Applied Physics Letters

RESEARCH ARTICLE | JANUARY 12 2015

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Appl. Phys. Lett. 106, 021102 (2015)
https://doi.org/10.1063/1.4905580

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Efficient conversion of surface-plasmon-like modes to spatial radiated modes

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(Received 28 September 2014; accepted 24 December 2014; published online 12 January 2015)

We propose a spoof surface plasmon polariton (SPP) emitter which is composed of ultrathin corrugated metallic strips, exhibiting the directional radiation property. The spoof SPP emitter provides a way to quickly convert the SPP mode to a radiated mode. By controlling phase modulations produced by the phase-gradient metasurface on the ultrathin metallic strips, we demonstrate theoretically and experimentally that spoof SPP waves are converted into spatial propagating waves with high efficiency, which are further radiated with flexible beam steering. The proposed method sets up a link between SPP waves and radiation waves in a highly controllable way, which would possibly open an avenue in designing new kinds of microwave and optical elements in engineering. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4905580]

Surface plasmon polaritons (SPPs) are highly localized electromagnetic (EM) waves in the optical frequency with exponential field decay from the interface of metal and dielectric. Owing to the advantages of confined EM waves in subwavelength scales, SPPs have a lot of potential applications. However, SPPs cannot be excited effectively on the flat metallic surface in microwave and terahertz frequencies. To overcome this problem, plasmonic metamaterials have been proposed,[1–5] which can be viewed as surface defects that modify the surface morphology, having similar properties to the natural SPPs in the optical frequency. For example, the periodic grooves,[6] holes,[7,8] slit,[9] blocks,[10] and heterostructures[11–13] have been studied to guide the spoof SPP modes. Recently, Shen *et al*. have presented an ultrathin corrugated metallic strip to support and propagate spoof SPP modes in the microwave frequency efficiently.[14,15]

The excitations of SPPs need a conversion from spatial propagating waves to the SPP modes. In the optical frequencies, SPPs are usually excited by bulky prisms[16] or subwavelength-period gratings,[17] but the conversion efficiency is relatively low. In addition, the excitation of SPPs requires a particular oblique angle of the incidence waves to meet the wave vector required by SPPs. Minor deviations from this fixed incidence angle will lead to significantly reduced efficiency, which greatly limit the practical applications. Metallic nanoparticles[18,19] support the resonant plasmon modes for coupling to the optical radiation field. Basically, slow-wave[20] on periodic loaded structures can support bound modes or SPPs. A gradient-index metasurface has been proposed to convert spatial propagating waves to surface waves with nearly 100% efficiency.[21] Recently, a plasmonic waveguide structure fed by coplanar waveguide (CPW) transmission line was investigated, which converts the guided waves to spoof SPPs with high efficiency in broadband.[22]

According to the optical principle of reversibility, SPPs can also be converted into free-space radiation. Ni *et al.* adopted a "V-shaped" plasmonic nano-antenna array,[23] which ensures identical amplitude of scattered wave at each unit, introducing a constant phase shift between two neighbor units. The manipulation of the phase of reflection coefficient plays a fundamental role in generating synthetic scattering diagrams of macroscopic objects. By using the phase discontinuities, the wavefront can be reshaped and a series of optical phenomena such as beaming, focusing, splitting, and beam shaping have been demonstrated theoretically and experimentally.[10,24]

In the microwave frequency, previous researches have been focused primarily on broadband unidirectional launching of spoof SPPs and propagation of spoof SPPs on the SPP waveguides. Conversion of localized energy into spatial propagating waves is an important application, which could play a critical role in the plasmonic waveguide information links, making the transfer of energy more efficient.[25] Therefore, it will make the near-field (NF) information be collected in far fields. In this problem, the high conversion efficiency is the crucial to measure whether the functionality is efficient or not. In order to produce high conversion efficiency from SPPs and spatial propagating waves, many efforts have been made.[26–29] However, the transmission efficiencies are still limited. Recently, an efficiency of only 65% has been verified by measuring a beam steering transmitter, which is composed of metasurface with coaxial annular apertures.[30]

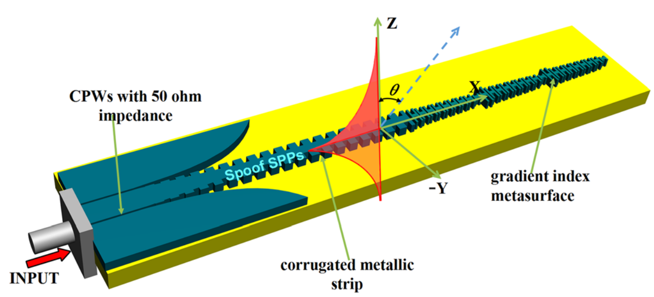

FIG. 1. A general view of the proposed spoof SPP emitter.

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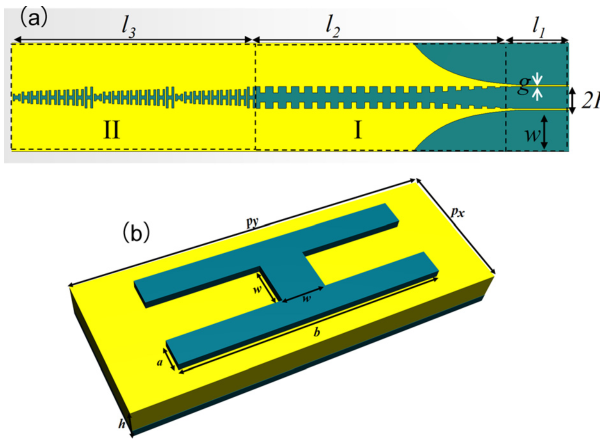

FIG. 2. (a) The schematic diagram of the proposed spoof SPP emitter structure, which is divided to two regions (I and II), in which $l_1 = 32.63$ mm, $l_2 = 127$ mm, $2H = 6.3$ mm, $w = 12$ mm, and $g = 0.53$ mm. (b) A unit cell of the phase-gradient metasurface, in which the lengths of the unit cell along x and y directions are $P_x = 2.6$ mm and $P_y = 8.4$ mm, and the other parameters are kept as $w = h = 1$ mm and $a = 0.6$ mm.

In this work, we study the wave vector control technology in the spoof SPP emitter for enhanced radiations. In fact, SPPs are in essence non-radiative EM modes. Due to the mismatch of momentum between SPP and spatial propagating modes, the excited spoof SPPs are confined on the structured metal surface, which are impossible to be converted to spatial waves directly. Here, we demonstrate theoretically and experimentally that a specially designed gradient metasurface can convert spoof SPPs to propagate waves in free space with high efficiency. By employing the wave-front modification, a tunable scanning beam can further be produced. Experiments in the microwave region, including both far-field and near-field characterizations, are in excellent agreements with the numerical simulations.

The layout of the proposed spoof SPP emitter is shown in Fig. 1, which consists of two regions. The first region (I) is a corrugated metallic strip, which is a plasmonic transmission line supporting spoof SPP modes with wave vector k_{spp}. The corrugated metallic strip is connected to a 50 Ω coplanar waveguide transmission line, which has the similar structure as discussed in Ref. 22. The good matching of both momentum and impedance between CPW and plasmonic waveguide ensures a high-efficiency transmission. Here, the depth of groove is

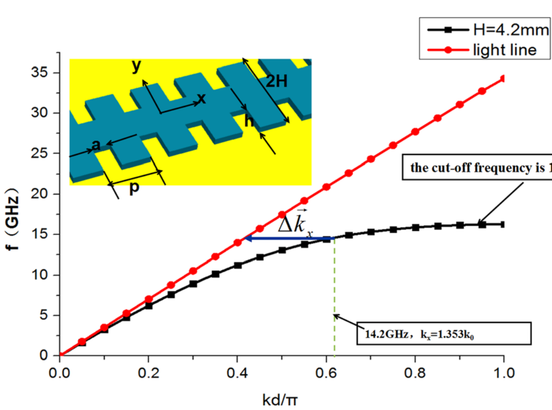

FIG. 3. The dispersion relations of spoof SPPs on the corrugated metal strip (see the inset for geometry) and in vacuum.

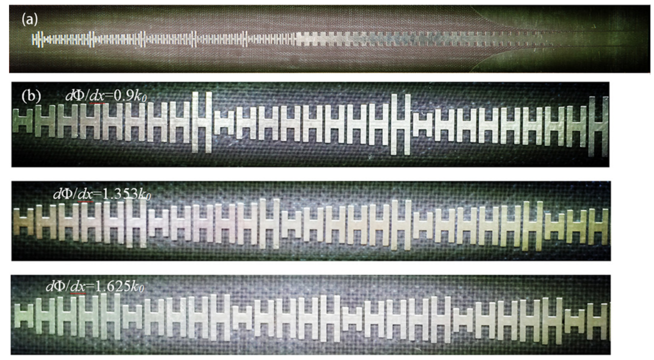

FIG. 4. (a) The photograph of the fabricated sample with $\frac{d\Phi}{dx} = 1.353\,k_0$. (b) The photographs of parts of the fabricated gradient metasurfaces with $\frac{d\Phi}{dx} = 0.9\,k_0$, $1.353\,k_0$, and $1.625\,k_0$.

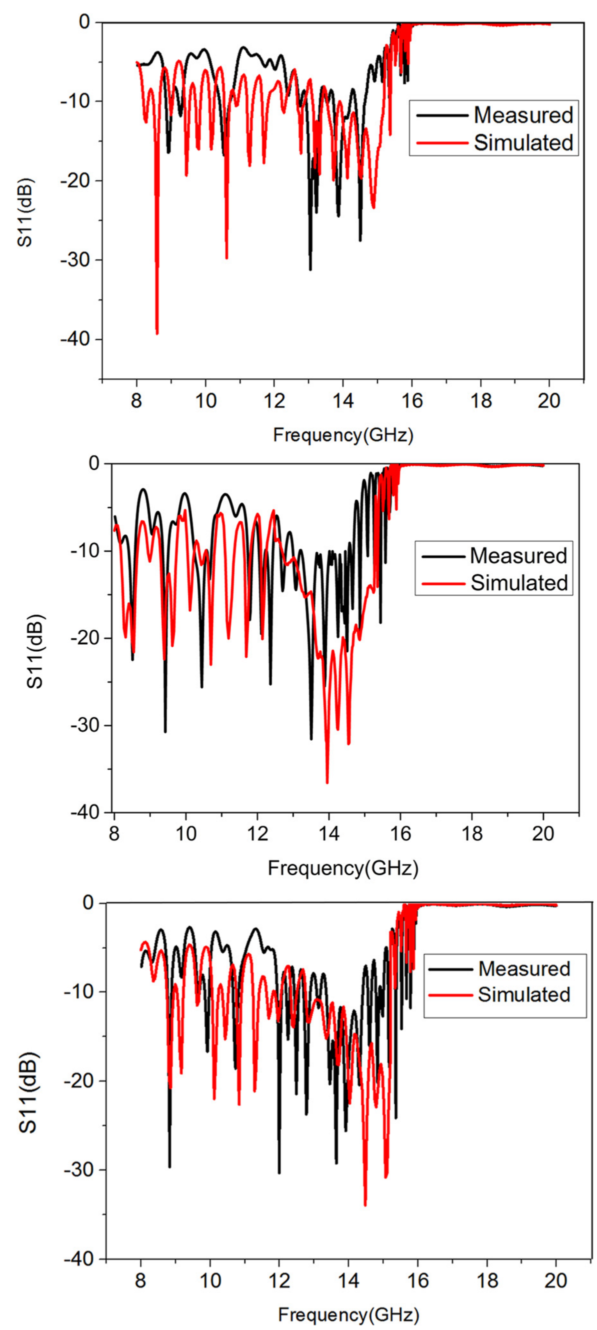

FIG. 5. The simulated and measured reflection coefficients (S11) on the CPW input port with $\frac{d\Phi}{dx} = 0.9\,k_0$, $1.353\,k_0$, and $1.625\,k_0$, respectively.

$h = 1.8$ mm, the thickness of dielectric film is $d = 1$ mm, and the period and width of grooves are $p = 3.76$ mm and $a = 1.5$ mm. Figure 3 shows the dispersion relations of spoof SPPs on the corrugated metallic strips, which exhibit SPPs properties. We notice that the spoof SPPs can propagate along an ultrathin metal strip by corrugating its edge with periodic array of grooves. The black curve shows the spoof SPPs on the interface of metal ($h = 1.8$ mm), while the red line denotes the dispersion relation of propagating wave in vacuum. As we can see in Fig. 3, when $h = 1.8$ mm, the asymptotic frequency is about $f_s = 16$ GHz, in which the confinement of spoof SPPs is tight with high transmission efficiency. When $h = 0$, the structure becomes a single bare metal strip, in which the asymptotic frequency approaches infinity ($k_x = k_0$) and the confinement of SPPs is loose with very low transmission efficiency. In Fig. 3, $\Delta\vec{k}_x$ represents the difference of wave vectors in vacuum and SPPs on the surface at the same frequency, which also denotes the momentum difference between the SPP and propagating waves. Therefore, the excitation of SPPs needs to increase the wave vector of incident waves. On the contrary, if we want to convert SPP mode into a radiated mode, we need to reduce the wave vector of SPPs under certain conditions.

The second region (II) is a one-dimensional phase-gradient metasurface. When spoof SPPs propagate along the gradient metasurface with periodic configuration, the wave vector along the x direction will be changed from k_{spp} to k_0, realizing the perfect momentum matching from the corrugated metallic strip (k_{spp}) to radiation waves (k_0). As shown in Fig. 2(b), the unit cells consist of a metallic "H" and a metal sheet, separated by a dielectric layer, which is the elementary component for designing gradient metasurface.

Changing the unit cell dimensions, we notice a remarkable property that the phase of the reflected wave can be adjusted to an arbitrary value (within 2π range). Hence, we can obtain a series of desired reflection phases for manipulation of wave vectors via adjusting the geometric parameters of the side bar b. Meanwhile, there is only a weak variation in the reflection amplitude due to the non-resonance property of unit cell. Periodically loading a basically slow-wave open structure will produce a spatial harmonic wave, which will continuously radiate powers. Using the Floquet's theorem, we can analyze the radiation properties of the phase-gradient metasurface. A time-harmonic (e^{jwt}) EM field $E(x,z)$ guided along an infinite periodic structure solely from the knowledge of the field distribution within the unit cell (i.e., a single period of width np) possesses the following property:

$$E(x + np, z) = e^{-jk_{x0}p}E(x,z), \quad k_{x0} = \beta_0 - j\alpha, \qquad (1)$$

in which k_{x0} is the complex propagation constant, β_0 is the free space propagation constant, and α is the corresponding attenuation constant which depends on the number of

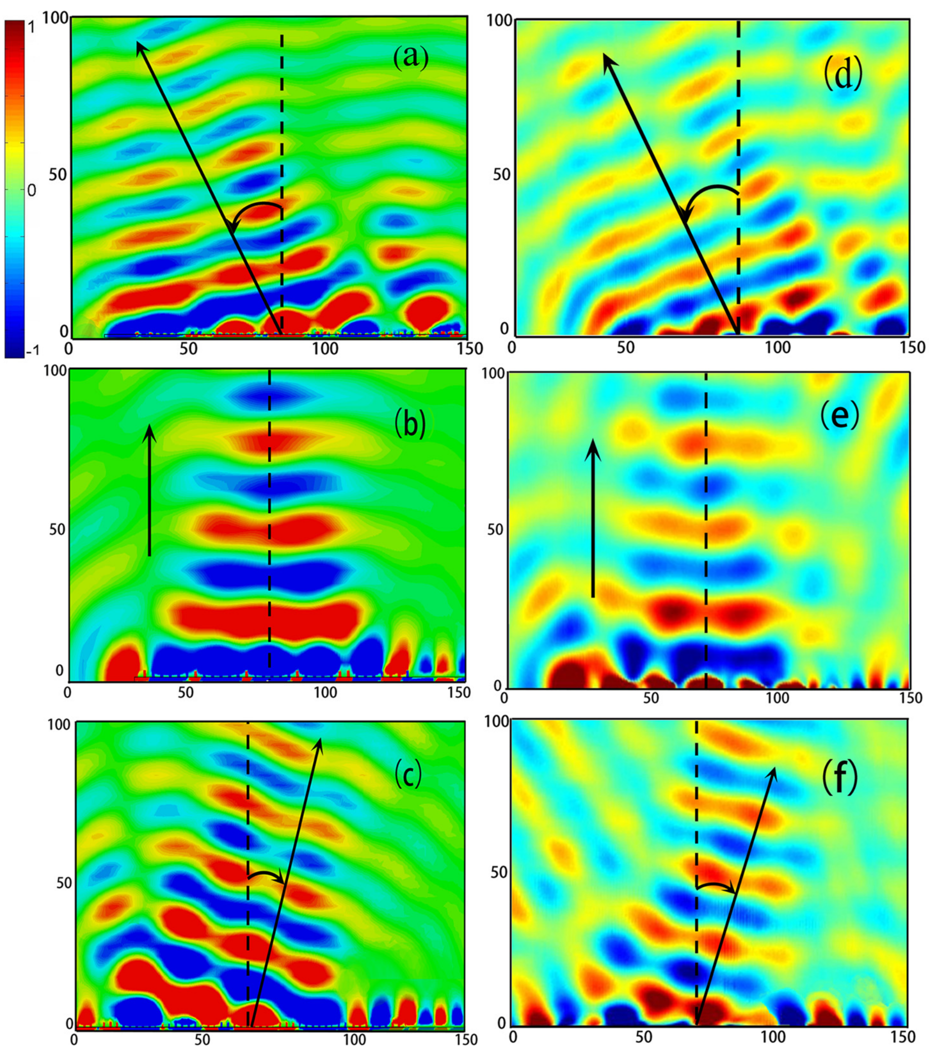

FIG. 6. The simulated and measured near-field (E_x) distributions (amplitudes) of the proposed spoof SPP emitters at 14.2 GHz with $\frac{d\Phi}{dx} = 0.9\ k_0$, 1.353 k_0, and 1.625 k_0, respectively, in which the solid black arrows indicate the propagation directions. (a)–(c) The simulated results. (d)–(f) The measured results.

cascaded cells M, providing flexible controls over the antenna's main beamwidth. When increasing the number M, the spoof SPPs emitter may enlarge the effective radiation aperture to achieve higher directivity. Adjusting the number of M can also make good impedance matching between the corrugated metallic strip and gradient metasurface. When the length b gradually decreases from 8.4 to 2 mm, the impedance of gradient metasurface will be gradually matched with that of corrugated metallic strip, enabling an efficient transition section from spoof SPP waves to free-space radiations.

According to the generalized Snell's law, the horizontal wave vectors on the two interfaces must satisfy the following relation:[3]

$$k_0 \sin\theta_r - k_x \sin\theta_i = \frac{d\Phi}{dx}, \tag{2}$$

where Φ is the phase discontinuities (i.e., phase difference) at a local point brought by the metasurface, k_x is the wave vector of the corrugated metallic strips, while $\theta_{\mathrm{r}}(\theta_i)$ is the reflected (incident) angle. A constant gradient of phase discontinuity $\frac{d\Phi}{dx}$ along the x axis is expected to deflect the reflected wave away from the horizontal ($+x$) direction. As the sample is placed in free space, we have

$$\theta_r = \arcsin\left[\frac{1}{k_0}\left(\frac{d\Phi}{dx} + k_x \sin\theta_i\right)\right]. \tag{3}$$

For the horizontal incidence ($\theta_i = 90°$), we have $k_x \sin\theta_i = k_x = k_{spp}$, where k_{spp} is the wave vector of SPPs, and the reflection angle is determined by the gradient of phase discontinuity. The mutual interaction of periodic elements is responsible for the mode-coupling resonances, thus affecting the operating bandwidth, the radiation properties, and the scanning angles.

From above discussions, by adjusting the wave vector, it is possible to control the angle of deflection. Therefore, by varying the geometric parameters of unit cell, gradient metasurface can function as a beam steering device, reaching both forward and backward quadrants scanning.

Encouraged by these theoretical predictions, we fabricate and measure the actual performance of the device as a spoof SPP emitter. Choosing the working frequency as $f = 14.2$ GHz, we have $k_x = 1.353\ k_0$ from Fig. 3. Then, we designed three gradient-index metasurfaces with $\frac{d\Phi}{dx} = -0.9\,\mathrm{k}_0$, $-1.353\,\mathrm{k}_0$, and $-1.625\,\mathrm{k}_0$, as shown in Fig. 4. Based on Eq. (2), we further obtain the corresponding reflection angles as $-26.9°$, $0°$, and $15.8°$, respectively. In the above design, the wave vectors of SPP and radiation modes are

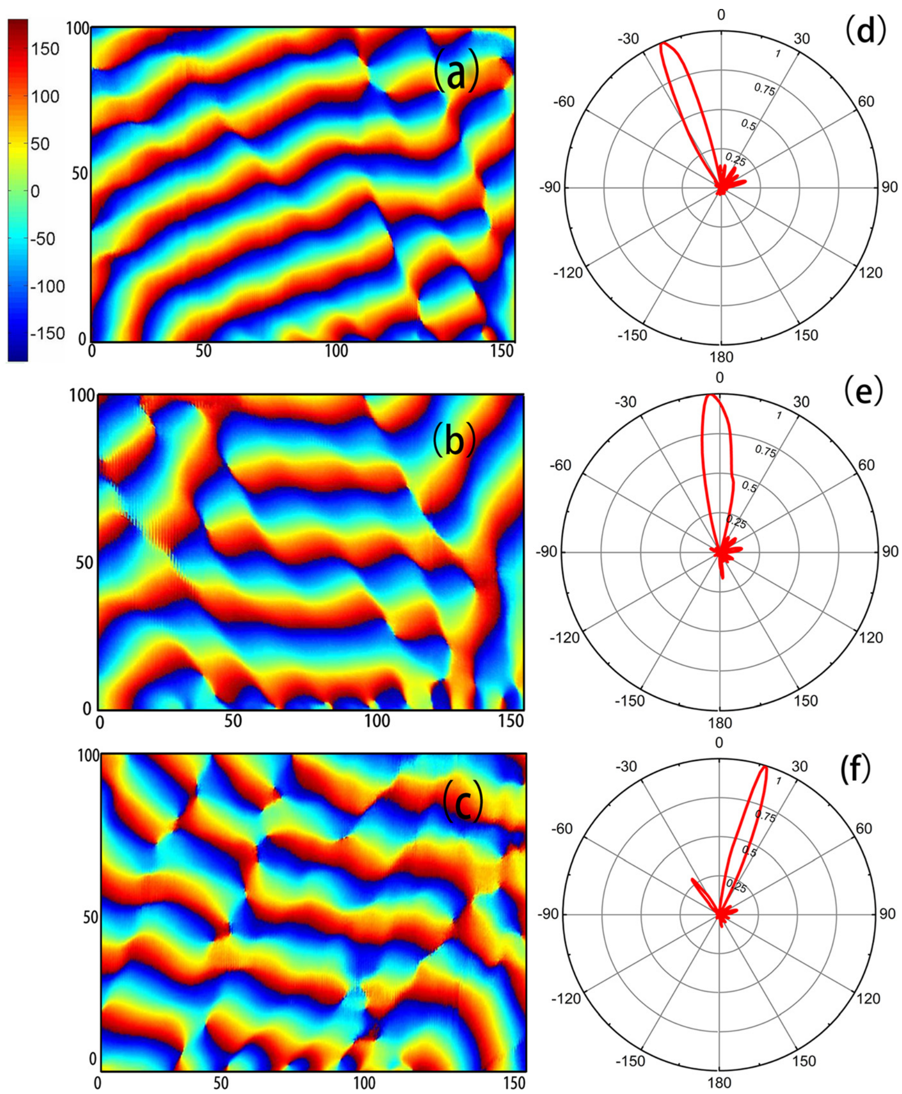

FIG. 7. (a)–(c) The measured near-field distributions (phases) of the proposed spoof SPP emitters at 14.2 GHz with $\frac{d\Phi}{dx} = 0.9\ k_0$, 1.353 k_0, and 1.625 k_0, respectively. (d)–(f) The measured far-field radiation patterns of the proposed spoof SPP emitters at 14.2 GHz with $\frac{d\Phi}{dx} = 0.9\ k_0$, 1.353 k_0, and 1.625 k_0, respectively, in which the beam deflection angles are $-22.5°$, $-2°$, and $16.1°$.

matched along the direction of periodicity x. Meanwhile, in order to satisfy the impedance matching, the values of M in the three structures are obtained by optimization as 47, 32, and 40, respectively.

We fabricate the three structures with gradient-index metasurfaces, as shown in Fig. 4. In experiment, we use a vector network analyzer (Agilent N5230C) to measure the reflection coefficients in the CPW input port. A high-efficiency transmission is achieved, in which the reflection coefficient S11 is lower than -10 dB at 14.2 GHz. Actually, most of the energy is radiated out, forming an anomalous reflection beam in free space. Three groups of simulated and measured reflection coefficients are shown in Fig. 5, in which the measured results have good agreements to simulations. We observe that the cut-off frequency in both simulations and measurements is 16 GHz, which satisfies the dispersion result analyzed in Fig. 3.

To demonstrate the characteristics of radiation beam more clearly, we provide the near-field distributions in the x-z plane using a NF scanning apparatus, as depicted in Fig. 6. Both numerical simulations and experiments demonstrate that the spoof SPPs, which are confined on the corrugated metallic strip, can indeed converted into spatial propagating waves. The phase distributions of the electric fields are given in Figs. 7(a)–7(c), correspondingly, while the normalized far-field patterns are illustrated in Figs. 7(d)–7(f) for the three samples. From Fig. 7, the directions of the maximum radiations are measured as $\theta_r = -22.5^\circ$, $\theta_r = -2^\circ$, and $\theta_r = 16.1^\circ$ for the cases of $\frac{d\Phi}{dx} = 0.9\ k_0$, 1.353 k_0, and 1.625 k_0, which are very close to the theoretical predictions. By performing a x-polarized wave, we find that the radiated beam is highly directive, i.e., most of the SPP energy is radiated into space.

In summary, a phase-gradient metasurface with ultrathin metallic strips has been proposed as a high-direction SPP emitter. Based on the phase discontinuity, we can provide pre-defined in-plane wave vectors to manipulate the direction of reflected waves. Numerical and experimental results have validated the functionality of the proposed SPP emitters, which are able to convert the spoof SPPs into spatial waves efficiently and thus greatly improve the antenna directivity. Despite the metal loss and discretization, the proposed plasmonic emitter has high radiation efficiency. However, since the phase gradient $\frac{d\Phi}{dx}$ is not a constant as the frequency changes, the working bandwidth is limited (0.6 GHz–1 GHz). With the proper optimization, this bandwidth may be further improved. The proposed method could be extended to the terahertz frequencies.

As a challenge for radiations on a slow-wave transmission system, the proposed conversion device may have wide applications, such as in the communication system, detector, focusing, and beam steering.

This work was supported in part by the National High Tech (863) Projects (2012AA030402 and 2011AA010202), in part by the National Science Foundation of China (61138001, 60990320, and 60990324), and in part by the 111 Project (111-2-05).

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