Band-stop filter based on spoof surface plasmon polaritons

Lei Zhao✉, Shuang Liu, Jun Wang, Xiaopeng Shen and Tie Jun Cui

A band-stop filter based on spoof surface plasmon polaritons for microwave applications is proposed, which can realise high-efficiency band rejections by etching gradient semi-circular grooves on both sides of the middle stripline of coplanar waveguide. The operating bandwidth and frequency of band-stop can be controlled by changing the radii of semi-circular holes and the length of unit cell, respectively. The operating principle of the designed band-stop filter is explained by the dispersion curves and electric field distributions. Parametric studies are also conducted to analyse the effects of key parameters on the performance of the band-stop filter, which is useful for practical designs. A prototype of the band-stop filter is fabricated and measured. The good agreements between the simulated and measured results validate the proposed design, which indicate that the presented band-stop filter can be potentially useful in many microwave applications.

Introduction: Spoof surface plasmon polariton (SSPP) modes are surface modes in the microwave frequencies, these modes have been widely used in the microwave components, such as circulator [1], antennas [2, 3], and various surface plasmonic filters [4–10]. Due to the characteristics of breaking through the diffraction limit, SSPP structures may be a good candidate for the future miniaturised design of the band-stop filter. Most of the SSPP designs were based on the traditional coplanar waveguides (CPWs), which use gradient corrugation grooves and specific flaring grounds for transmission and mode conversion [5, 6]. However, it is hard for these designs to enhance efficiency and miniaturisation. In order to improve the transmission efficiency, the microstrip line structures are proposed [7, 8]. Nevertheless, two-layer designs are difficult to design and integrate. Accordingly, a novel SSPP-based waveguide filter with periodic holes etched on the standard 50 Ω CPW has been proposed [9], which not only has a high-efficiency low-pass transmission but also realises a controllable multi-band performance. More importantly, this design removes the gradual structure for mode conversion, which is a benefit for miniaturisation. However, based on the above proposed SSPP-based filters [6, 9], and opening literature [10], these filters have the narrow band-stop characteristic. Hence, it is a technically very challenging problem to design a compact wideband band-stop filter based on the SSPPs.

In this Letter, we propose a band-stop filter based on SSPPs by etching gradient semi-circular grooves on both sides of the middle stripline of CPW, which achieves a high-efficiency band rejection and controllable operating bandwidth and frequency. The physical mechanisms are carefully investigated by dispersion curves and electric field distributions. The performance of the proposed band-stop filter is verified through the full-wave simulations and experimental verification. The proposed design has the following features: (i) the structure removes the gradual structure for mode conversion and achieves a compact size; (ii) high-efficiency band rejection; (iii) operating bandwidth and frequency can be controlled by changing different parameters; (iv) the single-layer conformal structure can be easily used in microwave applications.

Filter design and analysis: The geometry of the proposed band-stop filter is shown in Fig. 1. The filter is made by a standard CPW with periodic gradient semi-circular holes etched on the both sides of the middle stripline. The length and width of CPW feeding part are denoted as l and w, respectively (as shown in part I). The gap of CPW is marked as g. The radii of the gradient semi-circular holes vary uniformly from 0.1 r to r, respectively (as shown in part II). The length of unit cell is denoted as p (as shown in part III). The designed parameters of the proposed band-stop filter are $w = 3$ mm, $l = 4$ mm, $g = 0.1$ mm, $r = 0.65$ mm, and $p = 4$ mm. Additionally the proposed design is simulated by the full-wave electromagnetic (EM) simulation software CST.

Figs. 2*a* and *b* present the simulated dispersion curves of the proposed band-stop filter with different unit cell lengths and hole radii, respectively. It is seen that the dispersion curves deviate from the CPW line with the p and r increase and the bigger the radii of the hole and the longer the length of the unit cell are, the lower the dispersion curves are, which mean that the fundamental cut-off frequency of dispersion curves of the proposed band-stop filter are gradually decreases as the unit cell length and hole radii raises. Moreover, to further illustrate the quasi-TEM wave to SSPPs (TM) wave efficiently, Figs. 2*c* and *d* show the simulated electric field distribution on the x–y plane and the magnitudes of energy flows on cross-sections at 15 GHz when $p = 4$ mm. It is clearly observed that the majority of EM energy is distributed between the ground and the central stripline, which is localised within a small region around the CPW structure. Hence, the SSPP fields can be effectively supported by the proposed design with the gradient semi-circular holes etched on the CPW middle stripline.

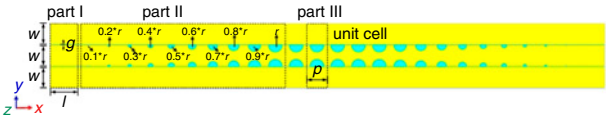

Fig. 1 *Geometry of the proposed band-stop filter*

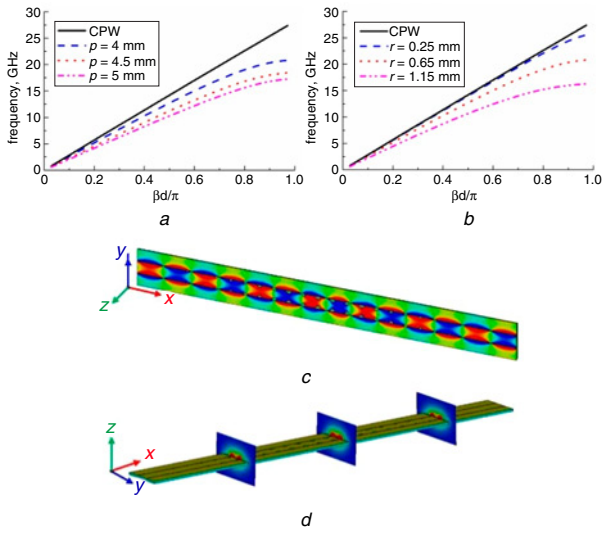

Fig. 2 *Dispersion curves and electric field distributions of the proposed band-stop filter*

a Dispersion curves with different unit cell length when $r = 0.65$ mm
b Dispersion curves with different hole radii when $p = 4$ mm
c Electric field distribution on the x–y plane at 15 GHz when $p = 4$ mm
d Magnitudes of energy flows on cross sections at 15 GHz when $p = 4$ mm

Simulated and measured results: The simulated S-parameters of the proposed filter are shown in Fig. 3*a*. It is obvious that the fundamental mode has a cut-off frequency at about 23 GHz, which has a good agreement with the simulated dispersion curves, and then the stop band appears. Moreover, due to the high-order modes of the filter are excited with the frequency increase, the stop band will disappear gradually and instead of the pass band. The bandwidth ($|S_{11}| > -0.5$ dB and $|S_{21}| < -10$ dB) of the stop band of the proposed band-stop filter is about 32.07% (from 23.3 to 32.2 GHz), and the highest $|S_{11}|$ is up to −0.1 dB. Additionally, Figs. 3*b*–*d* show the three electric field distributions on the x–y plane at 10, 27, 40 GHz, which represent pass band, stop band, and pass band, respectively. It is seen that the SSPP can be supported at 10 and 40 GHz and cannot propagate along x-direction at 27 GHz, which means that the proposed design has a good band-stop performance.

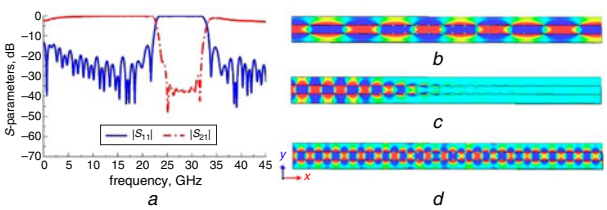

Fig. 3 *Simulated S-parameters and electric field distributions of the proposed band-stop filter*

a Simulated S-parameters
b Electric field distributions on the x–y plane at 10 GHz
c Electric field distributions on the x–y plane at 27 GHz
d Electric field distributions on the x–y plane at 40 GHz

In order to study the controllability of the proposed band-stop filter, parametric studies are conducted to analyse the effects of the key parameters on performance. In this design, the operating bandwidth and frequency can be independently controlled by the radii of semi-circular holes and length of unit cell, respectively. Figs. 4*a* and *b* show the simulated $|S_{21}|$ of the proposed band-stop filter with the different r and different unit cell length p, respectively. It is seen that the operating bandwidth is increased with the r raised and the operating frequency shifts to lower frequency with the p raises, which shows good controllability of the operating band-stop bandwidth and frequency by tuning r and p, indicating that the design can be used in many applications.

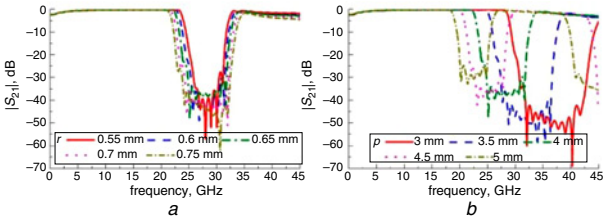

Fig. 4 *Simulated $|S_{21}|$ of the proposed band-stop filter*
a r changes from 0.55 to 0.75 mm when p is fixed as 4 mm
b p changes from 3 to 5 mm when r is fixed as 0.65 mm

For validation, a prototype is fabricated to characterise the performance of the proposed band-stop filter, as shown in Fig. 5*a*. The design is printed on 0.5 mm thick F4B substrate (relative permittivity is 2.65, loss tangent is 0.0015). Fig. 5*b* presents the simulated and measured results of the proposed band-stop filter. It is seen that the measured results have a good agreement with the simulated ones. The measured *S*-parameters are a little different with the simulated ones, which are maybe caused by the fabricated tolerances. As expected, the fabricated structure and measured results validate the proposed design and hold the promise to realise a good band-stop performance at the microwave frequency band.

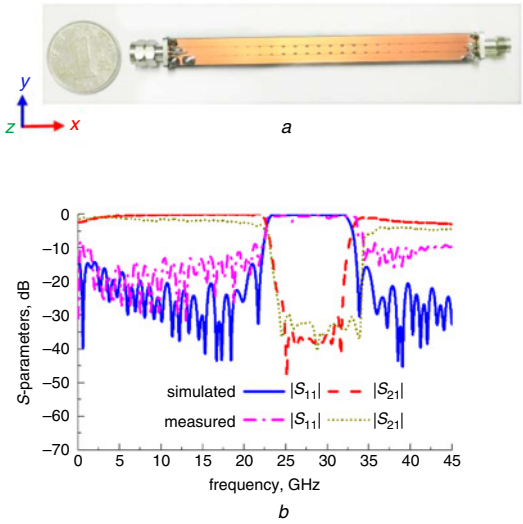

Fig. 5 *Photograph of the fabricated band-stop filter and measured S-parameters of the proposed band-stop filter*
a Photograph of the fabricated band-stop filter
b Measured and simulated *S*-parameters

Conclusion: In this Letter, a band-stop filter based on the SSPPs is proposed, which achieves high-efficiency band rejection and controllable operating bandwidth and frequency by changing the radii of semi-circular holes and length of unit cell, respectively. The proposed design is explained by the dispersion curves and electric field distributions. Both the simulation and measurement results of the proposed design show excellent rejection characteristic within the propagation band. This type of high-efficiency SSPP wave rejection structure is easy to design and fabricate which indicate that the proposed structure can be widely used in microwave applications.

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References

1 Qiu, T.S., Wang, J.F., Li, Y.F., *et al.*: 'Circulator based on spoof surface plasmon polaritons', *Antennas Wirel. Propag. Lett.*, 2017, **16**, pp. 821–824
2 Kianinejad, A., Chen, Z.N., Zhang, L., *et al.*: 'Spoof plasmon-based slow-wave excitation of dielectric resonator antennas', *Trans. Antennas Propag.*, 2016, **64**, (6), pp. 2094–2099
3 Han, Y.J., Li, Y.F., Ma, H., *et al.*: 'Multibeam antennas based on spoof surface plasmon polaritons mode coupling', *Trans. Antennas Propag.*, 2017, **65**, (3), pp. 1187–1192
4 Shibayama, J., Yamauchi, J., and Nakano, H.: 'Metal disc-type splitter with radially placed gratings for terahertz surface waves', *Electron. Lett.*, 2015, **51**, (4), pp. 352–353
5 Unutmaz, M.A., and Unlu, M.: 'Modelling of the effective dielectric constant of planar spoof surface plasmon polariton waveguides', *Electron. Lett.*, 2017, **53**, (21), pp. 1418–1420
6 Zhao, L., Zhang, X., Wang, J., *et al.*: '*A novel broadband band-pass filter based on spoof surface plasmon polaritons*', *Sci. Rep.*, 2016, **6**, p. 36069
7 Zhang, H.C., Liu, S., Shen, X.P., *et al.*: 'Broadband amplification of spoof surface plasmon polaritons at microwave frequencies', *Laser Photon. Rev.*, 2015, **9**, (1), pp. 83–90
8 Zhang, W.J., Zhu, G.Q., Sun, L.G., *et al.*: 'Trapping of surface plasmon wave through gradient corrugated strip with underlayer ground and manipulating its propagation', *Appl. Phys. Lett.*, 2015, **106**, (2), p. 021104
9 Wang, J., Zhao, L., Hao, Z.C., *et al.*: 'An ultra-thin coplanar waveguide filter based on the spoof surface plasmon polaritons', *Appl. Phys. Lett.*, 2018, **113**, (7), p. 071101
10 Zhou, Y.J., and Xiao, Q.X.: 'Electronically controlled rejections of spoof surface plasmons polaritons', *J. Appl. Phys.*, 2017, **121**, (12), p. 123109