due to the series resistance R_2,as shown in Fig. 2 (a), the equivalent circuit of the resonator. Because the resistance R_{p1} and R_{p2} of the parallel part do not change the resonant frequency of shunt resonance, Fig. 2 (b) is the simplified circuit of Fig. 2 (a) for modeling the resonance frequency deviation. For the MIM capacitor, an equivalent series resistance R_1 exists in the MIM circuit model and a maximum Q of about 80 was reported [1] (Burghartz & Soyuer, 1996).



(b)

Fig. 2 Equivalent circuit of the resonator

The resonator in Fig. 2 (b) has the following Y admittance:

$$Y = \frac{1}{R_2 + jwL_0} + \frac{1}{\frac{1}{jwC_0} + R_1} = \frac{R_2 - jwL_0}{R_2^2 + (wL_0)^2} + \frac{jwC_0(1 - jwR_1C_0)}{1 + (wR_1C_0)^2} \tag{2}$$

The imaginary part of Eq. (2) equals to zero for resonance,

$$\frac{-jwL_0}{R_2^2 + (wL_0)^2} + \frac{jwC_0}{1 + (wR_1C_0)^2} = 0 \tag{3}$$

The resonance frequency is derived from Eq. (3)

$$w_r = \frac{\sqrt{1 - \frac{C_o}{L_o} R_2^{\ 2}}}{\sqrt{L_o C_o - (R_1 C_o)^2}} \tag{4}$$

From Eq. (4), the resonance frequency of the circuit in Fig. 2 (b) using the quality factors is expressed as follows:

$$w_r = w_0 \frac{\sqrt{1 - \frac{1}{Q_L^2}}}{\sqrt{1 - \frac{1}{Q_C^2}}} \tag{5}$$

where Q_L is the quality factor of the distributed inductor,

$$Q_L = \frac{w_0 L_0}{R_2} \tag{6}$$

Q_C is the quality factor of the MIM capacitor,

$$Q_C = \frac{1}{w_0 R_1 C_0} \tag{7}$$

The corresponding operating resonance frequency ω_r in Eq.(5) will be smaller than the center frequency ω_0 of the lossless circuit. The deviation of center frequency assumes to be expressed as $\Delta\omega = \omega_0 - \omega_r$. In Fig. 3, the logarithm of $\Delta\omega/\omega_0$ versus Q_L factor is plotted. Three kinds of curves are shown for the case of Q_C= 40, 60, and 80 as the parameter, respectively. As Q_C increases, as shown in Fig3, $\log(\Delta\omega/\omega_0)$ increases. Usually the deviation of center frequency improves as Q increases. In contrast, this trend is to be notable as not

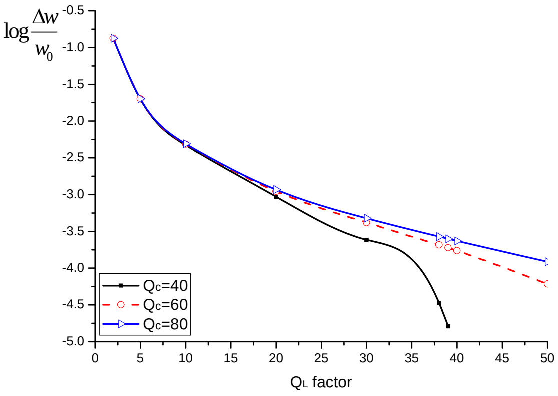


Fig. 3 The logarithm of $\Delta\omega/\omega_0$ versus the Q_L factor

to be expected. When $Q_C$is equal to Q_L in Fig. 3, ω_r becomes ω_0 and $\log(\Delta\omega/\omega_0)$ is zero. In case of the Q_C being lager than Q_L, ω_r becomes larger than ω_0. It means that the center frequency starts to be shifted to the higher frequency.

3. Results

To verify the approaches, two kinds of cascade miniaturized coupled line BPFs with one and six layers were considered. First, a one-stage bandpass filter was designed at 5.5 GHz. For the BPF with one layer, a coupled line of 7^0 electrical length was used. The coupled line width was 20 μm, the transmission line length was 570 μm and the separation between the two coupled lines of 140 μm was used to provide input/output impedance matching the system impedance Z_0 = 50 Ω. The six-layer filter also had a 20 μm line width, 570 μm line length, and 140 μm coupled line separation. Then, two similar one-stage filters with one and six layers were cascaded, respectively. This technology is well explained by [5](Kang & Zhang, 2009). The conductivity of the coupled lines is assumed by 2.4×10^7Siemens/mand the substrate is lossless for the simulation process.

These filters were fabricated using Magnachips 0.18 μm process with 10 Ω cm bulk silicon substrate and aluminum metal layers. The total die area, including the ground plane surrounding the integrated BPF, was 1440 μm ´ 410 μm. A photograph of the layout is shown in Fig. 4.

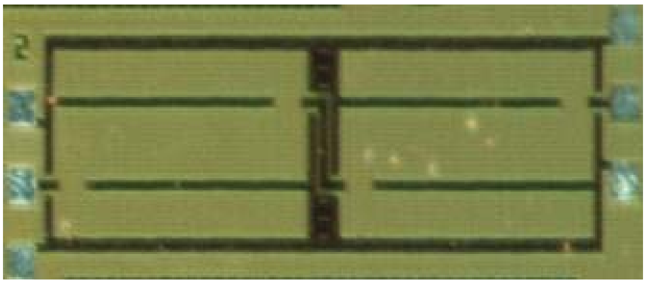
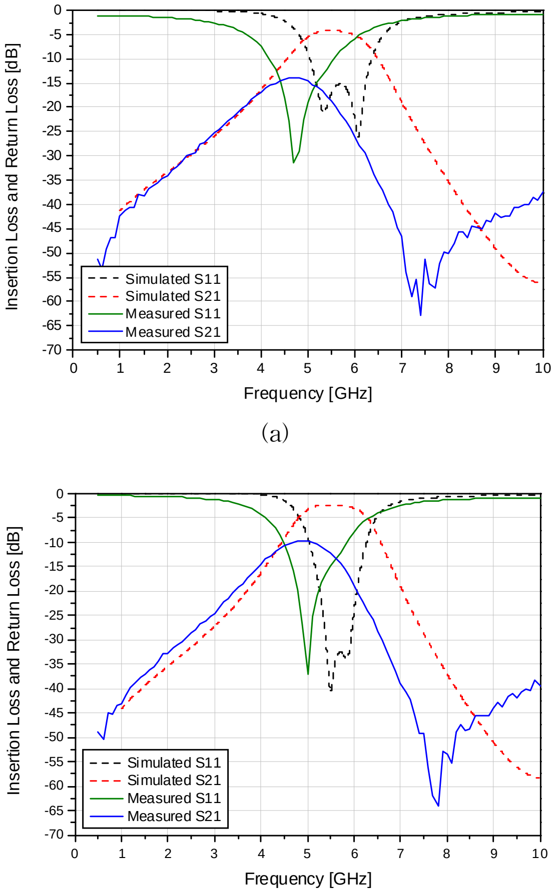


Fig. 4 Photograph of the fabricated bandpass filter.

In Fig. 5, the simulated and measured results of the circuit with one-layer and six-layer coupled lines are plotted. The Q_L of the BPF were found to be 4.9 and 14.8 for the one-layer and six-layer filters, respectively. The Q_L factor of the six-layer BPF circuit was better than that of the one-layer circuit. The dotted line was electro- magnetically simulated by HFSS (Ansoft). The measured center frequency of the one-layer coupled lines BPF was deviated from 5.5 GHz to 4.7 GHz with 0.8 GHz shift as shown in Fig. 5 (a), whereas in Fig. 5 (b), the measured center frequency of the six-layer circuit moved from 5.5 GHz to 5 GHz with 0.5 GHz shift. Both of them have the center frequency shifting to the lower frequency after fabrication. According to the simulation and measured results, the higher the Q_L factor, the less the center frequency shifts.



(a)

(b)

Fig. 5 (a) Simulated and measured results of the circuit with one-layer coupled lines, (b) six-layer coupled lines

4. Conclusion

In this paper, the greater difference between simulation and measurement of the miniaturized bandpass filter using diagonally end-shorted at their opposite sides and lumped capacitors in CMOS fabrication has been analyzed. The filters have suffered from inherent losses with silicon substrate and conductor losses. These losses are inclined to cause the center frequency to shift to the lower frequency. It is theoretically proven that the center frequency shifts are mainly caused by transmission losses and quality factors in the lossy distributed inductor of shunt resonator of the coupled lines BPF.

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