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RESEARCH ARTICLE

Spoof surface plasmon polaritons characteristics of band-stop slot resonators

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Abstract

By periodically patterning the conductor surface, the so-called spoof surface plasmon polaritons (SSPPs) in microwave band can be transmitted and SSPP mode devices with the cutoff frequency at high frequency end can be constructed. In this paper, the spiral slots are loaded in the edge and the feed port of a printed monopole antenna element and two rejection bands are achieved. The results indicate that in the intuitive physical sense, the slot-typed band-stop resonator in antenna structure actually works according to the SSPP mode mechanism. Furthermore, it is proposed that its structure size should be determined according to the principle that the slot resonant frequency is a bit lower than the asymptotic frequency of SSPP modes.

KEYWORDS

periodic cell structure, printed monopole antenna, slot-type band-stop resonator, spoof surface plasmon polaritons

1 | INTRODUCTION

Surface plasmon polaritons (SPPs) are electromagnetic modes caused by the coupling of free electrons on the metal surface and photons, and can propagate constrainedly along the interface.[1–3] In optical frequency band, metal behaves as a dispersive medium with negative permittivity. However, in the terahertz to microwave frequency range, metal is close to a perfect electric conductor, and electromagnetic fields cannot penetrate into the metal and resonate with free electrons. Nevertheless, by etching subwavelength-sized one- dimensional periodic grooves or two-dimensional periodic holes in the metal surface, mimicking SPP modes can be transmitted in this frequency range.[4–8] The special electromagnetic modes propagating on the periodic structures are also called SSPPs.

The SSPP transmission line can also be built using an ultra-thin conductor layer to realize a planar microwave circuit without the need of grounding metal for field confinement. In this regard, periodic cells are mostly based on the H-shaped conductor strip or its deformed structure.[9–12] It is conceivable that the slot periodic unit as its complementary structure should also be able to transmit SSPP modes. In essence, H-shaped conductor unit corresponds to the periodic structure of open slot. However, the complementary slot unit pays more attention to the size adjustment of the slot, rather than of the conductor strip. In addition to the complementary structure based on open slots, a periodic unit based on closed slots can also be constructed. Therefore, we analyze the SSPP mode characteristics of the open-slot and closed-slot periodic structure, respectively, and provide a theoretical basis for the periodic cell construction from another angle. To reduce structure size, the spiral slot is used as the periodic unit discussing its dispersion characteristics, and then they are loaded on the printed monopole antenna for application verification.

Printed monopole antenna is the commonly used antenna structure to realize ultra-wideband (UWB) communications and indoor positioning. It improves impedance and pattern bandwidth through the gradual structure of the radiator.[13–15] However, its ultra-wide frequency band may interfere with other communication systems such as 5th generation wireless communications or WiMAX (world interoperability for microwave access). In this case, UWB antennas with band-stop function are proposed, and most of them are realized by embedding slot resonators.[16–18]

Considering the high-frequency cutoff characteristics of SSPP mode and the strong confinement of its periodic structure to electromagnetic fields, in this paper, spiral slot units are introduced into the radiating element edge and feed port of the UWB antenna to achieve the nonradiation bands and also verify the transmission feature of the corresponding SSPP mode. Since the confinement ability of the slots loaded at the boundary of the conductor strip and loaded inside the conductor layer is different, the dispersion characteristics of their units are analyzed separately.

2 | SSPP UNIT WITH SPIRAL SLIT

The periodic units are constructed on the F4BM dielectric substrate with a thickness of 0.8 mm, a permittivity of 2.2, and a loss tangent of 0.001. The unit structure with the opening slot at the conductor layer edge is shown in Figure 1A. The unit period is $p = 5.0$ mm, the substrate height $L = 30.0$ mm, and the conductor strip height $H = 9.5$ mm. The slot width of the spiral slot is 0.5 mm, and there are five slot arms. The lengths of each section rotating inward from the opening are $S_1 = 3.5$ mm, $S_2 = 3.0$ mm, $S_3 = 2.5$ mm, $S_4 = 1.5$ mm and $S_5 = 1.0$ mm, and thus the total spiral arm length is $S_L = 11.5$ mm.

Similar to the spiral structure of conductor strip, the asymptotic frequency of dispersion curve is reduced as increasing the total length of slot arms. However, the introduction of the fourth and fifth slot arms will mainly increase the backward wave caused by the coupling effect and may show a negative group velocity, making the asymptotic frequency drop not obvious.[19] Considering that this slot unit will be loaded at the side edge of the antenna element, the dispersion variation with the metal layer height H is given as shown in Figure 1C. It can be seen that the dispersion curves do not change with the height H, and the asymptotic frequency f_a is about 5.4 GHz. This indicates that when it is loaded at the antenna element, it should be possible to form a radiation stop band near this frequency point, and the change of the radiating element radius R will not significantly affect this notch frequency.

A spiral slot can also be loaded inside the antenna element, especially near the feed port, which corresponds to a closed spiral slot unit. The periodic unit structure with the spiral slot inside the conductor layer is shown in Figure 1B. This spiral slot size is the same as Figure 1A, and the height of the metal layer is also $H = 9.5$ mm. The influence of the distance h between the spiral slot and the upper side edge of the metal layer on the dispersion is also shown in Figure 1C. It can be seen that the dispersion curves also overlap each other, while the asymptotic frequency is 11.2 GHz. Therefore, if the slot is embedded in the feed location, it should be able to achieve the notch effect at the high-frequency end. The overlapping characteristics of the dispersion curves indicate that the depth of the spiral slot embedded in the metal has little effect on the stopband frequency. However, it must be placed near the feeding position.

3 | BAND-STOP UWB ANTENNA

The printed monopole UWB antenna with coplanar waveguide (CPW) feedline is designed on the same F4BM substrate, as shown in Figure 2A. The dimension of this initial antenna is $W \times V = 30.0 \text{ mm} \times 38.3$ mm. The width of CPW central conductor strip is $F = 2.5$ mm, the spacing between the conductor strip and the ground plane $t = 0.5$ mm, so that the input impedance of CPW is 50 Ω. The radius of the circular radiator patch is $R = 14.0$ mm, and the distance between it and the ground plane is $g = 0.4$ mm.

The impedance performance of the initial monopole antenna is shown in Figure 2D. It can be seen that the band range with S_{11} less than –10 dB can reach within 2.6–14.0 GHz. The surface current distributions at 3.0, 9.0, and 12.0 GHz are shown in Figure 3, corresponding to the TM_{10}, TM_{20}, and TM_{30} modes of the antenna element, respectively. This indicates that the antenna band broadening is achieved by the superposition of adjacent resonant modes. Meanwhile, it is

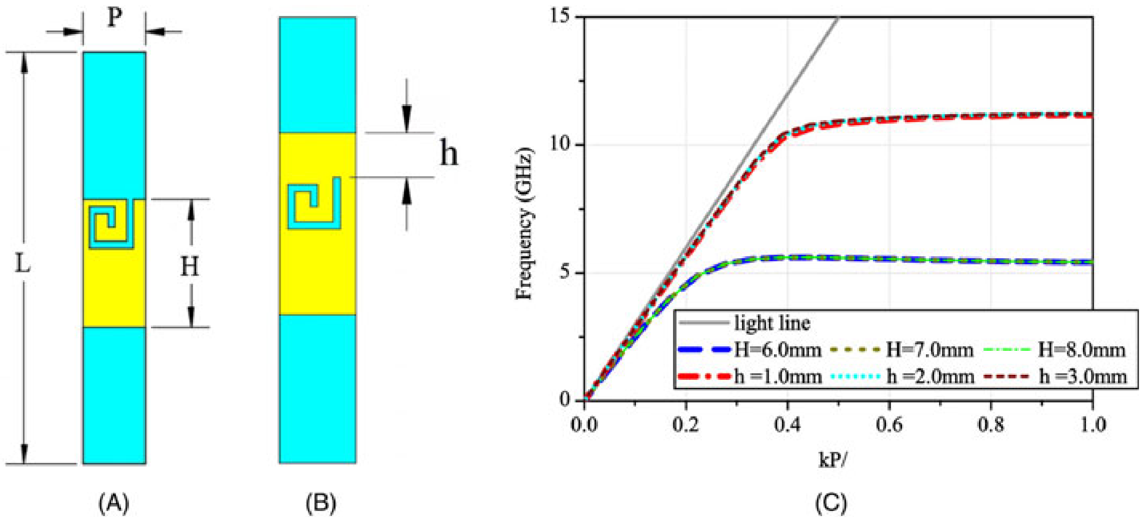

FIGURE 1 Periodic unit structures of (A) open spiral slot and (B) closed spiral slot where yellow is for copper layer and blue for dielectric substrate, and (C) their dispersion characteristics

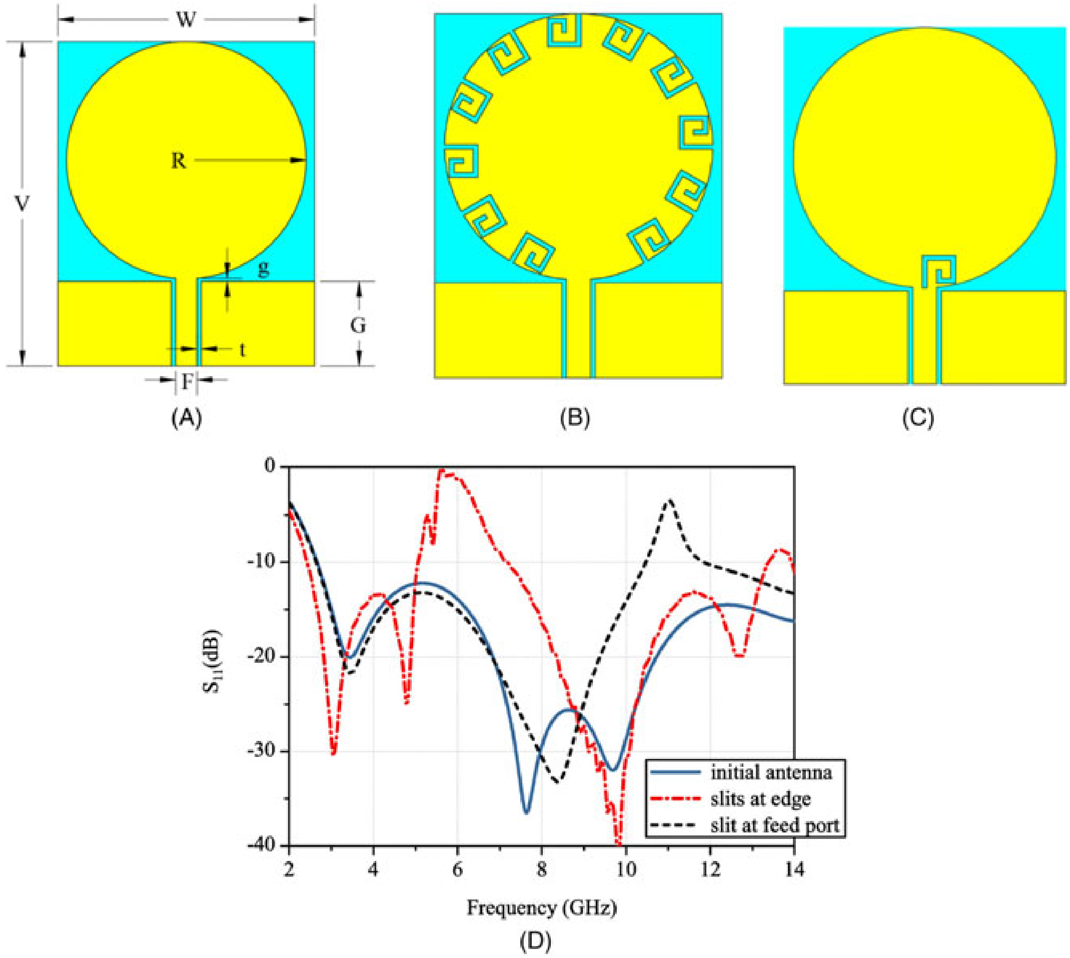

FIGURE 2 (A) Initial printed monopole antenna structure, (B) antenna with spiral slots at the side edge of radiating element, and (C) antenna with spiral slot loaded at the feed port, and (D) their input impedance characteristics

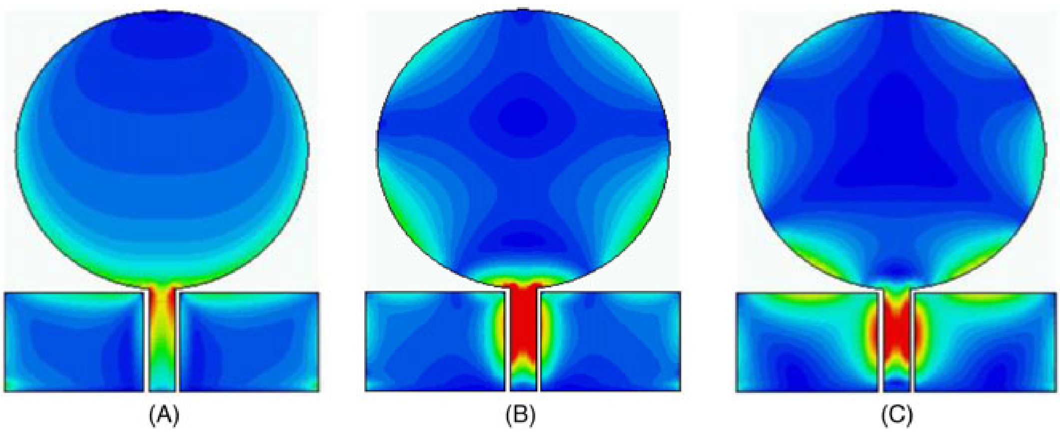

FIGURE 3 The current distributions of the initial printed monopole antenna at (A) 3.0 GHz, (B) 9.0 GHz, and (C) 12.0 GHz

also explained that by introducing a notch structure on the radiation side or the feed port, it should be possible to achieve a stop band within the broadband.

The antenna structure with the spiral slots loaded at the circular patch edge is shown in Figure 2B. The 11 periodic units in total are evenly distributed at a rotation angle of 30°. In this case, there is no slot loading near the connection position between the feedline and the circular patch. As shown in Figure 2D, compared with the initial antenna, the structure with side-loaded slots produces a stop band of 5.1–7.1 GHz, and the center notch frequency f_n is about 5.5 GHz, which is close to the dispersion asymptotic frequency. This shows that as the side edge of the patch element is loaded with spiral slots, the SSPP modes can be propagated along the edge below its asymptotic frequency, and the radiation stop band can be realized above the asymptotic frequency.

It is shown in Figure 1C that an SSPP mode with a high asymptotic frequency can be realized when the same spiral slot is loaded into the conductor layer. Therefore, a single spiral slot is introduced near the feed port as shown in Figure 2C to obtain a rejection band at high frequency end. We can see from Figure 2D that the stop band of 10.5–11.9 GHz is occurred in this case, and the best notch frequency is 11.1 GHz, which basically corresponds to the asymptotic frequency of the SSPP mode. In previous explanations, it was mostly said that the band stop of the antenna was caused by the resonance of the corresponding slot. This statement is actually very vague and not convincing. Now we see that the band stop is controlled by the field confinement of SSPP modes, and the physical meaning is clear.

The printed monopole antenna with two kinds of spiral slots at the same time should produce dual band stop. To this end, the antenna structure with 12 slot units uniformly loaded at the circular patch edge can be used. Combining the current distributions in Figure 3 and band rejection characteristics shown in Figure 2D, it can be completely confirmed that the radiation of the printed antenna is determined by the edge side currents. Therefore, removing the conductor in the center part of the circular patch to form a loop structure should have little effect on the radiation performance. In fact, the circular patch with spiral slots loaded at the edge can be regarded as a bent SSPP transmission line constructed with spiral slot as unit structure and a radius $R = 14.0$ mm as a conductor height H. Thus, for loop structure radiator, the loop patch width H can have a large range of variation according to the results shown in Figure 1C.

In this regard, the antenna structure as shown in the inset of Figure 4 is finally constructed. The radiator is a ring patch with an inner radius of 7.0 mm and an outer radius of 14.0 mm. The scattering parameters are measured using the vector network analyzer AV3629D and the results are shown in Figure 4. It can be seen that, compared to the initial antenna, this spiral slot-loaded antenna does produce notches in the two frequency bands, 5.0–7.1 GHz and

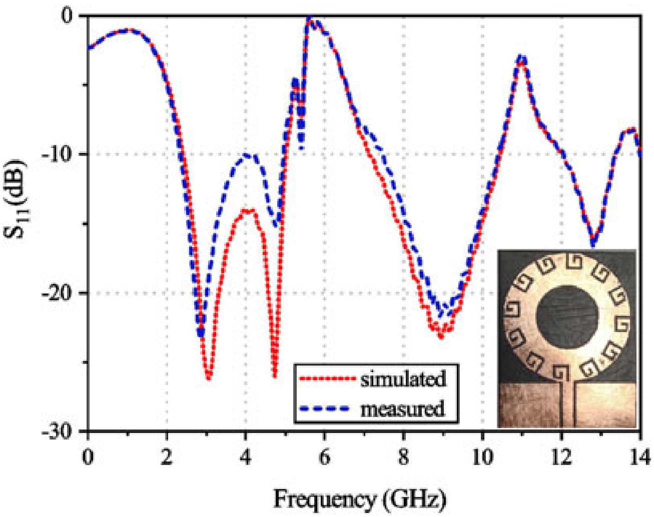

FIGURE 4 The final antenna structure (the inset) and its impedance characteristics

TABLE 1 The resonant frequency f_r, antenna notch frequency f_n, and SSPP asymptotic frequency f_a corresponding to two slot structures

Slot structure	f_a	f_n (Notch band)	f_r
λ/4 open slot	5.4 GHz	5.5 GHz (5.1–7.1 GHz)	5.1 GHz
λ/2 closed slot	11.2 GHz	11.1 GHz (10.5–11.9 GHz)	10.4 GHz

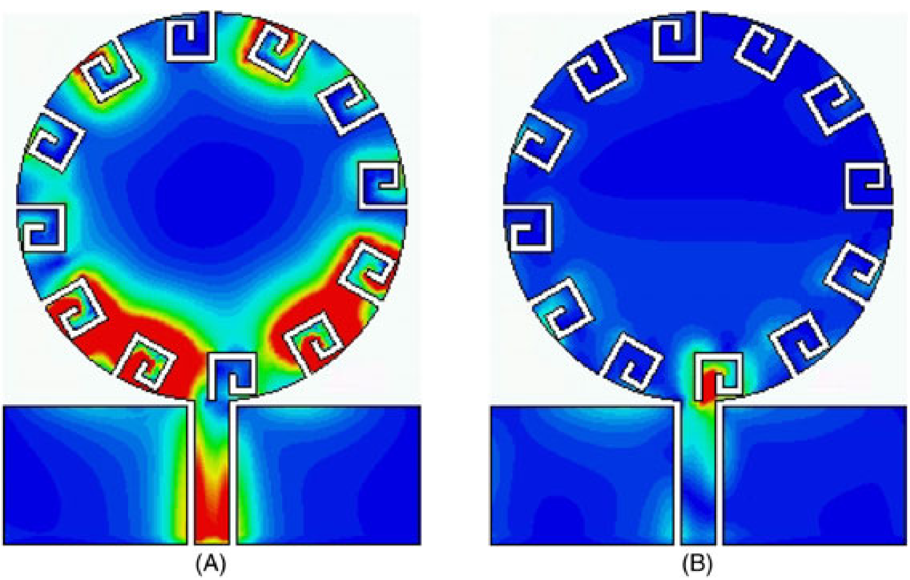

FIGURE 5 Current distributions of dual stopband antennas at two notch frequencies of (A) 5.5 GHz and (B) 11.0 GHz

10.4–12.0 GHz. The corresponding best notch frequencies are 5.5 GHz and 11.0 GHz, which correspond well to the frequency points as two kinds of slots are loaded independently. It can be inferred that for this dual band-stop antenna, the two stop bands can be adjusted independently without affecting each other.

4 | ANALYSIS AND DISCUSSION

From the perspective of slot resonance, as the antenna element is loaded with a slot to generate a notch, the center frequency of the notch band should be equal to the slot resonance frequency. For the closed slot of length l, it works as a 1/2-wavelength bandstop resonator and the resonance frequency should satisfy $f_r = c/\left(2l\sqrt{\varepsilon_{eff}}\right)$, where c is the light speed in vacuum and ε_{eff} is the equivalent permittivity. Thus the closed slot of $S_L = 11.5$ mm will resonate at $f_r = 10.4$ GHz. This resonant frequency f_r, as well as the corresponding antenna notch frequency f_n and the asymptotic frequency f_a of the SSPP mode are listed in Table 1. Similarly, various frequencies corresponding to the open slot as a 1/4-wavelength resonator are also listed in Table 1.

According to Table 1, the antenna notch frequency for each type of slot units is basically the same as the corresponding asymptotic frequency. This indicates that the SSPP transmission mode and band gap have been generated on the periodic slot units in the antenna structure. The notch frequency range centering at the asymptotic frequency corresponds to the forbidden band of the SSPP mode. Since they are higher than resonance frequencies of the slots, it is indicated that the antenna stop band is not just determined by the slot resonance. Furthermore, as shown in Figure 5, the currents at two band-stop frequency points are localized around the spiral slots at different positions, and the size of the occupied zone is also different. This indicates that the two kinds of slots have different band-stop resonance essences. When the operating frequency is lower than the asymptotic frequency, the currents on the antenna element behave as the SSPP modes, and their confinement ability decreases with the wavelength increase. Coupled with the open distribution of the slot units on the side edge of the antenna element, the SSPP modes can achieve effective radiation.[20]

5 | CONCLUSIONS

In summary, the electromagnetic confinement of the SSPP waveguide unit based on the slot structure is essentially the same as the band rejection effect of the slot resonator. In other words, the band-stop resonance of the slot structure is connected to the physical connotation of its SSPP mode. However, the resonant frequency of the opening λ/4 slot or the closed λ/2 is a bit lower than the asymptotic frequency of the corresponding SSPP modes. For structure compactness, the slot can be wound into a spiral shape. As the slot units are uniformly loaded on the side edge and feed port of the printed monopole antenna, it is easy to realize the UWB performance with double band stop. This analysis method that the band-stop characteristics of the slot resonator are explained by SSPP modes can also provide a clear design guide of the slot-typed SSPP waveguide. That is, the slot-typed SSPP waveguide device should be constructed according to the slot resonance frequency slightly lower than the asymptotic frequency.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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