A compact triple-band bandpass filter based on metamaterials*

ZHAO Ya-juan (赵亚娟)**, **JIANG Bo** (江波), **LI Bao-yi** (李宝毅), **and WANG Dong-hong** (王东红)
Key Laboratory of Electromagnetic Protection Materials and Technology of Shanxi Province, No.33 Research Institute of China Electronics Technology Group Corporation, Taiyuan 030006, China

(Received 31 March 2016; Revised 25 April 2016)

This paper presents a compact triple-band bandpass filter based on metamaterials. The miniaturization is realized by the principle of phase compensation of metamaterial. Compared with the conventional half-wavelength filter, the metamaterial filter has a small size of 10 mm×10 mm. The triple-band bandpass filter performance has been validated by the electromagnetic simulation software of high frequency structure simulator (HFSS). The results illustrate that the filter is designed with center frequencies of 2.4 GHz, 5.1 GHz and 8.8 GHz, bandwidths of about 7.9% (2.31—2.50 GHz), 7.8% (5.0—5.4 GHz) and 7.4% (8.50—9.15 GHz), respectively, and it shows good band pass characteristics.
Document code: A **Article ID:** 1673-1905(2016)04-0273-3
DOI 10.1007/s11801-016-6069-3

Tunable filter, as the key device in communication system, has been widely used in mobile communications, millimeter wave communications, satellite remote sensing, satellite communications, electronic countermeasure, and many other areas[1-4]. With the rapid development of communication system, frequency resources become increasingly nervous, especially of radio frequency (RF) and microwave frequency. It is very critical to improve the spectrum efficiency of filter. The traditional filter usually consists of different frequency filters, leading to the larger size of communication system. The metamaterials[5] are artificial periodic structures that have negative permittivity or permeability[6]. Because of the negative refraction[7], abnormal Doppler effect[8], and perfect lens[9], the metamaterials have been widely used in filter design. Also metamaterials can effectively realize the miniaturization, owing to the principle of phase compensation. In recent years, metamaterial filters have made great progress by many scholars[10-13].

A. K. Gorur[10] proposed a dual-band bandpass filter. Four loaded open-loop resonators were placed at the upper and lower sides of the main feedline to obtain two poles in each passband. Center frequencies of the designed filter were adjusted to be 2.45 GHz (WLAN) and 3.5 GHz (WiMAX). Chao Qin[11] designed the metamaterial filter structure with the center frequency of 7.8 GHz and the relative bandwidth of 8%—9%. Through increasing the lumped capacitance, we can reduce the volume of the device, but also reduce the loaded Q value of the filter. Zhi-gang You[12] designed a very high frequency (VHF) filter, by adding varactor diodes to achieve the maximum tunable frequency range. Kai Chen[13] proposed an interdigital bandpass filter with tunable center frequency based on the characteristics of varactor diode. The center frequency is 1.23—2.3 GHz, and the relative bandwidth is 6.5%—4.5%.

In this paper, we propose a triple-band bandpass filter based on metamaterials. By loading tunable devices in the metamaterials filter, we can realize tunable frequency. The triple-band bandpass filter is designed with center frequencies of 2.4 GHz, 5.1 GHz and 5.8 GHz, relative bandwidths of 7.9% (2.31—2.50 GHz), 7.8% (5.0—5.4 GHz) and 7.4% (8.50—9.15 GHz), and it shows good bandpass characteristics.

The size of the traditional filter is restricted by its work wavelength, which is generally half of the wavelength. The metamaterial filter, based on the principle of phase compensation, can effectively reduce the size and realize miniaturization of device. In this paper, we design a triple-band bandpass metamaterials filter, to realize the characteristics of multi frequencies and miniaturization.

The structure of the designed metamaterial filter is shown in Fig.1. The filter consists of two layers where the upper layer is etched as dumbbell slot structure and the lower layer is dielectric substrate. The metamaterial structure is symmetry on the x axis and y axis. The miniaturized metamaterial filter can work at 5.1 GHz based on the FR4 substrate with the dielectric constant of 4.4, loss angle tangent value of 0.02, and thickness of 0.8 mm. The metamaterial filter has a small size of 10 mm×10 mm ($0.35\lambda g \times 0.35\lambda g$, where λg is

* This work has been supported by the Key Laboratory Foundation of China Electronics Technology Group Corporation (No.ZX15ZS391), the International Science & Technology Cooperation Program of China (No.2014DFR10020), and the Natural Science Foundation of Shanxi Province (Nos.2014021020-1 and 2015021083).
** E-mail: tyzyj917@163.com

the guided wavelength of lower band). With the plane electromagnetic simulation software of high frequency structure simulator (HFSS), the optimized parameters in Fig.1 are as follows: l_g=10 mm, w_g=10 mm, p_1=2.8 mm, p_2=3.0 mm, p_3=3.2 mm, and p_4=7.8 mm.

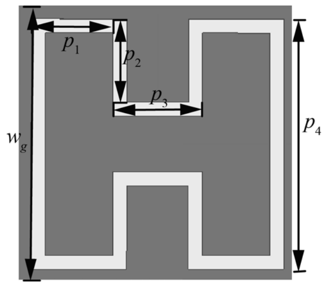

Fig.1 Structure of the miniaturized metamaterial filter

The scattering coefficients of the miniaturized metamaterial filter are shown in Fig.2, where S_{11} is reflection coefficient, and S_{21} is transmission coefficient. The simulation results show that the working frequency of the filter is 5.1 GHz, and bandwidth is 7.8% (5.0—5.4 GHz), with almost 0.4 dB insertion loss and minimum 23 dB return loss. However, the single band filter cannot meet the demand for communication system. Through tunable metamaterials, multi-frequency filters can be designed.

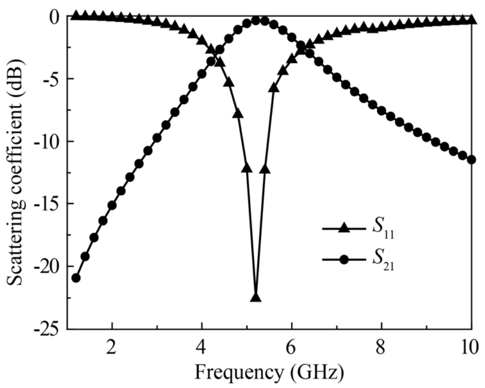

Fig.2 Scattering coefficients of the metamaterial filter

The mechanism of tunable metamaterials mainly includes three categories: The first, it is based on the method of the circuit, where the inserted microstructure can change the impedance circuit; The second, it is based on the method of geometric structure, which changes its equivalent parameters by changing the geometric structure; The last, it is based on metamaterial properties, where the metamaterial unit is made up of the tunable material.

In this paper, we can realize tunable frequency by inserting the tunable impedance circuit that can control the permittivity and permeability of metamaterial in different time and space distributions. The design of the proposed triple-band bandpass filter is achieved by inserting the tunable impedance circuit in two different stations. Fig.3 shows the structure of the designed tunable metamaterial filter. The first switch-off diode (it can be defined as K_1) is inserted in the middle of the station. The second switch-off diode (it can be defined as K_2) is inserted in the middle station of the filter. According to electromagnetic simulation software of HFSS, the triple-band bandpass filter performance can be validated.

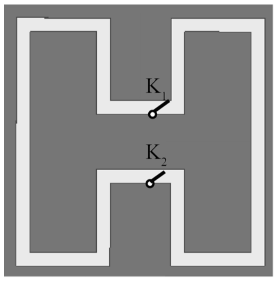

Fig.3 Structure of the triple-band bandpass metamaterial filter

The scattering coefficients of the metamaterial filter with switch-off K_1 are shown in Fig.4. It shows the influence of the switch-off K_1 on 2.4 GHz band and 5.1 GHz band, when the switch-off K_2 is opened. When K_1 is opened, the metamaterial filter can work at 5.1 GHz, with bandwidth of 7.8% (5.0—5.4 GHz). When K_1 is closed, it can work at 2.4 GHz, with bandwidth of 7.9% (2.31—2.50 GHz). As shown in Fig.4, the filter exhibits almost 0.4 dB insertion loss uniformly, and 18 dB and 23 dB return losses within the first and second passbands, respectively.

The scattering coefficients of the metamaterial filter with switch-off K_2 are shown in Fig.5. It shows the influence of the switch-off K_2 on 2.4 GHz band and 8.8 GHz band, when the switch-off K_1 is closed. When K_2 is opened, the metamaterial filter can work at 2.4 GHz, with bandwidth of 7.9% (2.31—2.50 GHz). When K_2 is closed, it can work at 8.8 GHz, with bandwidth of 7.4% (8.50—9.15 GHz). As shown in Fig.5, the filter exhibits almost 0.5 dB insertion loss, and 25 dB return loss within the 8.8 GHz band.

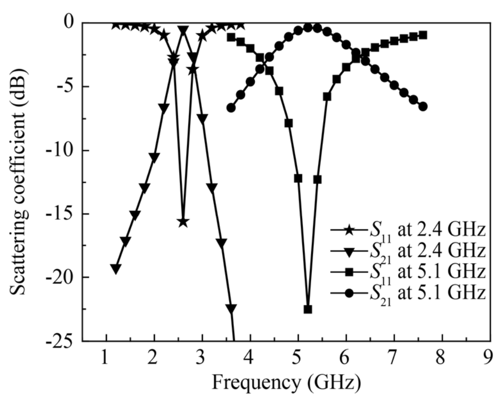

Fig.4 Scattering coefficients of the metamaterial filter with switch-off K_1

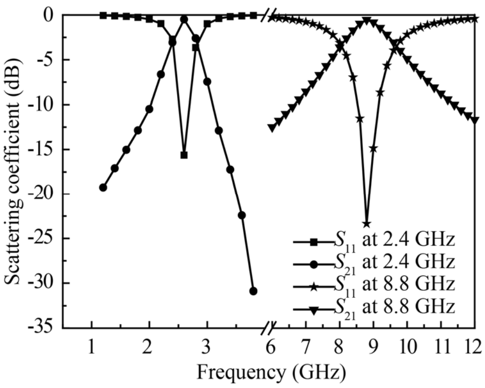

Fig.5 Scattering coefficients of the metamaterial filter with switch-off K_2

Accordingly, we can control the switch-off K_1 and K_2 to achieve tunable filter design. When K_1 and K_2 are opened, the metamaterial filter can work at 5.1 GHz, when K_1 is closed and K_2 is opened, it can work at 2.4 GHz, and when K_1 and K_2 are closed, it can work at 8.8 GHz. Comparing Fig.4 and Fig.5, relative bandwidths are about 7.9%, 7.8% and 7.4% within the 2.4 GHz band, 5.1 GHz band and 8.8 GHz band, respectively, so good agreement results have been achieved.

We propose a triple-band bandpass filter based on metamaterials. Compared with the conventional half-wavelength filter, the metamaterial filter has a small size of 10 mm×10 mm ($0.35\lambda g \times 0.35\lambda g$, where λg is the guided wavelength of lower band). By loading switch-off diode in the metamaterial filter, we can realize tunable frequency. The results show that the center frequencies are 2.4 GHz, 5.1 GHz and 5.8 GHz, and the bandwidths are about 7.9% (2.31—2.50 GHz), 7.8% (5.0—5.4 GHz) and 7.4% (8.50—9.15 GHz), so good filter characteristics can be obtained.

References

[1] L. Pantoli, V. Stornelli and G. Leuzzi, Electronics Letters **52**, 86 (2016).

[2] Hao Wang, Jun-feng Huang and Chun-guang Zhang, Journal of Optoelectronics·Laser **26**, 1255 (2015). (in Chinese)

[3] Jing Guo, Kui Wu and Yong-chuan Xiao, Journal of Optoelectronics·Laser **25**, 1274 (2014). (in Chinese)

[4] M. Safari, C. Shafai and L. Shafai, IEEE Transactions on Antennas and Propagation **63**, 1014 (2015).

[5] L. P. Carignan, A. Yelon and D. Menard, IEEE Transactions on Microwave Theory and Techniques **59**, 2568 (2011).

[6] Kuang Zhang, Qun Wu and Jia-hui Fu, IEEE Transactions on Magnetics **48**, 4289 (2012).

[7] S. M. Rudolph and A. Grbic, IEEE Transactions on Antennas and Propagation **60**, 3661 (2012).

[8] Jia Ran, Ye-wen Zhang and Kai Fang, Realization of the Inverse Doppler Effect in Tunable Transmission Lines, IEEE 4th Asia-Pacific Conference on Antennas and Propagation, 552 (2015).

[9] I. Aghanejad, H. Abiri and A. Yahaghi, IEEE Transactions on Antennas and Propagation **60**, 4074 (2012).

[10] A. K. Gorur, C. Karpuz and A. Ozek, Microwave and Optical Technology Letters **56**, 2211 (2014).

[11] Chao Qin, Yu Tan and Wen-jun Wang, Piezoelectrics and Acoustooptics **36**, 366 (2014).

[12] Zhi-gang You, Xian-qi Lin and Li-ke Deng, Communications Technology **44**, 162 (2011).

[13] Kai Chen, Chang-bao Song and Jing-shu Yang, Microelectronics **42**, 327 (2012).