Spoof Surface Plasmon Polariton Band-Stop Filter with Single-Loop Split Ring Resonators

DOI:

[10.1002/mmce.22267](https://doi.org/10.1002/mmce.22267)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Ling, H., Zhang, Y., Qian, P., Chen, P., Shi, Y., Wang, Y., Xin, Q., Huan, S., Wang, Q., & Song, A. (2020). Spoof Surface Plasmon Polariton Band-Stop Filter with Single-Loop Split Ring Resonators. *International Journal of RF and Microwave Computer-Aided Engineering*, 30(8), [e22267]. <https://doi.org/10.1002/mmce.22267>

Published in:

International Journal of RF and Microwave Computer-Aided Engineering

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

Spoof Surface Plasmon Polariton Band-Stop Filter with Single-Loop Split Ring Resonators

Haotian Ling, Yifei Zhang, *Member, IEEE*, Pengfei Qian, Pingjian Chen, Yanpeng Shi, Yiming Wang, Qian Xin, Sha Huan, Qingpu Wang, and Aimin Song, *Senior, IEEE*

Abstract— A novel band-stop filter with single-loop split ring resonators (SRRs) is proposed for spoof surface plasmon polaritons (SPPs) at millimeter wave frequencies, achieving a miniaturized size of $0.052\lambda_0 \times 0.278\lambda_0$ at its resonant frequency. The SRRs provide both a low-pass response as the rectangular corrugations used in the conventional SPPs and an additional band-stop response induced by the resonance of SRRs. To verify this design, a back-to-back device with two co-planar waveguides as the input and output feeding was fabricated and characterized, the measured S-parameters of which agree well with the simulation. The measured stop band is centered at 49 GHz with a -10-dB bandwidth of 4.1 GHz and a high Q-factor of 93, in which the maximum attenuation is 31 dB. The filter has a low insertion loss of less than 2.8 dB in the pass band. Such approaches may find many applications to achieve compact millimeter wave circuits.

Index Terms—spoof surface plasmon polaritons, split ring resonator, band-stop filter, miniaturization

I. INTRODUCTION

SURFACE plasmon polaritons (SPPs) are propagating surface waves with highly confined electric field at the interface between two different materials with opposite permittivities [1-4]. They overcome the optical diffraction limit due to their smaller effective wavelength, and thus have gained great interest in miniaturized antennas [5, 6], super-resolution imaging [7], subwavelength circuits [8], photolithography [9]

Manuscript received Sep. 27, 2019. This work was supported by the National Key Research and Development Program of China (2016YFA0301200 and 2016YFA0201800), the National Natural Science Foundation of China (61701283, 61805127, and 11404115), the European Commission through the FP7 ROOTHZ project (243845), the Engineering and Physical Sciences Research Council (EP/N021258/1), the China Postdoctoral Science Foundation funded project (2018T110689, 2017M622201, and 2016M590634), the Key Research and Development Program of Shandong Province (2017GGX10121 and 2017GGX10111), the Postdoctoral Innovation Program of Shandong Province (20171006), and the Fundamental Research Funds of Shandong University (2016WLJH44 and 2018TB002). (Corresponding authors: Yifei Zhang and Aimin Song)

H. Ling, Y. Zhang, P. Qian, P. Chen, Y. Shi, Y. Wang, Q. Xin, Q. Wang, and A. Song are with the Center of Nanoelectronics and School of Microelectronics, Shandong University, Jinan, Shandong, 250100 China. (e-mail: yifeizhang@sdu.edu.cn, songam@sdu.edu.cn).

S. Huan is with the School of Physics and Electronic Engineering, Guangzhou University, Guangzhou, Guangdong, 510006 China.

A. Song is also with the School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, United Kingdom (e-mail: a.song@manchester.ac.uk).

Fig. 1 (a) CPW-to-SPP waveguide transition ($L_1=3$ mm, $W_1=9$ mm, $R=7$ mm, $P_m=0.71$ mm, $W_s=82$ μ m, $W_g=62$ μ m, $T_1=43$ μ m, $T_2=86$ μ m, $T_3=130$ μ m); (b) simulated S-parameters of the transition with (solid line) and without rectangular corrugations (dash line).

etc. The conventional SPPs cannot operate at terahertz (THz) frequencies and below because metals intrinsically act as perfect electric conductors (PECs) at these frequencies, instead of plasmas with negative permittivity [10-16]. Recently, metal sheets and lines with holes or grooves have been reported for SPPs in microwave and THz range, which are typically referred to as spoof SPPs. They address many attractive advantages, including not only high electric field confinement and non-diffraction limit as their optical counterparts but also low transmission loss and simple integration with traditional transmission lines [17-19].

Based on spoof SPPs, several functional subwavelength devices for band-stop filtering have been reported on printed circuit boards [20-28], which may be utilized for active modulation of spoof SPPs [21]. Separated electric-LC metamaterials and split ring resonators (SRRs) have been distributed on the side of SPP lines with corrugations to get a strong band-stop attenuation [20-22]. However, their pass-band insertion loss is significant, e.g., 8 dB at 5 GHz [21]. H-Shaped unit cells, circular holes, and complementary SRRs were designed in SPP lines to introduce a stop band with low insertion loss within their pass band [23-28]. However, their working frequencies are below 15 GHz.

In this work, we propose a single-loop SRR based band-stop filter on silicon substrate for spoof SPPs at 49 GHz, whose active size is as small as $0.052\lambda_0 \times 0.278\lambda_0$ at the resonant frequency. The SRRs are distributed on a spoof SPP waveguide to generate two modes with different cut-off frequencies. The fundamental mode introduces large surface impedance mismatch and thus reflection for SPPs, and the second mode achieves a cut-off frequency as the rectangular corrugations. Both the simulated and measured data demonstrate a high band-stop attenuation of 31 dB at 49 GHz and a low insertion loss of less than 2.8 dB in the pass band. The -10-dB stop band is from 47.4 to 51.5 GHz, and the corresponding Q-factor is as high as 93.

II. DESIGN AND SIMULATION

To efficiently excite spoof SPPs, a co-planar waveguide (CPW)-to-SPP waveguide transition is designed on 200- μm thick silicon substrate with a relative permittivity of 11.9, as shown in Fig. 1a. The signal and gap width of the CPW is 80 and 60 μm , respectively, and the corresponding impedance is around 50 Ω . To suppress the transition loss, the CPW ground electrodes are exponentially flared out, and three rectangular corrugations with increasing length are introduced on the CPW signal line, which gradually matches the momentum between the SPP waveguide and CPW. The detailed design steps can be found in reference 20. Ansys High Frequency Structure Simulator (HFSS) was employed to build 3-D full wave models and optimize their performance. Fig. 1b depicts the simulated S-parameters of the devices with and without corrugations. By comparison, it can be seen that the corrugations introduce a cut-off frequency at around 60 GHz for spoof SPPs. The insertion loss of the back-to-back device is less than 2.5 dB from 25 to 55 GHz, and the pure insertion loss of two CPW-to-SPP waveguide transitions is less than 1.3 dB from 20 to 67 GHz, which was derived using the method presented in our previous paper [29].

Typically, rectangular corrugations are used for spoof SPPs to achieve a spectral cut-off response [20-24]. Here, we first designed single-loop SRRs on a SPP waveguide directly to get the same cut-off function, as shown in Fig. 2. In addition, the SRRs also introduce a band-stop response due to their strong resonance. To clarify the SPP cut-off properties, unit cells of SPP waveguides with rectangular corrugations and SRRs were simulated using HFSS Eigen Mode solver. Their dimensions are shown in Fig. 2a, and the corresponding dispersion

Fig. 2 (a) HFSS 3-D model of the proposed band-stop filter ($L_m=162 \mu\text{m}$, $W_m=44 \mu\text{m}$, $L_2=130 \mu\text{m}$, $W_2=20 \mu\text{m}$, $L_3=56 \mu\text{m}$, $W_{gap}=3 \mu\text{m}$); (b) Dispersion diagram of spoof SPP waveguides with rectangular corrugations and SRRs.

diagrams are illustrated in Fig. 2b. Periodic boundary with a period of $P_m=0.71 \text{ mm}$ is set in X-direction and PEC boundary are set in the other two directions. It can be seen that the dispersion curves of the SPP waveguides with corrugations and SRRs gradually deviate from that of the metal line and asymptotically approach a cut-off frequency, which is a similar phenomenon as the optical SPPs. The SPP waveguide with SRRs has two modes with diverse dispersion properties. The fundamental one is introduced by the SRR resonance, whose cut-off frequency is 47 GHz. The second mode shows a cut-off frequency of 63 GHz, which is close to its counterpart of the SPPs with corrugations.

Considering the push-to-limit fabrication tolerance (around 3 μm) of our laser direct writing machine, we designed the filter at around 50 GHz, whose detailed dimensions can be found in the caption of Fig. 2. The simulated S-parameters of the proposed spoof SPPs filter are shown in Fig.3b, and the field distribution is illustrated in Fig. 3a. At the rejection frequencies, e.g., 49 GHz, the SPPs will be attenuated significantly due to the strong resonance of the SRRs. However, their attenuation is very little at the non-resonant frequencies, e.g., 60 GHz. The simulated -10-dB stop band is from 47.4 to 51.5 GHz, and the maximum attenuation is -31 dB at 49 GHz. The pass band insertion loss is less than 2.2 dB from

Fig. 3 (a) Simulated electric field of the proposed band-stop filter at the metal-dielectric interface at 60 and 49 GHz; (b) simulated S-parameters of the filter and a spoof SPP waveguide with rectangular corrugations; (c) resonant frequency shift by varying dimensions.

20 to 47 GHz and less than 2.8 dB from 56 to 57 GHz. The actual pass-band loss can be extracted by subtracting the insertion loss of two CPW-to-SPP waveguide transitions from the total loss, which is less than 1.6 dB from 20 to 57 GHz. Typically, the mechanism of a SRR is a LC resonant circuit. The equivalent circuit modal of the proposed device is depicted in the inset of Fig. 3c, where L is the inductance of the SRR, C is the capacitance of the split gap. By varying the gap width W_{gap} and length L_2 , the working frequency of the band-stop

Fig. 4 (a) Photograph of a fabricated band-stop filter; (b) measured (solid line) and simulated (dash line) S-parameters.

filter can be shifted, as illustrated in Fig. 3c.

III. EXPERIMENT AND RESULT DISCUSSION

To verify the design, we fabricated the proposed structure on a 200- μm thick silicon substrate with a resistivity of 10000 $\Omega\cdot\text{mm}$ and a 100-nm SiO_2 insulator, as shown in Fig. 4a. The device electrodes, consisting of 10-nm titanium and 300-nm gold, were fabricated using standard UV exposure photolithography with laser direct writing, electron-beam evaporation and lift-off techniques. In our measurement, 50- Ω ground-signal-ground probes and an Agilent programmable network analyzer N5247 were used to characterize the performance of the fabricated device. The probes were first calibrated using short-load-open-transmission (SLOT) method with on-wafer calibration substrate from GGB Industries Inc. [30], and then launched on the CPWs for signal input and output.

The measured S-parameters of the proposed devices are illustrated in Fig. 4b, showing a good agreement with the simulated data. The device has a band-stop response centered at 49 GHz with a -10-dB bandwidth of 4.1 GHz and a Q-factor of 93. Its propagation attenuation is less than 2.8 dB in the pass band, which can be mainly attributed to the insertion loss of the two CPW-to-SPP waveguide transitions. Table 1 compares the proposed band-stop filter with the reported ones (Ref. 20-23). It should be noted our design offers many advantages, such as miniaturization, high working frequency, low insertion loss, and high rejection attenuation.

TABLE I
COMPARISON OF SPOOF SPP BAND-STOP FILTERS

	Freq. (GHz)	Stop band attenuation (dB)	Pass band loss w/ transitions(dB)	Q-factor	Device size w/ transitions (λ_0)	Device size w/o transitions (λ_0)	Substrate
[20]	7.6-9.5	15-17	<2	<90	1.12×4.4	0.6×1.17	F4B
[21]	3.5-5	30-47	<8	<100	0.67×3.147	0.285×1.17	Rogers 5880
[22]	9.5	36	<7	<70	1.62×11.05	0.32×5.75	Not Specified
[23]	8.1-10	20-38	<7	<80	2.44×10.28	0.3×1.5	F4B
This work	49	31	<2.8	93	0.49×1.47	0.052×0.278	Silicon

IV. CONCLUSION

To summarize, we designed and fabricated a novel spoof SPP band-stop filter with single-loop SRRs at millimeter wave frequencies, achieving miniaturization. The SRRs provide both the low-pass and band-stop function simultaneously. The proposed filter is suitable for millimeter wave applications due to its small size and low pass-band insertion loss, and may be combined with diodes, such as varactor diodes, to achieve active modulation.

REFERENCES

- [1] A. P. Hibbins, B. R. Evans and J. R. Sambles, "Experimental verification of designer surface plasmons," *Science*, vol. 308, no. 5722, pp. 670-672, Apr. 2003.
- [2] H. Zhang, Y. Fan, et al, "Second-harmonic generation of spoof surface plasmon polaritons using nonlinear plasmonic metamaterials," *ACS Photonics*, vol. 3, no. 1, pp. 139-146, Mar. 2015.
- [3] J. B. Pendry, L. Martin-Moreno and F. J. Garcia-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, vol. 305, no. 5685, pp. 847-848, Aug. 2004.
- [4] W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, pp. 824-830, Aug. 2003.
- [5] X. Chen and W. Fan, "Ultrasensitive terahertz metamaterial sensor based on spoof surface plasmon," *Scientific Reports*, vol. 7, 2092, May. 2017.
- [6] H. Tang and P. Liu, "Terahertz far-field superresolution imaging through spoof surface plasmons illumination," *Optics Letter*, vol. 40, no. 24, pp. 5822-5825, Dec. 2015.
- [7] H. Ren, X. Li, Q. Zhang and M. Gu, "On-chip noninterference angular momentum multiplexing of broadband light," *Science*, vol. 352, no. 6287, pp. 805-809, May. 2016.
- [8] H. Choo, M. Kim, et al, "Nanofocusing in a metal-insulator-metal gap plasmon waveguide with a three-dimensional linear taper," *Nature Photonics*, vol. 6, pp. 838-844, Nov. 2012.
- [9] A. Vakil and N. Engheta, "Transformation optics using graphene," *Science*, vol. 332, no. 6035, pp. 1291-1294, Jun. 2011.
- [10] L. Novotny and N. Van Hulst, "Antennas for light," *Nature Photonics*, vol. 5, pp. 83-90, Feb. 2011.
- [11] S. Dong, K. Zhang, Z. Yu and J. Fan, "Electrochemically programmable plasmonic antennas," *ACS nano*, vol. 10, no. 7, pp. 6716-6724, Jun. 2016.
- [12] X. Li, J. Zhu and B. Wei, "Hybrid nanostructures of metal/two-dimensional nanomaterials for plasmon-enhanced applications," *Chemical Society Reviews*, vol. 45, no. 11, pp. 3145-3187, Apr. 2016.
- [13] Q. Gan, Z. Fu, Y. Ding and F. J. Bartoli, "Ultrawide-bandwidth slow-light system based on THz plasmonic graded metallic grating structures," *Physical Review Letters*, vol. 100, no. 25, 256803, Jun. 2008.
- [14] K. Wang and D. M. Mittleman, "Metal wires for terahertz wave guiding," *Nature*, vol. 432, pp. 376-379, Nov. 2004.
- [15] L. Chen, Y. Wei, et al, "Excitation of dark multipolar plasmonic resonances at terahertz frequencies," *Scientific Reports*, vol. 6, 22027, Feb. 2016.
- [16] X. Liu, Y. Feng, et al, "Backward spoof surface wave in plasmonic metamaterial of ultrathin metallic structure," *Scientific Reports*, vol. 6, 20448, Feb. 2016.
- [17] B. Pan, H. Zhang and T. Cui, "Multilayer transmissions of spoof surface Plasmon polaritons for multifunctional applications," *Advanced Materials Technologies*, vol. 2, no. 1, 1600159, Nov. 2017.
- [18] G. Kong, H. Ma, B. Cai and T. Cui, "Continuous leaky-wave scanning using periodically modulated spoof plasmonic waveguide," *Scientific Reports*, vol. 6, 29600, Jul. 2016.
- [19] Z. Liao, X. Shen, et al, "Combined system for efficient excitation and capture of LSP resonances and flexible control of SPP transmissions," *ACS Photonics*, vol. 2, no. 6, pp. 738-743, Jun. 2015.
- [20] B. Pan, Z. Liao, J. Zhao and T. Cui, "Controlling rejections of spoof surface plasmon polaritons using metamaterial particles," *Optics Express*, vol. 22, no. 11, pp. 13940-13950, Jun. 2014.
- [21] J. Xu, H. Zhang, et al, "Transmission-spectrum-controllable spoof surface plasmon polaritons using tunable metamaterial particles," *Applied Physics Letters*, vol. 108, no. 19, 191906, May. 2016.
- [22] J. Yin, J. Ren, et al, "Capacitive-coupled series spoof surface plasmon polaritons," *Scientific Reports*, vol. 6, 24605, Apr. 2016.
- [23] Q. Zhang, H. Zhang, et al, "A series of compact rejection filters based on the interaction between spoof SPPs and CSRRs," *Scientific Reports*, vol. 6, 28256, Jun. 2016.
- [24] L. Ye, W. Zhang, et al, "Super subwavelength guiding and rejecting of terahertz spoof SPPs enabled by planar plasmonic waveguides and notch filters based on spiral-shaped units," *Journal of Lightwave Technology*, vol. 36, no. 20, pp. 4988-4994, Oct. 2018.
- [25] J. Wang, L. Zhao, Z. Hao and T. Cui, "An ultra-thin coplanar waveguide filter based on the spoof surface plasmon polaritons," *Applied Physics Letters*, vol. 113, no. 7, 071101, Aug. 2018.
- [26] L. Zhao, S. Liu, J. Wang, X. Shen and T. Cui, "Band-stop filter based on spoof surface plasmon polaritons," *Electronics Letters*, vol. 55, no. 10, pp. 607-609, May. 2019.
- [27] M. Wang, H. Ma, et al, "Programmable controls of multiple modes of spoof surface plasmon polaritons to reach reconfigurable plasmonic devices," *Advanced Materials Technologies*, vol. 4, 1800603, Jan. 2019.
- [28] Z.-M. Chen, Y. Liu, et al, "A high efficiency band-pass filter based on CPW and quasi-spoof surface plasmon polaritons," *IEEE Access*, vol. 8, pp. 4311-4317, Dec. 2019.
- [29] Y. Zhang, S. Shi, et al, "Substrate integrated waveguide filter on LCP substrate at 94 GHz," *Microwave and Optical Technology Letter*, vol. 58, no. 3, pp. 577-580, Jan. 2016.
- [30] Y. Zhang, S. Shi, et al, "Ultra-wideband vialess microstrip line-to-stripline transition in multilayer LCP substrate for E- and W- Band applications," *IEEE Microwave and Wireless Components Letters*, vol. 27, no. 12, pp. 1101-1103, Sep. 2017.