Wide-Angle Beam Scanning Leaky-Wave Antenna Array Based on Hole Array SSPPs

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***Abstract*—In this letter, a leaky-wave antenna (LWA) array based on hole array spoof surface plasmon polaritons (SSPPs) is proposed, which can realize wide frequency beam scanning angle. By etching periodic hole arrays on the upper metal of the defective ground structure, the SSPP structure is formed and the frequency scanning beam is generated by using its higher-order radiation mode characteristics. The radiation mechanisms of the design are explained by using the dispersion relationship, electric field distributions, and space harmonics. The LWA array is fed by a 1 to 4 power divider and achieves good impedance matching within 6-16 GHz bandwidth. The average peak gain value of the proposed LWA antenna array is about 16.86 dBi and the frequency beam scanning range is 91°. The antenna array has the characteristics of easy fabrication, low cost, and high gain performance, which provides a new design concept for wide-scanning-angle LWA Array and can meet the demand of high gain requirements in radar and other related fields.**

***Index Terms*—leaky-wave antenna array, higher-order modes, power divider, spoof surface plasmon polaritons.**

I. Introduction

Surface plasmon polaritons (SPPs) is a special electromagnetic (EM) mode propagating on the surface of medium [1]-[3]. In the optical band, the metal dielectric constant is negative and the SPP wave exists in the metal and air interface. In order to introduce the SPPs into microwave or terahertz band, spoof SPPs (SSPPs) was proposed by researchers, which inherits most of the advantages of SPPs in the terahertz and microwave bands and applied to the design of miscellaneous microwave components, such as antennas, filters, and circulators [4]-[9]. Moreover, the physical characteristics of SSPPs are the good candidate to design the end-fire and frequency beam scanning antennas [10]-[11].

Recently, some wide-angle leaky-wave antenna (LWA) based on the gradient corrugation grooves and specific flaring grounds SSPPs were proposed to achieve frequency beam scanning performance, whose scanning angle can up to 83° [12]-[13]. However, these structures were not beneficial to miniaturization design. Additionally, the circular polarization LWA based on microstrip SSPPs patch array and specific flaring ground SSPPs patch array were proposed in [14]-[15], which can achieve good circular polarization performance. Nevertheless, their bandwidth, size, and beam scanning angle are still limited by the structure. Meanwhile, various forms of frequency beam scanning antennas have been proposed by researchers for various applications [16]-[23]. For example, ref. [16] proposed a new design method for LWA, which designed based on the SSPPs and transmissive phase gradient metasurface. Moreover, the SSPP-based frequency beam scanning antenna combined with the periodically loaded patches above PEC and AMC ground planes to enhance 3 dBi gain values [17]. However, according to the opening literatures, most of the SSPPs were used as the feeding structure to generate the EM wave, less of them focused on the SSPPs higher-order radiation modes to design leaky-wave antennas. Therefore, ref. [21] proposed a coplanar waveguide (CPW) SSPP-based wide-angle and wide bandwidth LWA antenna based on the higher-order modes of SSPPs to radiate EM waves. Nevertheless, the structures proposed above are not benefit for further antenna array design. Therefore, designing a new structure which is conducive to design LWA antenna array is technically challenging.

In this letter, a wide-angle beam scanning LWA array is proposed based on the hole array SSPPs design. The LWA element etches periodic hole arrays on the upper metal of the defective ground structure, which can excite the higher-order fast wave modes of SSPPs and radiate frequency beam scanning waves into free space. The LWA radiation principle is explained by the dispersion relationship, electric field distributions, and space harmonics. The simulated results show that the designed LWA array realize a good impedance matching within 6-16 GHz bandwidth with average peak gain of 16.86 dBi and the frequency beam scanning range is 91°. Meanwhile, measured results are in good agreement with

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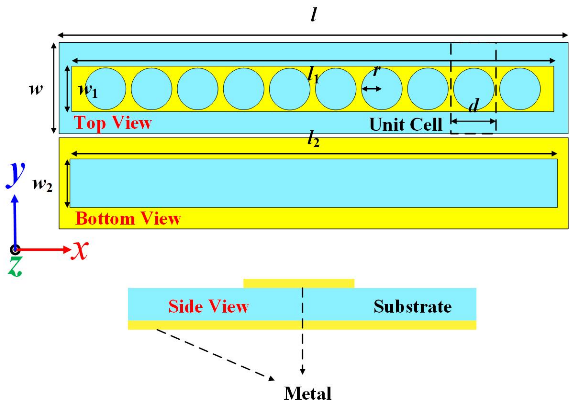


Fig. 1. Structure of the LWA array element

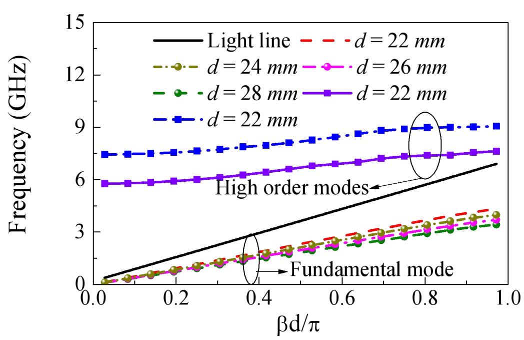


Fig. 2. Dispersion curves of unit cell

simulated ones, which indicating that the proposed LWA array has a high gain values and can be easily fabricated and used for potential applications in radar systems.

II. Antenna Design

A. LWA Element and Radiation Principle

Fig. 1 presents the structure of the LWA element, the antenna is designed on the 0.5 mm F4B substrate with dielectric constant of 2.65 and loss tangent of 0.0015. The structure of antenna unit cell is shown in the dashed box. The antenna physical parameters are as follows: w = 38 mm, w_1 = 20 mm, w_2 = 20, l = 240 mm, l_1 = 231.5 mm, l_2 = 232, r = 9.6 mm, and d = 22 mm. The hole array and the rectangular slot are etched on the top layer and bottom layer of the LWA element, respectively, which transform the quasi-TEM mode to TM mode and support the SSPPs wave propagates on the design.

The dispersion curves of antenna element are analyzed and presented in Fig. 2 to explain the antenna mode conversion. It can be clearly seen that the fundamental mode of the unit cell of the LWA element is lower than the light line, which means that the fundamental mode of SSPPs is located at slow wave region and can transmit the energy on its surface without radiation. However, the higher-order modes of the design are located above the light line, meaning that the EM wave is fast wave and can radiate into free space, which has frequency beam scanning performance. Moreover, the radiation performance of the structure realizes by a lot of radiating modes, which increases with the order number of the modes and can be expressed by -1 order space harmonics (Floquet modes) [21]:

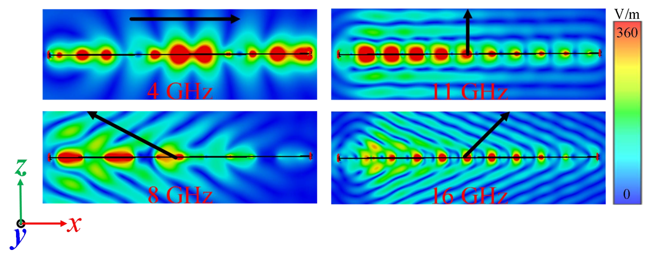
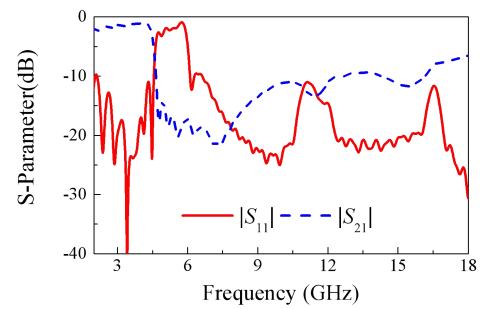
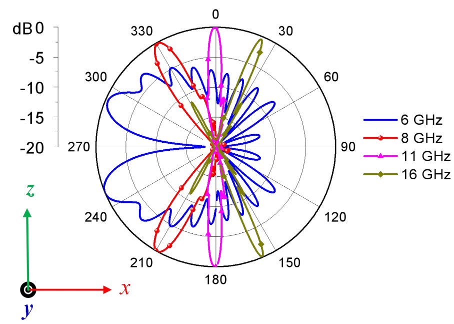


Fig. 3. Electric field distributions at *xoz* plane of the LWA array element at different frequencies.



(a)



(b)

Fig. 4. (a)S-parameters of LWA array element; (b) Normalized radiation pattern of LWA array element.

$$\beta_{-1} = \beta_0 - \frac{2\pi}{d}, \tag{1}$$

Furthermore, the radiation direction of main beam can be calculated from β_{-1} and expressed as:

$$\theta = \begin{cases} \arcsin\,(\beta_{-1}/k_0) \\ \pi - \arcsin\,(\beta_{-1}/k_0). \end{cases} \tag{2}$$

Where β_0 is wavenumber of the fundamental mode of the hole array SSPPs.

From the equation (2), the main beam at θ= 0 or π radiates broadside pattern, which results in β_{-1} = 0 and $\beta_0 d$=2π. From Fig. 2, it can find that the radiating mode starts from 5.6 GHz, meaning that $\beta_{0@5.6\ \mathrm{GHz}}\, d$ is equal to π. Hence, $\beta_{0@11.2\ \mathrm{GHz}}\, d$ is equal to 2π, the corresponding beam scanning angle frequency of the antenna element radiates into the broadside should be 11.2 GHz.

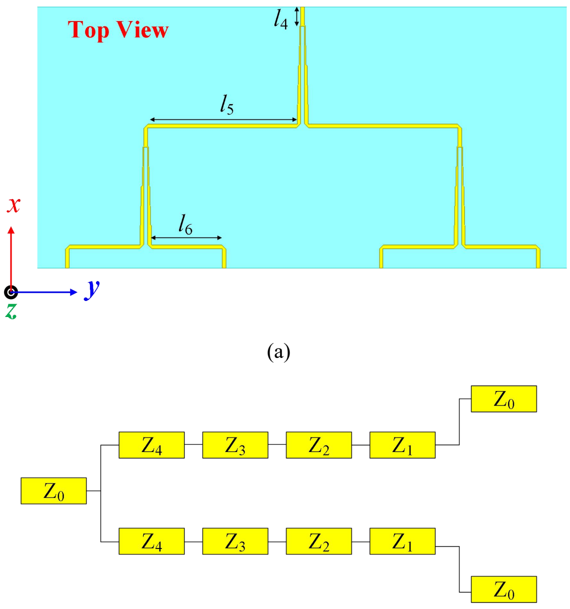


Fig. 5. (a)Structure of the ultra-wideband feeding network; (b) Schematic diagram of one to two power divider.

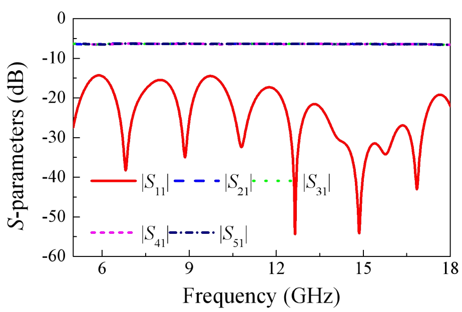


Fig. 6. S-parameters of the ultra-wideband feeding network.

In order to show the radiation performance clearly, Fig. 3 shows the simulated electric field of the proposed LWA element at different frequencies in the *xoz* plane. It is clearly seen that the design cannot radiate the wave in to space when the frequency is less than cutoff frequency. On the contrary, when the frequency is above cutoff frequency, the EM waves radiates into free space and the angle of the beam changes continuously with the change of frequency.

To present the antenna element characteristics clearly, the S-parameters and normalized radiation pattern are simulated when two ports are added in the structure. From Fig. 4(a), the structure has high transmission efficiency below 5.5 GHz and can radiate wave into free space above 5.5 GHz ($|S_{11}|$ and $|S_{21}| <$ -10 dB). Moreover, Fig. 4(b) shows that the antenna element can realize frequency beam scanning within 6-16 GHz and the scanning angle is 91°. Furthermore, the broadside radiation frequency is 11 GHz, which consistent well with the theoretical results.

B. The Feeding Network for the Proposed LWA Array

In order to excite the LWA array, a one to four feeding network is sketched in Fig. 5(a), which can be easily integrated with the antenna array design. The feeding network structure compose of three one to two power divider based on the multiple cascaded microstrip line. The schematic diagram of one to two power divider is presented in Fig. 5(b). The input and output terminals of the power divider are connected with 50 ohms microstrip lines and the middle lines are cascaded λ/4 impedance transformer to enhance the impedance bandwidth. Based on the even and odd mode theory, the impedance values of Z_0, Z_1, Z_2, Z_3, Z_4 can be obtained as follows: 50 ohm, 55.79 ohm, 64.79 ohm, 77.18 ohm, 89.63 ohm. The length (l_4) and width of feeding line are 3.5 mm and 0.7 mm, respectively. The length of the multiple cascaded microstrip line is 3.7 mm and the width of the multiple cascaded microstrip line are 0.2mm, 0.3mm, 0.5mm, 0.6mm, respectively. The parameters of l_5 and l_6 are 28.5 mm and 13.5 mm, respectively.

The ANSYS Electronics Desktop is used to simulate the performance of the feeding network. The performance of the design is shown in Fig. 6, the feeding network has a high transmission efficiency within 6-16 GHz. The $|S_{11}|$ is lower than -15 dB and $|S_{21}|$, $|S_{31}|$, $|S_{41}|$, $|S_{51}|$ are around -6.4 dB, which indicates that the structure can be used as the feeding structure for the proposed LWA array.

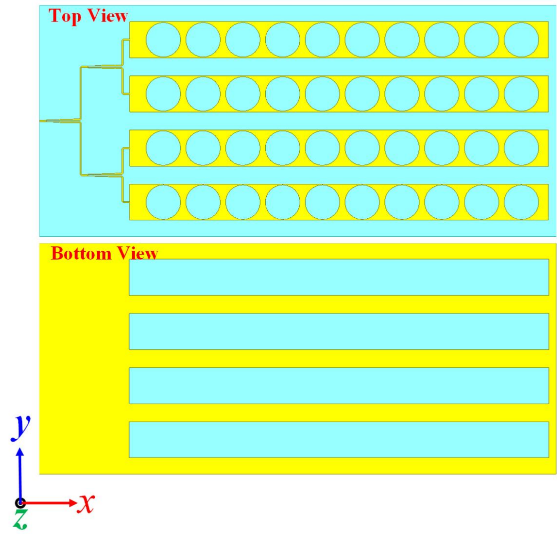


Fig. 7. Structure of the LWA antenna array.

C. Design of LWA Array

Fig. 7 shows the structure of the proposed LWA array, which is combined the feeding network and four antenna elements. The top layer of the feeding network is connected with the metal hole array of SSPPs and the bottom layer is connected with the defective ground structure. The distance of the LWA element is 30 mm. The performance of the antenna array performance will be presented in the next section.

III. Simulated and Experimental Results

The physical prototype of the proposed LWA array is fabricated on a 0.5 mm F4B substrate based on PCB technology. The photographs of fabricated LWA array and measured environment in a far-field anechoic chamber are shown in Fig. 8, which can be used to verify the simulated results.

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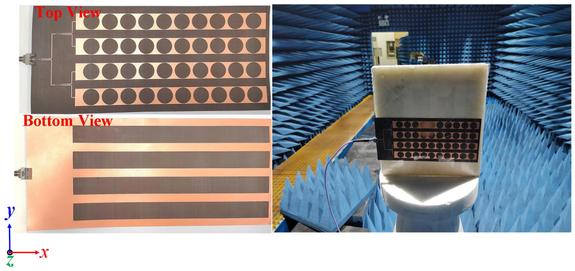

Fig. 8. Structure of the LWA array and measured environment.

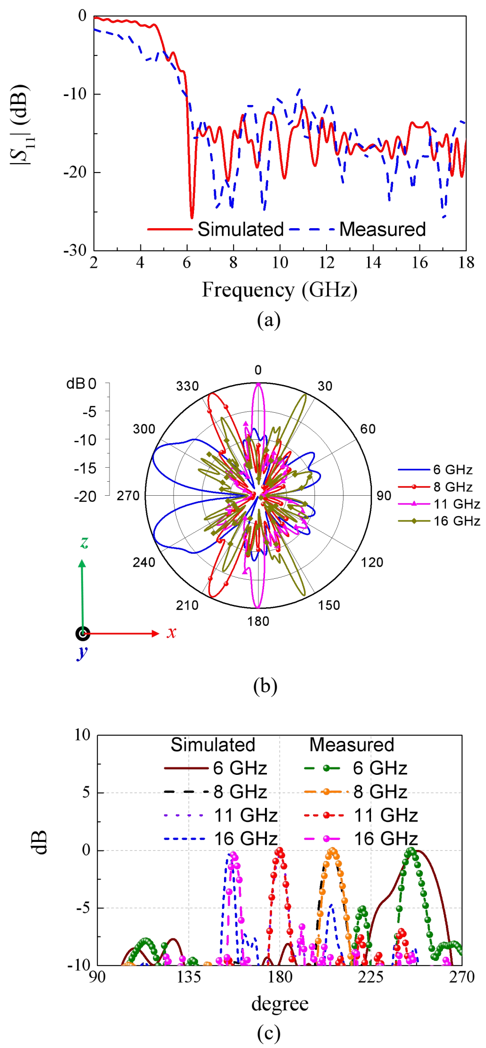

Fig. 9. (a)Simulated and measured S-parameters of LWA array; (b) Simulated normalized radiation patterns of LWA array. (c) Comparison of simulated and measured normalized radiation patterns of LWA array.

Fig. 9(a) presents the simulated and measured $|S_{11}|$ of the proposed LWA array, which shows that the antenna array can achieve a wide impedance matching within 6-18 GHz. Moreover, the simulated normalized radiation patterns of the proposed LWA array are given in Fig. 9(b), which shows that the antenna array realizes wide beam angle scans from −68° to 23° and the scanning ranges can reach 91°. Additionally, the comparison of simulated and measured normalized radiation patterns of antenna array are shown in Fig. 9(c), which have a good consistency each other. Moreover, the simulated and measured peak gain values of antenna element and LWA array are presented in Fig. 10, which can find that the antenna element and array can reach an average gain level of 11.86 dBi

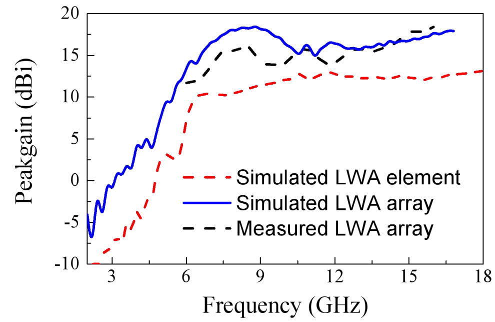

Fig. 10. Simulated and measured peak gain of antenna element and array.

TABLE I
PERFORMANCE COMPARISON OF EXISTING LWA ANTENNAS

Ref.	Antenna size (λ_0)	Band width (GHz)	Angle (deg)	Max gain (dBi)	Aperture efficiency	Array design
[10]	9.26×1.1	5-7	81°	19.4 (2 arrays)	34.7% (@7 GHz)	easy
[13]	9.72×1.8	9.2-16	83°	13.4 (element)	4.1% (@10 GHz)	hard
[22]	7.36×0.9	9-24	119°	14.2 (element)	10.9% (@10 GHz)	easy
[23]	3.6×1.9	6.6-7.7	29°	10.8 (element)	9.8% (@7 GHz)	hard
Pro. work	4.8×0.76	6-16	91°	13.2 (element)	12.6% (@10 GHz)	easy
Pro. work	5.7×2.56	6-16	91°	18.5 (4 arrays)	8.16% (@10 GHz)	easy

*λ_0 being the wavelength of the lowest frequency

and 16.86 dBi. The peak gain of the LWA array is about 5 dBi higher than the antenna element.

Table I summarizes the performance comparison of existing LWA antennas. It is seen that the ref. [10] proposed a LWA array design with 81° scanning angle and 19.4 dBi maximum gain. However, the antenna size should be further miniaturized. Refs. [13] and [23] proposed two LWAs based on specific flaring grounds. Nevertheless, these designs were not benefit to design antenna array. Therefore, compared to other antennas, our work proposed a miniaturized LWA element, which can be easily integrated with the feeding network. Additionally, it should be noted that the LWA proposed in [10] was designed based on Microstrip SSPPs-TL, which radiated single beam. Hence, this antenna has higher maximum gain compared with other dual beam antennas.

IV. CONCLUSION

In this letter, a LWA array based on SSPPs is proposed to achieve wide-angle scanning performance, which employs hole arrays etched on the defective ground structure to transform the slow wave as fast wave and generated frequency beam scanning wave by using its higher-order radiation mode characteristics. The antenna array is fed by a 1 to 4 power divider and achieves good impedance matching within 6-16 GHz bandwidth, the average peak gain of the antenna array is about 16.86 dBi and the frequency beam scanning range is 91°. The antenna array has the characteristics of easy fabrication, low cost, and high gain performance, which can meet the demand of high gain requirements in radar and other related fields.

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