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Highly Efficient Dual-Beam Frequency Scanning Based on SSPPs With Parasitic Patch Array

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A leaky-wave antenna (LWA) realizes radiation of travelling wave along guiding structures. Periodic modulation is an effective approach to turn non-radiating modes into radiating modes. A high-efficient LWA based on spoof surface plasmon polaritons (SSPPs) loaded with parasitic patch array is proposed. Sinusoidal modulation is used for the radiation of SSPPs, while parasitic array mitigates the open stopband (OSB) effect. A prototype is fabricated and measured. The measured and simulated results agree well with each other. Such design shows wide angle coverage of 83° from backward to forward and stable gain distribution of about 12 dB within the whole operating band.

Keywords: dual-beam, frequency scanning, SSPPs, highly efficient, parasitic patch array

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INTRODUCTION

Leaky-wave antennas (LWAs) was first introduced by Hansen in 1940, consisting of a slotted rectangular waveguide [1]. Since then, great improvements have been achieved in such field, taking advantages of low profile, wide frequency scanning coverage and ease of fabrication [2]. LWAs are popular in microwave designs because conical beam with good directivity related to frequency is achieved without complex feeding network. In recent years, they have been used in high-resolution radar systems, conformal antennas on aircraft, satellites, and guiding systems.

Spoof surface plasmon polaritons (SSPPs) are novel guiding modes excited on the surface of periodic metamaterial structures. Such modes mimic the dispersion property of surface plasmon polaritons (SPPs) that only exist in optical or near-infrared bands. SSPPs shows unique properties of low-pass, high field confinement, and shorter operating wavelength, which provides great reference to improve traditional microwave circuits and systems. In 2014, broadband excitement of SSPPs is reported, which makes great contributions to researches of SSPPs [3]. Since then, a series of passive and active functional devices based on SSPPs were reported [4–8].

However, the near electric field of SSPP modes locates around the metallic structure of the SSPP waveguides during propagation. It decays exponentially with the increasing distance away from the waveguide. Such distribution ensures low cross-talk between devices while increasing difficulties in designing radiation components. In order to turn the non-radiating mode into a radiating mode, periodical modulation and parasitic radiating patches are used. SSPP could work as excitation of certain patches to achieve effective radiation. Two rows of circular patch arrays were excited by SSPP transmission line with both perfect electric conductor (PEC) and artificial magnetic conductor (AMC) [9]. A single-beam scanning range of 40° is obtained. The circular patch array placed at only one side of the SSPP structures could also provide single-beam radiation [10]. In such circumstances, a lateral radiation with stable high gains is designed. Open-loop elements were also used as radiation

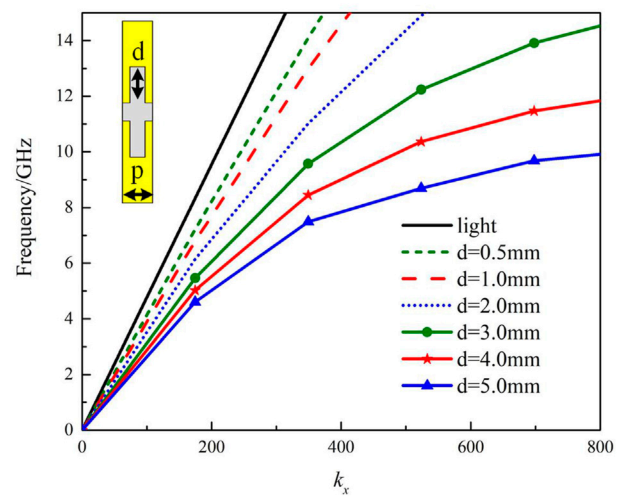

FIGURE 1 | The wavenumber k_x of SSPP unit under different dimensions. Inset: the structure of the complementary SSPP unit with dimensions labelled.

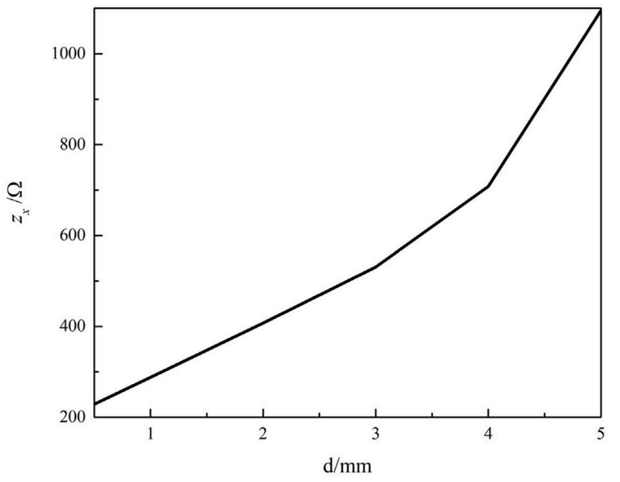

FIGURE 2 | Surface impedance of SSPP corresponding to different groove depth d.

elements to design two Ka-band LWA with frequency scanning in both E-plane and H-plane [11]. In 2021, a novel split-ring-shaped SSPP transmission line is proposed to excited two elliptical-shaped patch arrays [12]. The open stopband (OSB) effect is mitigated and a wide scanning range from −90° to 22° is demonstrated. Circular patches fed by symmetrical SSPP are able to form dual-linear polarization [13]. For different excitation of in-phase and out-phase on SSPP structures, horizontal and vertical polarizations are acquired. Despite of exciting patches as radiators, periodic modulation of SSPP units could also provide efficient radiation. A wide-scanning-angle LWA is proposed with shorting stubs loaded with metallic posts [14]. The scanning range reaches 80 ° with high realized gain. Periodic surface waveguide is cascaded between two SSPP transmission lines to form well-performed LWA [15]. Such antenna produces a single-side scanning beam of 8.7 dB gain with an overall efficiency of 75%. Backfire beam scanning is investigated based on the odd-mode SSPPs [16]. The main beam scans from backfire to broadside with high gain and radiation efficiency. Different order of space harmonics of periodic modulated SSPP is also used to provides extra radiation beam [17]. Both -1st and -2nd order space harmonics were proposed for forward and backward radiation respectively.

In this paper, a highly efficient LWA is proposed for wide beam scanning coverage from backward to forward. Periodically modulated grooves are used for the radiation of SSPP mode. And parasitic patch array is added inside the complementary SSPP line to improve radiation efficiency and mitigate the OSB effect.

Radiation of SSPPs

As a kind of TM surface modes, the surface impedance of SSPP mode could be obtained from its dispersion property according to the surface impedance theory. For SSPP mode, electric field decays exponentially with the distance away from the waveguide. The wavenumber along the direction perpendicular to the structure is imaginary. Thus, the wavenumber in transmission direction is real and it is larger than the that in free space. The surface impedance of SSPP could be expressed as:

$$\mathrm{Z} = Z_0\sqrt{1-\left(\frac{k_x}{k_0}\right)^2} \tag{1}$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ and k_0 are the wave impedance and wavenumber in free space, k_x is the wavenumber of SSPP along transmission direction.

The wavenumber of SSPP k_x could be calculated from its dispersion relationship. The dispersion relationship of traditional complementary SSPP grooves are shown in **Figure 1**. The structure of the unit is shown in the inset of **Figure 1**. The cycle of the unit p is 1 mm. The depth of the groove is d. And the widths of the center slot and groove are 2 and 0.5 mm, respectively. The cut-off frequencies of the units are directly controlled by the depths of the grooves. At a certain frequency, the deeper the groove is, the larger its wavenumber would be. From the figure we can also find that such mode located in slow wave area and it would not radiate. Hence, according to the LWA theory, periodic modulation is used. The dimensions of the grooves along transmission direction is designed under sinusoidal distribution. The surface impedance is expressed as

$$Z_x = jX_s\left[1 + M^{'}\cos\left(\frac{2\pi x}{P_n}\right)\right] \tag{2}$$

where X_s is the average surface impedance, $M^{'}$ is the modulation factor, P_n is the cycle of the composite modulated unit. Sinusoidal modulation could excite multiple space harmonics. The n-order space harmonic along transmission direction is

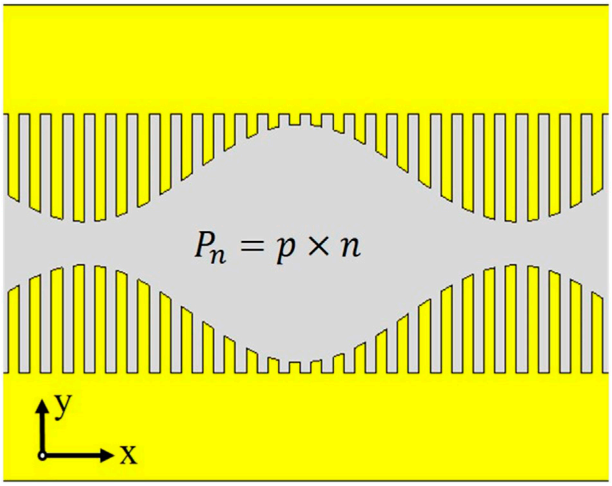

FIGURE 3 | The structure of the periodic modulated composite SSPP unit.

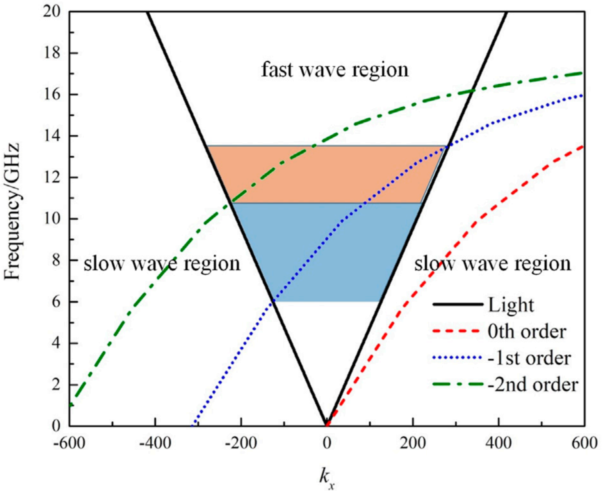

FIGURE 4 | The dispersion relationship of space harmonics.

$$k_{x,n} = k_{x,0} + \frac{2\pi n}{P_n} \tag{3}$$

According to the radiation theory of LWA, frequency scanning is valid as long as the condition of $|k_{x,-1}| \le k_0$ is met. And the radiation direction is calculated with

$$\theta_{-1} = \arcsin\left(\sqrt{1 + X'^2} - \frac{2\pi}{k_0 P_n}\right) \tag{4}$$

where $X^{'} = X_s/Z_0$ is normalized surface impedance.

The center frequency of the proposed radiator is designed to be around 9 GHz. Since the wavenumber of SSPP is dispersive, the surface impedance under different groove depths at 9 GHz is collected and shown in **Figure 2**. Since the cut-off frequency would be below 9 GHz when depth exceeds 6 mm. The maximum of the depth used is 5 mm. And the minimum of the depth is 0.5 mm. The surface impedance changes from 229 Ω to 1,095 Ω. The average surface impedance X_s is chose to be 500 Ω when the depth is 2.8 mm. The normalized surface impedance $X^{'} = 1.33$. Since the antenna shows broadside radiation at 9 GHz, the radiation direction $\theta_{-1} = 0°$. We got the modulated composite cycle $P_n = \lambda_0/\sqrt{1 + X'^2} = 20.032$ mm. The modulated number $n = 20$ is used. The structure of the modulated composite unit is shown in **Figure 3** with 20 sub-units of grooves per unit. The depth of each sub-unit follows the sinusoidal distribution. The maximum and minimum dimensions of grooves in the composite unit are 5 and 0.5 mm respectively.

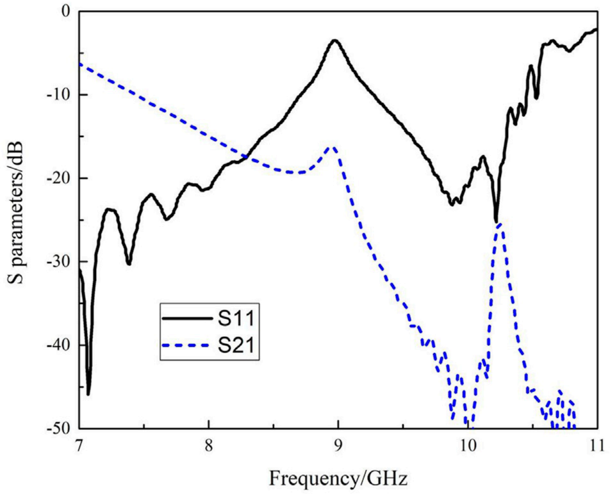

FIGURE 5 | The simulated S parameters of the LWA based on SSPP.

The modulated n-order space harmonics of the average wavenumber is shown in **Figure 4**. Most harmonics locate outside the symmetrical light axis. Within band from 6 to 10.5 GHz (blue marked area), only the -first order harmonic locates in the fast wave area. Good frequency scanning could be realized. Within band from 10.5 to 14 GHz (orange marked area), both -first and -2nd order harmonics locates in the fast wave area. In such circumstance, radiation beam would split into two lobes in both backward and forward directions. The efficiency and radiation pattern would be affected. So the antenna is designed for band in which only -first order harmonic works.

Periodic extension of the composite unit forms a high-performance leaky-wave radiation. The S parameters of such 2-port device is shown in **Figure 5**. Backward and forward frequency scanning are achieved around 8 and 9.5 GHz. However, within the operating band, a clearly uplift around 9 GHz is observed due to the OSB effect. The reflection at 9 GHz reaches -3.5 dB, which means most of the energy is reflected back to input. The radiation efficiency is damaged.

Improved Performance With Parasitic Patch Array

In order to improve the broadside radiation efficiency, parasitic circular patch array is introduced. The patches are excited by the

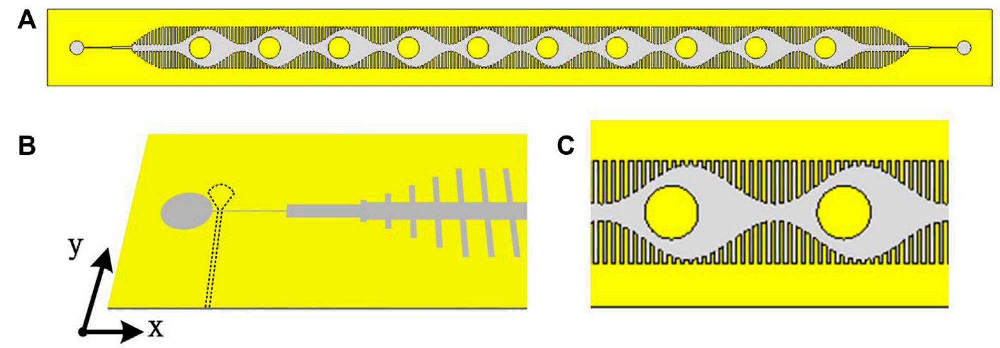

FIGURE 6 | Schematic structure of **(A)** the proposed device, **(B)** the feeding network and **(C)** the composite unit.

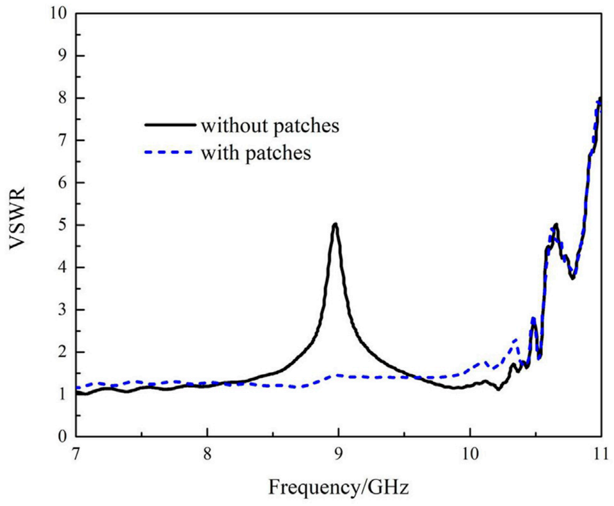

FIGURE 7 | VSWR of designs with and without parasitic patches.

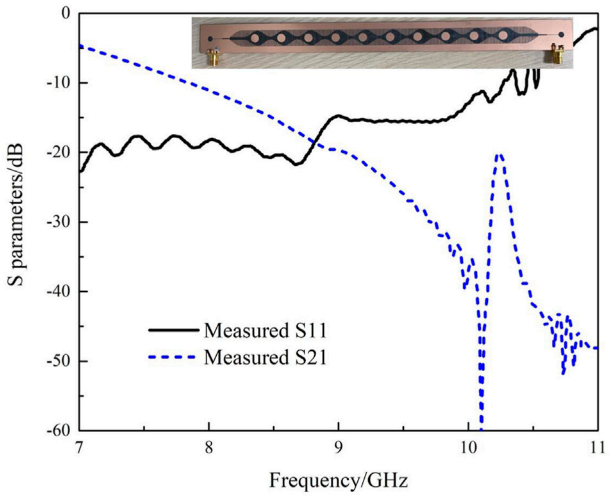

FIGURE 8 | Measured S parameters of the proposed design. Inset: Photo of the prototype.

SSPP mode inside the transmission structure and provide extra radiation. The operating wavelength of the SSPP transmission line can be obtained from the modulated average wavenumber as $\lambda_{8.8GHz} = 2\pi/k_x = 12.6$ mm. Thus, the radius of the circular patch is set to be 3.1 mm. As long as the patches locate in the same area, the phase different on the patches can be ignored and broadside radiation could be realized. On the other hand, limited by the space allocation, the cycle of the patch array is also 20 mm, larger than the operating wavelength. According to antenna theory of linear array in broadside design, grating lobe would occur. In addition, the patches are placed 2.2 mm to the left of the center of the composite unit. The center point of the composite unit is defined as the place where the minimum groove's depth appears. When the patches deviate from the center point, the symmetry of the composite unit is broken and the OSB effect can be mitigated. The schematic structure of the proposed design is shown in **Figure 6**. At both terminals, microstrip lines on the bottom layer is used for excitation and reception. Circular cavities are supposed to improve the coupling efficiency between the slot and microstrip lines. Six units of grooves with gradient depths are used for broadband excitation of SSPP mode. And ten-unit of the composite units are cascaded for leaky-wave radiation.

The voltage standing wave ratio (VSWR) of the design with and without parasitic patches are compared in **Figure 7**. Within the whole operating band, the design with parasitic patches keeps around 1.4, and the significant peak disappeared.

The prototype illustrated in the inset of **Figure 8** is fabricated on F4B substrate with whole dimensions of 270 mm × 20 mm. The thickness of the substrate is 0.5 mm and its relative dielectric constant is 2.65. The measured S parameters are shown in **Figure 8**. Both reflection and transmission are below -10 dB from 8 to 10 GHz, indicating a good radiation performance. OSB effect for broadside radiation around 9 GHz is clearly suppressed. And beam-scanning from backward to forward is realized. For band from 7 to 8 GHz, transmission is above -10dB. The total efficiency drops but the radiation pattern still shows high gain property, which would be discussed later.

The simulated and measured far-field radiation patterns are shown in **Figure 9**, corresponding to different frequencies. The

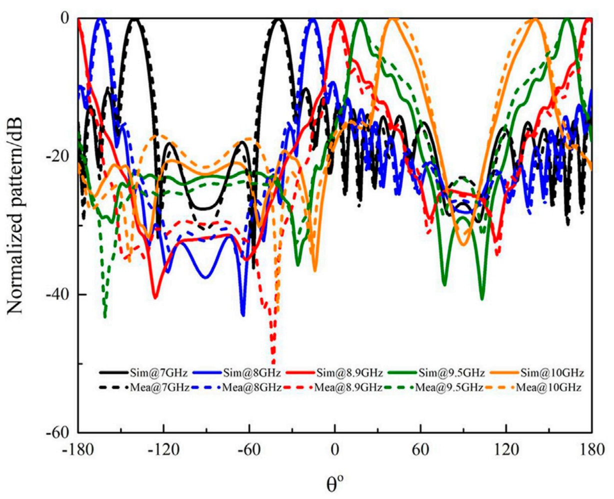

FIGURE 9 | Simulated and measured normalized pattern at different frequencies.

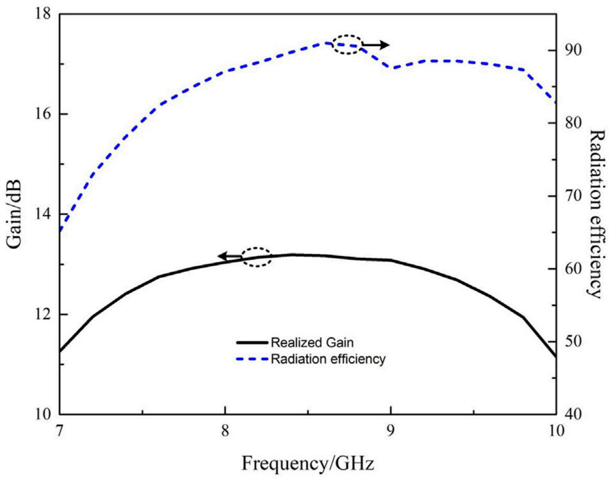

FIGURE 10 | Realized gain and radiation efficiency.

broadside radiation appears at 8.9 GHz. The measured results are in good agreement with the simulated results. Within band from 7 to 9 GHz, the design shows radiation of backward frequency scanning. And within band from 9 to 10 GHz, forward radiation is accomplished. the direction of the main lobe at 7 GHz, 8 GHz, 9.5 GHz and 10 GHz are -41°, -17°, 16° and 42°, respectively. The broadside radiation locates at 8.9 GHz with narrowest HPBW of 4.5 °. And it increases with the frequency increasing or decreasing. The HPBWs at 7 and 10 GHz are 6.4° and 8°, respectively. The measured HPBWs are about 1° smaller than the simulated ones. The simulated total efficiencies and measured gains are shown in **Figure 10**. The gain keep stable at around 12 dB within the whole operating band. And the maximum gain of 13.2 dB appears at 8.4 GHz.

CONCLUSION

In this letter, a high-efficient dual-beam LWA based on complementary SSPP modes has been proposed. Wide scanning coverage from backward radiation to forward radiation is achieved. Additional parasitic patch array is introduced in the modulated composite unit to improve the radiation efficiency and mitigates the OSB effect. The device shows stable gain distribution within the whole operating band, while scanning from −41 ° to 42 °. A prototype is fabricated and measured. The measured results agree with the simulated ones. Such design is available for conformal applications and other kinds of radiation systems.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.