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A Wide-Angle Narrow-Band Leaky-Wave Antenna Based on Substrate Integrated Waveguide-Spoof Surface Plasmon Polariton Structure

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***Abstract*—In this letter, a wide-angle narrow-band leaky-wave antenna (LWA) based on substrate integrated waveguide-spoof surface plasmon polariton (SIW-SSPP) structure is proposed. Periodic slots are etched on both the top and bottom surfaces of substrate integrated waveguide (SIW) to introduce spoof surface plasmon polariton (SSPP) mode. The periodic slots on the top surface are sinusoidally modulated to realize bi-directional LWA radiation. The problem of open stopband is solved by the asymmetrical design of the top and bottom slots. Thus, a wide bi-directional scanning range from −60° to +63° is achieved. Besides, the relative bandwidth of the fabricated antenna is reduced to only 9% by introducing the slow-wave effect of SSPP. It means the proposed antenna has a large scanning rate, or equivalently beam scanning range/bandwidth ratio.**

***Index Terms*—Leaky-wave antenna (LWA), narrow band, open stopband, substrate integrated waveguide (SIW), spoof surface plasmon polariton (SSPP).**

I. Introduction

THE leaky-wave antennas (LWAs) are a class of travelling wave antennas, which unique radiation characteristics have made them a hot spot in the field of antenna researches [1-2]. Substrate integrated waveguide (SIW) is an excellent planar guided wave structure with the similar characteristics of metallic waveguide. Therefore, LWAs based on SIW structures have been rapidly developed in recent decades and widely used in various fields such as conformal antennas on aircraft, high-resolution radar and satellite communication [3].

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Traditional LWAs can only realize beam scanning along the forward direction, which limits the applications of LWAs [4-5]. Many researches have been made on how to increase the scanning range of LWAs and realize backward to forward beam steering [6-8]. For example, composite right/left-handed (CRLH) SIW LWAs were proposed in [6] and zero-crossing scanning from the backward to the forward direction was realized. However, although wide angle scanning capability is obtained for the reported LWAs, large bandwidths are needed to operate beam steering, which is unacceptable for the applications with limited spectrum resources. The reason is that the guided wave length varies slowly with the frequency [9]. It is attractive to achieve wide angle scanning within a narrow frequency band. In [9], a linearly tapered rectangular waveguide slot array antenna was proposed by using the spatial angular filtering metasurface. The beam scanning angle is from 7° to 46° with only 3.1% relative bandwidth. Spoof surface plasmon polariton (SSPP) has high field confinement and slow-wave feature, which were also used in the design of LWAs [10-11]. In our previous work [12-13], SSPP was introduced to SIW structure and the proposed hybrid integrating SIW-SSPP waveguides have slow-wave characteristic. Then, we proposed a high scanning rate LWA based on SIW-SSPP structure [14]. Since the phase constant of a slow wave is much more sensitive to frequency variation, the proposed antenna can scan 35° within a narrow relative bandwidth of only 3%. However, although high scanning rate LWAs are obtained in [9] and [14], only forward scanning is achieved.

In this letter, we propose a wide-angle narrow-band LWA, which can realize backward to forward beam steering meanwhile has high scanning rate. Periodic slots are etched on both the top and bottom surfaces of SIW as the radiators. The sub-wavelength periodic slots can excite SSPP slow-wave mode in SIW to improve the antenna beam scanning rate. The slots on the top surface are sinusoidally modulated while those on the bottom surface are uniform. Due to the asymmetrical design, the open stopband is suppressed and the beam can scan from the backward to the forward direction. The prototype is simulated and measured. The experimental results show that

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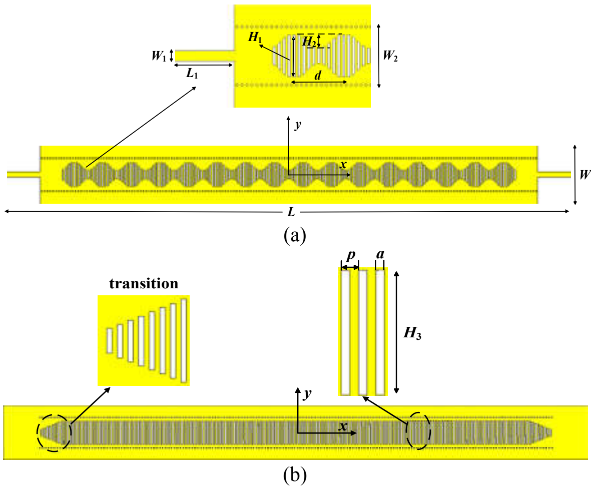

Fig. 1. Geometry of the proposed LWA: (a) top surface, (b) bottom surface.

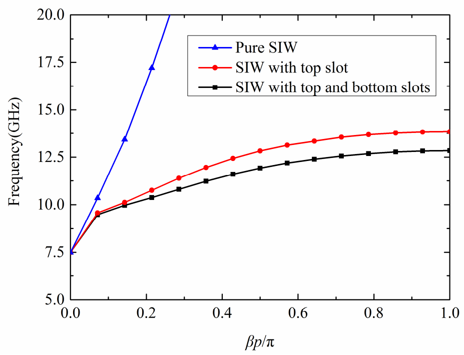

Fig. 2. Dispersion curves of the periodic units.

the proposed LWA has a bi-directional beam scanning range from −60° to +63° with only 9% relative bandwidth.

II. ANTENNA DESIGN

The geometry of the proposed SIW-SSPP LWA is shown in Fig. 1. The antenna size $L \times W$ is 200 mm × 20 mm, which is designed on the Rogers RT 5880 with thickness h = 0.508 mm, relative dielectric constant ε_r = 2.2, and loss tangent tanδ = 0.0009. As shown in the figure, SIW transmission line is formed by digging two rows of metallic via holes on printed circuit board (PCB) substrate with the width of W_2. For convenience of measurement, microstrip lines are added at the ends of SIW. The width and length of the microstrip lines are W_1 and L_1, respectively. Periodic transverse slots are etched on both the top and bottom surfaces of SIW to constitute LWA, so the energy can radiate out. The period of the slots p is set much less than the wavelength of the operational frequency. Previous works have certified that such sub-wavelength periodical structure can mimic the characteristics of SSPP and propagate slow-wave SSPP mode at microwave frequencies [12-13].

The dispersion characteristic of the proposed SIW-SSPP periodic unit is analyzed with commercial EM software CST under the Eigen mode. Fig. 2 is the simulated dispersion curves comparison among pure SIW, SIW with only top slot, and SIW with both top and bottom slots. It can be seen that the

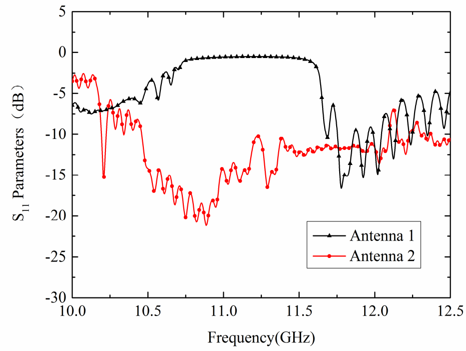

Fig. 3. Simulated reflection coefficients (S_{11}) of Antenna 1 and Antenna 2.

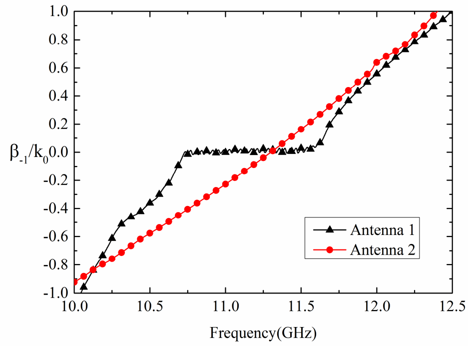

Fig. 4. Normalized simulated phase constants of Antenna 1 and Antenna 2.

SIW-SSPP structures have the same lower cutoff frequency as pure SIW. However, as the phase constant β increases, the slopes of SIW-SSPP curves decrease. It means the slow-wave feature emerges. Moreover, SIW with dual slots have stronger slow-wave effect. It is obvious in the figure that the propagation constants of SIW-SSPPs are much more sensitive to frequency variation. Therefore, a high scanning rate can be achieved based on the SIW-SSPP structure. It means the proposed antenna can reduce the operating bandwidth with the same scanning ability.

In order to realize leaky-wave radiation, the slots on the top surface are sinusoidally modulated. As shown in Fig. 1(a), the longest length of the slot is H_1 and the modulation amplitude is $H_2/2$. The width of the slot is a, and the modulated period is d. Infinite space harmonics can be introduced by periodic modulation. The $n = -1$ space harmonic is chosen to realize leaky-wave radiation. LWAs can scan beam in either the forward direction or the backward direction in this mode theoretically. In our previous work [14], an SIW LWA only with sinusoidally modulated slots on the top surface has been developed. However, there exist an open stopband around the broadside radiation. The LWA can not realize continuous beam scanning from the backward to the forward direction, thus only the band after the stopband was used in [14]. Although high scanning rate is obtained, the antenna can only scan 35° in forward direction.

The critical reason of the open stopband at the broadside is due to the even mode exhibiting a symmetry field at both transversal and longitudinal planes, leading to field offset at the broadside direction [15]. Using asymmetric model is an effective method to restrain the open stopband [15-16]. In this letter, we employ an additional SSPP on the bottom surface of

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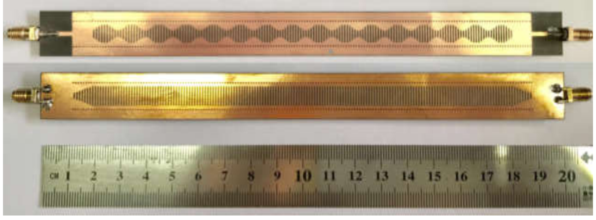

Fig. 5. Photograph of the proposed LWA.

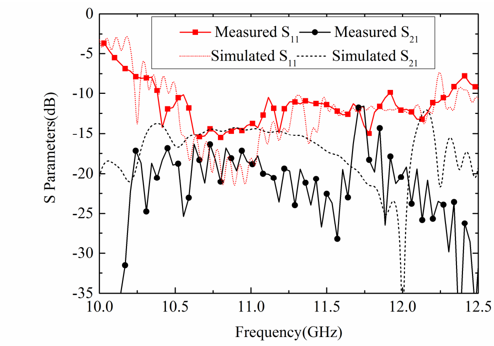

Fig. 6. Simulated and measured reflection coefficients (S_{11}) and transmission coefficients (S_{21}).

SIW to introduce asymmetric model. As shown in Fig. 1(b), the periodic slots on the bottom surface are not modulated and the length is H_3 in uniform. A smooth transition section with length varying from 0.3 H_3 to H_3 is employed to realize effective impedance matching.

It is noted that antenna with slots on only top surface is defined as Antenna 1 and antenna with slots on both surfaces is defined as Antenna 2 for comparison. Fig. 3 shows the simulated reflection coefficients (S_{11}) of Antenna 1 and Antenna 2. It is obvious that there exists a stopband from 10.7 GHz to 11.6 GHz for Antenna 1. In this frequency range, electromagnetic waves are almost reflected to input port. While the S_{11} of Antenna 2 is below -10 dB over the whole operating band. The reason is that the reflected waves on two surfaces are not in phase due to the asymmetric slots, thus electromagnetic waves are effectively fed into the LWA for broadside radiation. Fig. 4 is the normalized simulated phase constants of n = −1 space harmonic. It can be seen that the normalized phase constant of Antenna 1 remains zero in the open stopband range. For Antenna 2, the normalized phase constant varies from negative to positive continuously and β_{-1}/k_0 is zero at 11.3 GHz. Thus, the beam of Antenna 2 can scan from backward to forward without open stopband at the broadside.

III. SIMULATED AND MEASURED RESULTS

To verify the above analysis and demonstrate the antenna performance, the prototype of the proposed SIW-SSPP LWA is fabricated and measured. After optimization with CST Microwave Studio, geometry parameters of the antenna are fixed as: W_1 = 1.97 mm, W_2 = 5.65 mm, H_1 = 8 mm, H_2 = 2.2 mm, H_3 = 8.4 mm, p = 1 mm, a = 0.5 mm, d = 10.1 mm. The photograph of the prototype is shown in Fig. 5. Fig. 6 is the simulated and measured reflection coefficients (S_{11}) and transmission coefficients (S_{21}). It can be observed that the trend of the measured curves is accordant with the simulated ones. There exists a frequency shift between the simulated and measured results, which is caused by the dielectric constant difference between the fabricated and simulated substrates. From the figure it is obvious that the measured S_{11} and S_{21} are both below -10 dB covering the operating band from 10.6 GHz to 11.6 GHz. It means that most energy is radiated out by the antenna.

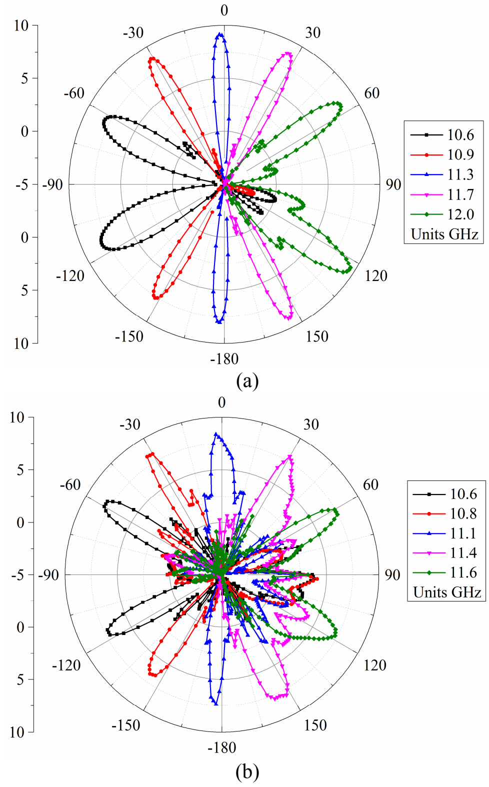

Fig. 7. Simulated and measured far-field radiation patterns of the proposed LWA: (a) Simulated results, (b) Measured results.

The simulated and measured radiation patterns of the proposed LWA are compared in Fig. 7. As shown in Fig. 7(a), when the frequency varies from 10.6 to 12.0 GHz, the simulated radiation beam scans from −63° to +56° and the total scanning range reaches up to 119°. Besides, symmetrical beam steering is obtained owing to the bi-directional radiators in the antenna. Therefore, the whole beam scanning coverage is 238°, covering nearly two-thirds space. It is proved that the proposed LWA has wide angle scanning ability. Fig. 7(b) is the measured radiation patterns. As the frequency varies from 10.6 to 11.6 GHz, the measured radiation beam scans from −60° to +63° and the total scanning range reaches up to 123°. The beam scanning range is similar to the simulated one but the band is reduced by 0.4 GHz. The frequency deviations between simulated and measured radiation patterns are mainly caused by the shift of cutoff frequency of SSPP. As shown in Fig.6, the upper cutoff frequency in the simulated S_{21} (the peak value) is 12.1 GHz, while that in the measured S_{21} is 11.7 GHz. The energy can't propagate through the LWA and radiate out in the fabricated antenna when the operating

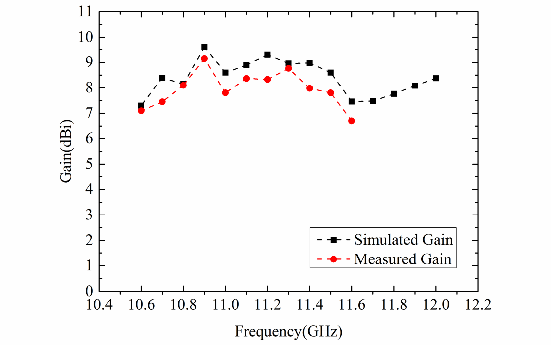

Fig. 8. Simulated and measured gains of the proposed LWA.

TABLE I
PERFORMANCE COMPARISONOF DIFFERENT LWAS

	Center frequency (GHz)	Scanning range (degree)	Bandwidth (%)	Scanning range/bandwidth ratio
[6]	16.25	130	39.3	3.3
[9]	9.6	39	3.1	12.6
[14]	13.7	35	3	11.7
This work	**11.1**	**123**	**9**	**13.7**

frequency is higher than the upper cutoff frequency of 11.7 GHz.

The simulated and measured gains are shown in Fig. 8. It can be seen that the simulated gains keep stable in the operating band, which are in the range of 7.3-9.6 dBi. The measured gains are within the range of 6.7-9.1 dBi. There exists less than 1 dB gain degeneration in the measured values, which is mainly due to the higher losses brought by the practical materials and the connectors weld. The radiation efficiency is the ratio between the radiated to accepted (input) power [17]. The measured antenna efficiency is above 40.2% over the operating band.

Table I is the performance comparison between this design and some representative SIW LWAs mentioned in the Introduction. The CRLH SIW LWAs in [6] has a wide steering angle of 130° but large bandwidth is needed. The scanning range/bandwidth ratio is improved in [9] and [14]. However, the beam can only scan in the forward direction. Compared to the LWA in [14], the major contribution of this letter is that the proposed antenna has a large scanning rate as well as a wide scanning angle from the forward to the backward direction without a stopband.

IV. CONCLUSION

A high scanning rate LWA has been proposed in this letter. Sub-wavelength periodic slots are etched on the top and bottom surfaces of SIW to realize bi-directional radiation. SSPP mode is excited in the proposed hybrid SIW-SSPP structure and this slow-wave mode is much more sensitive to frequency variation. Thus the proposed antenna can scan within a narrow bandwidth. Moreover, the slots on the top and bottom surfaces are designed in asymmetrical, which can suppress the open stopband and realize beam steering from the backward to the forward direction. The measured results demonstrate that the proposed LWA has the ability of bi-directional continuous beam scanning from −60° to +63° within a narrow operating band of only 9%. Considering the bi-directional beam feature, the beam steering range can cover nearly two-thirds space. Compared with other LWAs, the proposed antenna features wide scanning angle and narrow and communication systems.

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