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Endfire Antenna Based on Spoof Surface Plasmon Polaritons

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Abstract—We proposed an efficient method to radiate the spoof surface plasmon polaritons (sspps) to the endfire direction, which added two parasitic strips as directors in front of the dipole antenna fed by the sspps structure. The directors were used to enhance the endfire radiation due to its beam modified function. Both simulated and measured results suggest good performance of the proposed antenna in a narrow band from 6.5 to 6.9 GHz with about 7.5 dBi realized gain and a 5 dBi increase in the endfire direction at the center frequency of 6.8 GHz reference to the unloaded structure. Also, the surface electric field distributions of the unloaded and loaded sspps antenna were studied to verify the gain enhancement in the endfire direction in physical perspective. Our work tends to have better performance than other related work, such as broader bandwidth and higher realized gain with even greatly simplified design process. The proposed sspps antenna has potential applications in planer integrated circuits and communication systems.

1. INTRODUCTION

Spoof surface plasmon polaritons (sspps) have been a hot spot since Pendry et al. theoretically proved that periodically patterned structures had the ability to guide sspps waves in microwave and gigahertz frequency [1], which acted like natural spps (surface plasmon polaritons) in optical frequency. Due to the better characteristics of sspps than a microstrip line, such as low loss, high field confinement, single conductor configuration and the ability to keep signal integrity [2, 3], a great number of microwave devices based on sspps have been reported, such as sspps-based filters [4–11], power splitters [12, 13] and antennas [14–20], which will all make a difference in sspps-based wireless communications and other systems.

An sspps-based antenna is of vital importance in the sspps communication system, and some inspiring works have been done based on it. For example, Bai et al. realized a leaky-wave antenna using circularly patch array which was fed by the sspps structure [20], and Yin et al. achieved the radiation of sspps waves by a Vivaldi antenna and sspps feeding structure [16]. Although these structures are kind of bulky or complicated, they have opened an avenue to the application of sspps structures in antenna area. We hope to find a simple radiator to make the sspps wireless system more applicable, and the printed dipole antenna would be an ideal choice as its convenient fabrication and easy integration with the RF circuits. Indeed, it has been the mostly used and fundamental antenna because of its good characteristics. However, the dipole antenna has the defect of low gain performance in microwave and teraherz frequency. Fortunately, there are ways to overcome these defects, such as metamaterial loaded structure which has significant performance improvement. Yin et al. have used this method to enhance the gain of the endfire radiation of dipole antenna feed by sspps [15]. And directors loaded structure has been widely reported in dipole antenna high gain situation.

In this work, a simple design using directors loaded dipole antenna fed by sspps was proposed to achieve gain enhancement of endfire radiation. Sspps were utilized as a feed line. The radiator was

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realized by the printed dipole, and two directors were used to achieve gain enhancement in the endfire direction. The measured results have demonstrated great performance of the proposed structure, and they coincided well with the simulated ones, suggesting good performance of the proposed antenna from 6.5 to 6.9 GHz. About 7.5 dBi realized gain was realized at 6.8 GHz and was 5 dBi higher than the unloaded antenna. The narrowband is the characteristic of the quasi-Yagi antenna and dipole antenna which cannot be changed much. However, the directors loaded endfire antenna has much broader bandwidth and higher gain than the metamaterial loaded endfire antenna [15]. Also, the proposed endfire antenna has much simpler structure, while the metamaterial loaded endfire antenna has very complicated designing process. This is the first time that directors were used in the sspps antenna to achieve gain enhancement.

2. OPERATING PRINCIPLE

The proposed sspps antenna is shown in Fig. 1 with overall size of 32 mm∗100 mm, which was fabricated on a Rogers 5880 substrate with substrate thickness of 0.787 mm and copper thickness of 0.018 mm. The dielectric constant and loss tangent are 2.2 and 0.0009, respectively. The proposed structure can be divided into four parts, the microstrip part, the sspps transmission line part, the printed dipole part and the directors loaded part. The top layer metal structure is totally the same as the bottom layer except the opposite configuration directions in the sspps transmission line part, which is depicted explicitly in Fig. 1. The square and tapered parts were designed to achieve the impedance matching of 50 Ω with the coaxial cable to realize low reflection coefficient in the considered frequency range and to match the sspps transmission part, in which the parameters are set as follows: $w_1 = 10$ mm, $w_2 = 1.6$, $l_1 = 5$ mm and $l_2 = 10$ mm. After a series of optimization, the parameters of the gradient groove in the transition part are set to be varied from 0.2 to 1.2 to realize the impedance and momentum matching between the microstrip line and the sspps transmission line. The transmission characteristics of the sspps transmission line is determined by the dimensions of the unit cell of the sspps part. Finally, the period, width and depth of the unite cell are chosen as follows: $p = 2.6$ mm, $a = 1.2$ mm, $b = 1.4$ mm and $h = 1.2$ mm. When the central frequency of the system is expected to be 6.8 GHz, the length and width of the dipole antenna should be set as $l = 12$ mm and $w = 1.6$ mm after optimization.

Figure 2 describes the simulated radiation patterns of the sspps antenna without loads. The red line

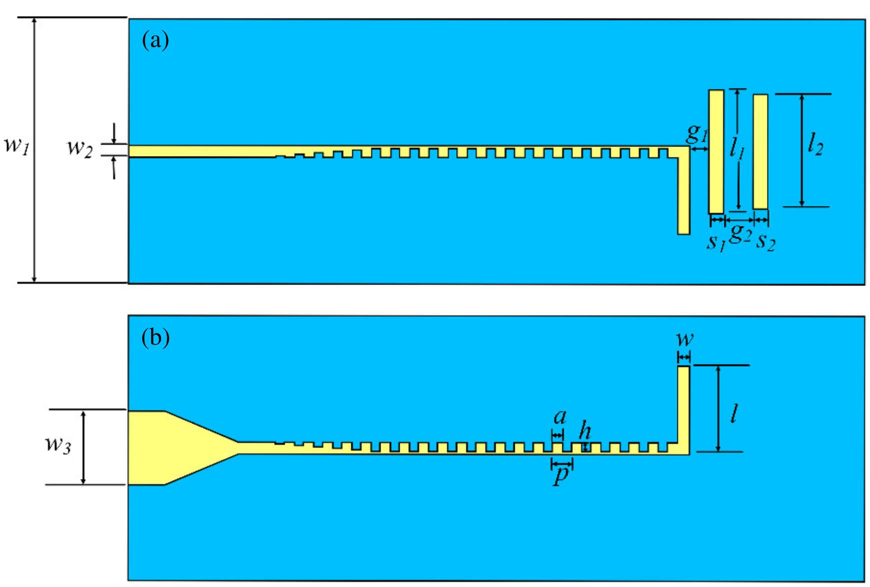

Figure 1. Schematic picture of the proposed endfire spoof radiation system. (a) Upper configuration of the structure. (b) Bottom configuration of the proposed structure.

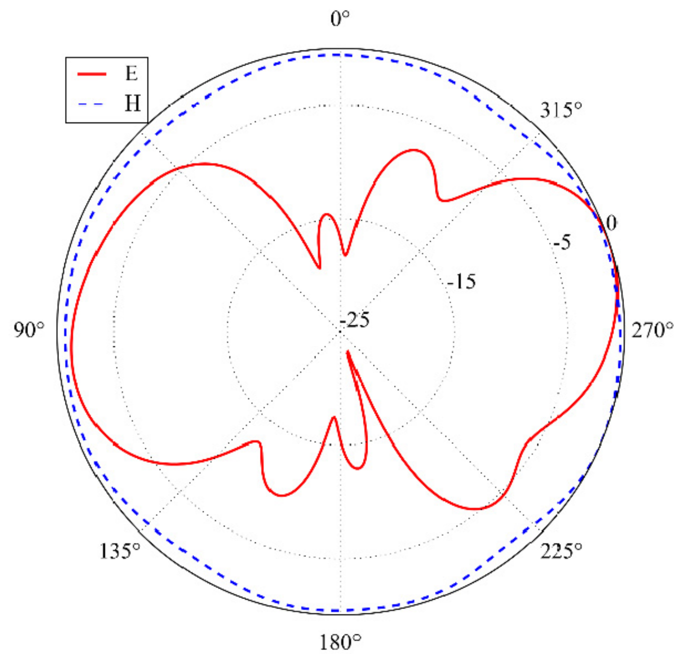

Figure 2. Simulated radiation of the unloaded sspps antenna, in which the red line indicate the E-plane radiation pattern while the black line depicts that of the H-plane.

represents the E-plane radiation pattern, and the blue line indicates the H-plane radiation pattern. We can conclude that the radiation pattern is similar to the traditional dipole antenna. The bad radiation pattern and low gain result from the scattered beam. In order to improve the antenna's performance, the directors were loaded to focus the beam and enhance the gain of the antenna.

Figure 3 shows the sketch map of the configuration directors. If all the impedance Z_{ij} is known, the current I_i can be calculated according to the following Equation (1), and then the total realized radiation pattern could be obtained. During the design process, the distance and length of the directors should be optimized to make I_i have appropriate phase, which would result in that the superposition of radiation pattern in the endfire direction can be achieved. In short, since the directors were used as passive antenna and would work as antenna array with the dipole antenna, the radiation beam would appear in the phase lag direction. Consequently, the endfire radiation pattern could be realized.

$$\begin{cases} V_0 = Z_{00}I_0 + Z_{01}I_1 + Z_{02}I_2 \\ 0 = Z_{10}I_0 + Z_{11}I_1 + Z_{12}I_2 \\ 0 = Z_{20}I_0 + Z_{21}I_1 + Z_{22}I_2 \end{cases} \tag{1}$$

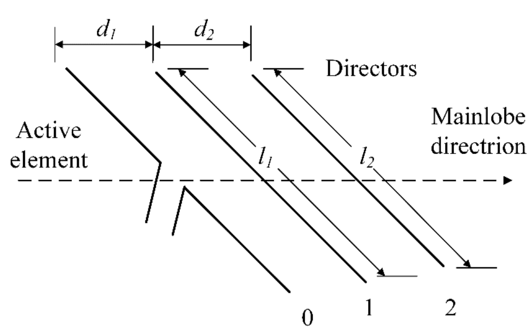

Figure 3. Design principle of the directors.

In the practical situation, the empirical equations are usually used rather than the theoretical equations. However, the empirical equation of Yagi antenna cannot be used directly here because the proposed antenna did not have a reflector compared to the traditional Yagi antenna. Hence, the length of the directors and the distance were optimized based on the parameters of empirical equation of Yagi antenna to get better results.

3. SIMULATED AND MEASURED RESULTS

In order to better understand the effects of the loaded directors, the z components of the surface electric field distribution of the unloaded and loaded sspps antenna are presented in Fig. 4(a) and Fig. 4(b). We can get the following conclusions by comparing Figs. 4(a) and (b). Firstly, the electric field distribution in the waveguide part proves the generation and transmission of the SPP wave. Secondly, comparing the surface electric field distributions of the unloaded and loaded antennas, it can be seen that the loaded directors have vital impact on the electric distribution. When the sspps antenna is unloaded with directors, the electric field distribution is quite weak in the endfire direction and focuses in the broadside direction, which indicates the broadside radiation of the unloaded antenna.

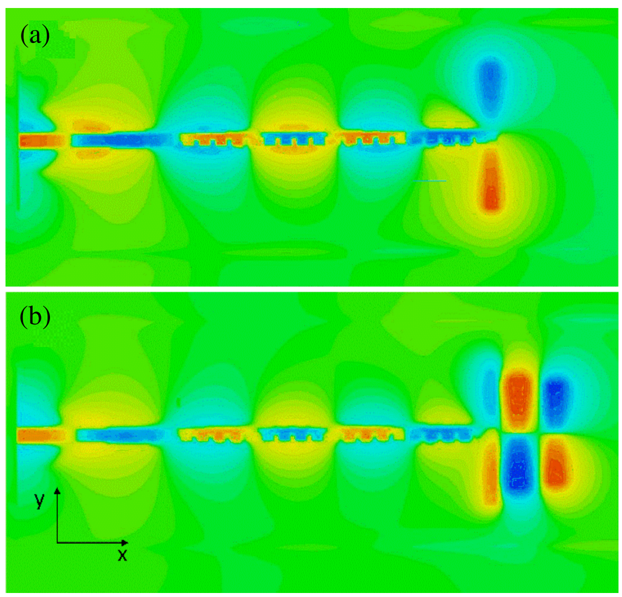

Figure 4. Simulated surface electric distribution without directors. (b) Simulated surface electric distribution with directors.

The surface electric field distribution has been greatly modified in the loaded sspps antenna to endfire direction, which is due to the reradiating of the energy coupled from the dipole antenna. Even though the loaded directors are with very simple structures, the number of the directors loaded is still limited because of the weaker coupling caused by longer distance. Compromising among the parameters of gain enhancement, cost and size, two directors loaded sspps antenna was chosen, depicted in Fig. 1. Comparing the realized gain patterns of the sspps antenna with and without directors in Fig. 5, it is clear that the gain has a nontrivial lift due to loaded directors, resulting in an 5.5 dBi improvement of the total realized gain.

The fabricated sample of the front and back sides of the proposed antenna is shown in Fig. 6(a), and the simulated and measured reflection coefficients are depicted in Fig. 6(b). The simulation was completed by the CST Microwave Studio, and the measured process was done by the Agilent vector analyzer. Except a little frequency deviation caused by the mismatch measured error, the simulated and measured reflection coefficients are generally in good accordance. For the proposed spoof sspps antenna, the reflected coefficient is less than -10 dB from 6.5 to 6.9 GHz, whose operating bandwidth is

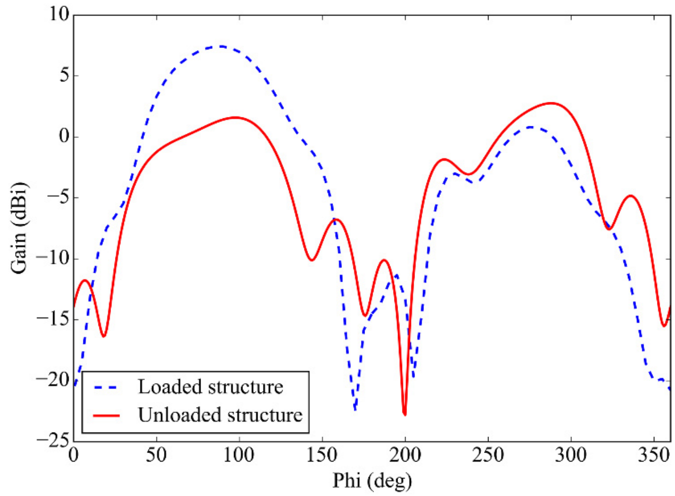

Figure 5. Simulated radiation pattern of unloaded and loaded antennas at 6.8 GHz.

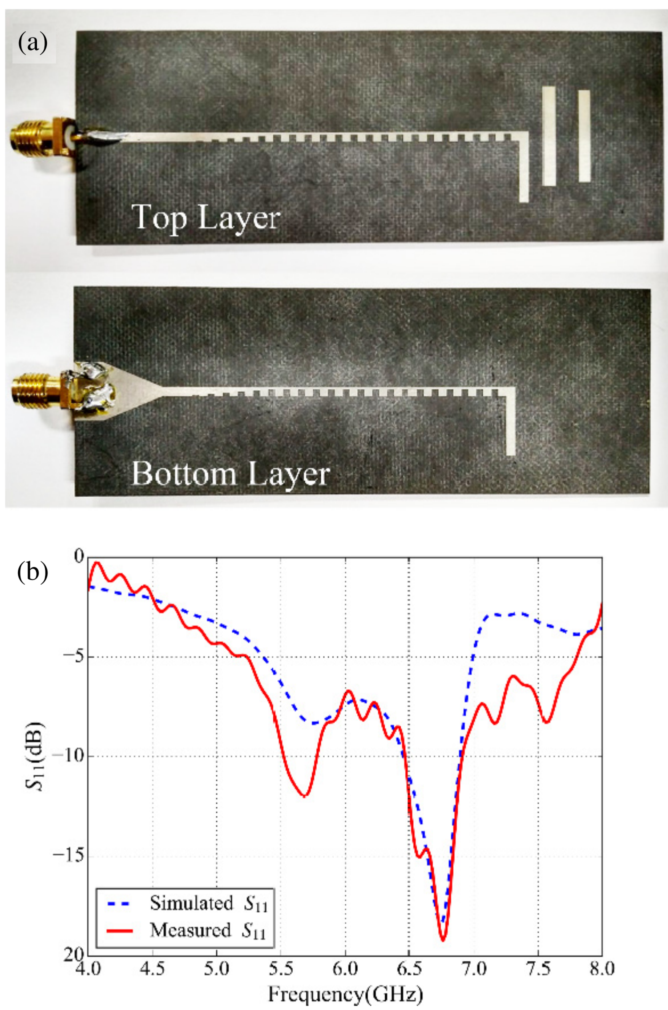

Figure 6. (a) The prototype of the proposed antenna. (b) The simulated and measured S_{11} of the proposed structure.

much wider than the I-shaped resonator (ISR) loaded sspps antenna working in nearly a single frequency point [15]. However, the bandwidth of such a structure is limited for the presence of the dipole antenna and directors both working in narrow band.

The variation of the gain curve and the realized gain curve against frequency are depicted in Fig. 7. It indicates that the realized gain reaches an average of 7 dBi while the average radiation efficiency reaches 90% in the considered frequency band. These two simulated results have proved the high efficiency of the loaded sspps antenna. Due to the limitation of the experiment instruments, the gain and efficiency curves cannot be measured. We have measured the normalized radiation pattern and presented it in the following content, which will prove the good characteristic of the sspps antenna.

To prove the radiation pattern of the proposed sspps antenna, the simulated and measured normalized radiation pattern of the proposed structure are given in Fig. 8. Comparing it with the radiation pattern of the unloaded structure in Fig. 2, obviously, the front to back ratio is largely enhanced. Also, the simulated and measured results are in good agreement, which validates the good radiation property.

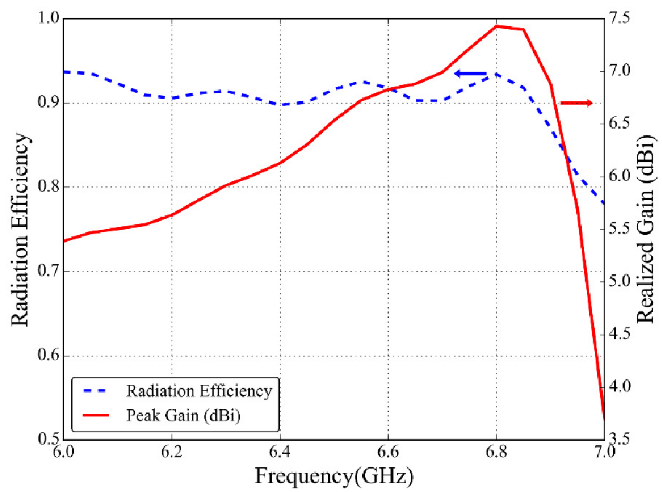

Figure 7. Simulated radiation efficiency and realized gain of the proposed structure.

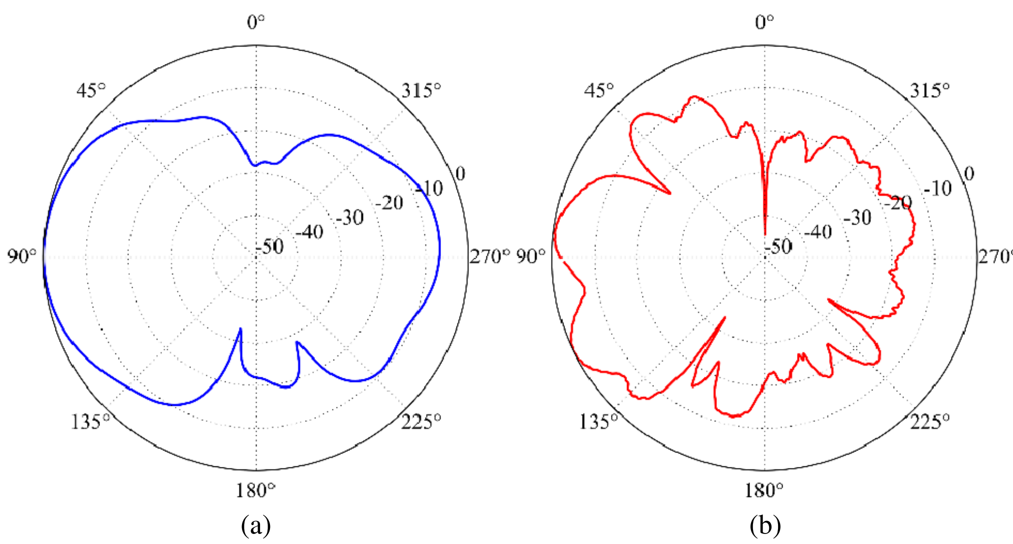

Figure 8. (a) The simulated E-plane radiation pattern of the proposed structure. (b) The measured E-plane radiation pattern of the proposed structure.

4. CONCLUSION

A new type of endfire radiation sspps antenna was proposed in the manuscript, which was loaded by two parasitic strips as directors. The gain enhancement has been proved by comparing the gain pattern of the sspps antenna loaded and unloaded with directors. Also, the endfire direction enhancement characteristic has been validated by the surface electric field distribution of the proposed antenna from the physical principle. The proposed sspps antenna has been fabricated and measured. Both simulated and measured results prove the good performance of the proposed antenna in the narrowband between 6.5 and 6.9 GHz with about 7.5 dBi realized gain and a 5 dBi increase in the end fire direction at the center frequency of 6.8 GHz. Also, the high performance of the antenna was validated by the simulated results of realized gain and radiation efficiency versus frequency. The proposed sspps antenna will have potential applications in planer integrated communication systems.

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