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The engineering way from spoof surface plasmon polaritons to radiations

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Abstract. In recent years, spoof surface plasmon polaritons (SPPs) have been investigated at microwave and THz frequencies for engineering purpose. Due to momentum mismatch, the SPP mode cannot be directly converted from the spatial mode, and vice versa. Stimulating schemes have been developed to transform spatial waveguide modes to SPP modes with high efficiency. On the other hand, the question may arise that, is it possible to transform the propagating SPP waves to directive radiating waves for wireless communication? In view of this, this paper introduces the new-concept antennas based on spoof SPPs at microwave frequencies. Methods of transforming SPP modes to radiating modes are studied, whilst a series of antenna designs are presented and discussed. Feeding networks for antenna arrays using SSPP TLs are also investigated. Most works reviewed in this paper are fulfilled at Southeast University in China.

Keywords: Spoof surface plasmon polaritons / antennas / metamaterials

1 Introduction

Surface plasmon polaritons (SPPs) exist at a metal/dielectric interface due to the interaction between the plasma of electrons near the surface of the metal and the electromagnetic (EM) waves. At frequencies below the optical regime, SPPs are not supported on bare surface of metals which behave close to perfectly electric conductors (PECs) rather than plasmas. Metallic surfaces with sub-wavelength decorations have been developed to support the propagation of spoof (or 'designer') SPPs at microwave and THz frequencies [1–3]. The spoof SPPs (SSPPs) possess natural SPP-like dispersion properties and strong confinement of EM fields, and therefore is a special kind of slow waves with a propagation constant (k_{spp}) larger than that in free space (k_0). Metasurfaces have been developed to support the propagation of SSPP waves in a various of circumstances. In particular, a one-dimensional (1D) metasurface, saying, the metallic strip with designed sub-wavelength corrugations, could be viewed as a new type of transmission line (TL) for SSPP waves [4]. The SSPP TL has flexible dispersion properties, strong sub-wavelength effects and low mutual couplings, and therefore may lead to new-concept compact circuits with exciting functionalities.

Because of momentum mismatch, the SPP mode cannot be directly transformed from the spatial mode. In view of this, converting sections have been created to feed SSPP TLs with different configurations [5–7]. In these works, spatial waveguide modes are transformed to SPP modes with high efficiency. On the other hand, antennas are as important as TLs for wireless communications. Therefore, another question may arise that, is it possible to transform the propagating SSPPs to radiations and consequently realize antennas with demanded directivities? In view of this, efforts have been taken and a series of SSPP antennas have been reported, most of which can be categorized into two main kinds: the one based on periodic modulation and the other one based on EM coupling.

In this paper, antennas based on SSPPs at microwave frequencies are reviewed, most of which are proposed and delivered in the State Key Laboratory of Millimeter Waves at Southeast University in China. Designing methods and examples of SSPP antennas are introduced, and feeding network for antenna arrays using SSPP TLs are also discussed.

2 Radiation based on periodic modulations

As a kind of slow wave, SSPPs are bonded to TLs and therefore cannot be radiated away directly. Fortunately, it has been demonstrated in theory and in experiment that periodical modulations help to convert the slow SPP waves

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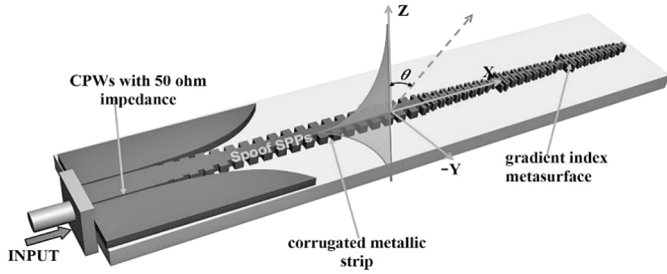
Fig. 1. An emitter proposed in [14] to convert SPP modes to radiated modes.

Fig. 2. The schematic of a sinusoidally modulated SSPP leaky-wave antenna proposed in [18].

to fast radiating waves through generating harmonics. Here, we introduce three types of modulation-led radiations.

2.1 Gradient-index emitters to convert SPP modes to radiated modes

It has been analyzed that the gradient-index metasurface serves as a bridge to convert propagating spatial waves to surface waves [8–10]. This idea could be reversely applied to convert SPP waves to radiated waves in free space [11–13] and limited to the 1D circumstance on the SSPP TLs [14]. Following the generalized Snell's law [15], there exists a relation that

$$k_0 \sin \theta_r - k_{\text{spp}} \sin \theta_i = \frac{d\Phi}{dx}, \qquad (1)$$

where θ_r and θ_i (θ defined in Fig. 1) are the reflected angle and incident angle, respectively. Here, we remark that for SSPPs propagating on TLs, the incident angle θ_i is 90°. Equation (1) indicates that a constant gradient of phase discontinuity $d\Phi/dx$ (x axis is given in Fig. 1) deflects the reflected wave away from the propagating direction. The radiation beam is determined by θ_r, which could be steered through changing the gradient index of $d\Phi/dx$. Figure 1 shows a periodically modulated structure with designed $d\Phi/dx$, which could be applied as a planar emitter. In addition, when fed with SSPP feeding networks, such emitters work as radiating elements for antenna arrays [16], as discussed in Section 4.

2.2 Leaky-wave antennas based on space harmonics

Leaky-wave radiations have been adopted in microwave engineering for years [17]. A leaky-wave antenna with periodic structure could provide frequency-dependent steerable beam in both forward quadrant and backward quadrant (except for broadside). Generally, the EM wave gradually leaks to radiate when travelling through the structure of antenna. In view of this, a series of schemes have been adopted to create fast waves from the propagating SSPPs [18–22].

In order to achieve the fast wave with $k < k_0$ on an SSPP TL, periodic modulations could be introduced to provide space harmonics k_N ($N = 0, \pm 1, \pm 2, \pm 3,...$). It is noticed that when N is negative, the condition $k_N < k_0$ is satisfied. In practice, $N = -1$ is usually chosen to prevent higher
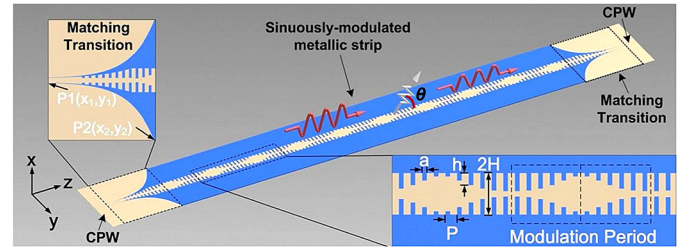
harmonics. An SSPP leaky-wave antenna is proposed and realized in reference [18], is illustrated in Figure 2. There is a relation between k_{-1} and the radiation angle θ (defined in Fig. 2) that

$$k_{-1} = nk_0 - \frac{2\pi}{A} = k_0 \cos \theta, \qquad (2)$$

where A is the modulation period as denoted in the inset of Figure 2 and n is an effective surface refractive index that can be calculated as

$$n \approx \sqrt{1 + \frac{X_s^2}{\eta_0^2}}. \qquad (3)$$

Here, η_0 is the wave impedance in free space and X_s is the average surface reactance. For a leaky-wave antenna design, A and θ could be firstly decided according to the engineering purpose. After that, n is calculated by (2) and X_s is consequently achieved by (3). We denote that X_s is related to the surface impedance (η_{surf}) of the physical structure as

$$\eta_{\text{surf}} = jX_s \left[1 + M \cos \left(\frac{2\pi}{A} z \right) \right]. \qquad (4)$$

In a modulation period, unit cells with gradually changed h (see the inset of Fig. 2 for detail) are designed to satisfy the sinusoidal distribution of η_{surf} which corresponds to M (the degree of modulation).

The above discussed method has been successfully applied to realize a leaky wave antenna whose radiation beam can be steered from 67.1° to 42.7° as the frequency changes from 8.4 to 9.9 GHz. We denote that the dispersion curve of SSPPs could be tuned to approach or depart from the light line, which consequently decides the bandwidth of the leaky-wave antenna. In this way, both fast sweep and slow sweep of the beam is achievable.

In addition, to solve the problem of "open stop band" and increase radiation efficiency near the broadside direction ($\theta = 90°$ in Fig. 2), asymmetric SSPP structure in which the modulation period on the upper side and the lower side has a $\lambda/4$ offset along the propagation direction could be applied [18]. This design has also been proved to improve the radiation efficiency in all directions due to the reduction of reflection. In fact, as a travelling wave antenna, the radiation efficiency is also proportional to the longitudinal length of the SSPP leaky-wave antenna.

Most recently, an electronically controllable leaky-wave antenna has been reported [19]. Firstly, triangular modulation of surface impedance (see the inset of Fig. 3 for detail) is adopted to realize a beam towards 15.5° at a fixed frequency point. After this static design, a varactor diode is added in each unit cell of the modulation period. Instead of changing the geometry of the unit cell or change the operating frequency, one is able to tune the modulation of surface impedance at the fixed frequency by changing the capacitance of varactor diode through dc bias voltage. In this way, a frequency-fixed beam-scanning leaky-wave antenna is realized and demonstrated. According to equation (2), the frequency-fixed beam scanning can also be designed through dynamic variation of the modulation period. In [20], switches are adopted to provide real-time control of modulation period. It is also noted that the radiation efficiency of the electronically controlled leaky-wave antenna is also decided by the parasitic resistance of the varactor diodes.

Fig. 3. Schematic of a leaky-wave antenna loaded with varactor diodes [19].

2.3 Diffraction radiations with phase-reversal geometry

Another kind of periodic modulation has also been investigated to generate space harmonics for radiation by introducing 180° phase shift between adjacent unit cells in the SSPP TL, as illustrated in Figure 4a [23]. Phase-reversal geometry is designed to produce the 180° phase shift into the dual-strip SSPP TL, as well as present abrupt discontinuity for space harmonics. Different from the gradient index modulation, in this case, k_n of the nth harmonic is simply a repetition of k_0 with a period of 2π, as indicated by the dispersion curves in Figure 4b. The extra 180° phase shift brings in a horizontal shift of the dispersion curve for the $n = -1$ harmonic, as presented by the red dashed line. In this way, wide-angle beam scanning is achievable in designed frequency range.

From the physical point of view, such diffraction radiation caused by periodically reversed currents is an analogue to the Cherenkov radiation wakes. In 2015, Genevet et al. have observed the Cherenkov surface plasmon wakes [24]. In fact, due to the wave-particle duality, Cherenkov radiation is the same phenomenon as the leaky-wave radiation.

3 Radiation based on electromagnetic coupling

As discussed above, SSPPs propagate with enhanced field enhancement and strong sub-wavelength effects. Therefore, radiators located close to SSPP TLs can be efficiently excited through EM coupling, and then radiate EM waves to free space.

3.1 Radiation from magnetic coupling

When a circular patch is located next to the SSPP TL, as depicted in Figure 5, electric currents are induced flowing around the patch due to magnetic coupling (see the inset of
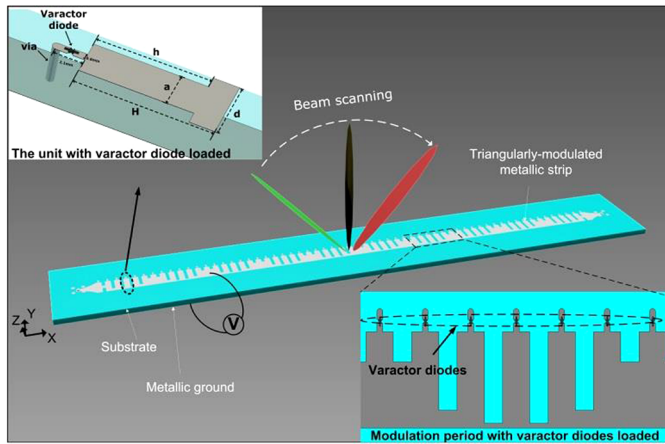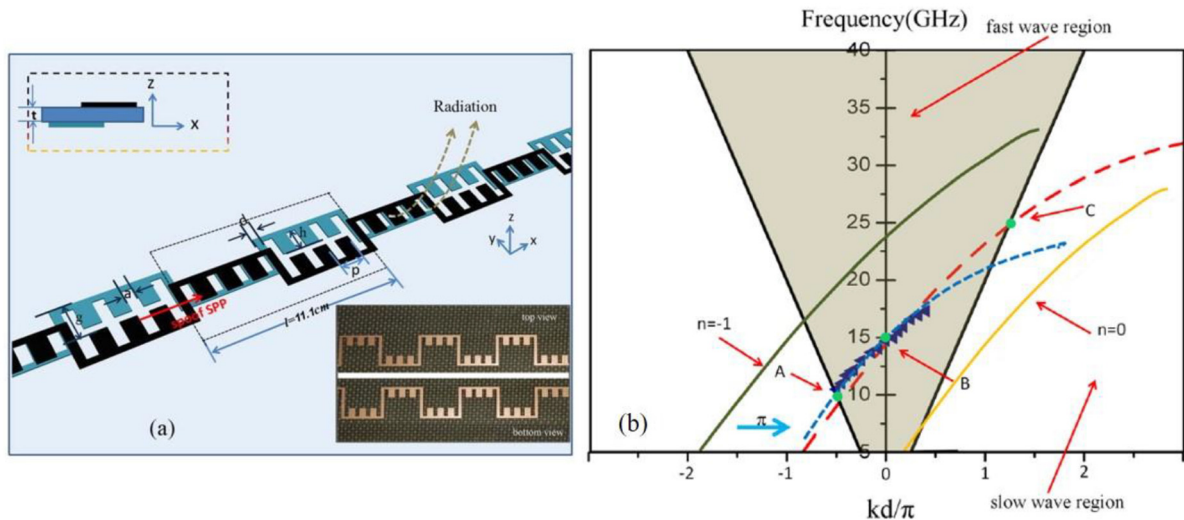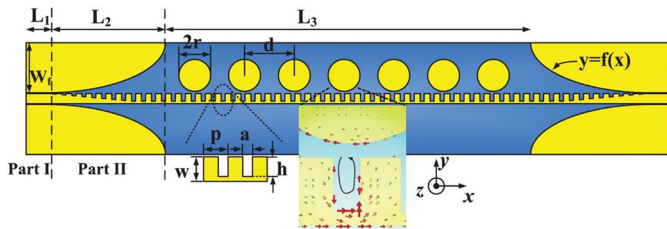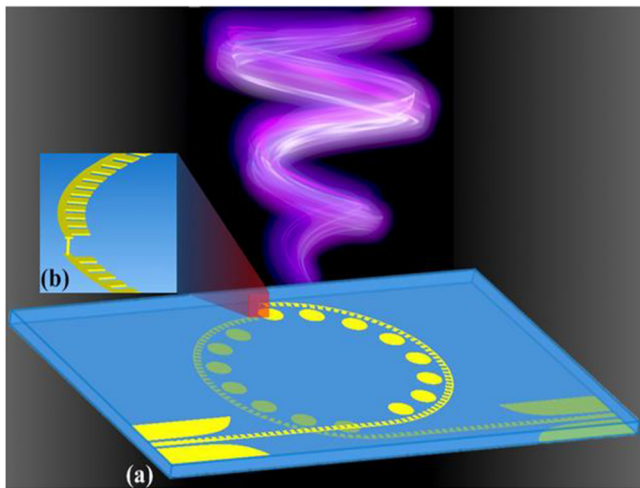

Fig. 4. (a) Structure for the diffraction radiations with phase-reversal geometry. (b) The Brillouin diagram (vs. frequency) [23].

Fig. 5. An SSPP TL fed patch array with frequency-controlled broad-angle beam scanning [25]. The inset shows simulated electric current distribution at coupling part.

Fig. 6. A microwave vortex-beam emitter based on SSPPs [29].

Fig. 5 for detail) [25]. Energy is therefore coupled from the SSPP TL to the patch and then radiated through the patch to the free space. When a series of patches are aligned, frequency controlled beam scanning is achievable from backward to forward direction based on the phased array theory. It is noted that for the antenna array the SSPP TL could serve as a compact feeding network with significantly reduced longitudinal size [26,27]. When a series of circular patches are placed as radiating elements, wide-angle and circularly polarized beam-scanning antenna is also available through the SSPP feeding network [28].

Moreover, it is also discovered that the circular patch as a resonator can bring in an effective phase-shift difference of 2π. In other words, the circular patches perform not only as radiation units but also resonant phase shifters. This feature has been utilized to create an interesting SSPP-based vortex beam emitter, which contains a looped double-layer SSPP TL and a series of circular patches aligned with it, as sketched in Figure 6 [29]. According to the theory of orbital angular momentum (OAM), when the phase change along the whole SSPP TL is l times of 2π, the l-mode OAM-carried EM waves are radiated to the space [30]. The SSPP array antenna has also been adopted for generating beams carrying OAM with arbitrary modes. An example design with a single OAM mode and two mixed OAM modes around 94 GHz has been reported in [31]. The
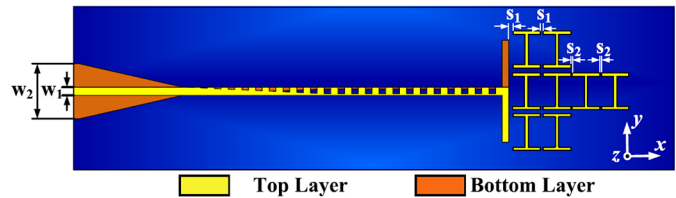
Fig. 7. An end-fire SSPP antenna based on electric coupling [32].

OAM wave carries more communication capacity without requiring more bandwidth, and hence are highly expected to play an important role in future wireless communication systems.

3.2 Endfire radiation from electric coupling

Electric coupling has also been adopted in the conversion from SSPP waves to radiated waves. Figure 7 shows an end-fire SSPP antenna design [32]. The radiator is a printed dipole connected to a dual-strip SSPP TL. However, the dipole itself creates very limited gain at the end-fire direction because of inadequate aperture and EM distribution. To enhance the gain, I-shaped resonator (ISR) array has been designed to increase the effective index of refraction so as to re-radiate more energy to the end-fire direction. In this mechanism, EM energy is coupled from the dipole to the ISRs through electric resonance. The electric coupling has also been adopted to realize multibeam SSPP antennas, in which a series of SSPP branches can be fed simultaneously and almost equally by a single monopole [33].

4 Feeding networks

Aside from radiators, feeding networks containing dividers, combiners and so on also play an important role in antenna systems. Feeding networks in SSPP circuits inherently possess advantages, mainly in the two aspects: (1) Thanks to the depressed mutual coupling, the feeding networks can be rather compact. (2) Due to the designable EM properties, the feeding networks are more flexible and more adaptive.

As pointed out in Section 2.1, the gradient-index emitters could be arranged in antenna arrays as radiating elements. Figure 8a depicts the configuration of a two-element array which is fed by a power divider realized with the SSPP TLs [16]. Two channels are driven by a single input and obtain almost the same energy for radiation. The two channels can be put close to each other with low crosstalks. In addition, more channels can be added in a more compact and complicated feeding network for a larger antenna array.

Another example, a broadband decoupling network for dual-band patch antennas, is shown in Figure 8b [34]. A microstrip patch is designed to have two operating bands and fed from two ports by the substrate integrated waveguide (SIW) and the SSPP TL, respectively. Due to the high-pass nature of the SIW and the low-pass nature of the SSPP TL, the two inputs can be highly isolated as long as the cut-off frequency of the SSPP TL is carefully
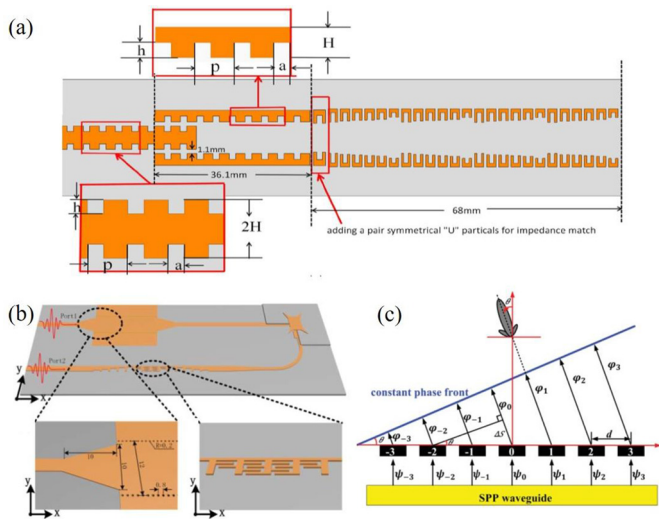
Fig. 8. (a) A two-element array fed by a compact SSPP feeding network [16]. (b) A broadband decoupling network for dual-band patch antennas [34]. (c) Sketch of the feeding with designable phase shift in [25].

designed to make sure that no overlapped pass-band exists in the whole frequency band. Such a feeding network is flexible and simple, without bringing in extra occupation of space.

The third network (see Fig. 8c) with controllable phase shift was proposed in [25] to feed the circular patch array discussed in Section 3.1. Because the patches are located at different positions along the SPP waveguide (e.g., the SSPP TL in Fig. 5) with different phases, the radiation pattern is expected to have a corresponding emergence angle. Since the phase difference introduced by the SSPP TL is frequency-dependent, frequency-controlled beam-scanning patch array is therefore achieved. In this way, the SSPP TL offers a new method of realizing compact phase-shift network for phased arrays.

5 Conclusions and discussions

In this review paper, we introduce several engineering ways to transform spoof SPPs in TLs to radiations in free space. Schemes of converting the slow SPP waves to fast waves and then radiated waves are discussed. Based on these methods, a series of SSPP antennas have been designed and realized. Among these designs, the gradient-index SSPP antennas in Section 2.1 are especially suitable for emitters and emitter array at the transmitter or receiver end of communication systems. Such designs possess high radiation efficiency but limited working bandwidth since the phase gradient index is not constant as the frequency changes. The leaky-wave antennas and diffraction antenna discussed in Sections 2.2 and 2.3 are travelling wave antennas whose radiation efficiency is proportional to the longitudinal length. This kind of SSPP antennas can be designed to generate both frequency-dependent and frequency-independent radiations with forward, backward and broadside radiations. In addition, both linear polarization and circular polarization

are achievable in this mechanism. In Section 3, SSPP structures are introduced as feeding networks for existing electric or magnetic radiators. The radiation efficiency is mainly related to the aperture size whereas the bandwidth to the resonant feature of the radiators. Due to the designable dispersion property and flexible structure, such SSPP fed antennas and phased arrays could be reconfigurable, structural-flexible and more compact compared to the conventional ones.

Compared with traditional planar antennas such as patch antennas and CRLH antennas, the SSPP-based antennas possess compact sizes, comparable gains and efficiencies, and can be composed of single conductor without a ground plane. Thanks to the sub-wavelength structure and designable dispersion property, the bandwidth is tunable (both broadband and narrowband SSPP antennas are achievable), and the gain can be consistent within the working band. Moreover, the SSPP emitters are extremely suitable to construct low-profile and reconfigurable phased arrays with SSPP dividers.

The works presented in this paper have shown the great potential of the SSPP antennas. In fact, such new-concept antennas, together with the SSPP TLs, should be further developed and verified in integrated circuits and system-level designs and applications. We expect them to play an important role for next-generation wireless communication technology.

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