ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.9, No.21, 1630–1636

A compact quad-band bandstop filter using dual-plane defected structures and open-loop resonators

Huansheng Ning[1a), Jun Wang[1], Qingxu Xiong[1], Hong Liu[1], and Lingfeng Mao[2]

[1] *School of Electronic and Information Engineering, Beihang University, No. 37, Xueyuan Road, Haidian District, Beijing 100191, China*

[2] *Institue of Intelligent Structure and System, Soochow University, No. 1, Shizi Street, Suzhou 215006, Jiangsu, China*

a) *ninghuansheng@buaa.edu.cn*

Abstract: A novel approach for designing a quad-band bandstop filter is proposed by using dual-plane E-shaped defected structures and open-loop resonators coupled to the microstrip line. Through this design, the proposed filter features four conveniently adjusted stopbands, compact size and simple design procedure. The equivalent circuit model of the quad-band bandstop filter is derived before the design procedure is summarized. To facilitate the filter design, an approximate design rule for the resonant frequency of the E-shaped defected structure and the open-loop resonator is presented. As an illustrated example, a quad-band bandstop filter is designed and fabricated. The fabricated filter has four stopbands with center frequency at 2.37/3.52/5.20/5.76 GHz and the rejection levels of the stopbands are all better than 31 dB, verifying our proposed design concept.

Keywords: bandstop filter, quad-band, defected microstrip structure, defected ground structure

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] H. Uchida, H. Kamino, K. Totani, N. Yoneda, M. Miyazaki, Y. Konishi, S. Makino, J. Hirokawa, and M. Ando, "Dual-band-rejection filter for distortion reduction in RF transmitters," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 11, pp. 2550–2556, Nov. 2004.

[2] K.-S. Chin, J.-H. Yeh, and S.-H. Chao, "Compact dual-band bandstop filters using stepped-impedance resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 12, pp. 849–851, Dec. 2007.

[3] H.-K. Chiou and C.-F. Tai, "Dual-band microstrip bandstop filter using dual-mode loop resonator," *Electron. Lett.*, vol. 45, no. 10, pp. 507–509, May 2009.

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

ELectronics EXpress

[4] S. Vegesna and M. Saed, "Microstrip dual-band bandpass and bandstop filters," *Microw. Opt. Technol. Lett.*, vol. 54, no. 1, pp. 168–171, Jan. 2012.
[5] K. Michael, Y.-W. Chia, K. M. Chan, and J. Bornemann, "Design of multiple-stopband filters for interference suppression in UWB applications," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 8, pp. 3333–3338, Aug. 2006.
[6] Y. Wang, J. Zhou, and W. Hong, "A multiband bandstop filters using a single ring resonator for a wireless access communication system," *Microw. Journal*, vol. 54, no. 3, pp. 102–108, March 2011.
[7] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, John Wiley & Sons, New York, 2001.
[8] K.-C. Gupta, R. Garg, I. Bahl, and P. Bhartia, *Microstrip Lines and Slotlines*, second edition, Artech House, Norwood, 1996.

1 Introduction

With the development of highly integrated and multifunctional wireless communication systems, multi-band bandstop filters play an important role and are extremely desired, which can suppress the concurrent unwanted signals at separate frequencies. Some effective approaches have been proposed to implement dual-band bandstop filters [1, 2, 3, 4], like the utilization of two-section stepped-impedance resonators or a dual-mode loop resonator. However, the discussions about triple-band bandstop filters are relatively less, partly resulted from the design difficulties. In [5], a multi-band bandstop filter is presented by using quarter-wavelength straight and bent resonators for interference suppression in UWB applications. Recently, the triple stopbands response is obtained by using a spurline and a single ring resonator in [6]. Nevertheless, to the best of the authors' knowledge, the realization of quad-band bandstop filter with conveniently controlled stopbands and compact size has not been reported and remains a great challenge.

In this paper, we present a novel approach for designing a quad-band bandstop filter. By using the prominent stopbands generated by the E-shaped defected microstrip structure (DMS) and E-shaped defected ground structure (DGS) as well as the open-loop resonators coupled to the microstrip line, a compact quad-band bandstop filter may be implemented. First, the configuration of the proposed quad-band bandstop filter is described and its equivalent circuit model is developed. It is shown that the mutual coupling of the four stopbands is slight, which will make the four stopbands easily controlled and bring much convenience to the filter design. Then, a quad-band bandstop filter is designed and implemented to verify the above design concept. Discussion about the discrepancy between the circuit and full-wave simulation of the fabricated filter is also provided.

2 Quad-band bandstop filter design

The configuration of the proposed quad-band bandstop filter is shown in Fig. 1, where two E-shaped structures are simultaneously etched in the mi-

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

IEICE Electronics Express, Vol.9, No.21, 1630–1636

crostrip line and ground plane, and the open-loop resonators are located at both sides of the microstrip line. The corresponding equivalent circuit model of the proposed filter is illustrated in Fig. 2. To achieve compactness and the spurious resonance suppression, the E-shaped DMS is employed to establish the first stopband and represented by the parallel RLC circuit $R_1L_1C_1$. The second stopband depends on the E-shaped DGS, whose response is described by the parallel RLC circuit $R_2L_2C_2$. Here, the parallel resistances R_1 and R_2 are introduced to depict the radiation effects of the E-shaped defected structures. The open-loop resonators at both sides of the microstrip line are used to generate the third and fourth stopband and denoted by the parallel circuits L_3C_3 and L_4C_4. The transmission lines with different lengths l_i ($i = 1, 2, 3, 4$) and characteristic impedance Z_0 are utilized as admittance inverters.

Since each resonator of the presented quad-band bandstop filter (i.e., E-shaped DMS, E-shaped DGS or open-loop resonator) operates at different frequencies, the mutual coupling between them may be very slight, which will be shown in the following section. This demonstrates that the four stopbands can be conveniently adjusted. Thus, the design procedure of the proposed filter can start by implementing each stopband individually based on the conventional design methodology of bandstop filter [7]. Then, a fine-tuning process may be used to obtain the optimized performance. To facilitate this design process, an approximate design rule of the each resonator is analyzed

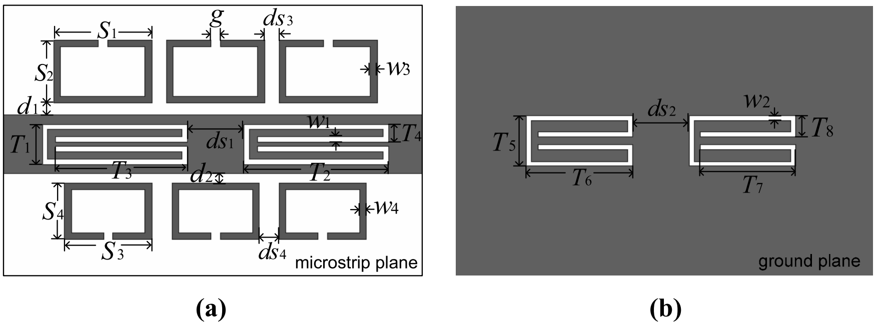

Fig. 1. Configuration of the proposed quad-band bandstop filter. (a) Top microstrip plane. (b) Bottom ground plane.

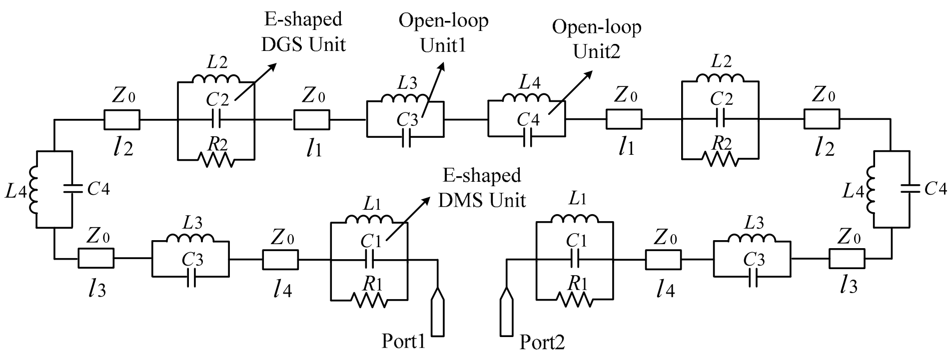

Fig. 2. Equivalent circuit model of the proposed filter.

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

IEICE Electronics Express, Vol.9, No.21, 1630–1636

in the following.

The center frequencies of the third and fourth stopband f_3 and f_4 are determined by the half guided wavelength open-loop resonators as:

$$f_i = \frac{c}{2T_i\sqrt{\varepsilon_{eff}^i}} \quad i = 3, 4 \tag{1}$$

$$\varepsilon_{eff}^i = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12\,h/w_i}} \quad i = 3, 4 \tag{2}$$

where c is the free-space speed of light, T_i and w_i $(i = 3, 4)$ are the length and width of the open-loop resonators correspondingly, ε_r and h are the relative dielectric constant and thickness of the substrate respectively.

The resonant frequencies of the E-shaped DMS and E-shaped DGS f_1 and f_2 can be approximately estimated as:

$$f_i = \frac{c}{2D_i\sqrt{\varepsilon_{eff\_slot}^i}} \quad i = 1, 2 \tag{3}$$

where $D_1 = T_1 + 2T_2 + 2T_3 + 2T_4$ and $D_2 = T_5 + 2T_6 + 2T_7 + 2T_8$ are the total length of the meandered slots of the E-shaped DMS and E-shaped DGS respectively, $\varepsilon_{eff\_slot}^1$ and $\varepsilon_{eff\_slot}^2$ are the effective dielectric constant of the slots, which can be obtained by the closed-form expressions in [8]. For the substrate with a relative dielectric constant of 2.55 and a thickness of 1.5 mm used in our case, the effective dielectric constant $\varepsilon_{eff\_slot}^i$ is expressed by:

$$\begin{aligned}\frac{1}{\sqrt{\varepsilon_{eff\_slot}^i}} &= 1.045 - 0.365\ln(\varepsilon_r) + \frac{6.3\,(w_i/h)\,\varepsilon_r^{0.945}}{(238.64 + 100\,w_i/h)} \\ &\quad - \left[0.148 - \frac{8.81\,(\varepsilon_r + 0.95)}{100\varepsilon_r}\right] * \ln(hf_i/c) \quad i = 1, 2\end{aligned} \tag{4}$$

where w_i $(i = 1, 2)$ are the widths of the slots of the E-shaped defected structures.

Table I shows a comparison between the full-wave simulated and theoretically predicted resonant frequency of the E-shaped DMS and E-shaped DGS

Table I. Comparison between the simulated and predicted resonant frequency of E-shaped DMS and E-shaped DGS.

Total length (mm)	Prediction (GHz)	Simulation (GHz)	
		E-shaped DMS	E-shaped DGS
35	3.55	3.60	3.62
39	3.19	3.18	3.19
43	2.91	2.84	2.87
47	2.67	2.58	2.61
51	2.46	2.36	2.38

* The dimensions of the simulated E-shaped structures are: $T_1 = T_5 = 3.3$ mm, $w_1 = w_2 = 0.4$ mm, $T_4 = T_8 = 1.35$ mm, $T_2 = T_3 + 1$ mm, $T_6 = T_7 + 1$ mm.

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

as their total length varies, where the simulations have a good agreement with the predictions. Hence, we can use Eq. (3) and Eq. (4) to define the initial total length of the E-shaped defected structure. The final dimensions may be obtained with the aid of numerical simulations.

3 Experimental result and discussion

A quad-band bandstop filter is realized following the aforementioned design procedure to verify the proposed design method. The substrate with a relative dielectric constant of 2.55 and a thickness of 1.5 mm is used. The characteristic impedances of the input/output transmission lines are chosen as 50 Ω. The final detailed dimensions of this filter are obtained as: $T_1 = 2.4$, $T_2 = 10.8$, $T_3 = 10.2$, $T_4 = 1.05$, $w_1 = 0.3$, $ds_1 = 10.9$, $T_5 = 3.0$, $T_6 = 7.5$, $T_7 = 6.6$, $T_8 = 1.2$, $w_2 = 0.3$, $ds_2 = 7.2$, $S_1 = 7.4$, $S_2 = 4.7$, $w_3 = 0.5$, $g = 0.3$, $d_1 = 0.25$, $ds_3 = 1.1$, $S_3 = 6.5$, $S_4 = 4.5$, $w_4 = 0.5$, $d_2 = 0.2$, $ds_4 = 1.3$ (all units are in mm). The proposed filter with above dimensions is simulated by full-wave EM solver Ansoft HFSS and fabricated on Arlon Cuclad 250GX(tm). Fig. 3 shows the photograph of the fabricated filter.

The simulated and measured S-parameters of the fabricated filter are depicted in Fig. 4, where a good agreement is obtained between the two and four stopbands can be clearly observed. A small frequency shift between the simulation and measurement is due to the fabrication tolerance. The measured quad-band of the fabricated filter is centered at 2.37/3.52/5.20/5.76 GHz with rejection level of 36.7/32.3/32.2/31.4 dB respectively. The 3-dB fractional bandwidths of the four stopbands are 7.8/5.7/4.6/4.9% correspondingly. Detailed data of the measurement show that the minimum insertion losses between adjacent stopbands are 0.5/0.6/0.9 dB separately.

It is found that the simulated center frequencies of each stopband caused by the separate E-shaped DMS, E-shaped DGS or open-loop resonators with the same dimensions of the fabricated filter are 2.40/3.57/5.34/5.95 GHz, rather close to the simulated center frequencies of the quad-band filter (2.41/3.57/5.28/5.92 GHz). The minor frequency discrepancy indicates that each stopband has very small impact on the other stopbands.

To further demonstrate the slight coupling of the four stopbands, the circuit simulation of the presented filter is also conducted. It is worth mentioning that the equivalent circuit parameters in Fig. 2 are extracted from

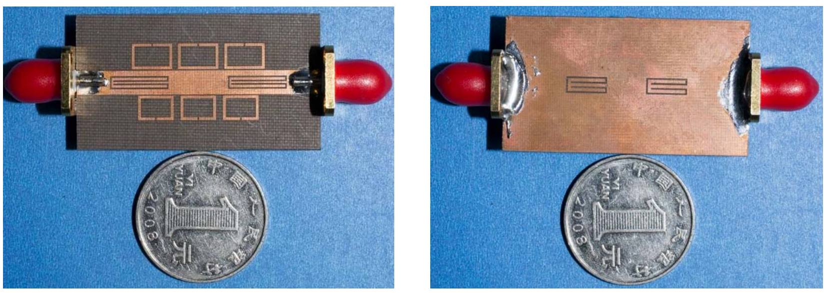

Fig. 3. Photograph of the fabricated quad-band bandstop filter.

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

ELectronics EXpress

IEICE Electronics Express, Vol.9, No.21, 1630–1636

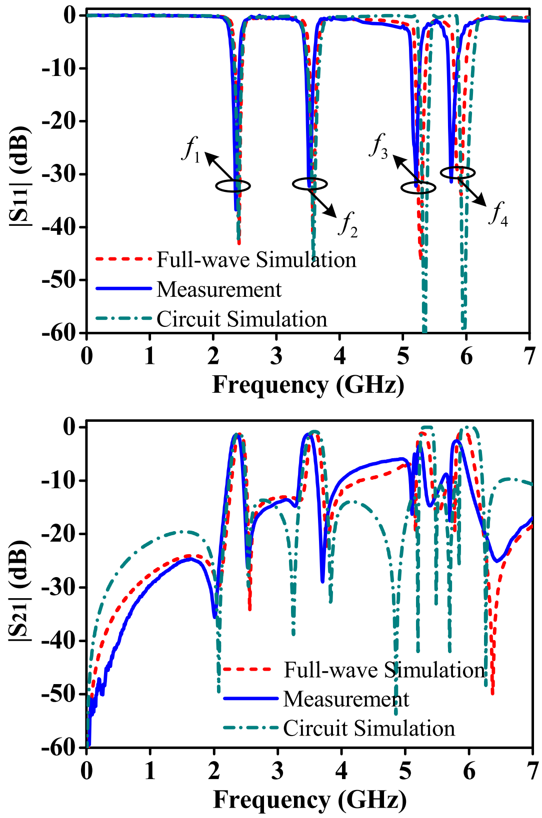

Fig. 4. Simulated and measured S-parameters of the fabricated filter.

each separate resonator. The concrete values are as following: $L_1 = 0.38\,\mathrm{nH}$, $L_2 = 0.26\,\mathrm{nH}$, $L_3 = 0.1\,\mathrm{nH}$, $L_4 = 0.09\,\mathrm{nH}$, $C_1 = 11.5\,\mathrm{pF}$, $C_2 = 7.5\,\mathrm{pF}$, $C_3 = 9.2\,\mathrm{pF}$, $C_4 = 7.6\,\mathrm{pF}$, $R_1 = 824.2\,\Omega$, $Z_0 = 50\,\Omega$, $R_2 = 978.8\,\Omega$, $l_1 = 7.35\,\mathrm{mm}$, $l_2 = 0.45\,\mathrm{mm}$, $l_3 = 0.7\,\mathrm{mm}$, $l_4 = 2.35\,\mathrm{mm}$. The circuit simulated results of the quad-band bandstop filter is plotted in Fig. 4, where a reasonable agreement is obtained between the circuit simulation and full-wave simulation. The discrepancy between the circuit and full-wave simulation will be discussed in detail as following.

Firstly, minor center frequency shift of the stopbands is attributed to the slight mutual coupling of each resonator. Secondly, because the dissipation loss from the open-loop resonators, which will prevent the attenuation of bandstop filter from going to infinity [7], is not included in the equivalent circuit model, the difference in the circuit and full-wave simulated rejection levels of the third and fourth stopband can be understood. Finally, based on the full-wave simulation, it is observed that the E-shaped DMS and E-shaped DGS will bring relatively high insertion loss and reflection at some high frequencies, while this is not considered in the equivalent circuit. The simulated result shows that the reflection caused by the E-shaped defected structures of the fabricated filter is obvious and larger than 10 dB from 4.55 GHz to 6.01 GHz. This leads to the high reflection at the passband between the second and third stopband of the quad-band bandstop filter, which does not occur in the circuit simulation. Apart from above discrepancies, the design

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012

IEICE Electronics Express, Vol.9, No.21, 1630–1636

concept of the proposed filter with conveniently tuned four stopbands can be still verified.

4 Conclusion

In this paper, a quad-band bandstop filter is reported and implemented based on dual-plane E-shaped defected structures and open-loop resonators. The equivalent circuit model of the proposed filter is developed and the design procedure is outlined. Both the simulation and measurement of the fabricated filter validates our proposed design concept. The proposed filter exhibits compactness, high rejection level and four easily controllable stopband, making it very attractive for the multifunctional wireless systems to suppress unwanted signals at four concurrent separate frequencies.

Acknowledgments

This work was jointly funded by National Natural Science Foundation of China and Civil Aviation Administration of China (61079019).

DOI: 10.1587/elex.9.1630
Received September 10, 2012
Accepted October 10, 2012
Published November 01, 2012