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Design, Analysis and Characterisation of Spoof Surface Plasmon Polaritons based Wideband Bandpass Filter at Microwave Frequency

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ABSTRACT

This paper presents the wideband bandpass filter (BPF) in the microwave frequency domain. The realisation approach is based on spoof surface plasmon polaritons (SSPPs) phenomenon using plasmonic metamaterial. A novel unit cell is designed for filter design using an LC resonator concept. Then SSPPs BPF is realised using an optimised mode converter and five unit cells. This paper includes a brief design detail of the proposed novel unit cell. The passband of BPF is achieved at approximately 1.20 - 5.80 GHz, 3dB bandwidth is tentatively 4.60 GHz and the insertion loss is less than 2 dB approximately over the passband. The overall dimension of fabricated filter is (90 x 45) mm. A basic schematic of transmission line representation is also proposed to evaluate the BPF structure.

Keywords: Wideband bandpass filter; Mode converter; Plasmonic metamaterial; Spoof surface plasmon polariton; Unit cell

1. INTRODUCTION

Surface plasmon polaritons (SPPs) that originally exist at optical frequency regimes present high spatial confinement by reducing the effective wavelength of surface waves[1-9]. Recently, artificial plasmonic metamaterials have been reported to generate the spoof SPPs (SSPPs) that can propagate surface waves within the same features as SPPs in the lower -frequency band, thus significantly extending the application of SPPs from optical regimes to microwave fields[10]. Metamaterials are periodic (or quasi-periodic) structures with unit cells consisting of a combination of metals and/or dielectrics[11]. A significant benefit of this metamaterial is that the asymptotic frequency and dispersion characteristics of the SSPPs can be regulated by the geometrical parameters of the unit element[12-13].

Although many works are available on SSPPs filter structure[14-23] , this paper introduces a new dimension for filter design in microwave frequency domain based on novel SSPP structure using plasmonic metamaterial. This method is better in respect of sub wavelength confinement. One main aspect is that different to conventional lines, the metamaterial transmission line structure shows frequency - dependent characteristic impedance, which is very useful in tunable filter design[11].

SSPPs have inherited most of the interesting features of optical SPPs, such as the field confinement, slow wave propagation and the non-diffraction limit. Defence operations frequently require a secure and timely transmission of a huge amount of data from one place to another. Optical or plasmonic components have always been the field of attraction for airborne and ground - based defence applications due to their ease of installation, immunity to electromagnetic interference (EMI) and reduction in size, weight and power. Slow light wave structure helps in realising the dream of future on chip optical processing of signal. The slow light - based structures can be made with the smallest possible footprint.

This paper explores the existence of the surface electromagnetic modes on corrugated surface of perfect conductors. It also investigates the unit-cell effect on the dispersion relation of SSPPs. To the best of authors knowledge, considering the LC resonator phenomenon in SSPP structure for filter design at microwave frequency, this type of unit cell has not been reported so far. The proposed planar wideband BPF shows a key role in filtering SPPs wave in SSPPs circuits and systems.

2. DESIGN AND ANALYSIS OF UNIT CELL

A traditional pie-shape unit cell for SSPPs structure, as shown in Fig. 1, is reported to offer general understanding of spoof surface plasmon polariton transmission line (SSPP-TL)[24]. The dimensions of reported unit cell are a = 1 mm, b = 2 mm, h = 4 mm, d = 5 mm. This unit cell is periodically arranged for the realisation of SSPP-TL and kept back to back so that the unit cell[25] effectively appears as shown in Fig. 2. This can also be understood by equivalence of pie to T circuit conversion. The dimensions of the equivalent unit cell are a = 1 mm, d = 5 mm, e = 3 mm, h = 4 mm. The main arm of the equivalent unit cell behaves like capacitor (thick line having low impedance represents capacitive line).

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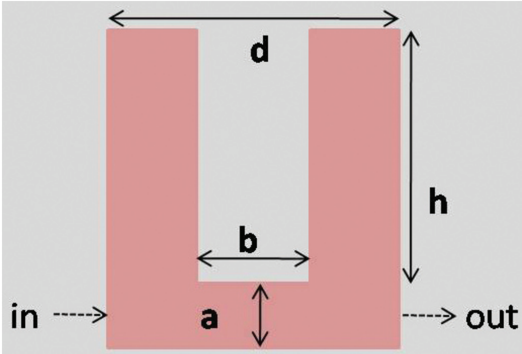

Figure 1. Reported unit cell.

It is evident that the dispersion relation, which is relation between frequency (f) and normalised wave vector, mainly depends on the geometrical parameter such as groove depth (h), groove width (e) and lattice constant (d) (Fig. 2).

The dispersion plot of the SSPP structure can be calculated by the following Eqn. (1)[26]:

$$\sqrt{k^2 - \varepsilon_{eff} k_0^2} = \sqrt{\varepsilon_{eff}}\, k_0 \left(\frac{e}{d}\right) \tan(\sqrt{\varepsilon_{eff}}\, k_0 h) \quad (1)$$

where ε_{eff}, k_0, and k are the effective permittivity of the substrate, the wave vector in vacuum and the wave vector in substrate, respectively.

From Eqn. (1), wave number can be obtained, corresponding to the intersection as shown in Eqn. (2), where N is a positive integer denoting the order of the mode –

$$k = N\frac{\pi}{h} \quad (2)$$

In the paper only fundamental/single TM mode propagation is considered. The normalised dispersion curve comparison of Figs. 1 and 2 with light line is as shown in Fig. 3, which is obtained by the eigen mode solver of the commercial software tool, CST microwave studio. It is noticed:

(i) For quasi-transverse electromagnetic (QTEM) wave, for which $k = k_0$, the relation between frequency (f) and normalised wave vector (kd/π) is a straight line called light line while dispersion curve for SSPP for which $k > k_0$ deviates from the straight line.

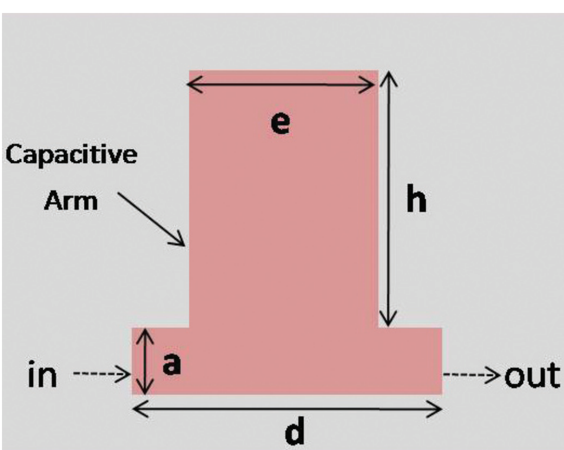

Figure 2. Equivalent unit cell.

(ii) The asymptotic frequency for both unit cells is similar, as mentioned in Fig. 3; it is approximately 11 GHz.
(iii) It means properties of both reported and equivalent unit cells are similar.
(iv) The obtained dispersion curve shows that SSPP wave is slower than light wave, which means SSPP wave travels slowly but it is more tightly confined to the corrugated metal surface.

On the basis of the LC resonant circuit theory in lumped domain, as shown in Fig. 4, a new unit cell is designed by introducing inductive element (L) in series with capacitive arm[27](C). Each of these elements (L and C) is realised from a short section of transmission line having a length smaller than quarter wavelength. The proposed novel unit cell is shown in Fig. 5. Herein, the unit cell has groove of capacitive arm with depth h = 4.0 mm, width e = 3 mm, groove of inductive arm with same depth h = 4.0 mm, width f = 0.5 mm, lattice constant/period of unit cell d = 5 mm, central line width a = 1mm and g = 1 mm. This unit cell is implemented as LC resonator for SSPP structure in the filter design. The impedance of inductive arm Z_2 is higher than the impedance of capacitive arm Z_1 and the central line has the impedance value of Z, as shown in Fig. 5.

The dispersion curve which is obtained by comparison using eigen - mode solver of CST software tool is plotted in Fig. 6. It is observed that the asymptotic frequency for the proposed unit cell having inductive element is much lower than the reported and equivalent unit cell and it is around 7 GHz.

3. SSPPs BANDPASS FILTER

The SSPP functional circuit needs to be joined to the

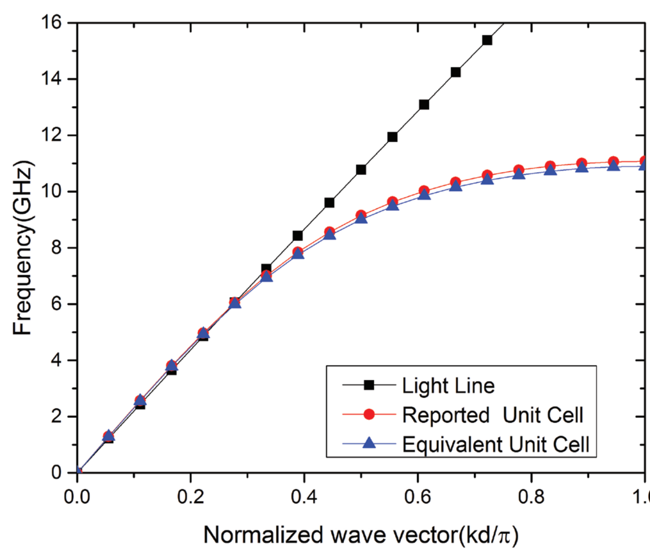

Figure 3. Dispersion curve comparison of unit cell.

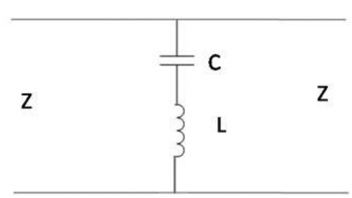

Figure 4. LC resonator circuit in lumped domain.

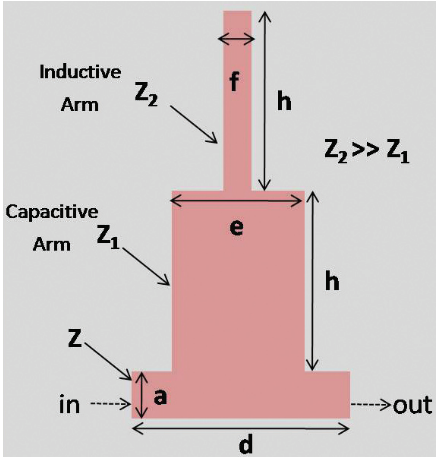

Figure 5. Proposed unit cell.

conventional microwave circuits having two conductor transmission lines such as microstrip or coplanar waveguide (CPW). So it is essential to translate the spatial wave supported by conventional transmission line to SSPP modes supported by the SSPPs structure.

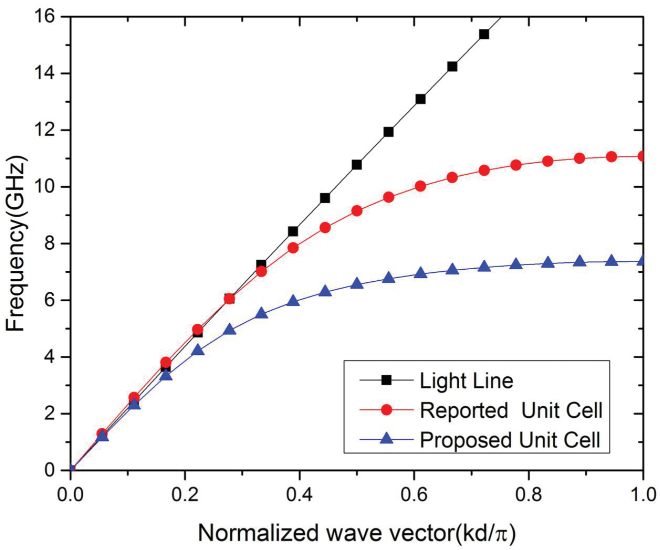

Figure 6. Dispersion curve comparison of unit cell.

For highly efficient conversion, it is essential to match two transmission structures in term of momentum and impedance[28]. A broadband and an efficient conversion from conventional guided waves to SSPP in the microwave frequency have been proposed[24] (in which three element strip connector and ground regulator is proposed). The transition is further optimised (ground at bottom) for the new proposed unit cell, as shown in Fig. 7. Here the mode transition is optimised from 1 GHz to 7 GHz.

As seen in the dispersion curve of unit cell in Fig. 6, the value of the wave number of SSPP, k, is always greater than that of the guided waves in the microstrip, k_0 at any given frequency, where k_0 is wave number corresponding to light line/microstrip line, and k is wave number corresponding to SSPP line

Thus, there exists a large momentum mismatch between microstrip and the corrugated strip. To solve the momentum mismatch, it is important to bridge the gap between the

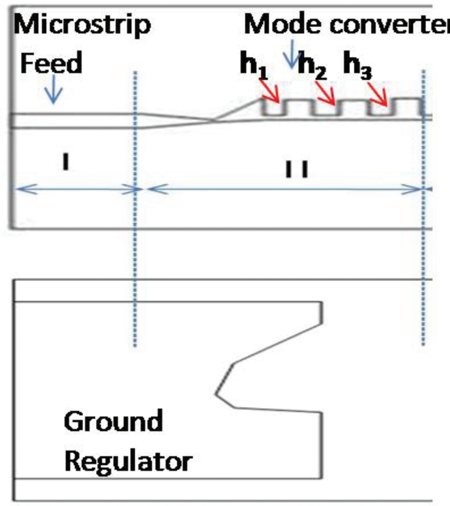

Figure 7. Optimised mode converter.

momentums of two modes.

$$k = \frac{\omega}{c}\sqrt{1+\left(\frac{2g}{d}\right)^2 \tan^2\left(h\frac{\omega}{c}\right)} \quad (3)$$

From Eqn. (3), it is clear that k is closer to k_0 when h is smaller. Therefore, the metallic strip of transition structure is corrugated in a way that the depth of the grooves is changing gradually from h_1= 3.5 mm to h_3= 3.8 mm (Fig. 7) so that the momentum mismatch can be reduced in each period, d, at all desired frequencies.

On the contrary, impedance matching is an important consideration in designing the transmission structure. The reflection coefficient, of a wave incident on a line having impedance Z_q from a medium with impedance Z_p is given by the Eqn. (4):

$$\Gamma = \frac{Z_q - Z_p}{Z_b + Z_a} \quad (4)$$

Hence, the difference in impedance of any two adjacent points along the waveguide must not be big so that the reflection at the interface can be minimised. Therefore, the transition structure (bottom side) consists of a flaring ground that is designed to match the impedance that allows high-efficiency broadband conversion of guided wave to SSPPs without too much of reflection.

On the basis of the proposed unit cell and optimised mode converter, a prototype SSPP BPF is designed and modelled in CST design studio as shown in Fig. 8. This BPF includes three parts: (i) microstrip transmission line (ii) optimised matching transition and, (iii) SSPP structure that is constructed by the proposed unit cell.

The first part is for the purpose of feeding or receiving the EM field. The microstrip line parameters are chosen to achieve 50 ohm. The second part is a transition section between microstrip line and the SSPP section. This second part is very important because this transition is responsible for mode conversion from quasi TEM mode to TM mode. The third part is the main SSPP structure having one unit cell.

When the structure shown in Fig. 8 is simulated in CST software tool having substrate RT duriode 5880, it is observed

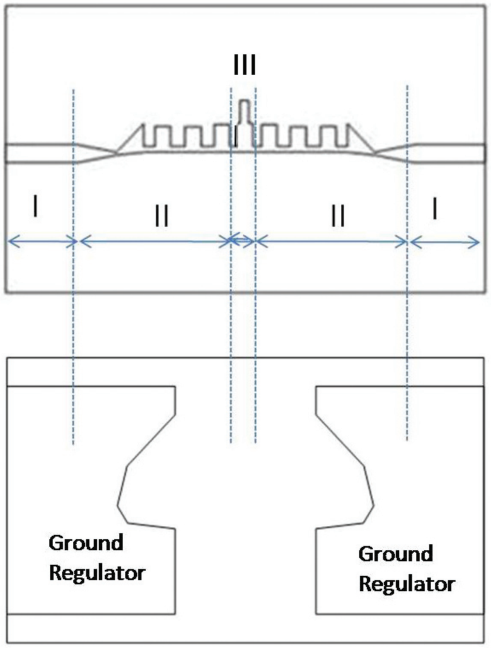

Figure 8. Prototype SSPP bandpass filter

that the filter roll off is not good[25]. So to improve the filter roll off, rejection and taking consideration of size, five units' cells are used in SSPP structure. Using five unit cells and an optimised input – output transition, a better SSPP BPF is designed, as shown in Fig. 9.

4. CHARACTERISATION OF SSPP BANDPASS FILTER

The RT duriode Rogers's 5880 substrate is used for the fabrication of the design shown in Fig. 9. The fabricated SSPP BPF is as shown in Fig. 10. The overall dimension of fabricated filter is (90 x 45) mm. Figure 11 shows the comparison between the measured and simulated results of S-parameter. The broadband BPF has passband of approximately 1.20 GHz - 5.80 GHz and the insertion loss over the passband is less than 2 dB. The mismatches between simulated and measured results are due to manual fabrication. The transmission loss is marginally higher than that of conventional microstrip line structure because of the mode converter and subwavelength nature of SPP structures[29]. The insertion loss of SSPP filter is approximately same as back to back transition structure, which means the main loss in the SSPP BPF is due to the mode converter[25]. The characterisation of the fabricated filter has been carried out by Rohde & Schwarz vector network analyser ZVA24. The proposed SSPP BPF size is half in length compare to earlier reported work[24] having length (180 x 45) mm approx.

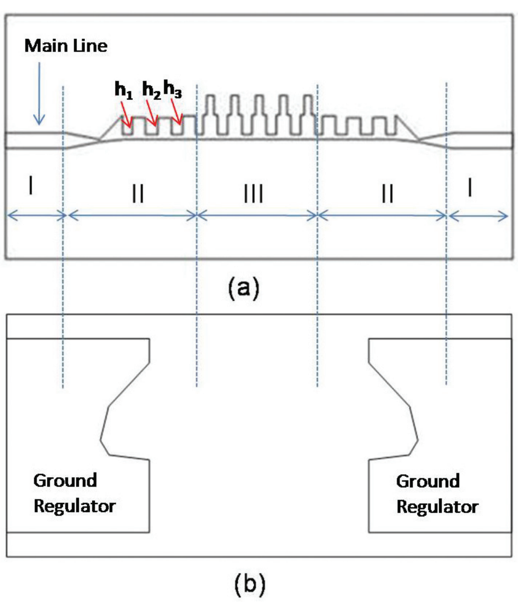

Figure 9. SSPP BPF filter (a) Top of SSPP filter having 5 units cell (b) Ground regulator (Bottom).

The verification of the conversion of guided waves in a conventional microstrip to SSPPs in plasmonic metamaterial waveguide and vice versa confirms the possibility of convenient transformation of signals that might take several forms during the course of their transmission from a source to destination.

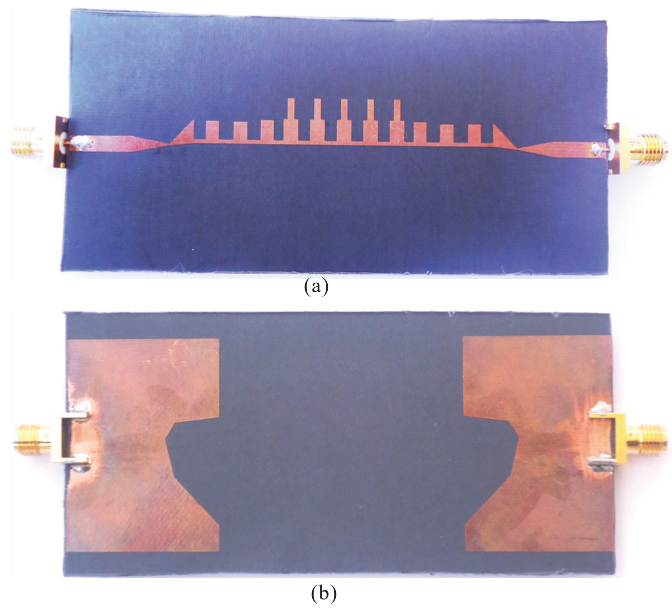

Figure10. Fabricated SSPP Filter (a) Top of filter, and (b) bottom having ground regulator.

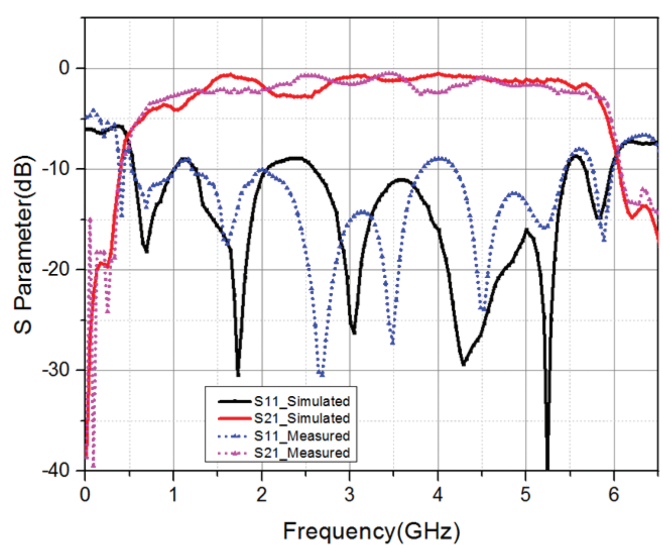

Figure 11. Comparison of S-parameters results.

Such kind of conversion is highly important because it bridges the conventional transmission line technology to the newer science of plasmonic metamaterials.

5. EQUIVALENT TRANSMISSION LINE SCHEMATIC AND FUTURE SCOPE

The SSPP section includes a single conductor (without ground) and appears different from the conventional planar microwave transmission line structure. Since the SSPP structure transmits the signal by coupling between the grooves, its equivalent transmission line schematic can be analysed by assuming that ground plane is very far away, near to infinity. On the basis of this assumption, we can calculate network element such as impedance, capacitance and inductance.

The unit cell is further modelled using a circuit theory[30], as shown in Fig. 12. On the basis of section III of Fig. 9, the proposed transmission line schematic for SSPP section is as shown in Fig. 13. The network parameters, such as transmission and scattering matrix of the periodic structure, can be calculated using ABCD matrix concept.

The mathematical analysis of this proposed transmission line schematic can be done in the future to generalise the SSPPs BPF synthesis using plasmonic metamaterial. The various free parameters of SSPP structure (compared to conventional lines) are helpful for the realisation of multiband components through dispersion and impedance engineering for future work. Better mode converter can also be designed in the future for better performance of BPF.

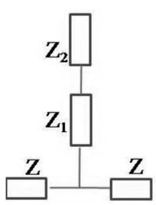

Figure 12. Transmission line schematic of new unit cell.

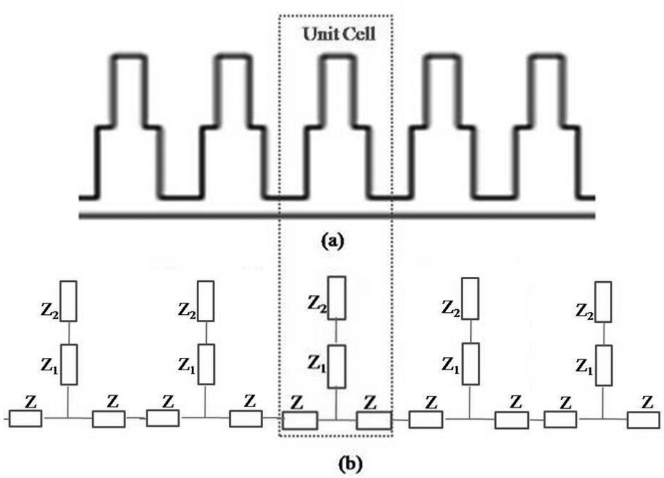

Figure 13. Schematic diagram of the proposed SSPP structure (unit cell is enclosed with a dashed line) (a) SSPP waveguide section and (b) Transmission line schematic of the SSPP section.

6. CONCLUSIONS

This paper provides the realisation approach for filter design based on SSPPs structure using plasmonics metamaterial, which is useful to produce filter in microwave frequency domain by taking advantage of optical phenomenon. A good agreement between the measured and simulated results of S-parameter is obtained. The wideband BPF 1.20 GHz - 5.80 GHz may pave a way for advanced plasmonic integrated microwave devices and circuits.

It is useful in multilayer structure (as no ground plane is required in main SSPPs structure) for high level of integration and compact structure. It is observed that the insertion loss in the passband is mainly due to the mode converter structure. The developed BPF and its enhanced version using SSPPs methodology are very useful to develop RF systems in defence applications.

REFERENCES

1. Moreno, M. & Garcia -Vidal, F.J. Guiding terahertz waves along subwavelength channels. *Physical Rev. B*, 2009, **79**.
doi: 10.1103/PhysRevB.79.233104
2. Yong, J.Z.; Quan, J. & Tie, J.C. Bidirectional bending splitter of designer surface plasmons. *Applied Phys. Lett.*, 2011, **99**.
doi: 10.1063/1.3639277
3. Kumar, G.; Pandey, S.; Cui, A. & Nahata, A. Planar plasmonic terahertz waveguides based on periodically corrugated metal films. *New J. Phys*., 2011, **13**.
doi: 10.1088/1367-2630/13/3/033024
4. Gan, Q.Q.; Fu, Z.; Ding, Y.J. & Bartoli, F.J. Ultra wide-bandwidth slow-light system based on Thz plasmonic graded metallic grating structures. *Physical Rev. Lett.*, 2008, **100**.
doi: 10.1103 /Phys RevLett.100.256803
5. Krasavin, A.V. & Zayats, A.V. Three – dim. Numerical modeling of photonic integration with dielectric-loaded SPP waveguides. *Physical Rev. B*, 2008, **78**.
doi: 10.1103/PhysRevB.78.045425
6. Sondergaard, T. Surface- plasmon polariton resonances in triangular-groove metal gratings. *Physical Rev. B*, 2009, **80**.
doi: 10.1103 /PhysRevB. 80.195407
7. Xu, J.; Cui, Y.; Guo, J.; Xu, Z.B.; Qian, C. & Li, W.Y. Broadband transition between microstrip line and spoof SP waveguide. *Electronics letters*, 2016, **52**(20), 1694-1695.
doi:10.1049/el.2016.2027
8. Kianinejad, A.; Chen, Z.N. & Qiu, C.W. Low-loss spoof surface plasmon slow-wave transmission lines with compact transition and high isolation. *IEEE Trans. on MTT*, 2016, **64**(10), 3078-3086.
doi: 10.1109/TMTT.2016.2604807
9. Liu, X.; Feng, Y.; Chen, K.; Zhu, B.; Zhao, J. & Jiang, T. Planar surface plasmonic waveguide devices based on symmetric corrugated thin film structures. *Optics express*, 2014, **22**(17), 20107-20116.
doi: 10.1364 /OE. 22.020107

10. Jiang, Z.H.; Lin, L.; Bossard, J.A. & Werner, D.H. Bi-functional plasmonic metamaterials enabled by subwavelength nano - notches for broadband, polarization - independent enhanced optical transmission and passive beam-steering. *Optics Express*, 2013, **21**(25), 31492-31503.
doi: 10.1364 /OE .21.031492
11. Martin, F. Artificial transmission line for RF and Microwave application. John wiley & Sons Inc., 2015, 119-214.
doi:10.1002/9781119058403
12. Zhang, J. & Hsiang, T.Y. Dispersion characteristics of coplanar waveguides at subterahertz frequencies. *In* Progress in Electromagnetic Research Symposium, Cambridge, USA, March 26-29, 2006, 232-235.
doi:10.1163/156939306779276767
13. Kim, J. Surface plasmon - polariton waveguiding characteristics of metal/dielectric quasi-coplanar structures. *Optics Letters*, 2007, **32**(23), 3405-3407.
doi: 10.1364/OL.32.003405
14. Mittal, G. & Pathak, N.P. Techniques of Reconfigurable bandpass filter for realization of adaptable RF system. *In* 14th IEEE India council International Conference (INDICON), IIT- Roorkee, 2017.
15. Mittal, G. & Pathak, N.P. Realization of bandpass filter on spoof surface plasmon polariton technique at Microwave Frequency. *In* 3rd International conference on computing, communication and signal processing (ICCASP), DBATU – Raigad, 2018.
16. Li, Z.; Liu, L.L.; Gu, C.Q.; Ning, P.P.; Xu, B.Z.; Niu, Z.Y. & Zhao, Y.J. Multi-band localized spoof plasmons with texturing closed surfaces. *App. Phys. Letters*, 2014, 104.
doi: 10.1063/1.4868126
17. Li, Z.; Xu, B.Z.; Gu, C.Q.; Ning, P.P.; Liu, L.L.; Niu, Z.Y. & Zhao, Y.J. Localized spoof plasmons in closed textured cavities. *App. Phys. Lett.*, 2014, **104**.
doi: 10.1063/1.4885046
18. Xu, B.Z. ; Li, Z. ; Liu, L.L. ; Xu, J.; Chen, C.; Ning, P.P.; Chen, X.L. & Gu, C.Q. Tunable band-notched coplanar waveguide based on localized spoof surface plasmons. *Optics Letters*, **40**(20), 4683-4686.
doi : 10.1364/OL.40.004683
19. Liu, L.L.; Li, Z.; Xu, B.Z.; Xu, J.; Chen, C. & Gu, C.Q. Fishbone-like high-efficiency low-pass plasmonic filter based on double-layered conformal surface plasmons. *Plasmonics*, 2017, **12**(2), 439-444.
doi: 10.1007/S11468-016-0283-5
20. Li, Z.; Xu, J.; Chen, C.; Sun, Y.H.; Xu, B.Z.; Liu, L.L. & Gu, C.Q. Coplanar waveguide wideband band-stop filter based on localized spoof surface plasmons. *Applied Optics*, 2016, **55**(36), 10323-10328.
doi: 10.1364/AO.55.010323
21. Xu, J.; Li, Z.; Liu, L.L.; Chen, C.; Xu, B.Z.; Ning, P.P. & Gu, C.Q. Low-pass plasmonic filter and its miniaturization based on spoof surface plasmon polaritons. *Optics Communications*, 2016, **372**, 155–159.
doi: 10.1016/j.optcom.2016.04.017
22. Xu, B.Z.; Li, Z.; Liu, L.L.; Xu, J.; Chen, C. & Gu, C.Q. Bandwidth tunable microstrip bandstop filters based on localized spoof surface plasmons. *J. Opt. Soc. Am. B*, 2016, **33**(7), 1388-1391.
doi: 10.1364/JOSAB.33.001388
23. Li, Z.; Liu, L.L.; Sun, H.Y.; Sun, Y.H.; Gu, C.Q. ; Chen, X.L.; Liu, Y. & Luo, Y. Effective surface plasmon polaritons induced by modal dispersion in a waveguide. *Phys. Rev. Applied*, 2017, 7(4).
doi: 10.1103/PhysRevApplied.7.044028
24. Kianinejad, A.; Chen, Z.N. & Qiu, C.W. Design and modeling of Spoof surface plasmon modes-based microwave slow-wave transmission line. *IEEE Trans. MTT,* 2015, **63**(6), 1817-1825.
doi: 10.1109/JSTQE.2008.918107
25. Mittal, G. & Pathak, N.P. Hybrid mode transmission line and band pass filter implementation using plasmonic metamaterial at microwave frequency. *In* proceedings of 11th International conference on industrial and Information systems (ICIIS), IIT-Roorkee, 2016.
doi: 10.1109/ ICIINFS .2016. 8262936p
26. Liu, X.; Zhu, L. & Feng, Y. Spoof surface plasmon-based bandpass filter with extremely wide upper stopband. *Chin. Phys. B*, **25**(3).
doi: 10.1088/1674-1056/25/3/034101
27. Bhat, B. & Koul, S.K. Stipline like transmission lines for microwave integrated circuits. New Age International Publishers, 2007, 601 p.
28. Fung, T.Y. & Kim, O.C. The study of Spoof surface plasmon polaritons (SSPPs) on a hybrid waveguide in microwave frequencies. National University of Singapore(NUS,) 2015. (PhD Thesis)
29. Zhang, H.C.; Liu, S.; Shen,X.; Chen, L.H.; Li, L. & Cui, T.J. Broadband amplification of spoof surface plasmon polariton at microwave frequencies. *Laser Photonics Rev*., 2015, **9**(1), 83-90.
doi: 10.1002/lpor.201400131
30. Zhao, L.; Zhang, X.; Wang, J.; Yu, W.; Li, J.; Su, H. & Shen, X. A novel broadband bands pass filter based on spoof surface plasmon polariton. *Scientific report,* 2016.
doi: 10.1038/srep36069

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Contribution in the current study, he has done design, analysis and characterisation of SSPPs based unit cell and bandpass filter.

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Contribution in the current study, he has given concept and guidance for design, analysis and characterisation of SSPPs based unit cell and bandpass filter.