A COMPACT CASCADE QUADRUPLEBandpass filter with lowtemperature cofired ceramic technologyHong-Ching Lin,1 Pang Lin,1 Ching-Wen Tang,2 and Sea-Fue Wang31 Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu, Taiwan, Republic of China; 2 Department of Communications Engineering, National Chung Cheng University, Chiayi, Taiwan, Republic of China; 3 Department of Materials and Resources Engineering, National Taipei University of Technology, Taipei, Taiwan, Republic of ChinaReceived 31 March 2008ABSTRACT: In this article, a compact cascade quadruplet bandpass filter has been proposed. This bandpass filter has been realized with the semilumped method and can generate a pair of transmission zeros at the two sides of passband by using the nonadjacent cross coupling. The analysis and design procedures are provided in this article. To miniaturize the size of the circuit and improve its performance, multilayered structure and the low-temperature cofired ceramic technology are employed to design and fabricate the filter. Measurement results agree well with the electromagnetic simulation, which can validate the proposed structure. © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 3218–3220, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23910Key words: bandpass filter; low-temperature cofired ceramic; compact filters

1. INTRODUCTIONCompact size and low insertion loss are essential specifications within the modern telecommunication systems. To realize multiband behavior, RF transceivers with more bandwidth and flexibility are utilized. Meanwhile, the technologies for integrating passive circuits to achieve multifunction, high performance, and chip-size are attractive for the microwave and millimeter-wave applications. Therefore, the low-temperature cofired ceramic (LTCC) [1–6] seems to be one of the most efficient methods for miniaturizing and packaging technologies [7–10] because LTCC can integrate both passive and active components in a module to achieve the system-in-a-package (SiP) approach.

The bandpass filter is one of the most important components in the RF front-end. It can select passband frequencies and reduce the influence from frequencies of the adjacent channels. The lowpass prototypes have been discussed in several articles [11, 12]. Levy [13] has proposed a unified theory for the synthesis of exactly equiripple lowpass prototypes. To realize a single pair of attenuation poles at finite frequencies, Yu and Chang [14] and Hong and Lancaster [15] adopt the microstrip open-loop resonators. Hsu et al. [16] have also adopted the coupled-resonators to design the group-delay equalizers. In this article, the coupling scheme is proposed to control the locations of transmission zeros at both sides of passband skirts. Detailed analyses of coupling scheme and design equations are introduced in Section 2. The multilayered structure of bandpass filter and fabricated unit are provided in Section 3.

2. THEORY OF FILTERThe immittance inverter is adopted to analyze our proposed filter [17, 18]. The four-ordered quasi-elliptic bandpass filter with cross-coupling can generate a first pair of transmission zeros at finite frequencies. As shown in Figure 1, the inverter J14 is connected to nodes A and B. The condition of generating the first pair of transmission zeros is Y21 path ACD + Y23 path AB = 0. Assuming all of the resonators B(ω) are equal to B(ω), the equation can be derived as

\[
\frac{J_{12}J_{23}J_{34}}{B(\omega)} = -J_{14}
\]  

(1)

Within the susceptance B(ω), both the inductor L and capacitor C are combined. This result may make the denominator of Eq. (1) greater than zero. Table 1 shows the relation between J12, J23, J34, and J14. The positive value of J-inverter represents the circuit using the inductive coupling for the feedback loop, and the negative value of J-inverter represents the circuit using the capacitive coupling for the feedback loop.

Using the combine filter as an example, the center frequency and bandwidth ratio are defined as 2.4 GHz and 0.1, respectively, and the characteristic impedance Z0 and the electric length θ of transmission line are chosen as 25 Ω and 25°, respectively. If the ripple of Chebyshev response is 0.01 dB, then the values of each inverter, as shown in Figure 1, can be calculated as J12 = 0.016, J14 = 0.00992, and J23 = 0.00729. Here, the frequency of transmission zero is located at the lower side of the passband at 1.9 GHz, and J14 can be derived, by Eq. (1), as −0.000394. Figure 2 shows the simulated results of four-ordered bandpass filters with and without the cross-coupled inverter J14. For simplification, the inverters can be replaced with quarter-
wavelength transmission lines. It depicts that the two transmission zeros of the simulated filter with cross-coupling \( J_{14} \) are located at 1.93 and 2.97 GHz, respectively.

In Figure 2, the return loss of the filter with cross-coupling is less than the filter without cross-coupling. Moreover, the closer the two frequencies of transmission zeros to the center frequency, the worse is the return loss. If two admittances \( Y_i \) at the inputs of inverter \( J_{01} \) and \( J_{45} \) are modified, the performance of return loss can be improved as shown in Figure 3. The admittance \( Y_i \) is matched at the central frequency and can be derived as in (2), and two inverters \( J_{01} \) and \( J_{45} \) are also modified as (3) and (4). As a result, the two inverters \( J_{01} \) and \( J_{45} \) are revised as 0.01667. Figure 4 shows the simulated results of modified four-ordered quasi-elliptic bandpass filter and the original filter with cross-coupling \( J_{14} \).

\[
Y_i = \frac{J_{12}J_{14} - J_{23}J_{14}}{J_{23}} \quad (2)
\]

\[
J_{01} = \sqrt{\frac{J_{12}J_{14} - J_{23}J_{14}}{J_{23}R_5}} \quad (3)
\]

\[
J_{45} = \sqrt{\frac{J_{12}J_{14} - J_{23}J_{14}}{J_{23}R_L}} \quad (4)
\]

3. FABRICATION AND MEASUREMENT

The cross-coupled four-ordered bandpass filter as an example. This filter is fabricated with the substrate of Dupont 951. Its dielectric constant and loss tangent are 7.8 and 0.0045, respectively. The 2.4-GHz LTCC filter is designed on four upper layers with the sheet of 1.57 mil, followed by six layers with the sheet of 3.6 mil, six layers with the sheet of 1.57 mil, and finally two layers with the sheet of 3.6 mil at the bottom. Its overall size is 132 mil \( \times \) 92 mil \( \times \) 41.4 mil. The simulation is carried out with the assistance of full-wave electromagnetic (EM) simulator, namely Sonnet. To improve the accuracy of measurement, the on-wafer tester has been chosen. The network analyzer, Agilent N5230A PNA_L, is used to measure, and the short-open-load-through (SOLT) is adopted for calibration. To design the cross-coupled bandpass filter, with multilayered structure, the semi-lumped method is suitable to realize four resonators. This semilumped method is composed of a transmission line section shunted with a capacitor. These capacitors within four resonators simply use the metal-insulator-metal (MIM) architecture to realize. The inductance coupling of \( L_{14} \) is realized by the edge coupling between the transmission lines of first and fourth resonators. The other inductance couplings of \( L_{12} \) and \( L_{34} \) adopt the broadside-coupled transmission lines. The capacitance coupling of \( C_{23} \) uses the MIM capacitor directly. Figure 5(a) reveals the detailed three-dimensional (3D) structure of 2.4-GHz LTCC bandpass filter.

As shown in Figures 5(b), the pair of frequencies of measured and EM simulated transmission zeros are 1.93, 3.1 GHz, and 1.9, 3 GHz, respectively. At the frequency of 2.4 GHz, the measured and EM simulated insertion losses are less than 3.3 and 3 dB, respectively, whereas the return losses are greater than 19.6 and 27.3 dB. At the neighboring of passband, the outband rejection is more than the level of 40 dB.

4. CONCLUSION

The LTCC bandpass filter with coupling scheme has been proposed in this article. The theory of generating the transmission zero...
zeros and the design procedures of filters have been analyzed. The proposed bandpass filter fabricated with the multi-layered structure is realized using the semi-lumped method. The fabricated bandpass filter with the characteristics of high integration and small size is very suitable for the implementation in the multichip module. Agreement between measurement and theoretical prediction has evidenced the feasibility of our study.

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