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RESEARCH ARTICLE



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Novel crest-trough shaped spoof surface plasmon polaritons for low pass filtering applications

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Abstract

In this letter, a novel periodic crest-trough (CT) shaped groove structure is proposed to excite and propagate spoof surface plasmon polaritons (SSPPs) at microwave frequency. Such a groove shape solves the problem of high transmission losses found in traditional microstrip transmission lines and presents tighter field confinement. Lower dispersion band is achieved by proposed CT-SSPPs as compared to traditional structures, with 28% reduced asymptotic frequency than rectangular groove. Influence of some geometrical parameters is also explored. Further, planar low-pass plasmonic filters with low reflection and high efficiency are investigated with compact transition circuitry for smooth and fast conversion between SSPPs and guided waves. To validate the proposed performance, two plasmonic filter structures are fabricated and measured. Full agreement is observed between the simulated and measured results for which reflection coefficient is lower than -10 dB in passband up to 3.07 and 2.52 GHz, respectively for both filters. The rejection level is higher than -15 dB in the whole stopband.

KEYWORDS

lowpass filter, microwave frequency, spoof surface plasmon polaritons, subwavelength

1 | INTRODUCTION

Surface plasmon polaritons (SPPs) exist naturally at optical frequencies only due to the plasma nature of metals with negative permittivity and are highly localized electromagnetic waves propagating along the metal-dielectric interface and decay exponentially and perpendicularly to this boundary.¹ However, metal behaves as perfect electric conductor at microwave, terahertz, and far-infrared regimes and this drawback has been overcome by the concept of spoof SPPs (SSPPs).²⁻⁴ These highly confined surface waves mimic the properties of SPPs, realized by surface decorations of subwavelength periodic grooves or holes and their dispersion properties can conveniently be controlled simply by adjusting the geometric parameters.⁵⁻⁸ Corrugated planar metallic strips manufactured by standard PCB fabrication technology are the focus of plasmonic metamaterial community due to simple and low-cost fabrication, flexibility, low-loss, and reduced interference.

Different SSPPs transmission lines (TLs) structures have been proposed for filtering applications including rectangular gratings,^{6,7,9,10} semi-elliptical grooves,¹¹ etched grounds on coplanar waveguide,¹² circular grooves,¹³ hybrid substrate integrated waveguide,¹⁴ and many others.¹⁵⁻¹⁹ Recently, modal-dispersion-induced effective SPPs have been proposed by designing transverse electric modes on rectangular waveguides.²⁰ Regardless of dynamic advances in this field, some characteristics are of practical importance and yet challenging to be solved such as bulky structures due to additional conversion circuitry, higher asymptotic frequency, complicated manufacturing, high propagation loss, poor frequency selectivity, and low out-band rejections (OBR).

Therefore, more feasible solutions are necessary to meet the stringent requirements in plasmonic circuits and systems. In this article, we propose a novel plasmonic structure with periodic crest-trough (CT) grooves on a planar metal strip which are based on the well-recognized family of radial grooves. Such grooves are considered ideal candidate for Spoof SPP applications at microwave regime, since their propagation modes offer gradual cutoff due to the presence of radial coordinate and can efficiently isolate the spatial

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propagating sectors from the non-propagating ones of the waveguide.^{21,22} Higher attenuation in short propagation lengths is desired in SSPP case; hence, employing radial grooves enhances the mimic-ability of real SPPs with reduced depth (shallow) grooves. References 23 and 24 have already addressed this matter for the trapezoidal grooves by means of full wave simulations. In Reference 21, radial grooves has been demonstrated as a feasible configuration to efficiently support and confine SSPP with reduced groove depth in comparison to broadly used rectangular groove through analytical derivations. In present case, we consider rectangular coordinates and cover different grooves geometries (with the same dimension) corresponding to the same volumes.

In this letter, it has been proved that proposed CT based SSPPs are strongly bound to the surface, demonstrating a lower dispersion band compared to traditional structures and pose 28% reduced asymptotic frequency than rectangular groove. Based on these corrugations, two low pass plasmonic filters are proposed and manufactured achieving high transmission efficiency and improved return loss with cutoff frequencies of 3.07 and 2.52 GHz, respectively. Measured results agree well with the ones predicted in the simulations, and microwave energy is tightly confined with reduced propagation loss due to perfect momentum matching between microstrip guided waves and SSPPs.

2 | DISPERSION CHARACTERISTICS OF PROPOSED CT GROOVE STRUCTURE

It is known that propagation constant ($\gamma = \propto + j\beta$) has imaginary part directly affecting the field confinement of SSPPs and can be related parametrically as⁶:

$$\propto = \sqrt{k_x^2 - k_0^2} \tag{1}$$

Where $k_x = \beta$ for a transverse-magnetic wave and represents the wavenumber in the propagation direction, k_0 is the wave number in free space, and \propto is the tangential direction decay constant. It can be interpreted that larger the wavenumber (k_x), larger will be the decay constant in a perpendicular direction and therefore, the confinement of field will be stronger. Therefore, wavenumber of different transmission lines can be investigated for the field confinement characteristics. Eigen mode simulations give a fast methodology to compute the wavenumber of these transmission lines, although a little blue shift of frequency spectrum is encountered which is ignorable.⁶ For the said purpose, the geometric parameters of the structures can be used in pre-designing the dispersion curves including operating band, propagation length, transmission losses, and confinement of fields.

The propagation characteristics of the proposed CT based SSPPs are analyzed through dispersion curves by using Eigen mode solver of the commercial software package, Ansoft's High Frequency Structure Simulator (HFSS) which uses finite element method. Periodic boundary conditions are assigned to the unit cell with CT shaped groove as shown in Figure 1A along x-axis while perfect electric boundaries are set to both y- and z-axis. TM-polarized waves propagate along the corrugated metal strip (x-direction) which is assumed as a perfect electric conductor. we compare different types of grooves (Microstrip, Rectangular, Vee groove) and their geometrical parameters, P, H, w, and h_G represent the period, height of the metal strip, width, and depth of the groove, respectively and are kept same for all types of grooves. The height of microstrip is taken as 12 mm. The radius of CT groove in crest and trough part is 6 and 4 mm, respectively and hence the total groove depth becomes 10 mm. The width w and depth of groove $h_{\rm G}$ for rectangular and Vee grooves structures is kept 8 and 10 mm, respectively, hence making total height of metallic strip 12 mm and period of 20 mm. The thickness of metallic strip is 0.018 mm. A dielectric substrate with a thickness (t) of 2.6 mm, dielectric constant of 2.65, and loss tangent (LT) of 0.02 is used. The calculated dispersion curves are presented in Figure 1B in which a comparison with traditional structures (Microstrip, Rectangular, Vee groove) is shown for the fundamental mode of propagation, where β represents the propagation constant in the x-direction. All the dispersions curves deviate significantly from the light line proving their capability of confining the electromagnetic waves on the metal surface; however, this deviation is more conspicuous for the CT groove in which lowest asymptotic frequency is achieved than all others. This is 28% and 75% reduction as compared to rectangular (Rec) groove and conventional microstrip, respectively thus shows its tendency to strongly and better confine the SSPPs field on the surface of the metallic strip.

A comparison of dispersion relations is investigated among different grooved structures in which groove depth is increased from 10 to 11.4 mm and displayed in Figure 1C. It is observed that all the grating structures are capable of confining electromagnetic waves on their surfaces with the increase in depth of groove, and the cutoff frequency clearly depends on the groove depth. Nevertheless, it is indicated that proposed structure attains lowest cutoff frequency as its deviation from the light line is highest, proving its stronger ability of confining surface wave as compared to conventional rectangular grooves.²¹ The key reason is the realization of gradual cutoff mode for proposed geometry (analogous to annular sector waveguides) showing greater attenuation of wave in contrast to rectangular groove.²²

Considering the group velocity which is defined by $v_g = d\omega/dk$, where ω is the radian frequency and *k* represents the propagation factor. Lower dispersive characteristics are related to the group velocity which can be obtained from dispersion relations. Slow wave propagation is supported by SSPPs which represents better electromagnetic field confinement. Group velocities of different groove SSPP structures



FIGURE 1 A, Unit cell of proposed crest-trough groove. B, Dispersion relations of suggested groove SSPPs along with traditional structures and light line. C, Comparison of dispersion relations of different SSPP structures with increased depth of groove. D, Comparison of group velocities. SSPPs, spoof surface plasmon polaritons [Color figure can be viewed at wileyonlinelibrary.com]

can be calculated from the dispersion curves and are shown in Figure 1D. Rectangular and Vee grooves exhibit higher group velocities as compared to CT grooves. This is due to the slow propagation of SPP waves on the corrugated CT groove, and is more pronounced when the groove depth is increased.²⁵ Hence, a tight confinement of field is achieved in the proposed CT groove structure.

Explicit role of varying physical parameters on the dispersion relations is investigated in which one parameter is varied while all others are kept the same as for Figure 1. Here, we focus on the analyzing the depth, width of groove structure and also period of the unit cell. It is shown in Figure 2A when the depth of CT groove increases, a significant reduction in asymptotic frequency is observed whereas frequency is noticeably reduced for higher periodicity of the unit cell as seen in Figure 2B. Furthermore, there is an increase of wave number with higher values of P and h_G which means tighter confinement of spatial field on the surface of metal is achieved. It can be noticed from Figures 1C and 2A that same lower level of cutoff frequency can be achieved by proposed CT SSPP with a shallower groove (6 mm) in contrast to deeper rectangular groove (11.4 mm) structure. This is the desired property of the SSPP in general, to preserve the original boundary which can be achieved by the shallow grooves.²¹ The benefit of compact plasmonic structure can be obtained by designing shallow gratings. We also evaluate the dispersion curves for the dependence of width of the groove (*w*) but a weaker impact is found and can be seen from Figure 2C. These phenomena confirm that depth, width of groove and period of unit cell can improve the ability of field confinement in SSPPs since these geometric variables have a direct relationship with the wavevector k_x .²⁶

From above analysis, it is understood that geometric parameters effectively impact the dispersion characteristics of the SSPPs and therefore on the confinement of field. Figure 2D compiles the effects of these geometric structure features. Clearly, all the factors have specific role in defining



FIGURE 2 A-C, Dispersion relations showing the effect of geometrical parameters. A, Depth of the groove, h_G . B, Period of the unit cell, *P*. C, Width of the groove, *w*. D, Cutoff frequency as a function of proposed structure geometric parameters [Color figure can be viewed at wileyonlinelibrary.com]

the cutoff frequency. The depth of groove $h_{\rm G}$ and period of single cell have an evident influence on lowering the cutoff frequency; however, considering the shape of the groove, the structure size may enlarge. Hence, appropriate selection of the structure dimension is highly defined by the practical application. To analyze the level of propagation loss during the transmission of SSPPs, we calculate and compare the propagation length "*L*" of two types of structures which is given by.²⁷

$$L = \frac{1}{2\alpha} \tag{2}$$

Where, \propto is attenuation constant. The propagation lengths are calculated for proposed SSPP with shallower groove of 6 mm depth and conventional rectangular structure of 11.4 mm groove depth so that the dispersion curves are closer to each other (Both exhibits same cut off frequency level). It is pointed here that all the geometric parameters are kept same as in Figure 1B except groove depth h_G which is considered from comparison of Figures 1C and 2A in which proposed CT and rectangular groove SSPPs exhibit same cut off frequency level. Figure 3A shows the normalized propagation lengths confirming that the transmission frequency bands are same for both cases (proposed CT and rectangular groove SSPPs) and with the increase in working frequency, the propagation lengths decreases until the cutoff frequency is approached where it quickly reaches zero. The reason is the tight confinement of electromagnetic field of SSPPs, making the propagation loss bigger at high frequency region as compared to low frequency. Noticeably, the propagation length for the CT groove structure is relatively longer than the conventional rectangular groove SSPPs; hence the propagation loss for proposed structure is lower in the transmission region.

3 | PROPOSED DESIGN OF SSPPS FILTER

Keeping in view the objective of stronger confined field, lower cutoff frequency along with the compact configuration, periodic arrangement of proposed CT based unit cells with design parameters of dispersion curves acquired in Section 2 are treated as the basis for the final optimized lowpass plasmonic filter. It consists of double sided structure with CT grooves based TL on top and ground bottom. The schematic view of the proposed structure is shown in Figure 3B which consists of three sections (A-C) in which section A is a traditional microstrip line and characteristics impedance of 50 Ω at the port end is achieved with height $H_{\rm M} = 6$ mm and $L_1 = 2.5$ mm (Figure 3C Left).

As seen in Figure 1B, the wave vector of SSPPs is highly mismatched to the light line, particularly when the frequency reaches the corresponding asymptotic frequency.²⁸ This can lead to serious lower transmission efficiency of the plasmonic filter. Hence, section B is the conversion part for attaining smooth and fast transition from microstrip guided waves to SSPPs with length $L_2 = 60$ mm and consists of gradient CT grooves whose depth vary from $h_1 = 4 \text{ mm}$ to $h_3 = 8$ mm with a step of 2 mm shown in Figure 3C middle. Momentum matching between the microstrip line and the proposed SSPPs waveguide is enhanced with the increasing depth of the grooves (h) in this section, and so the stronger field confinement is realized along with the elimination of reflections through superior impedance matching. Section C is the SSPPs waveguide part with length $L_3 = 100$ mm, H = 12 mm, and composed of uniform CT grooves with depth h₀ shown in Figure 3C right.



FIGURE 3 A, Normalized propagation lengths of two types of SSPPs. B, Configuration of the proposed CT groove based plasmonic filter with top view of three sections. C, Detailed view of regions A, B, and C. CT, crest-trough; SSPPs, spoof surface plasmon polaritons [Color figure can be viewed at wileyonlinelibrary.com]

The effect of gradient CT groove on the conversion efficiency is studied, and comparison of *S*-parameters with and without gradient grooves is presented here, Figure 4A shows the transmission coefficients of both cases and it is observed that signal is seriously distorted due to the momentum



FIGURE 4 A and B, *S*-parameters with and without gradient CT grooves in the bridge section. A, Transmission coefficient. B, Reflection coefficient. C, Simulated *S*-parameters of proposed SSPP and microstrip transmission lines. CT, crest-trough; SSPP, spoof surface plasmon polariton [Color figure can be viewed at wileyonlinelibrary.com]

mismatch in the absence of gradient grooves and higher insertion loss is seen. Figure 4B confirms that electromagnetic waves are remarkably reflected without gradient grooves as compared to matched case with gradient grooves. Hence, higher efficiency is achieved due to outstanding conversion by the smooth bridge of gradient grooves resulting in matched impedance and momentum between microstrip and SSPPs transmission lines. For comparison, a microstrip line is also designed of the same length and width as that of Spoof SPP transmission line and is kept tapered at both ends for smooth conversion from 50 Ω line. Figure 4C presents the transmission and reflection coefficients of both cases (proposed SSPPs and Microstrip) and it is seen that proposed plasmonic structure achieves a cutoff frequency with high transmission efficiency implying that a smooth conversion is attained.

Туре	Distinctive parameter (mm)	LT	f_c (GHz)	IL (dB)	Max. OBR (dB)
Type 1	$h_0 = 10$	0.02	3.01	3.52	-63.56
Type 2	$h_0 = 11.4$	0.02	2.51	4.04	-96.01
Type 3	$h_0 = 10, H = 10.6$	0.02	2.91	4.02	-75.34
Type 4	$h_0 = 10, t = 0.25$	0.02	2.41	3.83	-99.70
Type 5	$h_0 = 10$	0.001	3.01	0.81	-63.61
Туре 6	$h_0 = 11.4$	0.001	2.51	0.72	-94.80
Type 7	$h_0 = 10, t = 0.25$	0.001	2.41	0.45	-95.72

TABLE 1 Comparison of different plasmonic filters

Abbreviations: IL, insertion loss; LT, loss tangent; OBR, out-band rejections.



FIGURE 5 A and B, The simulated S-parameters of different types of plasmonic filters with a substrate of LT. A, 0.02. B, 0.001. C, Transmission spectra with different LT. D, Transmission coefficients with different thickness of dielectric substrate. LT, loss tangent [Color figure can be viewed at wileyonlinelibrary.com]

We investigate some structures and categorize them into different types with all geometrical parameters defined earlier in this section except for some distinctive parameters as given in Table 1. Full wave simulation results of transmission (S_{21}) and reflection (S_{11}) coefficients for all above types are shown in Figure 5. For type 1 with a lossless substrate, it is clearly observed that S_{11} is less than -20 dB and S_{21} is greater than -3 dB up to the frequency range of 3.01 GHz showing an efficient low pass filtering performance as seen in Figure 5A.

The cutoff frequency is principally determined by the corrugated structure in section C and numerically confirms the asymptotic frequency of the SSPPs modes derived from dispersion relations in the previous section (Figure 2). Besides, a high rejection level in the stopband is obtained from 3.31 to 5.7 GHz, with more than -20 dB for S_{21} reaching its lowest trench of -64.2 dB at 4.6 GHz. Overall OBR level is less than -16 dB in whole stopband. The sharp rise and fall of transmission coefficient is observed in stopband and may be due to spurious resonance and can be pushed out to higher frequencies by adjusting the geometrical variables.²⁶ Table 1 shows the cutoff frequencies achieved by different structures along with critical performance parameters. It is seen that cutoff frequency decreases with the increased height of groove $h_0 = 11.4 \text{ mm}$ (type 2). Furthermore, if we keep h_0 as in type 1 but reduce the height of the transmission line H, still the cutoff frequency decreases (type 3).

Taking into account the dielectric substrate of different thicknesses is common in plasmonic circuits and systems, here comparison of *S*-parameters are given when substrate height is decreased to 0.25 mm in type 4 structure. Influence of thinner substrate explicitly decreases the cutoff frequency to 2.41 GHz and slightly lowering the insertion loss (IL); however, the level of return loss rises negligibly. Furthermore, the impact of decreasing the LT from 0.02 to 0.001 on the performance is investigated in Figure 5B and improvement in transmission characteristics is noted. The cutoff frequency remains same but IL is reduced significantly as shown in Table 1.

It has been proved in Reference 12 that a decrease in relative permittivity and LT results in the increase of asymptotic frequency and consequently, the cutoff frequency. To preserve the original frequency to the lower level, the only way is to increase the groove's depth; however, in that case, the structure dimensions may enlarge. In our investigation, with the decrease of LT, the cutoff frequency is preserved. Figure 5C compiles the numerical simulations of transmission responses with different loss tangents. It is prominent that the transmission loss of SSPP increases as the loss tangent is augmented from 0.001 to 0.02 in the passband region. The transmission characteristics of proposed SSPP with different substrate thicknesses are compared in Figure 5D. It is evident that transmission loss increases negligibly as dielectric substrate thickness is increased from 0.25 to 2.6 mm, however there is a notable decrease in cutoff frequency. This is in agreement with the theoretical and

numerical predictions in Reference 6. Since the fields distribute in the dielectric substrate and the air space, hence the electromagnetic fields remains in the substrate region when its thickness is increased. This results in the increasing the transmission loss in the passband of plasmonic filter.

To get an insight of conversion sequence from guided to SSPPs mode, four planes vertically placed to the *x*-axis show this transition process and their positions are marked in Figure 3B from (i) to (iv). Figure 6A depicts the amplitude distribution of electric field on these planes at 2GHz, and it is closely seen that energy gets confined as transits from (i) to (iv) within the SSPPs waveguide section. Figure 6B illustrates the magnetic field distribution on *x*-*y* plane placed 1 mm above the structure at an in-band frequency of 2 GHz and explicitly shows the higher magnetic field intensity in the central SSPPs section C.

Capacity of field confinement is compared between microstrip and proposed structure (type 5), the magnitude distributions of electrical fields on the cross-section to the



FIGURE 6 A, Simulated magnitude electric field distribution at the cross sections of metal strips. B, Simulated magnitude magnetic field on *xy* plane [Color figure can be viewed at wileyonlinelibrary.com]



FIGURE 7 Magnitude *E* field distribution on the cross-section of A, Microstrip and B, proposed SSPPs structure. SSPPs, spoof surface plasmon polaritons [Color figure can be viewed at wileyonlinelibrary.com]



FIGURE 8 Photographs of the fabricated SSPPs filter structures. A, Type 5. B, Type 6. SSPPs, spoof surface plasmon polaritons [Color figure can be viewed at wileyonlinelibrary.com]



FIGURE 9 Simulated and measured *S*-parameters. A, Type 5. B, Type 6 [Color figure can be viewed at wileyonlinelibrary.com]

metal stripes at 2 GHz are plotted in Figure 7A and Figure 7B. The free-space environment is imitated by setting the open boundary conditions. It is observed that electromagnetic field is mostly confined in the substrate region for the microstrip case (Figure 7A) as compared to proposed CT

TABLE 2 Comparison of the proposed designs with earlier researches

Ref	f_c (GHz)	IL (dB)	RL (dB)	Max. OBR (dB)
10	11.4	1.9	10	-60
12	4.91	0.97	12.5	-90
6	12.4	7	9	-42
11	7.9	3	9	-50
8	12.3	2.5	9	-25
9	14.2	6	_	62
This work	3.07	1.9	12	-47
This work	2.52	2	10	-48

Abbreviations: OBR, out-band rejections; IL, insertion loss.

SSPPs where it is distributed in both air and substrate regions (Figure 7B). By the application of perturbation theory, field distribution in the substrate area decides the attenuation of the transmission line.⁶ Since, in comparison to dielectric substrate, losses in microwave metallic transmission lines can be neglected. Hence, looser the field confinement inside the substrate area, lower will be the attenuation constant and thus reduced transmission loss. It is indicated from Figure 7B that the electric field of the proposed SSPP in the dielectric substrate is quite less than that of microstrip, hence presented structure has stronger field confinement of SSPPs.

4 | FABRICATION AND EXPERIMENT OF SSPPS FILTERS

For validation of the proposed design, we fabricate two samples of proposed filters with design parameters of type 5 and type 6, taking advantage of already available substrate material and are shown in Figure 8A,B. Two SMA connectors are soldered on each end of the TLs to connect them to the Agilent vector network analyzer (VNA N5230C) and resulting transmission and reflection coefficients are shown in Figure 9A,B for both types. It is noticed that simulated and measured results are in good agreement and cutoff frequencies of 3.07 and 2.52 GHz, respectively are achieved. Some fabrication and measurement errors contribute to the deterioration of the final performance. We compare the proposed low pass plasmonic filter with earlier published researches in Table 2. Comparatively, our proposed filters exhibit the lowest cutoff frequencies with reduced IL and better return loss (RL) in the passband and a good stopband rejection level.

5 | CONCLUSION

A novel CT based groove structure is proposed for the excitation of SSPPs. The effect of shape and geometrical parameters is investigated on the dispersion and propagation properties. It is found that such corrugated structure can achieve a lower dispersion band as compared to other traditional TLs. Numerical analysis of group velocities of SSPPs confirms the slow wave propagation thus representing better field confinement. Two low-pass plasmonic filters are designed and fabricated, the experimental results validate the simulation ones with high transmission performance (IL < 2 dB approximately for both). With the variation of geometric and dielectric substrate parameters, the cutoff frequency can be altered at will, giving huge flexibility to design SSPPs dispersion curves for desired applications. It is expected that this proposal can benefit in realizing plasmonic low pass filtering circuits and devices with reduced loss and stronger field confinement.

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