A novel dual-beam terahertz leaky-wave antenna based on spoof surface plasmon waveguide*

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A novel dual-beam terahertz (THz) leaky-wave antenna (LWA) based on triple-periodically (TP) modulated spoof surface plasmon (SSP) waveguide is proposed. It is shown that SSP can be effectively excited and propagated along the surface of parallel corrugated metallic strips. Through proper design, the n=−1 and n=−2 Floquet modes are brought into the leakage radiation region simultaneously. Consequently, the forward and backward propagating waves corresponding to the two modes respectively generate two radiation beams in the far-field region. The proposed antenna is capable of steering the forward beam within a range of 34° and the backward beam within a range of 48° when frequency is swept between 0.23 THz and 0.29 THz. A simulated peak gain of 11.4 dBi and gain variation of 2.87 dBi are achieved within the band. The proposed LWA can be applied in THz wireless communication and radar systems.

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Surface plasmon (SP) has attracted great attention from researchers[1,2]. Because the SP is tightly constrained in the vicinity of metal/dielectric interface, its electromagnetic energy density is significantly enhanced[3]. Usually, its plasmonic frequency appears in the infrared band, so it cannot be strongly supported in the microwave and terahertz (THz) bands. Later, spoof SP (SSP) was proposed by cutting grooves or drilling holes on a metal surface. SSP has the characteristics similar to SP, except that the field confinement is within a subwavelength dimension at much lower frequencies[4-8]. More importantly, we can get the desired dispersion characteristics and cut-off frequency by changing the geometric parameters of the SSP. Until now, people have proposed a variety of devices based on SSP, such as filters[9], antennas[10,11] and wave splitters[12].

Multi-beam antenna can transmit and receive signals in multiple directions simultaneously. Therefore, it can perform the functions of a multi-input multi-output (MIMO) system with just one antenna, greatly simplifying the system. Moreover, the antenna has the flexibility in communication with multiple targets. For the system that needs to cover multiple areas, dual-beam antenna and multi-beam antenna can also reduce the number of antennas, thus simplifying the complexity of the systems. In the existing research, many methods have been proposed to build an effective two-beam antenna[13-19]. In Ref.[15], a dual-beam leaky-wave antenna (LWA) with wide beam scanning range based on substrate integrated waveguide (SIW) was proposed. Two kinds of microstrip LWAs based on multi-periodic structures realized asymmetric scanning of dual beams[16,17]. As to the dual-beam LWAs based on SSP waveguides, two parallel single-periodic modulations or double-periodic modulation on SPP waveguides have been demonstrated to achieve dual-beam radiation in the microwave regime[18,19].

In this letter, a novel dual-beam LWA operating in the THz band based on the SSP waveguide with triple-periodic (TP) modulation is proposed. The structure is composed of two ultra-thin corrugated metal strips and a dielectric substrate sandwiched in between. With the two metal strips being mirror symmetric, the fundamental mode (TM mode) of the transmission line does not produce radiation, because the electric field is very strongly confined between the two metal strips. When a one-dimensional TP structure is adopted, the introduced discontinuity will stimulate leaky Floquet higher-order modes. The feeding network is very simple, and only two end-feeding ports connected to 50-Ω coax are needed.

As well known, a comb-shaped ultra-thin corrugated metal strip forms a plasmonic waveguide which has very strong field confinement. By introducing triple-periodicities

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along the waveguide, a dual-beam LWA can be realized. In Fig.1(a), we show the overall structure of the antenna. At its two ends, there are transition sections for the matching of microstrip lines to the periodically-modulated plasmonic waveguide. The first part of the transition section is formed by a linear tapering of a microstrip line. The second part is a section of SSP waveguide with a gradually changing groove depth h from 2 μm to 36 μm with a step size of 2 μm. The gradual transition design helps to increase the operating bandwidth of the antenna. The optimized dimensions are V=300 μm, L=14 000 μm, L_1=560 μm, and L_2=850 μm.

Fig.1(b) depicts the TP structure of the antenna, where the length of the unit is L_4=1 059 μm and the width of the stub is m=19 μm.

Fig.1(c) shows the geometric parameters of metallic corrugations as follows, p=40 μm, g=20 μm, w=50 μm, h=36 μm, and d=25 μm. In our simulation, the dielectric substrate F4B has a dielectric constant of ε_r=2.65 and loss tangent of tanδ=0.001. The metal is assumed to be perfect electric conductor (PEC).

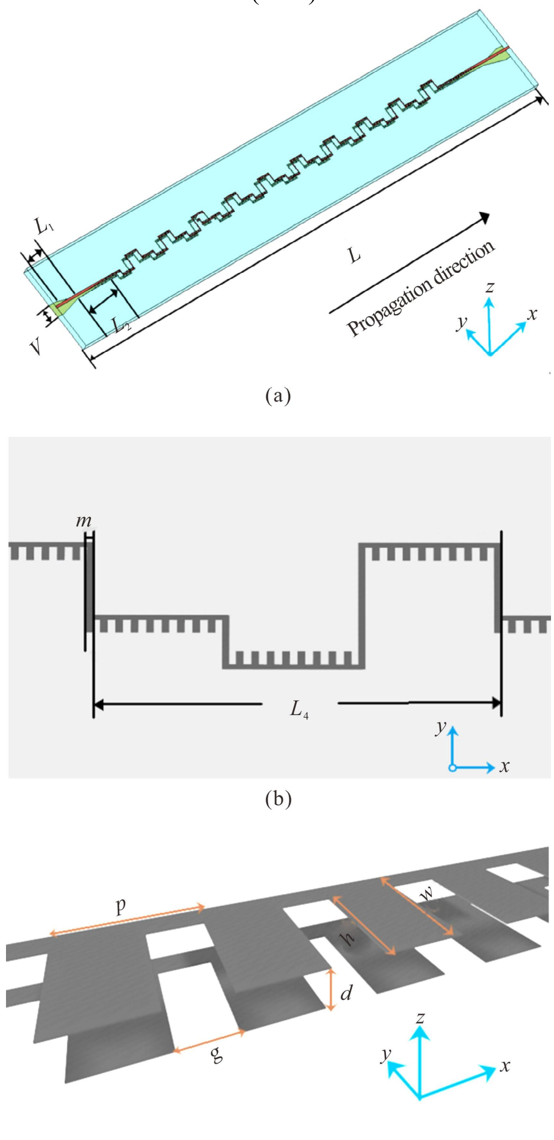


Fig.1 (a) Schematic diagram of overall structure of the proposed antenna; (b) Top view of TP unit structure of the proposed antenna; (c) Geometrical configuration of a plasmonic waveguide made of two ultrathin corrugated metallic strips on the top and bottom surfaces of a substrate with translational symmetry

A TP inversion is introduced into the uniform plasmonic waveguide to make it perform as an LWA. The SP mode is mainly confined to the surface of metal structure and exhibits slow-wave dispersion behavior. An inverse geometry can destroy the electrical boundary of the local surface field.

The inversion structure realizes the periodic modulation of the plasmonic waveguide and excites infinite spatial harmonics around the disturbance. According to the Floquet theory, the phase constant of the n-th harmonic can be expressed as

$$\beta_n = \beta_0 + 2n\pi/p, n = 0, \pm 1, \pm 2, ..., \quad (1)$$

where β_0 is the phase constant of the n=0 space harmonic and p is the period of the modulation. We use the eigen-mode solver of CST microwave studio to simulate the dispersion characteristics of the TP structure. In Fig.2, the shadow regions represent the stop bands. It can be seen from the figure that two spatial harmonics lie above the air line, and they correspond to the n=−1 and n=−2 spatial harmonics, respectively. Corresponding to the two spatial harmonics, two radiation beams will be produced simultaneously.

It is well known that the relationship between the phase constant β_n and the radiation angle θ of an LWA measured from the Z axis is

$$\sin\theta = \beta_n / k_0 . \quad (2)$$

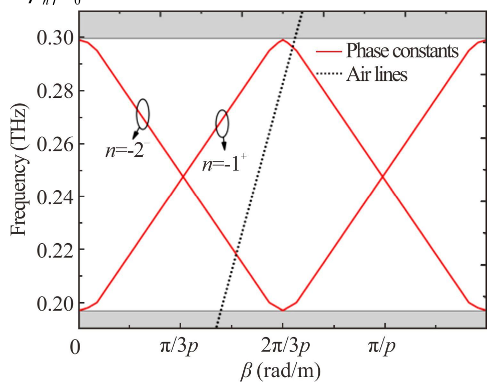


Fig.2 Dispersion relations of TP structure of the proposed antenna

According to the above formula, the two beams generated by the antenna can be steered by the operating frequency, which is different from the situation of the traditional dual-beam directional antennas.

The LWA comprised of ten units is further investigated using full-wave simulation. Fig.3 shows the simulated S_{11} and S_{21} parameters. The S_{11} is below −10 dB from 0.2 THz to 0.28 THz, showing very good impedance matching over a broad bandwidth.

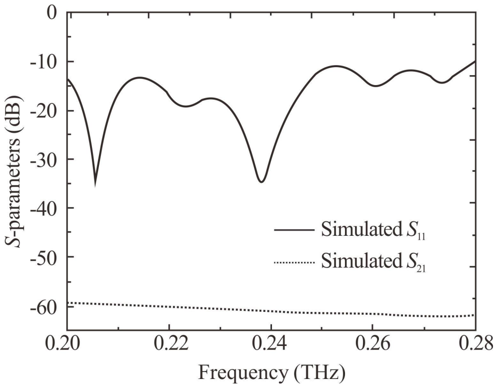
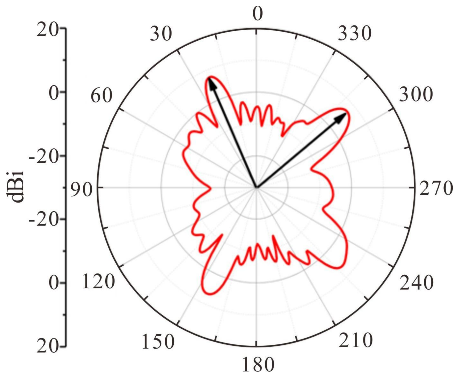


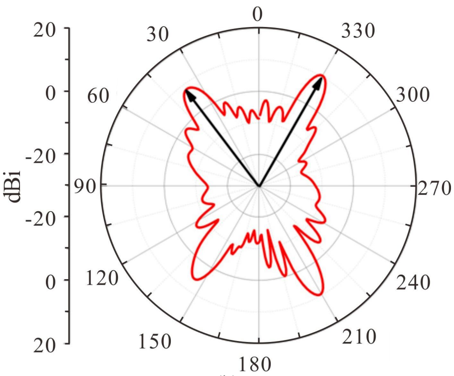
Fig.3 Simulated results of *S*-parameters

In Fig.4, the radiation patterns of the antenna at 0.24 THz, 0.26 THz, and 0.28 THz are shown. The black arrow represents the radiation direction of the main beam. We can clearly see two radiation beams for all the cases, for example, a forward beam pointing at +37° and a backward beam pointing at −30° at 0.26 THz.

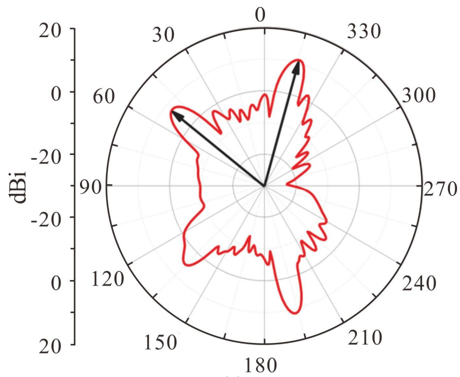
From Fig.4, we can observe that when the frequency changes, the two beams scan in the same direction. In Fig.5, the simulated radiation angles of forward and backward beams in the frequency range from 0.23 THz to 0.29 THz are given. The scanning angle of the forward beam is from +16° to +57° and that of the backward beam is from −64° to −8°. Therefore, a total scanning range of 97° is achieved across the given band, which is almost twice the value of a single-beam LWA.



(a)



(b)



(c)

Fig.4 Simulated radiation patterns in *xz*-plane at (a) 0.24 THz, (b) 0.26 THz, and (c) 0.28 THz

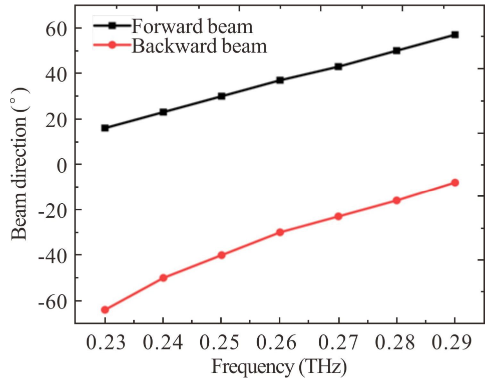


Fig.5 Simulated radiation angles (from the broadside direction) of the forward and backward beams

In Fig.6, the simulated gains of the forward and backward beams of the proposed antenna are given. At 0.26 THz, the gain of the forward beam is 10.4 dBi and that of the backward beam is 9.5 dBi. It can be seen that a high beam gain in the operating band is realized.

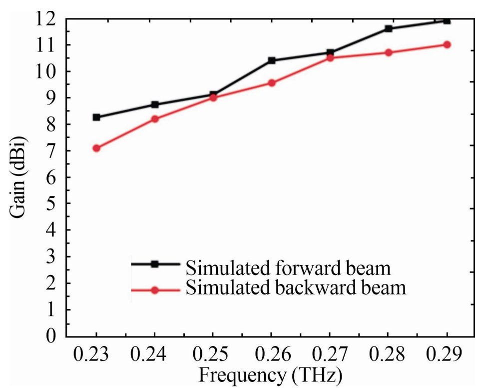


Fig.6 Simulated gain curves of the forward and backward beams

A comparison between the proposed LWA and other previously published results are shown in Tab.1. The proposed conformal SSP-based LWA achieves dual-beam operation in the THz frequency regime with satisfactory performance.

Tab.1 Comparison between the proposed LWA and those in the previously published literatures

Reference	Antenna type	Centre frequency	Dual-beam	Scanning range
[16]	Waveguide	5.8 GHz	Yes	36°—42° −46°—−34°
[15]	SIW	14 GHz	Yes	−45°—−5° 15°—40°
[18]	SSP	10.5 GHz	Yes	−60°—−20° 10°—50°
[10]	SSP	60 GHz	No	−40°—−10°
[5]	SSP	0.19 THz	No	−20°—10°
This work	SSP	0.26 THz	Yes	16°—57° −64°—−8°

In this letter, a novel dual-beam LWA based on a TP modulated SSP waveguide is proposed at terahertz frequency regime. The simulation results show that the proposed antenna can excite two radiation beams and achieve beam scanning when frequency varies. A total scanning range of 97° and an average gain of almost 10 dBi in the band from 0.23 THz to 0.29 THz are achieved with the given LWA. For application scenarios operating in different frequency bands, the dimensions of the antenna can be adjusted to satisfy the various application requirements. The concept of multi-periodic modulation on SPP waveguides can be extended to realize multi-beam THz antennas.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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