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Low-pass plasmonic filter and its miniaturization based on spoof surface plasmon polaritons

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ABSTRACT

In this work, a low-pass plasmonic filter based on spoof surface plasmon polaritons (SSPPs) is reported by etching the two grounds of coplanar waveguide with periodic grooves. The cutoff frequency of the filter coincides with the asymptotic frequency of the SSPPs that are supported by the periodic grooves, which can be tuned by the depth of the grooves at will. In addition, a T-shaped groove is designed to increase the equivalent depth of the groove so as to realize the miniaturization of the proposed filter by decreasing the equivalent cutoff frequency of the SSPPs. Measured S-parameters of the two proposed low-pass plasmonic filters agree well with the simulated ones, which validates our ideas and designs. This simple low-pass plasmonic filter can find potential applications in plasmonic circuits and systems.

1. Introduction

Surface plasmon polaritons (SPPs) are special surface electromagnetic (EM) mode propagating on the interface between metal and dielectric in optical frequencies [1–3]. However, in the microwave and terahertz (THz) frequencies, metals behave like perfect electric conductors (PECs), which cannot support SPP modes. To address it, a method of etching metal surface with periodic grooves or holes has been proposed and verified in the past decade to support spoof surface plasmon polaritons [4–11]. The SSPPs inherit most of the exotic features of natural SPPs as confining electromagnetic fields in a deep subwavelength scale with high intensity to overcome the diffraction limit. More importantly, their physical characteristics can be engineered at will by tuning the geometrical parameters.

In recent years, SSPPs have attracted much attention and a series of researches have been carried out on the high-efficiency excitation and propagation of SSPPs in broadband. The so-called conformal surface plasmons (CSPs), which can propagate on ultrathin and flexible films with long distances in a wide band from microwave to mid-infrared frequencies, has been proposed [12,13] and are regarded as one of the most potential candidates in developing practical ultrathin planar circuitry for microwave and THz applications. However, it is hard to operate the CSPs devices independently due to the difficulties in feeding and extracting signals efficiently in conventional planar microwave circuits [14,15], which are mostly composed of two-conductor transmission line structures. To address it, a scheme of broadband and high-efficiency conversion between the conventional guided waves and the SSPPs, was firstly reported [16] to realize feeding energies into and extracting signals from conventional functional devices or circuits. Afterwards, several interesting works have been reported to realize smooth transition between the SSPPs devices and the conventional planar transmission lines (such as coplanar waveguide (CPW) [17–20], microstrip line [21,22], slot line [23,24]), coaxial waveguide [25] and rectangular waveguide [26].

However, among these works, all the periodically corrugated grooves have been designed and etched on the signal line to support the SSPPs. In addition, how to realize the miniaturization of the SSPPs devices has attracted a lot of attention and is necessary for large-scale advanced microwave and THz integrated devices and circuits [27,28].

Metallic gratings structure has attracted a lot of discuss for its plasmonic effect [29–31]. And in this work, we report a high-efficiency low-pass plasmonic filter by etching the two grounds of CPW with gradient periodic grooves. The cutoff frequency of the plasmonic filter is determined by the asymptotic frequency of the SSPPs, which can be tuned by the depth of the grooves at will. By

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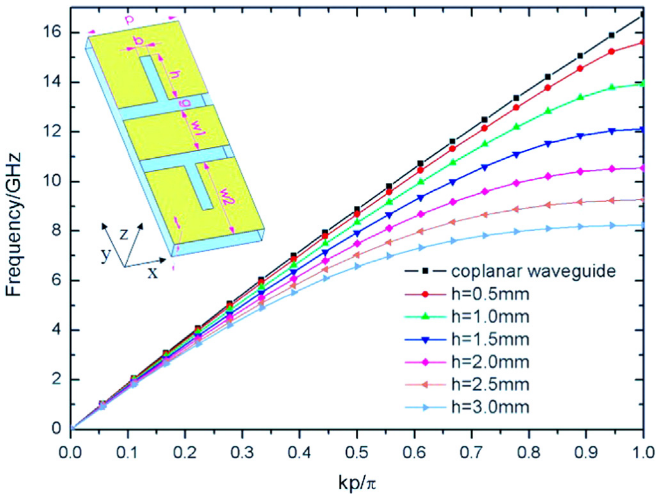

Fig. 1. Evolution of the dispersion curves for the fundamental SSPPs mode of the unit cell shown in the inset with the variations of h, in which t=1 mm, p=4 mm, b=0.5 mm, g=0.8 mm, $w1$=2.7 mm, $w2$=7.85 mm and h varies from 0.5 mm to 3 mm by a step of 0.5 mm.

introducing gradient grooves on the two side ground of the CPW, the high-efficiency conversion from guided waves in the CPW to SSPPs on the corrugated ground is realized. Moreover, a T-shaped groove is designed in this work to increase the equivalent depth of the groove, which realizes the miniaturization of the filter. Measurement and simulation results validate our ideas and designs. And simple low-pass plasmonic filters can find potential applications in plasmonic circuits and systems.

2. Dispersion relation of the symmetrical rectangular grooves

We first study the dispersion relation of the unit cell shown as the inset in Fig. 1. The dielectric substrate is selected as Rogers 6010 (with relative permittivity $\varepsilon_r = 10.2$ and the loss tangent $\tan\delta = 0.0023$) with the thickness t=1 mm. The period and width of the grooves are p=4 mm and b=0.5 mm, respectively. The width of signal line, slot and ground are $w1$=2.7 mm, g=0.8 mm and $w2$=7.85 mm, respectively. The evolution of the dispersion curves of the SSPPs with depth h varying from h=0.5 mm to h=3.0 mm is calculated by the eigen mode solver of the commercial software CST Microwave Studio and shown in Fig. 1.

The simulation results clearly show that the asymptotic frequency of the SSPPs is related to the depth of grooves. Furthermore, we can find that the deeper the grooves the lower the asymptotic frequency. It can also be observed that the momentum k gradually approaches $k0$, the momentum of CPW, with the decrease of h. Thus, gradient SSPP waveguide is designed in this work to realize momentum and impedance matching between the CPW and the plasmonic waveguide.

3. High-efficiency low-pass plasmonic filter

The proposed plasmonic filter is shown in Fig. 2(a) and the details of each region are shown in Fig. 2(b)–(d). Region I, as shown in Fig. 2(b), is the CPW connected with coaxial cable via SMA connectors. The dimensions $w1$=2.7 mm and g=0.8 mm are designed to achieve 50 Ω input impedance. Region II in Fig. 2(c) is the mode conversion section with gradient corrugated ground ($h1$ increases from 0.3 mm to $h10$=3 mm with a step of 0.3 mm). Region III in Fig. 2(d) is the CPW with corrugated metallic ground, which supports SSPPs waves. The period of grooves is set as p=4 mm, while the width between grooves and depth of grooves are set as a=3.6 mm and $h0 = 3$ mm. By introducing gradient grooves on the two grounds of CPW, the conversion from guided waves to SSPPs is realized. By etching grooves on the ground instead of using flaring ground with a planar Goubau line [32] , we can minimize the radiation losses and simplify the momentum matching.

We fabricate the proposed filter shown in Fig. 3(a) and conduct experiments on the S parameters. The simulation (solid lines) and measurement results (dotted lines) of the reflection and transmission coefficients shown in Fig. 3(d) agree with each other quite well and validate our design. The cutoff frequency of the filter is about 7.9 GHz, which is mainly determined by the asymptotic frequency of the SSPPs mode that is supported by the plasmonic waveguide in Region III. We also observe the electric field distributions at in band frequency 6.3 GHz and out of band frequency 9 GHz as illustrated in Fig. 3(b) and (c), respectively. It is clear that at 6.3 GHz the wave smoothly propagate from one end of the plasmonic filter to the other, however, at 9 GHz the waves are cutoff at the very beginning of Region III, which verify the theory very well.

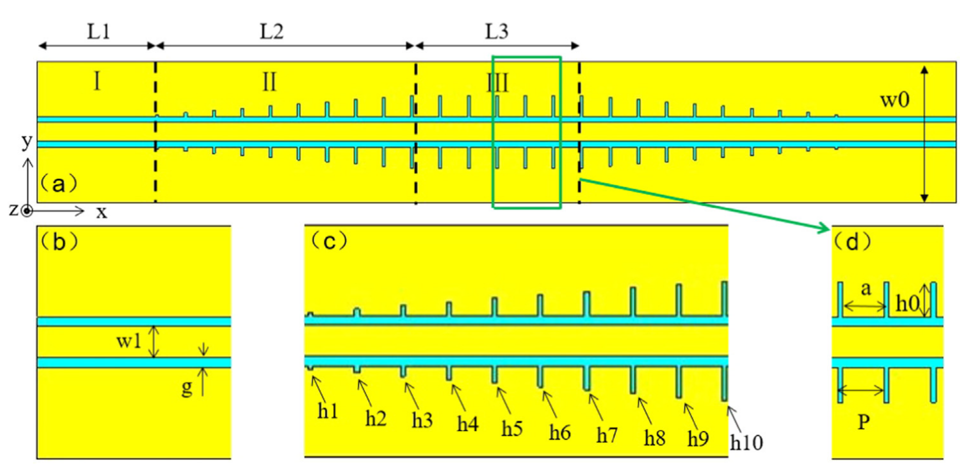

Fig. 2. The schematic configuration of the plasmonic filter. (a) Top view of the structure. Lengths of Region I, Region II and Region III are $L1 = 16.8$ mm, $L2 = 36$ mm, and $L3 = 24.4$ mm. Width $w0 = 20$ mm and the thickness of the dielectric substrate (Rogers 6010) t=1 mm. (b) Region I: CPW region with $w1 = 2.7$ mm, g=0.8 mm. (c) Region II: Mode conversion region with depths of grooves varying from $h1 = 0.3$ mm to $h10 = 3$ mm with a step of 0.3 mm. (d) Region III : The CPW with corrugated ground, in which a=3.6 mm, p=4 mm, $h0 = 3$ mm.

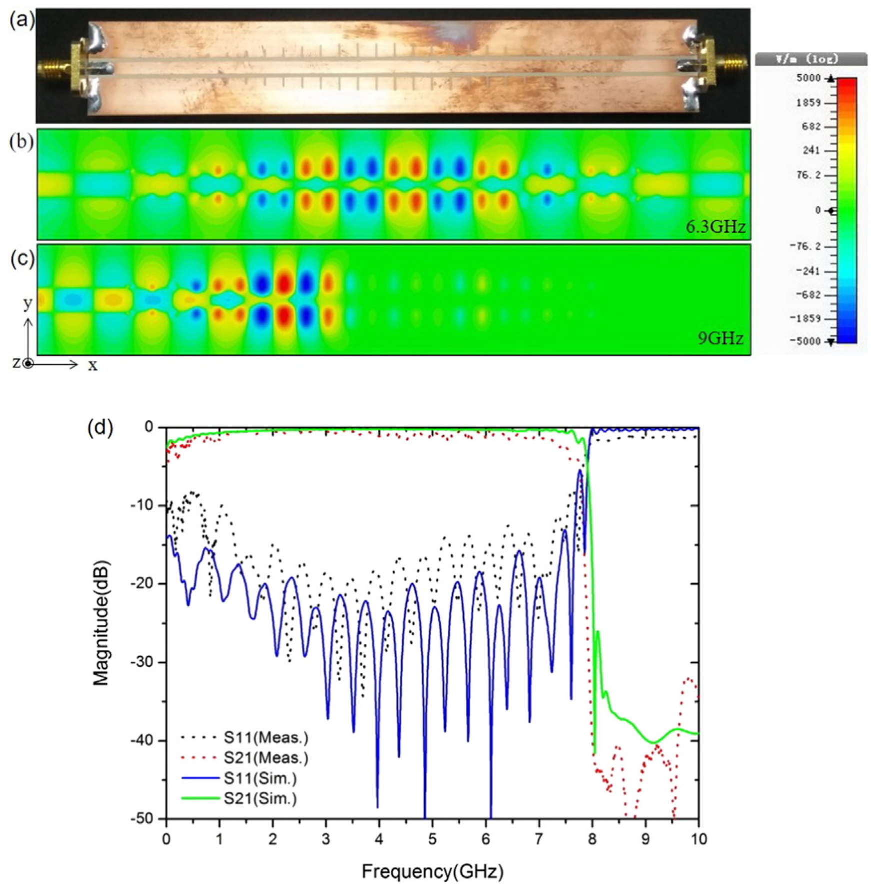

Fig. 3. (a) The plasmonic filter. The simulated electric fields distributions at 6.3 GHz (b) and 9 GHz (c). (d) The simulated (solid lines) and measured (dotted lines) S parameters of the filter.

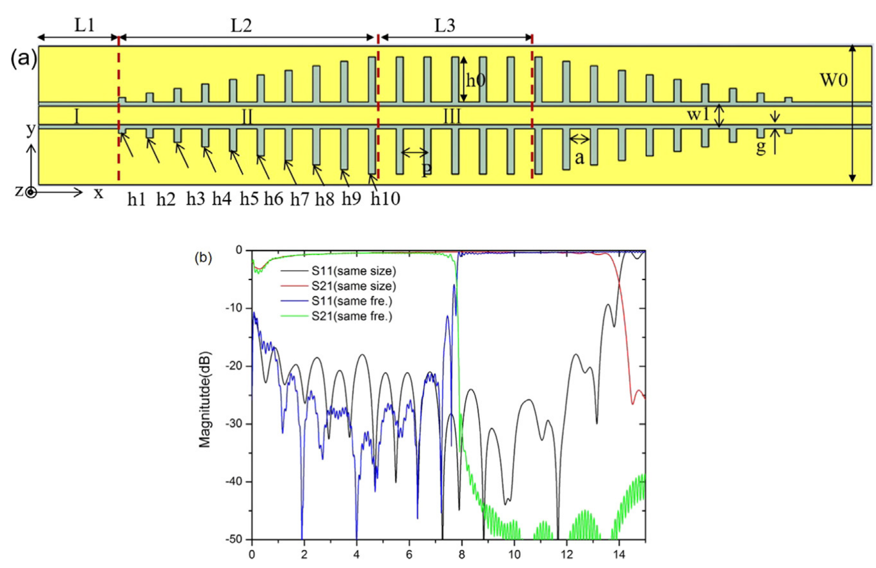

Fig. 4. (a) The schematic configuration of the plasmonic filter with Rogers 5880 as the substrate, in which $w1=4$ mm, $g=0.2$ mm, thickness of the dielectric substrate $t=1$ mm. Depths of grooves in Region II increases from $h1$ to $h10$ with the same step. (b) The simulated S parameters of the filter with the same grooves' depths ($h1=0.3$ mm, $h10=3$ mm and $h0=3$ mm) of that in Fig. 2(a) and the filter with enlarged grooves' depths ($h1=0.65$ mm, $h10=6.5$ mm and $h0=6.5$ mm) to achieve the same cut-off frequency of the one in Fig. 3(d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Miniaturization of the plasmonic filter with T grooves

From the above design we find that the cutoff frequency of the filter is determined by the asymptotic frequency of SSPPs, which can be tuned by the depth of grooves at will. However, the asymptotic frequency of SSPPs is not only determined by the depth of grooves as Region III in Fig. 2(d), but changed with the material of the substrate dielectric. If we use Rogers 5880 (with relative permittivity $\varepsilon_r = 2.2$ and the loss tangent $\tan\delta = 0.0009$) instead of Rogers 6010 as the substrate and keep all the geometric

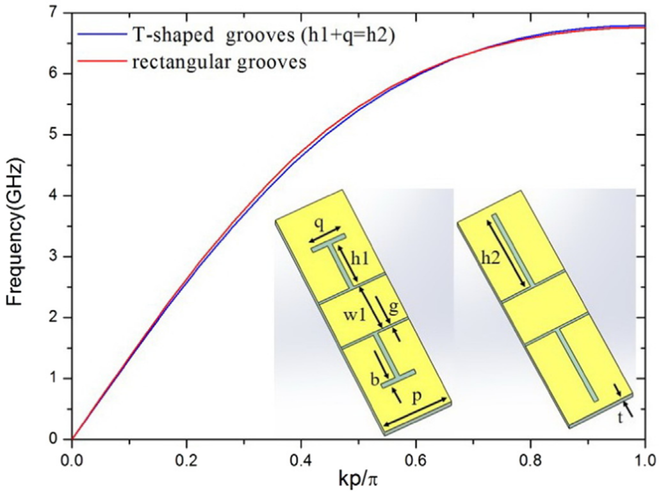

Fig. 5. The dispersion curves of the unit cells with T-shaped and rectangular grooves respectively, in which $p=6$ mm, $b=0.4$ mm, $g=0.2$ mm, $w1=4$ mm, $t=1$ mm, $q=3$ mm, $h1=4$ mm, $h2=7$ mm and $h2=h1+q$.

parameters of grooves unchanged, the asymptotic frequency of the SSPPs as well as the cutoff frequency of the filter will also change. The simulated S parameters (black and red curves) are shown in Fig.4(b), from which we can find that the cutoff frequency rises to 14 GHz. If we want to keep the cutoff frequency as 7.9 GHz with Rogers 5880 substrate, the depth of grooves h must be set as 6.5 mm and the simulation results are given as green and blue curves in Fig. 4(b).

Thus, as h increases, the dimension of the filter will become much larger, which demands structure miniaturization. A bent structure to increase the effective height of metal was proposed [27] to decrease the cut-off frequency of SSPPs. Here we utilize a T-shaped groove structure shown as the inset in Fig. 5 to increase the equivalent depth of the grooves, in which $h1 = 4$ mm and $q=3$ mm. Meanwhile a unit cell with straight grooves is also given as a comparison and the depth of grooves $h2 = h1 + q$. The substrate is selected as Rogers 5880 and the other basic geometric parameters of the two unit cells are set the same $p=6$ mm, $b=0.4$ mm, $g=0.2$ mm, $w1 = 4$ mm, $t=1$ mm. We calculate the dispersion curves of the two unit cells shown in Fig. 5 and find that the two curves agree with each other quite well, which indicates that the T-shaped groove unit cell has nearly the same asymptotic frequency and field confinement as the straight groove unit cell. In this way, the filter miniaturization can be achieved.

We also design and fabricate a sample of the plasmonic filter with T-shaped grooves in Fig. 6(a), in which $p=6$ mm, $q=4$ mm and $h=4$ mm, $b=0.2$ mm, $c=0.5$ mm. Gradient grooves vary from 0.5 mm to 4 mm with a step of 0.5 mm. During the design we find that large value of b will have a negative effect on transmission performance and set it as 0.2 mm. The simulated and measured S parameters in Fig. 6(d) show that the filter has a cut-off frequency of 7.5 GHz and the electric field distributions at in band frequency 6 GHz and out of band frequency 9 GHz are shown in Fig. 6(b) and (c), which validate our design above.

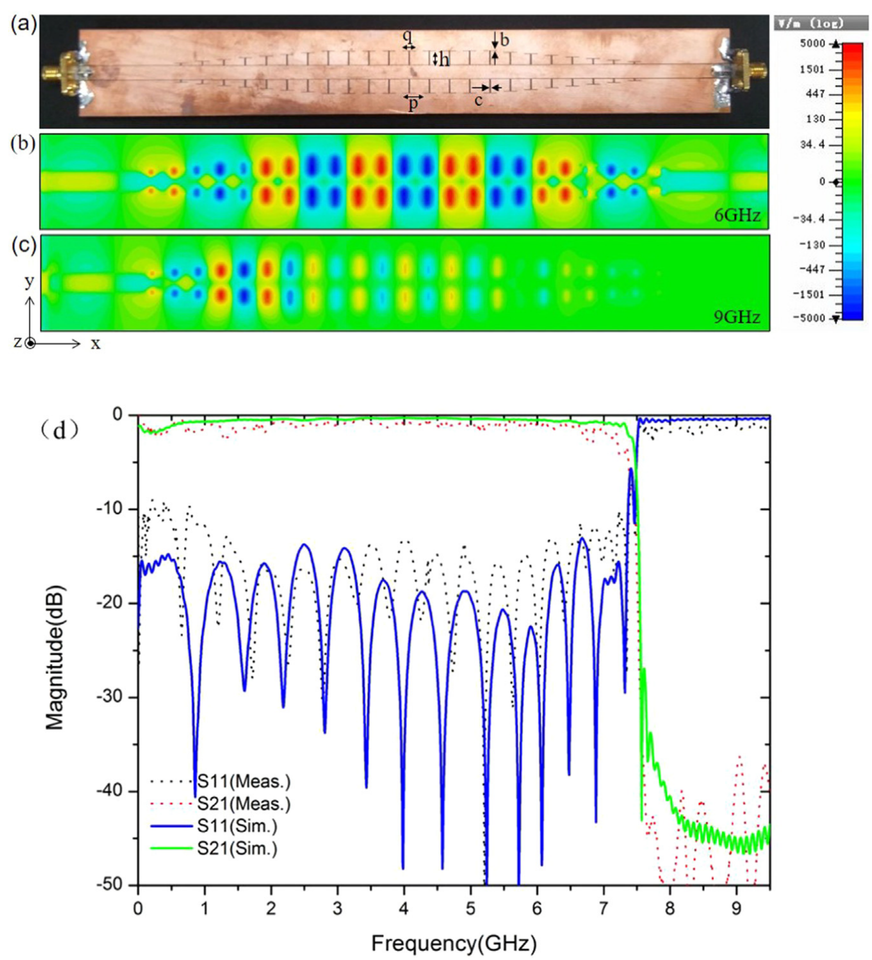

Fig. 6. (a) The schematic configuration of the spoof SPP waveguide with T-shaped grooves. Electric field distributions simulated at 6 GHz (b) and 9 GHz (c). (d) The simulated and measured S parameters of T-shaped grooves filter.

5. Conclusion

In summary, a simple low-pass plasmonic filter is proposed with the cut-off frequency determined by the depth of the grooves. To further miniaturize the filter, T-shaped grooves are used instead to lower the equivalent asymptotic frequency of the SSPPs that are supported by the plasmonic waveguide. Experimental results agree quite well with the simulation ones, which validates our design. This kind of design can find potential applications in plasmonic circuits and systems.

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