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A Miniaturized Co-planar Waveguide End-fire Antenna Based on Spoof Surface Plasmon Polaritons Excited Along Metal-substrate Interface

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Abstract. With the continuous development of materials technology, the microwave-excited spoof surface plasmon polaritons (SSPPs) has drew attention. In this paper, we designed a co-planar waveguide antenna based on SSPPs mode coupling excited along metal-substrate interface to achieve good effect of end-fire radiation. This antenna consists of a spearhead-shaped co-planar waveguide (CPW) monopole antenna as radiation element, a reflector made of metallic strip and a director based on SSPPs mode coupling. The director is made of suitably sized corrugated metallic strips to realize SSPPs mode coupling. The electric fields of the radiation element are coupled into director that propagate along the strips and radiate at the end. A prototype working in X-band is designed, fabricated and measured. The numerical simulation results manifest that the designed antenna can get good directivity with high gain. The antenna works at 8.6-10.8 GHz with the directivity larger than 8.71 dBi.

1. Introduction

With the continuous exploration and research of materials, many properties that are not found in nature can already be realized by using artificial materials. Among them, metamaterials are the representative [1]-[2]. Since the Pendry *et al.* first demonstrated the achievability of metamaterials in *Physical Review Letters* [3], various electronic devices made from metamaterials have emerged one after another [3]-[4]. Surface plasmon polaritons (SPPs) mode as a special propagation mode of materials is often excited at near-infrared and visible frequency which has also drew attention of researchers [5]. With the development of research, people discovered that corrugated metallic structures can be regarded as special metamaterials which have the ability to realize SPPs mode coupling in microwave frequencies. This kind of SPPs is called spoof surface plasmon polaritons (SSPPs) [6].

SSPPs are surface mode propagating along the metal-dielectric interface at microwave and terahertz frequencies which decays exponentially in the direction vertical to the interface [7]. As same as SPPs, SSPPs mode can also deliver high efficient confinement, deep sub-wavelength, and nonlinear frequency dispersion properties [5]-[7]. It has been proved that the ultrathin periodic or quasi-periodic corrugated metallic metamaterials, such as grooves, blocks, holes and slits have the ability to excite and guide SSPPs [8]-[11]. Due to the advantages that they are easy to designed and fabricated (by printed circuit board technology), the method of using SSPPs mode coupling became more and more



popular to design miniaturized microwave devices and circuits, especially antennas and their accessories[12]-[13].

Co-planar waveguide (CPW) antenna as a kind of compact sized antenna has a wide application in communications, thus it becomes a hotspot for engineering [14]. CPW is a uniplanar waveguide which consists of a median metallic strip and a grounded metallic sheet in the same plane, separated by two narrow slits [15]. This structure is not only easy to acquire miniaturization and simplification, but also has good broadband characteristics. However, it is still a difficulty to realized end-fire radiation by CPW antennas. In order to fill this gap, we devoted ourselves to it. Fortunately, the idea of resorting SSPPs mode coupling flash into our mind.

Inspired by the idea of using SSPPs mode coupling, we proposed a miniaturized co-planar waveguide antenna for end-fire radiation. In this work, we designed an omnidirectional spearhead-shaped co-planar waveguide antenna as radiation element, and an adequate length of corrugated metallic strips as director. Relying on the SSPPs mode excited by corrugated metallic metamaterials, the omnidirectional antenna becomes an end-fire antenna. In order to ensure as much energy as possible is guided by the director, we added two long metallic strips behind the omnidirectional spearhead-shaped co-planar waveguide antenna as reflector.

This paper organized as follows: Section 2 analyzed the principle of the SSPPs. Section 3 specifically describes how the antenna is designed. And the simulation results are present in Section 4. Finally, the conclusions are drawn in Section 5.

2. Principle analysis

As is well known, CPW antennas are a kind of omnidirectional antenna whose far-field patterns are doughnut shaped. Because of the energy is radiated in all directions, such antennas cannot get larger gain. However, these omnidirectional far-field patterns can be modulated into unidirectional one by attach parasitic elements in their near-field zone. The most convenient method is using director, and the gain is proportional to the length of director according to the Hanson–Woodyard condition. Furthermore, when the director is long enough, the gain enhancement is rather minor by increasing the length. Thus, optimizing the adequate length is important.

Among the design of numerous parasitic elements, the SSPPs based method is advantageous for miniaturization, design and manufacture. Here, the corrugated metallic metamaterials are selected as the component of director. The corrugations located the near-field electric field and rely on the coupling to realized end-fire. In order to satisfy the impedance matching and mode conversion, both ends of the corrugated metallic metamaterials are shaped parabolic. The Fig.1 depicts the sketch picture of the Z-component electric fields coupling (feed from the left end). As can be seen, the electric fields are confined tightly in the strips of corrugated metallic metamaterials and propagate along the strips.

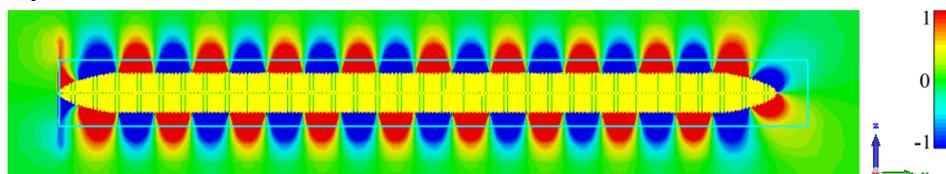


Figure 1. Sketch picture of the distribution of Z-component of the electric fields

Hanson-Woodyard condition also indicated that the optimum guided propagation constant β should be larger than which in the air. And in the dispersion curves diagram, the curve should stay below the air line within a short distance. In our design, the propagation constant β is related to the strip height h of the corrugated metallic metamaterials. The simulated dispersion relation versus the h with the structure model is shown in Fig.2. It is obvious that with the increase of h , β increases accordingly. And there curves eventually tend to be horizontal illustrate the existence of the cut-off frequency f_{cut} , the SSPPs mode will be cut-off when $f > f_{cut}$. Using the special property of the SSPPs excited by materials, a perfect transmission line can be obtained to design the director. In the subsequent design steps, the parameters are optimized to achieve good results.

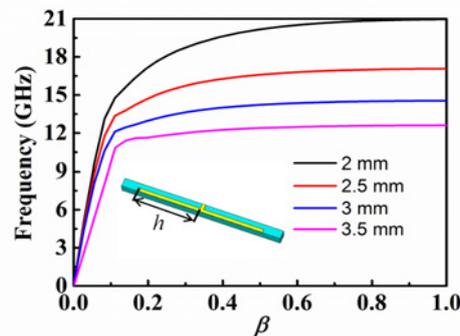


Figure 2. Simulated dispersion curves versus h , where the inset depicts the calculated model.

3. Design of the antenna

The designed end-fire antenna is mainly composed of three parts: radiation element, director and reflector. Fig.3 illustrates the front view of the end-fire antenna model.

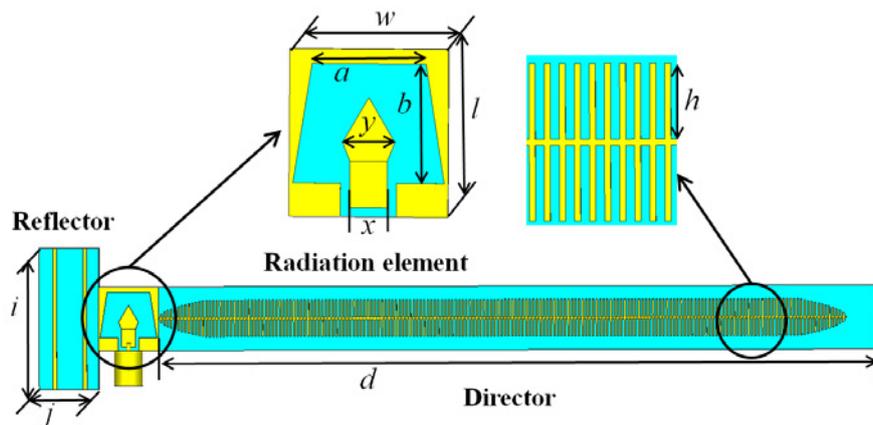


Figure 3. The front view of the designed end-fire antenna with insets of radiation element and zoom view of corrugated metallic metamaterials

3.1 Design of the radiation element

The radiation element is made of a spearhead-shaped CPW antenna and a 50Ω coaxial probe. Through a careful parameter sweep, we got the optimized structure. Where $w=8.5$ mm, $l=9$ mm, $a=6.1$ mm, $b=6.3$ mm, $x=2$ mm, $y=2.8$ mm. The performance of the radiation element is shown in Fig.4. Fig.4 (a) shows the S_{11} of the CPW antenna, it can be seen, over 8.4-11.1 GHz, the S_{11} is below than -10 dB. Fig.4 (b) depicted the 3-D far-field pattern of the antenna at center frequency. The standard doughnut shape appears as we predict above.

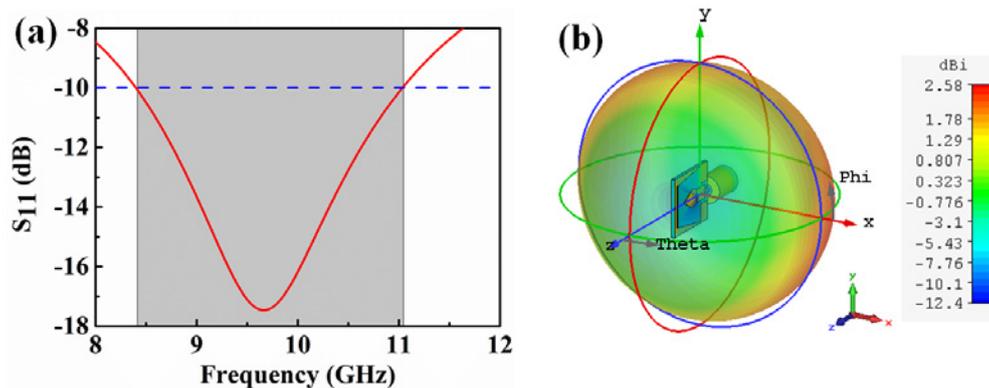


Figure 4. Performance of the CPW radiation element: (a) S_{11} , (b) 3-D far-field pattern.

3.2 Design of the director

The director is made of the corrugated metallic metamaterials. This special metamaterials are composed of corrugated copper sheet and FR-4 substrate ($\epsilon_r=4.3$, $\tan\delta=0.025$). The SSPPs mode is excited along the interface of these two materials. The spacing between each metallic strips $d_0=0.3$ mm, the width of the metallic strip $d_1=0.2$ mm, the long of the director $d=100$ mm and the height of the strips h is 3.5 mm. As the core component of the entire end-fire antenna, the director stimulated SSPPs mode let most of the energy to be transmitted in predetermined direction. Therefore, it can achieve the end-fire radiation.

3.3 Design of the reflector

Noticed that the energy radiated by the radiation element in the back direction is considerable, it is necessary to place a reflector behind the radiation element. In order to reflect as much energy as possible to the corrugated metallic metamaterials, we use double metallic strips as the reflector. The height of the reflector $i=20$ mm, the width $j=8.5$ mm. The two metal strips is 0.5 mm width with an interval of 3.8 mm.

4. Simulation results of the designed end-fire CPW antenna

To verify the feasibility of our idea, the simulated results operated by CST studio are depicted as following: We got the S_{11} of the end-fire antenna in Fig.5 (a). It obvious over 8.6-10.8 GHz the S_{11} is lower than -10 dB. Its trend is roughly the same as S_{11} of the radiation element. That manifest the end-fire antenna can work in this frequency band theoretically. But there is a little discrepancy which is due to the influence of the coupling of radiation element and corrugated metallic metamaterials. Fig.5 (b)-(f) shows the 3-D far-field pattern of the designed antenna at 8.8 GHz, 9.2 GHz, 9.6 GHz, 10 GHz and 10.4 GHz, respectively. It is obvious that a distinct main lobe can be obtained with high gain. Fig.5 (g) depicts the Z-component electric fields distribution at center frequency of the entire end-fire antenna. The electric fields are confining tightly by the corrugated metallic metamaterials and propagate along them.

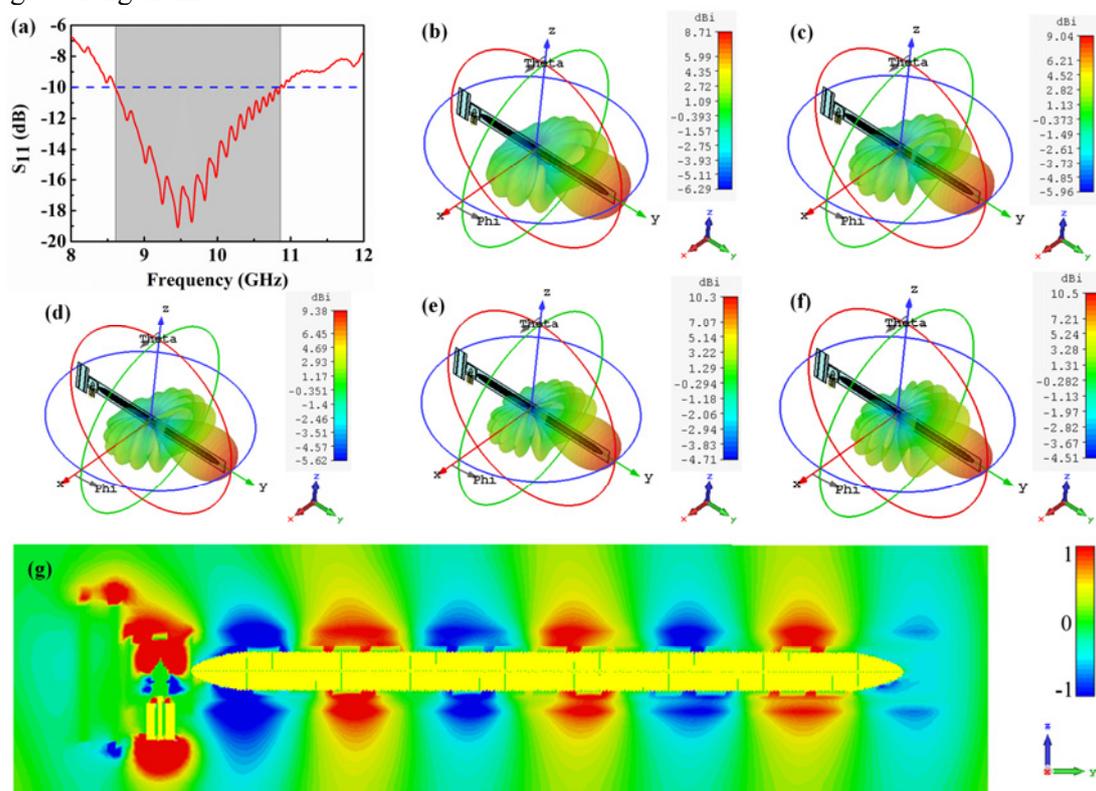


Figure 5. Performance of the end-fire antenna: (a) S_{11} , (b)-(f) 3-D far-field pattern at 8.8 GHz, 9.2 GHz, 9.6 GHz, 10 GHz and 10.4 GHz, (g) Z-component electric field distribution.

5. Conclusion

In this work, through the full exploration of the special properties of material in microwave frequency, we selected SSPPs mode coupling which is produced along metal-dielectric interface to realize the end-fire of CPW antenna. Meanwhile, we achieve a miniaturized size. The simulated results are given in the Section 4 which demonstrate our design is feasible. As a result, the designed end-fire antenna can operate at 8.6-10.8 GHz with directivity upper than 8.71 dBi.

Acknowledgments

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