Millimeter-wave Endfire Antenna Based on Spoof Surface Plasmon Polaritons

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***Abstract*—A novel spoof surface plasmon polaritons (SPPs) radiation structure is proposed to design a millimeter-wave (MM-wave) endfire antenna. The radiation aperture is constructed by gradually decreasing the grooves of an odd-mode plasmonic structure. The mechanism of the SPPs radiation through the aperture is investigated in detail. For demonstration, a spoof SPPs traveling-wave antenna is designed and measured. The results show that high gain (~15 dB) and high radiating efficiency (~90%) can be obtained at millimeter-wave frequency. The narrow beam width of far-field patterns in endfire direction indicates it is useful to construct switched beam arrays.**

Keywords—Surface plasmon polaritons (SPPs); Millimeter-wave; Antenna

I. INTRODUCTION

With rapid progress of fifth generation (5G) wireless communications, millimeter-wave (MM-wave) frequencies have attracted a great deal of attention for the capability of achieving high data rate [1]. However, the propagation loss at mm-wave band is a troubling issue. Thus, the mm-Wave antenna should be able to provide high gain, high radiation efficiency, and wide bandwidth characteristics [2].

Recently, planar spoof SPPs structures have drawn considerable interesting for the features of subwavelength confinement, slow wave, and low transmission loss. Various planar plasmonic transmission lines (TLs) and functional devices have been proposed to improve the performance of microwave and MM-wave circuits and systems [3-11]. Among them, spoof SPPs-based antennas have been designed to improve the gain by utilizing the low transmission loss of SPPs [7-9,11]. In these designs, the spoof SPPs structures only serve as the TLs, where the actual radiating elements are dipoles or patches. For a dipole antenna, director or reflector is commonly necessary to enhance its directivity, which makes the antenna bulky. Moreover, the narrow bandwidth of dipole antenna or patch antenna limits their applications.

In this study, instead of using dipole or patch as a radiator, we proposed a method of direct radiating the guiding plasmonic wave to free space through an equivalent aperture at the ends of odd-mode SPPs TLs. This approach allows us to obtain two merits, i.e. simple and compact antenna structure, by eliminating the dipole or patch used in the traditional designs. To show the feasibility of the approach, a MM-wave endfire antenna is designed and its characteristics such as far filed pattern, realized gains, and efficiency are presented.

II. DIRECT RADIATIONS FROM SPOOF SPPS TO FREE SPACE

The dispersion relationship of conventional spoof SPPs TL with groove periodicity p and groove depth h is approximated by

$$\beta = k_0\sqrt{1+\left(a / p\right)^2 \tan^2\left(k_0 h\right)} \tag{1}$$

where β is the prorogation constant and k_0 is the wave number in free space. The fields of spoof SPPs are confined at the interface of corrugated metal strip and dielectric, and exponentially decay away from the SPP TL's edges. The confinement of plasmonic surface wave is characterized by the exponential decay constant α, which is determined by the difference of β and k_0, i.e.

$$\alpha = 1\Big/\sqrt{\beta^2 - {k_0}^2}\ . \tag{2}$$

Smaller α means looser confinement on SPPs EM fields, i.e., larger extension of EM wave into free space. Equations (1) and (2) imply that tuning the groove depth h can manipulate the prorogation constant β and thus get desired decay constant α. If the groove depth is decreased, the bounded transverse EM field gradually extends into free space, as schematically shown in Fig. 1 (a). Consequently, Poynting vector becomes parallel to the x-direction, resulting in endfire radiation. Above analyses are valid for the SPPs TL with an infinite metal strip in the low half space as shown in Fig. 1 (a), where the transvers fields (E_y and H_z) are asymmetrical about the *xoz* plane. Therefore, an equivalent flared-out aperture, which is similar to that in a half-horn antenna, comes into being at the ends of the SPPs TL. With decreasing the decay constant α, the equivalent aperture becomes larger. Unfortunately, for an actual SPPs TL with a finite thickness metal strip, the transverse EM fields (E_t and H_t) of the dominant mode are always mirror symmetrical (even-mode) about the *xoz* plane, as shown in Fig. 1 (b). The opposite EM fields (E_t and H_t) distributing in the up-aperture and the low-aperture cause the opposite orientation of equivalent

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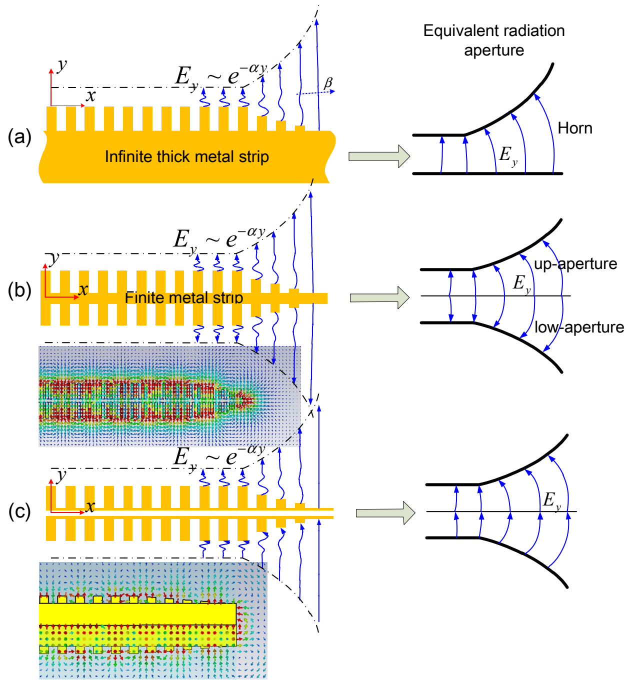

Fig. 1. Schematic description of the radiating mechanism of EM from spoof SPPs. (a) The gradual release of SPPs mode into free space in single side SPPs TL with infinity metal strip and the equivalent radiation aperture of it, (b) the even mode SPPs and the corresponding apertures, where radiations from the reversely-oriented equivalent magnetic current are canceled, (c) the equivalent apertures in odd mode SPPs antenna where the oriented equivalent magnetic currents contribute the far-field radiations in phase.

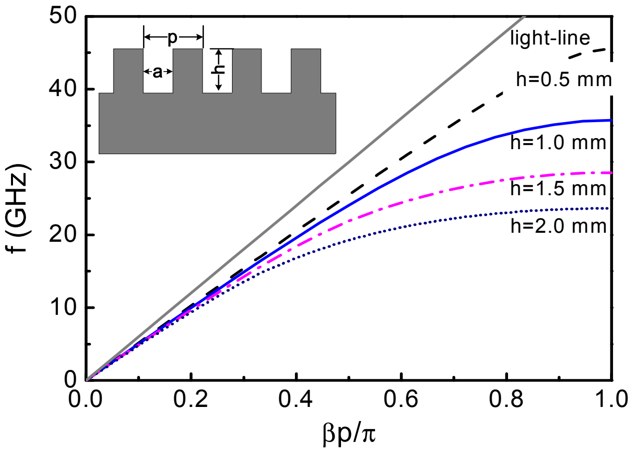

Fig. 2. Simulated dispersion curves versus groove depth h, where the inset depicts the corrugated metal film with the period p=2.5mm and the strip-width a=p/2 on a dielectric substrate.

radiation currents. The radiations are unable to be invoked effectively. Therefore, co-directional equivalent radiation currents are necessary to radiate EM energy from the SPPs TL into free space effectively. In this work, two SPPs TLs are utilized to provide the required odd mode, where the transverse electric fields are in the same direction as shown in Fig. 1(c).

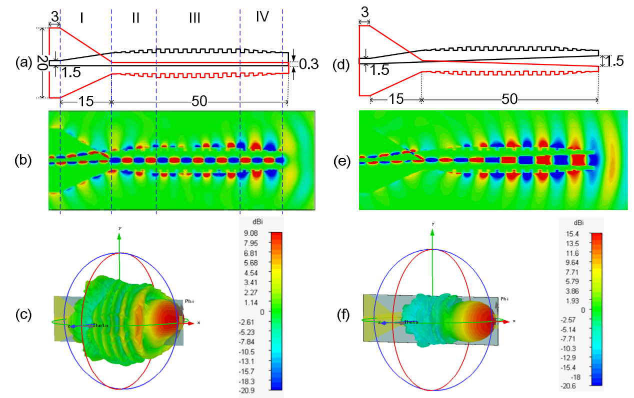

Fig. 3. (a) The proposed odd-mode traveling SPPs structure and the corresponding near-field distribution (b) and the far-field pattern (c). The modified odd-mode SPPs structure (d) and its near-field distribution (e) and the simulated far-field pattern (f). The numbers in above figures indicate the dimensions of the structure (in unit of mm).

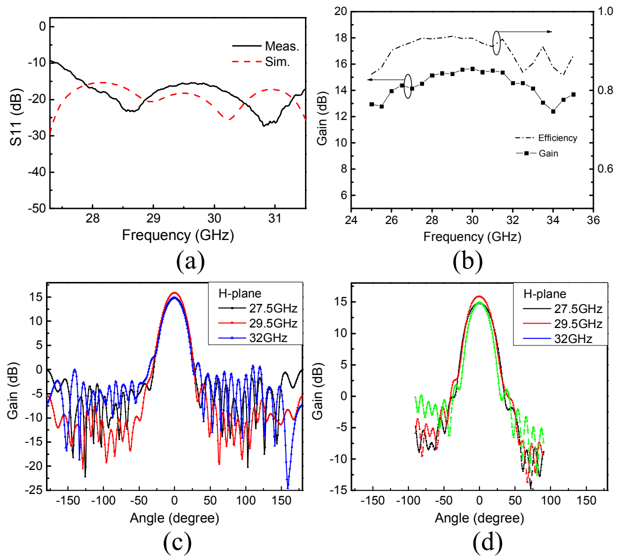

Fig. 4. (a) The simulated (in dash line) and the measured (in solid line) reflection coefficient S11, (b) the simulated realized gain and efficiency of the proposed antenna, where the inset displays the efficiency, (c) and (d) far field pattern in E- and H-plane respectively.

III. DESIGNING ODD-MODE SPOOF SPPS TRAVELONG WAVE ANTENNA

To operate at Ka-band, the cut-off frequency of the spoof SPPs mode is designed above 35 GHz by setting periodicity p=2.5 mm and groove depth h=1 mm according to the simulated dispersion curves shown in Fig. 2. The basic structure of the SPPs traveling-wave antenna is shown in Fig. 3 (a) and the corresponding near field distribution of E_y from full wave simulations (CST Microwave Studio), is displayed in Fig. 3(b). The evolvement of EM wave from the bounded SPPs mode to the radiating mode is clearly observed in this figure. The electric field (E_y) is confined on the corrugated border of the metal strips in the region III and then gradually extends in y-direction in region IV when reducing groove depth h. Near the ends of spoof SPPs TLs, the equivalent radiation aperture comes into being and radiation occurs. Fig. 3(c) displays the far-field pattern at frequency 30 GHz corresponding to the structure in Fig. 3(a). To reduce the reflection arising from the abrupt break of TLs in region IV, the above basic antenna structure is modified by gradually reducing the strip width (Fig. 3(d)). The modification improves radiations and directivity. Accordingly, the simulated far field pattern has a narrower 3 dB beam-width and a larger gain as illustrated in Fig. 3(e) and (f).

IV. RESULTS AND DISSCUSIONS

For verification, the simulated and measured reflection coefficients (S11) are displayed in Fig. 4 (a). A wide impedance bandwidth from 27.5 GHz to 32 GHz is obtained. The simulated gain in endfire direction is up to 15 dB in the operating frequency range. Thanks to the low transmission loss of spoof SPPs TLs and the large equivalent radiation aperture, the efficiency of above 90% is achieved in the frequency range of interest. The simulated E-plane and H-plane far-field patterns at 27.5 GHz, 29.5 GHz, and 32 GHz are shown in Fig. 5.

V. CONCLUSION

In this work, a method of directly radiating SPPs wave into free space is proposed. The radiation mechanism is investigated in details. A MM-wave spoof SPPs antenna is designed for verification. The simulated results for this antenna show a high gain as well as high efficiency at the frequencies of 27.5 GHz to 32 GHz. Considering the narrow transverse dimensions and the high directivity of this antenna, it should be appealing for future 5G communication applications.

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