JOURNAL OF THE KOREA ELECTROMAGNETIC ENGINEERING SOCIETY, VOL. 3, NO. 1, MAY 2003 JKEES 2003-3-1-07

A Compact Lumped-Element Low-Pass Filter with Transmission Zeros

Byoung-Hwa Lee · Sang-Soo Park

Abstract

In this paper, compact lumped-element low-pass filter structure with two transmission zeros at second and third harmonics is presented. The use of lumped-elements and transmission zeros can provide the advantages of compact size, sharp cutoff and wide stop-band frequency response. The proposed low-pass filter is a modified Chebyshev low-pass filter type and is implemented by the use of low temperature co-fired ceramic (LTCC) technology. This filter has been verified by both simulation and experiment. The simulated and experimental results agree very well.

Key words : Lumped-Element, Low-Pass Filter, Transmission Zero, LTCC.

I. Introduction

Using a low-pass filter to suppress harmonics and spurious is a common technique in designing wireless communication systems such as the wireless local area network (LAN) and Bluetooth applications. Therefore, to reduce the size and improve the performance of those applications, a compact and high perfor- mance microwave low-pass filter is essential. Various types of low-pass filters such as open stub low-pass filter, stepped impedance low-pass filter were proposed.[1],[2] However, due to the periodic characteristics of the distributed transmission lines with respect to frequency, these filters show very poor spurious response in the stop-band. In addition, for the sharper cutoff, the order of the stepped impedance low-pass filter must be high. This results in large filter size and large insertion loss. Some research has been performed to overcome these disadvantages. One of them is semi-lumped low-pass filter proposed by Sheen.[3] This filter is composed of a lumped capacitor and a section of transmission line. The parallel connection of these two elements causes transmission zeros, which ideally mean there is no transmission between input and output.[4] Therefore, the sharper cutoff and lower insertion loss can be achieved. Similarly, low-pass filter using stepped impedance hairpin resonator with direct-connected feed is presented by Hsieh.[5] This filter also can have transmission zeros due to the combination of a capacitor and transmission line. However, both of these low-pass filters are too large for the modern wireless communication systems because of the use of distributed transmission line, and Hsieh's filter still shows poor spurious response in the stop-band even though the stepped impedance resonator is used. A low-pass filter using defected ground structure (DGS) by Ahn is another approach for the wider and deeper stop-band frequency response,[6] but the large size of DGS section is required to lower the cutoff frequency and transmission zero location, and so it may limit the use of this novel filter. More recently, a low-pass filter using film resistor for the spurious suppression is introduced by Lee.[7] The function of this resistor is to degrade the quality factor in the high frequency-band, and thus to mitigate the spurious responses in the stop-band. Therefore, this filter can effectively suppress the spurious. However, the resistors also have effect on the pass-band response and insertion loss is heavily deteriorated.

In this paper, we propose a very small size lumped-element low-pass filter, which has two transmission zeros to suppress the second and the third harmonics. This filter is a modified Chebyshev low-pass filter type and the use of lumped-elements and transmission zeros can provide the advantages of compact size, sharp cutoff and wide stop-band frequency response. This proposed low-pass filter has been implemented by the use of low temperature co-fired ceramic (LTCC) technology. The low-pass filter size presented is 2.0 mm × 1.25 mm × 0.95 mm.

II. Low-Pass Filter Design

Fig. 1 shows the circuit of Chebyshev type five-

Manuscript received December 16, 2002 ; revised February 14, 2003.

CAE Team, R&D center, Samsung Electro-Mechanics Co., Ltd, 314, Maetan-3Dong, Paldal-Gu, Suwon, Kyunggi-Do, 442-743, Korea.

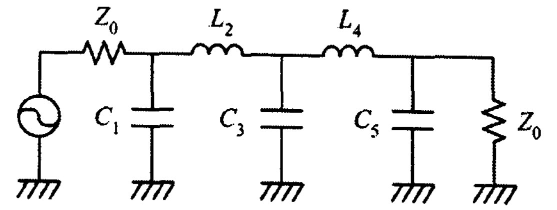

Fig. 1. Chebyshev type five-element low-pass filter.

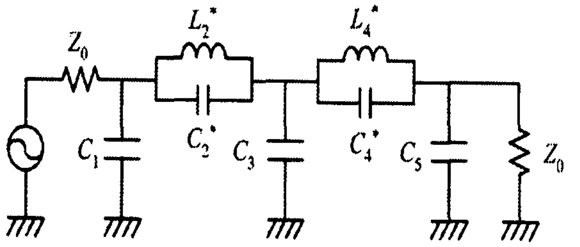

Fig. 2. Low-pass filter circuit with transmission zeros.

element low-pass filter. The reactance values in Fig. 1 can be written as follows:

$$C_i=\left(\frac{1}{Z_0}\right)\left(\frac{1}{\omega_c}\right)g_i \qquad i=1,3,5 \tag{1}$$

$$L_j=Z_0\left(\frac{1}{\omega_c}\right)g_j \qquad j=2,4 \tag{2}$$

where ω_c denotes the cutoff angular frequency, Z_0 denotes the impedance of the in/out terminated ports, and g_i or g_j is given by the prototype value of the Chebyshev type low-pass filter.

In order for the circuit, shown in Fig. 1, to have transmission zeros, L_2 and L_4 are replaced by parallel LC resonator circuits as shown in Fig. 2. The inductance and capacitance values of parallel LC resonator circuits can be extracted from the transmission zero locations, which are parallel resonant frequencies, and low-pass filter characteristics by using following procedure.

The capacitance values of parallel LC resonator circuits can be expressed as follows:

$$C_2^*=\left(\frac{1}{\omega_1^2 L_2^*}\right) \quad C_4^*=\left(\frac{1}{\omega_2^2 L_4^*}\right) \tag{3}$$

where ω_1 and ω_2 are the resonant angular frequencies of the parallel LC resonators. In order to have the low-pass filter characteristics, the circuit, shown in Fig. 2, should be equal to the Chebyshev low-pass filter circuit, shown in Fig. 1, at the cutoff frequency. Using the equation (2) and (3), the equality is given by the following:

$$L_2^*=\frac{Z_0 g_2}{\omega_1}\left(\frac{\omega_1}{\omega_c}-\frac{\omega_c}{\omega_1}\right)$$

$$L_4^*=\frac{Z_0 g_4}{\omega_2}\left(\frac{\omega_2}{\omega_c}-\frac{\omega_c}{\omega_2}\right) \tag{4}$$

Therefore, the inductance and capacitance values of parallel LC resonator circuits can be extracted by using (3) and (4). For instance, the proposed low-pass filter has transmission zeros at the second and third harmonics, when ω_1 and ω_2 are set to be angular frequencies of the second and third harmonics, respectively.

Ⅲ. Design Example

In this section, we will show the low-pass filter with cutoff frequency at 3 GHz and 0.01 dB ripple within the pass-band for the 2.4~2.5 GHz wireless LAN and Bluetooth applications as an example. Generally these applications require a minimum 20 dB attenuation at the 4.8~5.0 and 7.2~7.5 GHz frequency ranges which are the second and third harmonics of their operating frequency ranges, and maximum 0.5 dB insertion loss at the pass-band.

The designed Chebyshev low-pass filter circuit with transmis- sion zeros is shown in Fig. 3. ω_1 and ω_2 are set to be angular frequencies of the second (4.8 GHz) and third harmonics (7.2 GHz), respectively and the extracted L_2^*, C_2^*, L_4^* and C_4^* using (3) and (4) are 2.11 nH, 0.521 pF, 2.86 nH and 0.171 pF.

Actual frequency response of the equivalent circuit, shown in Fig. 3, is presented in Fig. 4. The circuit simulation is carried out with Serenade Ver. 8.5 for windows (Ansoft Co., Ltd.) under lossless condition. Transmission zeros appear at the second and third harmonics.

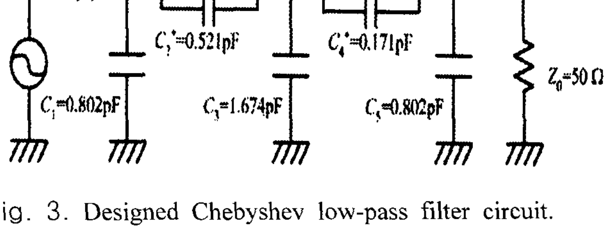

Fig. 3. Designed Chebyshev low-pass filter circuit.

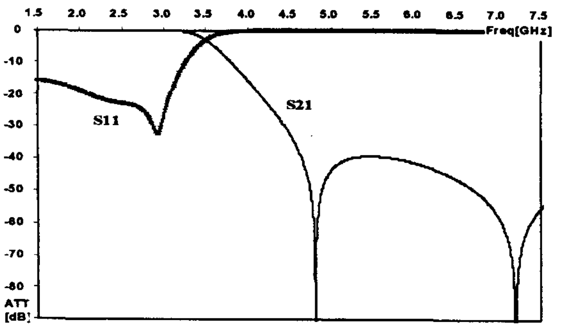

Fig. 4. Frequency response.

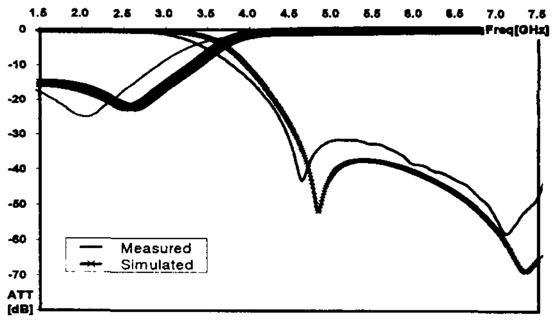

Fig. 6. Measured results and Simulated results for comparison.

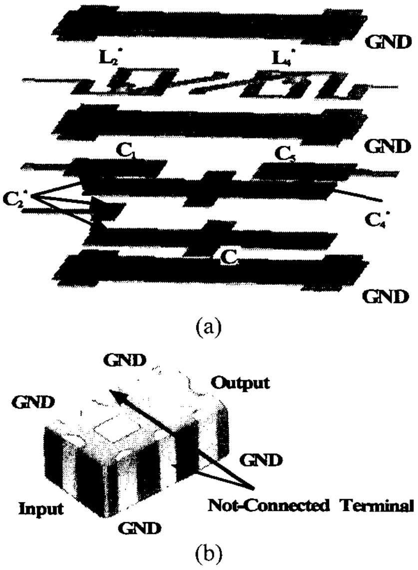

Fig. 5. Designed Filter Structure(a) and Appearance(b).

The proposed low-pass structure and appearance are shown in Fig. 5 It is designed and fabricated by using multi-layer ceramic with a relative dielectric constant and loss tangent of 5.6 and 0.003, respectively. The total number of layer is 9, and the designed thickness of each layer is 120 μm, 30 μm, 30 μm, 60 μm, 30 μm, 180 μm, 30 μm and 180 μm, respectively, from the bottom to top ground.

The capacitors used are all parallel plate type and spiral type inductors are used for the compact size. All individual components are designed by ADS Momentum Ver. 4.6 (Agilent Co., Ltd.) using the Moment Method and verified by using a circuit simulator, Serenade. Due to the close proximity between components within LTCC structure, the mutual coupling associated physical layout may corrupt the low-pass filter performance. As a result, the electrical characteristics of the complete layout including the parasitic effects should be considered using a full-wave electromagnetic simulation. For this proposed low-pass filter, manual tuning is applied to obtain a low-pass filter with some reasonable performance.

The final full-wave electromagnetic simulation results by HFSS Ver. 7.0 (Ansoft. Co., Ltd.) are compared with the measured ones in Fig. 6. Although the overall measured results show good agreement with the simulated ones, minor discrepancy is observed. To investigate the gap between the measured and simulated results, the fabricated low-pass filter is grinded by using polishing machine, and each layer thickness is observed. The measured thickness of each layer is 111 μm, 28.5 μm, 29.1 μm, 56 μm, 28 μm, 171 μm, 28.7 μm and 173 μm, respectively from the bottom to top ground. That is, each layer thickness of the fabricated low-pass filter is thinner than that of the designed low-pass filter, which cause each capacitance value to be larger than the designed one. It can be estimated that due to the fabrication error, the measured frequency response is shifted down when compared to the simulated one. In spite of the gap between the measured and simulated results, the proposed low-pass filter shows the great performance. The measured pass-band insertion loss is 0.42 dB and the attenuation at 4.8 GHz~5.0 GHz range is 31.7 dB and at 7.2 GHz~7.5 GHz range is 46.9 dB.

Ⅳ. Conclusion

A very small size lumped-element low-pass filter is presented which has transmission zeros at the second and third harmonics. Insertion loss is less than 0.5 dB and minimum 30 dB harmonic suppression can be achieved. This distinctive performance is very favorable for a wireless LAN and Bluetooth applications.

References

[1] G. L. Matthaei, L. Young and E. M. T. Jones, *Micro-wave filters, impedance-matching networks, and coupling structures*, Artech House, 1980.

[2] D. M. Pozar, *Microwave Engineering*, Wiley, Chap 8, 1998.

[3] J. W. Sheen, "A Compact Semi-Lumped Low-Pass Filter for Harmonics and Spurious Suppression", *IEEE Microwave and Guided Wave Letters*, vol. 10, no. 3, pp. 92-93, Mar. 2000.

[4] Randall W. Rhea, "Transmission Zeros in Filter Design", *Applied Microwave & Wireless*, pp. 92-96, Jan. 2001.

[5] Lung-Hwa Hsieh, Kai Chang, "Compact lowpass filter using stepped impedance hairpin resonator", *Electronics Letters*, vol. 37, pp. 899-900, Jul. 2001.

[6] Dal Ahn, Jun-Seok Park, Chul-Soo Kim, Juno Kim, Yongxi Qian and Tatsuo Itoh, "A Design of the Low-Pass Filter Using the Novel Microstrip Defected Ground Structure", *IEEE Trans. Microwave Theory and Techniques*, vol. 49, pp. 86-93, Jan. 2001.

[7] M.-Q. Lee, K.-K. Ryu, I.-B, Yom and S.-P. Lee, "Lowpass filter for spurious suppression", *Electronics Letters*, vol. 38, pp. 227-228, Feb. 2002.

Byoung-Hwa Lee

received the B.S from Inha University, Incheon, Korea, in 1993 and Ph. D. Degree from Imperial College, London, UK, in 1997. Since 1997, he has worked in Samsung Electro-Mechanics Co., Korea. His principal research is microwave passive device design.

Sang-Soo Park

received the BS in electrical engineering from the University of Suwon, Suwon, Korea, in 1998 and the MS in electrical engineering from Chung Ang University, Seoul, Korea, in 2000. Since 2000, he has worked in Samsung Electro-Mechanics Co., Korea. His principal research is microwave passive device design.