Dual-Beam Leaky-Wave Radiations with Independent Controls of Amplitude, Angle, and Polarization Based on SSPP Waveguide

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New dual-beam leaky-wave radiations based on spoof surface plasmon polariton (SSPP) waveguide, in which the amplitude, radiation, angle and polarization of each beam can be designed independently, is proposed. The proposed SSPP waveguide is made of a corrugated metallic strip with bilateral 45°-tilted grooves, whose surface impedance is flexibly designed by changing the depth of grooves. To realize dual-beam leaky-wave radiations, the surface impedance of SSPP waveguide is modulated periodically based on the superposition theory of aperture fields. By simply adjusting the modulation factors, modulation periods, and initial phase differences of the modulated surface impedance, the amplitude, radiation angle, and polarization of each beam can be further controlled independently as well. The results have been validated by both numerical simulations and experimental measurements, which show good agreement with the theoretical predictions.

1. Introduction

The response produced by the coupling of electromagnetic (EM) waves and free electrons on the metal surface is called as surface plasmon polariton (SPP).[1,2] In order to mimic SPPs in the lower frequency bands (e.g., terahertz, millimeter wave, and microwave), spoof surface plasmon polariton (SSPP) waveguide was proposed and designed to support the surface EM waves with strong confinements, whose characteristics are very similar to those of natural SPPs.[3-8] In addition, the structural waveguide dispersion provides another approach to mimic SPPs at low frequencies.[9-11] However, these structures, including some grating structures,[12,13] are usually bulky and hardly integrated with the microwave circuits. The proposal of the ultrathin and flexible SSPP waveguide makes it possible to reach practical applications of compact SSPP devices and circuits in the microwave and terahertz frequencies.[14-22]

In addition, the SSPP leaky-wave antennas (LWAs) have attracted much attention in recent years, which have advantages of low profile, low cost, and flexible design.[23-24] As the rapid development of wireless communications, the technology of multibeam radiations and multpolarization modulations has attracted more and more attention and may find practical application in point-to-multipoint communications (e.g., satellite communications and personal terminals). Many efforts have been made to achieve dual-beam radiations of leaky waves, such as symmetrical side-beam radiations,[15] dual-beam radiations based on dual-mode SSPPs,[16] or multiperiod structures,[17,18] but these works were only limited to the single polarization. In addition, dual-beam radiations with orthogonal polarizations also have been proposed based on the one-dimensional (1D) half-mode substrate integrated waveguide (HMSIW)[19] or the two-dimensional (2D) holographic metasurfaces.[20,21] However, all above-mentioned LWAs are difficult to achieve dual-beam radiations with independent controls of amplitude, radiation angle, and polarization, which limit the modulation freedom of leaky waves.

Here, we propose a method for designing dual-beam leaky-wave radiations based on a 1D SSPP waveguide, from which the amplitude, radiation angle, and polarization of each beam can be freely and independently customized. The proposed SSPP waveguide is made of corrugated metallic strip with bilateral 45°-tilted grooves perpendicular to each other on both sides. The dual-beam leaky-wave radiations can be easily achieved when the surface impedance of SSPP waveguide is periodically modulated based on the superposition theory of aperture fields. Then, the required surface impedance distributions can be quickly constructed by designing the groove depths of the unit structures. In addition, the amplitude and angle of each beam can be controlled independently by adjusting the modulation factor and modulation period of surface impedance, respectively. More importantly, benefit from the bilateral 45°-tilted grooves, the phase difference of the two orthogonal electric-field components for
each beam can be designed independently and flexibly, so that the polarization state of each beam can be customized independently as well. The design method is validated by both numerical simulations and experimental measurements, which are consistent very well with the theoretical predictions.

2. Theoretical Analysis

The schematic of the proposed SSPP waveguide is illustrated in Figure 1, which is composed of a bilateral 45°-tilted corrugated metallic strip and a metal ground spaced by a kind of commercial polytetrafluoroethylene (PTFE) resin-based dielectric substrate of F4BK225 with relative permittivity of 2.25 and loss tangent of 0.001. The thickness of the dielectric substrate is 2 mm covered by copper with thickness of 0.018 mm. The main body of the SSPP waveguide is connected to two 50 Ω wave ports through the matching transitions, whose dimensions are \( w_1 = 6 \), \( w_2 = 18 \), \( w_3 = 4 \), \( l_2 = 6 \), \( l_1 = 50 \), and \( g = 0.4 \) mm. The main body of SSPP waveguide with length of \( l_1 = 296 \) mm is a metallic strip etched with bilateral 45°-tilted grooves, in which the strip width is \( 2H = 6 \) mm, the period of unit is \( d = 1.7 \) mm, the groove width is \( a = 1.2 \) mm, and the groove depth \( h \) is variable. The dispersion curves of unit structure with different groove depth \( h \) are demonstrated in Figure 2, which show that the deeper groove depth \( h \) is, the larger propagation wave number \( k_x \) is.

According to Maxwell’s equations, the surface impedance \( \eta_{\text{surf}} \) can be calculated based on the propagating wave number \( k_x \):

\[
\eta_{\text{surf}} = j\eta_0 \sqrt{\frac{k_x}{k_0}} - 1
\]

where \( k_0 \) is the free-space wave number, \( \eta_0 \) is the free-space wave impedance, and \( j \) is the imaginary unit. According to Equation (1), the calculated surface reactance of \( \eta_{\text{surf}} \) varying with groove depth \( h \) at 9.8 GHz is also given in Figure 2, which shows that the surface reactance \( \eta_{\text{surf}} \) gradually increases from 350 to 1040 Ω as groove depth \( h \) increases from 0.1 to 2.9 mm.

It is well known that the SSPPs are tightly confined around the SSPP waveguide and efficiently propagate when the SSPP waveguide has an uniform surface impedance,\(^{[14,15]}\) and the greater the surface impedance, the stronger the confinement. However, when the surface impedance of SSPP waveguide is periodically modulated, the discontinuity of surface impedance is introduced along the propagation direction. Then the propagating SSPPs will be modulated and radiated to the free space, which have been widely studied in LWAs with periodically modulated surface impedance.\(^{[23,42]}\) Usually, the sinusoidal periodic impedance modulation is used in design:

\[
\eta_{\text{surf}}(x) = jX_s \left[ 1 + M \cos \left( \frac{2\pi x}{P} + \varphi \right) \right]
\]

in which \( X_s \) is the average surface reactance, \( M \) is the modulation factor, and \( P \) is the modulation period. According to Equation (2),

![Figure 1](image-url)  
Figure 1. Schematic of the proposed SSPP waveguide made of ultrathin corrugated metallic strip with tilted grooves.

![Figure 2](image-url)  
Figure 2. The dispersion curves and surface impedance of tilted unit with different groove depths \( h \) at 9.8 GHz.
the larger $M$, the larger modulation depth of waveguide impedance, resulting in more SSPP energy radiation. Hence, if one wants to achieve as much radiation energy as possible, $M$ should be chosen as large as possible.\(^{[23]}\)

In order to achieve dual-beam radiations, the surface impedance of the SSPP waveguide is designed to satisfy the compound sinusoidal periodic modulation based on the superposition theory of aperture fields

$$
\eta_{\text{surf}}(x) = jX_s \left[ 1 + M_1 \cos \left( \frac{2\pi x}{P_1} + \phi_1 \right) + M_2 \cos \left( \frac{2\pi x}{P_2} + \phi_2 \right) \right]
$$

(3)

in which $M_1$ and $M_2$ are the modulation factors, $P_1$ and $P_2$ are the modulation periods, and $\phi_1$ and $\phi_2$ are the initial phases for Beam 1 and Beam 2, respectively. To ensure the maximum radiation energy of Beam 1 and Beam 2, respectively. Hence, once $X_s$ is approximately chosen as

$$
X_s \approx \frac{Z_{\text{max}} + Z_{\text{min}}}{2}
$$

(4)

in which $Z_{\text{max}}$ and $Z_{\text{min}}$ are the maximum and the minimum surface reactances of unit structures. Then, in order to limit the value of $\eta_{\text{surf}}(x)$ to the range of $[Z_{\text{min}}, Z_{\text{max}}]$, the choice of $M_1$ and $M_2$ should meet the following requirement

$$
(M_1 + M_2) \leq \frac{|Z_{\text{max}} - Z_{\text{min}}|}{Z_{\text{max}} + Z_{\text{min}}}
$$

(5)

The total radiation energy of two beams is determined by the sum of $M_1 + M_2$, and the larger $M_1 + M_2$, the larger radiation efficiency, while the radiation energy of Beam 1 and Beam 2 is independently controlled by $M_1$ and $M_2$, respectively. The radiation angles of the leaky-wave beams away from the broadside can be calculated by\(^{[23]}\)

$$
\theta_i = \arcsin \left( \sqrt{1 + X_s^2 - \frac{2\pi}{k_0 P_i}} \right), i = 1 \text{ or } 2
$$

(6)

in which $X_s = X_s/\eta_0$ is the normalized average surface reactance, and $\theta_1$ and $\theta_2$ are the radiation angles of Beam 1 and Beam 2, respectively. Hence, once $X_s$ is fixed, the radiation angles of Beam 1 and Beam 2 are only determined by $P_1$ and $P_2$, respectively.

Because of the bilateral design, the surface impedances on both sides ($+y$ and $-y$ sides) of the SSPP waveguide can be independently designed as

$$
\eta_{+\text{surf}}(x) = jX_s \left[ 1 + M_1 \cos \left( \frac{2\pi x}{P_1} + \phi_{1+y} \right) + M_2 \cos \left( \frac{2\pi x}{P_2} + \phi_{1-y} \right) \right]
$$

and

$$
\eta_{-\text{surf}}(x) = jX_s \left[ 1 + M_1 \cos \left( \frac{2\pi x}{P_1} + \phi_{2+y} \right) + M_2 \cos \left( \frac{2\pi x}{P_2} + \phi_{2-y} \right) \right]
$$

(7)

in which $\phi_{1+y}$ and $\phi_{2+y}$ are the initial phases of Beam 1 and Beam 2 generated by $+y$ sides of the SSPP waveguide, respectively. The same $X_s$, $M_1$, $M_2$, $P_1$, and $P_2$ are used in the design of surface impedance on both $+y$ and $-y$ sides, so that the two beams generated by both sides radiate to the same direction with the same amplitude. In addition, because the 45°-tilted grooves on both sides of the SSPP waveguide are designed perpendicularly to each other, the electric field components of radiation beams generated by both sides are orthogonal, but the phase differences between these two orthogonal components are determined by $\Delta \phi_1 = \phi_{2-y} - \phi_{1+y}$ and $\Delta \phi_2 = \phi_{2+y} - \phi_{1+y}$ for Beam 1 and Beam 2, respectively. Hence, the polarization states of Beam 1 and Beam 2 can be arbitrarily and independently customized only by controlling the $\Delta \phi_1$ and $\Delta \phi_2$, respectively.

To summarize, one can first determine the average surface reactance $X_s$ according to Equation (4), in which $Z_{\text{max}}$ and $Z_{\text{min}}$ can be achieved from the $\eta \approx h$ curve (red line) shown in Figure 2, and then selects the modulation factors $M_1$ and $M_2$ according to the requirement of Equation (5). Further, the modulation periods $P_1$ and $P_2$ can be achieved from Equation (6) based on the known radiation angles $\theta_1$ and $\theta_2$. At last, the $\eta_{+\text{surf}}(x)$ and $\eta_{-\text{surf}}(x)$ of the SSPP waveguide can be achieved according to Equation (7), in which $\phi_{1+y}$ and $\phi_{2+y}$ are the phase constants. Once the $\eta_{+\text{surf}}(x)$ and $\eta_{-\text{surf}}(x)$ are obtained, the groove depth $h$ of each unit of SSPP waveguide can be finally determined according to the $\eta \approx h$ curve (red line) shown in Figure 2. In addition, benefit from the design of bilateral 45°-tilted grooves, not only the dual-beam leaky-wave radiations can be achieved based on the proposed designing method but also their amplitudes, angles, and polarizations can be independently and flexibly controlled by applying different modulation factors ($M_1$, $M_2$), modulation periods ($P_1$, $P_2$), and initial phase differences ($\Delta \phi_1$, $\Delta \phi_2$), respectively.

### 3. Numerical Simulations

In this section, full-wave simulations are performed to verify the above theory. According to the value range of surface reactance shown in Figure 2, $Z_{\text{max}} = 995$ and $Z_{\text{min}} = 365 \Omega$ are chosen to construct the SSPP waveguides, then the average surface reactance $X_s \approx 680 \Omega$ and the modulated factor $M_{\text{max}} = M_1 + M_2 \approx 0.46$ are determined according to Equation (4) and (5), respectively. The total length of each SSPP waveguide is $l = l_1 + 2l_2 = 396$ mm, working at 9.8 GHz.

#### 3.1. Control of Amplitude by the Modulation Factor $M$

In these designs, the modulation periods are fixed as $P_1 = 21.6$, $P_2 = 11.6$ mm, and the phase differences are chosen as $\Delta \phi_1 = \Delta \phi_2 = 0$, only $M_1$ and $M_2$ are adjusted to show their ability in manipulation of the amplitudes of radiation beams. When $M_1 = M_2 = 0$, the surface impedance of the SSPP waveguide is uniformly modulated, so that the SSPPs are propagated along the SSPP waveguide efficiently without radiation, as shown in Figure 3a. When $M_1 = M_{\text{max}} = 0.46$, $M_2 = 0$ or $M_2 = 0.46$, the surface impedance of SSPP waveguide is periodically modulated, and the SSPPs are converted to a single-beam leaky-wave radiation directing to $\theta_1 = 40^\circ$ or $\theta_2 = -35^\circ$, as shown in Figure 3b,c, respectively. However, when $M_1 = M_2 = 0.23$, the SSPPs can be converted to two leaky-wave radiations with the same amplitude, as shown in Figure 3d,
which direct to $\theta_1 = 40^\circ$ (Beam 1) and $\theta_2 = -35^\circ$ (Beam 2), respectively. All the above results show that the radiations of Beam 1 and Beam 2 are independently related to the modulation factors $M_1$ and $M_2$, respectively.

In addition, the radiation energy proportions of the Beam 1 and Beam 2 also can be further independently controlled by choosing different modulation factors $M_1$ and $M_2$. For example, when $M_2$ is fixed as 0.23 and $\left(\frac{M_1}{M_2}\right)^2$ are designed as 1:1, 2:3, and 1:3, respectively, the radiation energy of Beam 1 can be manipulated according to the change of $M_1$, while the radiation energy of Beam 2 keeps unchanged due to the fixed $M_2$, whose three-dimensional (3D) far-field radiation patterns are demonstrated in Figure 4a-c. The results show that the radiation energy of Beam 2 is almost unchanged with gain about $G_2 = 17.5$ (linear scale), while the radiation energy of Beam 1 is manipulated to achieve $G_1 = 17$, 10.5, and 5.5 as $\left(\frac{M_1}{M_2}\right)^2 = 1.1, 2.3$, and 1:3, respectively, as shown in Figure 4d. In addition, the results also show that the linear value of radiation gain ($G_1$) nearly is approximately proportional to the square of modulation factor ($M_1$). It is worth mentioning that the amplitude of Beam 2 also can be accurately controlled by changing the modulation factor $M_2$.

3.2. Control of Radiation Angle by the Modulation Period $P$

In these designs, the modulation factors are fixed as $M_1 = M_2 = 0.23$ to generate two radiation beams with the same amplitude, and the phase differences are still fixed as $\Delta \phi_1 = \Delta \phi_2 = 0$. Three groups of modulation periods with $P_1 = 21.6$ and $P_2 = 11.6$ mm, $P_1 = 18.7$ and $P_2 = 11.6$ mm, $P_1 = 24.6$ and $P_2 = 12.7$ mm are chosen, respectively, to demonstrate the control of radiation angles by the modulation periods. The simulated far-field radiation patterns are demonstrated in Figure 5, in which Figure 5a–c are the 3D far-field radiations, while Figure 5d shows the 2D far-field radiation patterns of $E_x$ in xoz plane. The results show that the radiation angles of Beam 1 ($\theta_1$) and Beam 2 ($\theta_2$) are independently related to the modulation periods $P_1$ and $P_2$, respectively. When $P_2$ is fixed as 11.6 mm, the radiation angle of Beam 2 always keeps unchanged ($\theta_2 = -35^\circ$), and no matter $P_1$ is designed as 21.6 or 18.7 mm, which makes Beam 1 radiate to $\theta_1 = 40^\circ$ or $25^\circ$. Only when the $P_1$ and $P_2$ are simultaneously changed, such as $P_1 = 24.6$ and $P_2 = 12.7$ mm, then the radiation angles of Beam 1 and Beam 2 are correspondingly changed and radiate to $\theta_1 = 55^\circ$ and $\theta_2 = -20^\circ$, respectively. All simulation results
are consistent very well with the theoretical calculations by Equation (6).

3.3. Control of Polarization by the Phase Difference $\Delta \phi$

In these designs, the $M_1 = M_2 = 0.23$ is chosen to generate two radiation beams with the same amplitude, and $P_1 = 21.6$ mm and $P_2 = 11.6$ mm are chosen to make the beams radiate to $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively. The phase differences for the orthogonal electric field components of Beam 1 and Beam 2 are defined as $\Delta \phi_1 = \phi_{yz1} - \phi_{yz1}$ and $\Delta \phi_2 = \phi_{yz2} - \phi_{yz2}$, respectively. For simplicity, we choose $\phi_{yz1} = \phi_{yz2} = 0$, resulting in $\Delta \phi_1 = \phi_{yz1}$ and $\Delta \phi_2 = \phi_{yz2}$. Then, the required surface impedance distributions of SSPP waveguides can be calculated by Equation (7), and the final configurations of SSPP waveguides can be determined by the relationship between the surface reactance and groove depth, as shown in Figure 2. Four examples are designed to demonstrate independent polarization controls of Beam 1 and Beam 2 by changing the phase differences $\Delta \phi_1$ and $\Delta \phi_2$.

When $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 0$, there is no phase difference between the orthogonal electric-field components for both Beam 1 and Beam 2, and two radiation beams are x polarizations. The simulated near-field distributions of $E_x$ and $E_y$ at 9.8 GHz in the plane of $y = 0$ are demonstrated in Figure 6a, which show that the SSPPs are completely converted into horizontally polarized spatial waves ($E_x$) radiating to the directions of $\theta_1$ and $\theta_2$, respectively, without $E_y$ component. The simulated far-field radiation patterns are demonstrated in Figure 6b, which further verify that each radiation beam is an x-polarized wave with a high cross-polarization level over 22 dB. Both radiation beams almost have the same gain of 12.5 dB, directing to $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively, which agrees well with the theoretical expectation.

When $\Delta \phi_1 = -180^\circ$ and $\Delta \phi_2 = 0$, Beam 1 will change to $y$ polarization because $-180^\circ$ phase difference is introduced to the orthogonal electric-field components of Beam 1, while the Beam 2 is still x polarization for $\Delta \phi_2 = 0$ is unchanged. Figure 6c demonstrates the simulated near-field distributions of $E_x$ and $E_y$ at 9.8 GHz in the plane of $y = 0$, which show that the Beam 1 becomes $y$ polarization with only $E_y$ component, while Beam 2 is still x polarization with only $E_x$ component. The simulated far-field radiation patterns are illustrated in Figure 6d, which also verify that Beam 1 is a $y$-polarized wave and the Beam 2 is an x-polarized wave, radiating to $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively.

When $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 90^\circ$, Beam 1 is still x polarization, while Beam 2 becomes circular polarization because $90^\circ$ phase difference is introduced between the orthogonal electric-field components. The simulated near-field distributions of $E_x$ and
Ey at 9.8 GHz in the plane of $y = 0$ are demonstrated in Figure 6e. There is only $E_x$ component for Beam 1, while Beam 2 has both $E_x$ and $E_y$ components with nearly the same amplitude and a phase difference of $90^\circ$. The simulated far-field radiation patterns are demonstrated in Figure 6f, which further verify that Beam 1 is an $x$-polarized wave and Beam 2 is a left-handed circularly polarized (LHCP) wave, radiating to $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively.

When $\Delta \phi_1 = -90^\circ$ and $\Delta \phi_2 = 90^\circ$, both Beam 1 and Beam 2 will be converted to circularly polarized waves because $-90^\circ$ and $90^\circ$ phase differences are introduced to the orthogonal electric-field components of Beam 1 and Beam 2, respectively.
The simulated near-field distributions of electric fields at 9.8 GHz in the plane of $\gamma = 0$ are illustrated in Figure 6g, showing that $E_x$ and $E_y$ components nearly have the same amplitude for both beams, but $E_y$ is 90° behind of $E_x$ in phase for Beam 1 while 90° ahead of $E_x$ in phase for Beam 2. Figure 6h demonstrates the 2D far-field radiation patterns at 9.8 GHz, which show that Beam 1 is a right-handed circularly polarized (RHCP) wave, while Beam 2 is a left-handed circularly...
polarized (LHCP) wave, radiating to $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively.

All simulation results have good agreements with the theoretical predictions, validating that the polarization states of Beam 1 and Beam 2 can be independently customized by only changing the phase differences $\Delta \varphi_1$ and $\Delta \varphi_2$, respectively.

4. Experimental Measurements

Several SSPP waveguides are fabricated and measured to further validate their abilities in manipulating the amplitudes, radiation angles, and polarizations of the radiation beams. Figure 7a shows the photographs of some SSPP waveguides with different modulation factors, in which $M_2$ is fixed as 0.23 and $(M_1/M_2)^2$ is designed as 1:1, 2:3, 1:3, respectively. The phase differences are $\Delta \varphi_1 = \Delta \varphi_2 = 0$ ($\varphi_1 + \varphi_2 = 0$), and modulation periods are $P_1 = 21.6$ mm and $P_2 = 11.6$ mm. The measured far-field radiation patterns show that the radiation energy of Beam 2 keeps unchanged, whose gain in linear scale is about $G_2 = 17.5$ at 9.8 GHz, while the gain of Beam 1 is efficiently controlled to $G_1 = 17.5$, 10.6, and 5.4 as $(M_1/M_2)^2 = 1:1$, 2:3, 1:3, respectively, as shown in Figure 7b. The S parameters are shown in Figure 7c,d, in which the reflection coefficient ($S_{11}$)
Figure 10. The measured S parameters, axis ratios, and far-field radiation patterns of SSPP waveguides with different $\Delta \phi_1$ and $\Delta \phi_2$: a,e) $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 0$. b,f) $\Delta \phi_1 = -180^\circ$ and $\Delta \phi_2 = 0$. c,g) $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 90^\circ$. d,h) $\Delta \phi_1 = -90^\circ$ and $\Delta \phi_2 = 90^\circ$. 
is lower than $-10$ dB, but the transmission coefficient ($S_{21}$) is slightly increased as $M_1$ decreases. All measurement results are consistent very well with the simulation results, as shown in Figure 3.

Figure 8a shows the photographs of SSPP waveguides with different modulation periods, which are designed as $P_1 = 21.6$ and $P_2 = 11.6$ mm, $P_1 = 18.7$ and $P_2 = 11.6$ mm, $P_1 = 24.6$ and $P_2 = 12.7$ mm, respectively. The modulation factors are $M_1 = M_2 = 0.23$, and the phase differences are chosen as $\Delta \phi_1 = \Delta \phi_2 = 0$. The measurement results show that the radiation angles of Beam 1 and Beam 2 are only independently related to the modulation periods $P_1$ and $P_2$, respectively, as shown in Figure 8b. The $S$ parameters of three SSPP waveguides are demonstrated in Figure 8c,d, which show that the SSPP waveguides have low reflection coefficient and transmission coefficient, indicating that most of the energy is radiated efficiently. All the measurement results have a good agreement with the simulations, as shown in Figure 5.

Figure 9a shows photographs of SSPP waveguides with different phase differences, which are designed as $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 0$, $\Delta \phi_1 = -180^\circ$ and $\Delta \phi_2 = 0$, $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 90^\circ$, $\Delta \phi_1 = -90^\circ$ and $\Delta \phi_2 = 90^\circ$, respectively. The modulation factors are $M_1 = M_2 = 0.23$, and modulation periods are $P_1 = 21.6$ and $P_2 = 11.6$ mm. The measured far-field radiation patterns of SSPP waveguides are demonstrated in Figure 9b–e, which show that Beam 1 and Beam 2 always radiate to the directions of $\theta_1 = 40^\circ$ and $\theta_2 = -35^\circ$, respectively, but their polarization states vary with $\Delta \phi_1$ and $\Delta \phi_2$, respectively. When $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 0$, each radiation beam is an $x$-polarized wave with a high cross-polarization level over 20 dB, as shown in Figure 9b. When $\Delta \phi_1 = -180^\circ$ and $\Delta \phi_2 = 0$, Beam 1 becomes a $y$-polarized wave and Beam 2 is still an $x$-polarized wave, as shown in Figure 9c. When $\Delta \phi_1 = 0$ and $\Delta \phi_2 = 90^\circ$, Beam 1 is an $x$-polarized wave, while Beam 2 is an LHCP wave, as shown in Figure 9d. When $\Delta \phi_1 = -90^\circ$ and $\Delta \phi_2 = 90^\circ$, Beam 1 and Beam 2 become an RHCP wave and an LHCP wave, respectively, as shown in Figure 9e. All the measured results have a good agreement with the simulations shown in Figure 6, and further prove that the polarization state of each beam can be independently controlled by the phase differences $\Delta \phi_1$ and $\Delta \phi_2$, respectively. In addition, Figure 10a–d demonstrate the measured $S$ parameters and the axis ratios of circularly polarized radiation beams, which show that both $S_{11}$ and $S_{21}$ are almost smaller than $-10$ dB, indicating good radiation efficiency, and the axis ratios of circularly polarized waves are not larger than 2 dB, indicating the good circular polarization performances. The far-field radiation patterns of SSPP waveguides at different frequencies are demonstrated in Figure 10e–h, showing that the SSPP waveguides can work in a broad frequency band from 9.3 GHz to 10.3 GHz and two radiation beams scan as frequency changes. Figure 11 demonstrates the gains and efficiencies of different SSPP waveguides. The results show that the gain is larger than 10 dB, the radiation

![Figure 11](image-url)
efficiency is almost larger than 80% in whole frequency band of each beam from 9.3 to 10.3 GHz, and the experimental results are in good agreement with the simulations.

5. Conclusion

In summary, a method that can realize the dual-beam leaky-wave radiations and independently control of their amplitudes, angles, and polarizations of radiation beams has been proposed in this paper. The results show that the dual-beam leaky-wave radiations can be generated by designing SSPP waveguide with periodically modulated surface impedance, and the amplitude, angle, and polarization of each beam can be independently customized by the modulation factor, modulation period, and initial phase difference, respectively. The simulation and measurement results have a good agreement with each other, which are consistent very well with the theoretical expectations. It is a simple and flexible way to realize dual-beam radiation with independent controls of their amplitudes, angles, and polarizations based on the proposed SSPP waveguide, and the method also can be extended to realize more beam radiations. The dual-beam or multibeam LWAs can be constructed based on the proposed method, which may have the potential applications in modern point-to-multipoint communications, and have advantages of multiple degrees of freedom modulation of space diversity, polarization diversity, and arbitrary channel energy allocation. In addition, these LWAs may be suitable for some specific environments due to their 1D design, such as highways, subways, tunnels, and so on.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

amplitude control, dual-beam radiation, polarization control, radiation angle control, spoof surface plasmon polaritons

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