Received: 9 November 2018 | Accepted: 12 November 2018
DOI: 10.1002/mmce.21617

WILEY INTERNATIONAL JOURNAL OF RF AND MICROWAVE COMPUTER-AIDED ENGINEERING

RESEARCH ARTICLE

A compact leaky-wave antenna using a planar spoof surface plasmon polariton structure

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 61471118 and the Research Program of 2017-JCJQ-ZD-041-05

Abstract
This article presents and validates a leaky-wave antenna by using the spoof surface plasmon polariton (SSPP) technique. By properly designing the proposed SSPP unit, the SSPP wave can be switched between the confinement and radiation modes. A large radiation efficiency can be achieved by properly designing the modulation depth, which ensures that a compact SSPP leaky-wave array can be realized by using a small number of SSPP radiation units. To verify the design, a prototype which consists of a SSPP feeding network and a 4 by 4 SSPP radiation units has been fabricated by using a low cost FR-4 substrate. A good agreement between simulated and measured results has been obtained. The proposed array antenna shows the promising capability of the SSPP technique for leaky-wave antenna applications.

KEYWORDS
dispersion curve, SSPP antenna array, SSPP power divider, the spoof surface plasmon polariton (SSPP)

1 | INTRODUCTION

The spoof surface plasmon polariton (SSPP) wave is bound on the interface of metal or dielectric.[1,2] It propagates along the surface of the conductor and decay exponentially in the direction vertical to the interface owing to the negative permittivity of metals. A number of components that using SSPP waves have been reported in recent. By utilizing the strong confinement and high-efficiency transmission characteristics of the SSPP, power-dividers, transmission lines, and couplers are reported in Refs. 3–7. Moreover, by utilizing a fast wave SSPP with $k < k_0$, leaky-wave antennas are investigated with scanning radiation beams.[8–17] Those achievements show promising applications of the SSPP technique for microwave and millimeter-wave wireless systems. In this article, a compact SSPP array antenna is investigated with a wide beam scanning range in a relatively narrow frequency band. In Section 2, the design of the proposed SSPP leaky-wave antenna is explained in detail, and experiments are carried out to validate the designed prototype in Section 3, whose results are well agree with simulated results. Finally, conclusions are drawn in Section 4.

2 | THE COMPACT SSPP ARRAY WITH LOW WAVE-CONFINEMENT SSPP UNIT

The structure of the proposed SSPP antenna is shown in Figure 1, where a coplanar waveguide (CPW) to SSPP transition is used for excitation, and a SSPP feeding network composed by a four-way SSPP power-divider is adopted to feeding the 4 by 4 SSPP array. The FR-4 substrate is used to support the proposed array, which has a thickness of 0.254 mm, a relative dielectric constant of 4.4 and a high loss tangent of 0.02. The SSPP unit is designed on the top surface of the substrate whose bottom surface is left as blank. Although the dielectric loss of the FR-4 substrate is much larger than that of the traditional low loss microwave substrate such as the Rogers5880 substrate, the proposed antenna can have a good radiation performance due to the electromagnetic waves are mainly transmitted along the surface of the copper. In addition, different to the traditional leaky-wave antenna, the proposed SSPP array does not requires loading terminals at the end of the array though only four radiation elements are employed in the design. This is because the designed SSPP radiation unit has a high radiation efficiency. Thus, a compact footprint can be realized as well. Detailed designs are explained in the following sections.

2.1 | Feeding network using the diamond SSPP unit

A diamond SSPP unit shown in Figure 2 is proposed for designing the feeding network of the leaky-wave antenna. Like the traditional SSPP units,[6] the proposed diamond SSPP unit can support SSPP modes in the microwave frequencies. Its wavenumber, k, can be designed to achieve a tight electromagnetic confinement by adjusting its geometries. The cutoff frequency is determined mainly by parameters of H and h, while parameter a, b, and p are used for fine tuning. Figure 2B shows the extracted wavenumber for the proposed diamond SSPP unit with varied h. It can be seen that the wavenumbers k becomes larger as h decreasing. And the dispersion curve bends away from the light line ($k > k_0$), which means the electromagnetic wave is confined tightly on the surface of the SSPP waveguide and cannot be radiated into the free space. Generally, the larger k leads to a smaller radiation. This feature ensures that the proposed diamond SSPP unit can be used to design a low loss feeding network even using a relatively lossy substrate.

To investigate the transmission loss of the proposed SSPP, a transmission line is developed with the diamond SSPP unit shown in Figure 2, whose electric field distribution is shown in Figure 3. A coplanar waveguide to SSPP transition is designed to transform the slot-wave to the SSPP wave.[6,7] It can be seen in Figure 3 that the electromagnetic waves are confined tightly along the SSPP transmission line. To extract the transmission loss of individual parts such as the SSPP and the CPW-SSPP transition, SSPP transmission lines are designed with different lengths. Then transmission losses of different parts are extracted by comparing the S21 of those transmission lines, and they are illustrated in Figure 3. Within 5.5-7.0 GHz, the loss of the CPW-SSPP transition is around 1.38 dB, and it is around 0.35 dB/wavelength in free space for the SSPP transition line with a high lossy substrate.

A four-way power-divider is developed by using the proposed SSPP unit for feeding the leaky-wave array. Its layouts and geometries are illustrated in Figure 4A. The full-wave simulator HFSS is adopted to finalize the design. The space angle between two outputs of the two-way SSPP power-divider is optimized as 126° for reducing mutual couplings between output ports. The final geometries are listed in Table 1. The electric field distribution of the designed SSPP power-divider is shown in Figure 4B, where it can be seen that the electromagnetic waves are confined tightly around the SSPP and divided equivalently at four output ports. Moreover, although there existing discontinuities in the two-way SSPP power-divider, the space coupling between two output branches are pretty small owing to the excellent electromagnetic-wave confinement character of the SSPP.

Figure 5 shows simulated S-parameters of the designed power-divider. It should be mentioned that the insertion loss from two CPW-SSPP transitions are included in Figure 5A. To compare the insertion loss of the proposed SSPP power-divider with its microstrip counterpart, a microstrip four-way power-divider is designed with the same FR-4 substrate as well. Figure 5B shows the simulated insertion loss of the microstrip four-way power-divider and the proposed SSPP power-divider, where the insertion from two CPW-SSPP are excluded

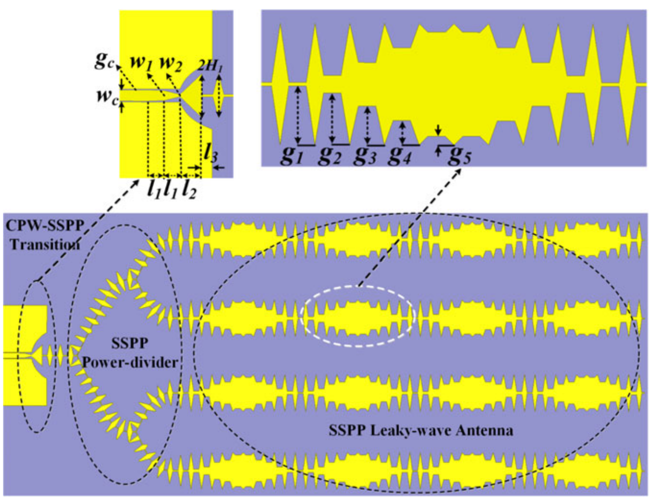

FIGURE 1 The planar layout of the proposed 4x4 SSPP leaky-wave array

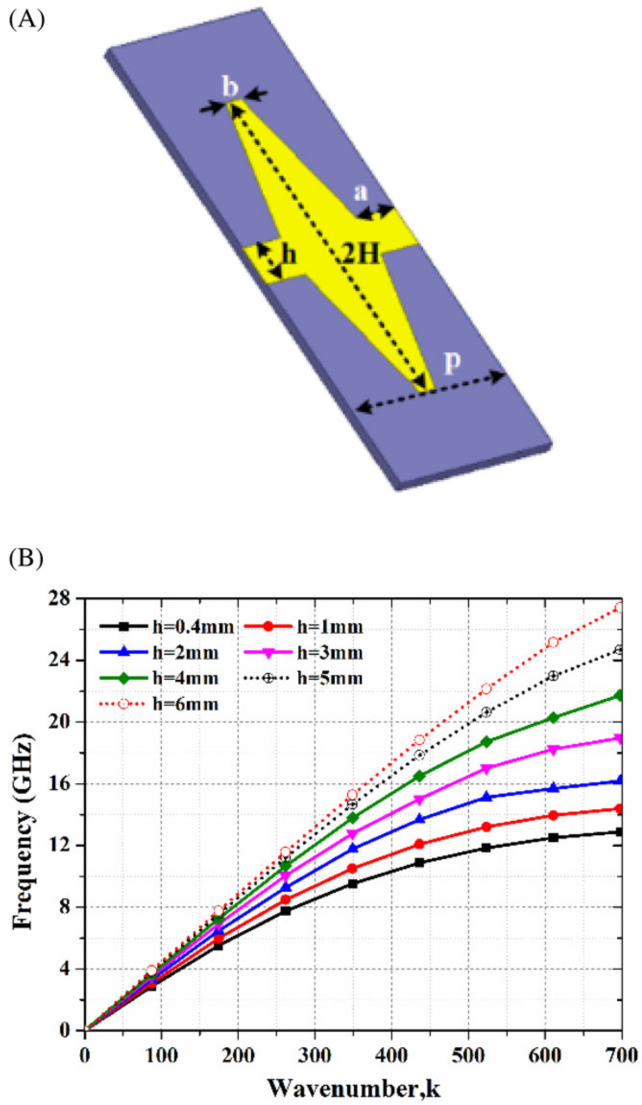

FIGURE 2 A, The proposed diamond SSPP unit (H = 4.0 mm, a = 1.0 mm, P = 4.0 mm, b = 0.2 mm); B, dispersion curves

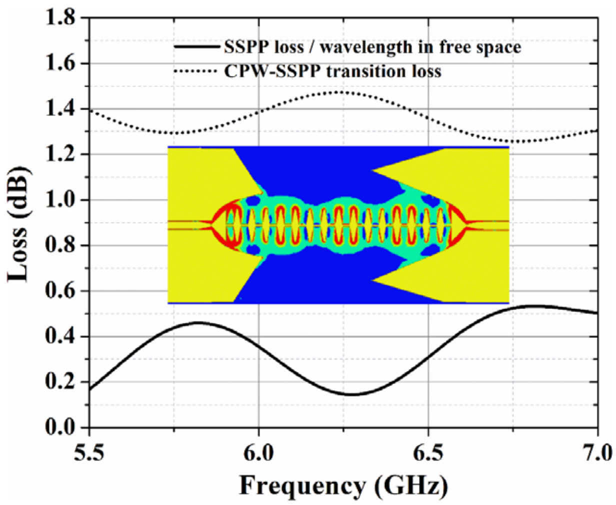

FIGURE 3 Extracted loss for the SSPP transmission line and the transition

for a fair comparison. As it can be seen, the insertion loss of the SSPP power-divider is much smaller than that of the microstrip power-divider across a wide frequency range from 5.5 to 7.5 GHz. In the simulation, various types of losses are considered, including the dielectric loss, the radiation loss and the metal loss from the copper. Since all electromagnetic waves are confined tightly around the copper, the SSPP has very weak radiation and dielectric loss. On the contrary, the transmission loss of the microstrip structure increase as operating

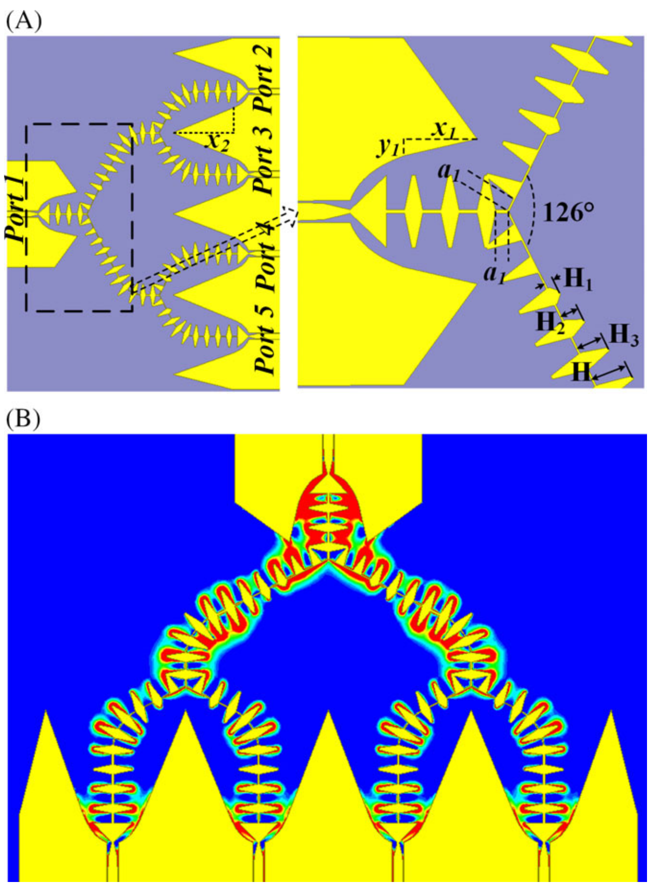

FIGURE 4 A, The structure of the proposed SSPP power-divider with its enlarged view. B, Electrical field distribution of the proposed SSPP power-divider at 6 GHz

TABLE 1 Geometries of the SSPP power-divider (in millimeters)

x_1	x_2	y_1	a_1	H_1	H_2	H_3
8	20	2	1.38	1	2	3

frequency becomes higher. Those factors result in the microstrip power-divider has a larger transmission loss than that of the SSPP power-divider, especial at high operating frequencies. Generally, the more output ports of the feeding network, the larger transmission loss difference between the microstrip and SSPP power-dividers. Thus, for a large array application, the insertion loss of the microstrip feeding network may have a much larger transmission loss than its SSPP counterpart, even considering the loss from the CPW-SSPP transition. Hence, the designed SSPP power-divider is adopted to feed the SSPP array in following sections.

2.2 | The diamond SSPP radiation unit

In order to convert the confined waves on SSPP to the radiated waves, the SSPP unit can be modulated with its surface impedance:[18]

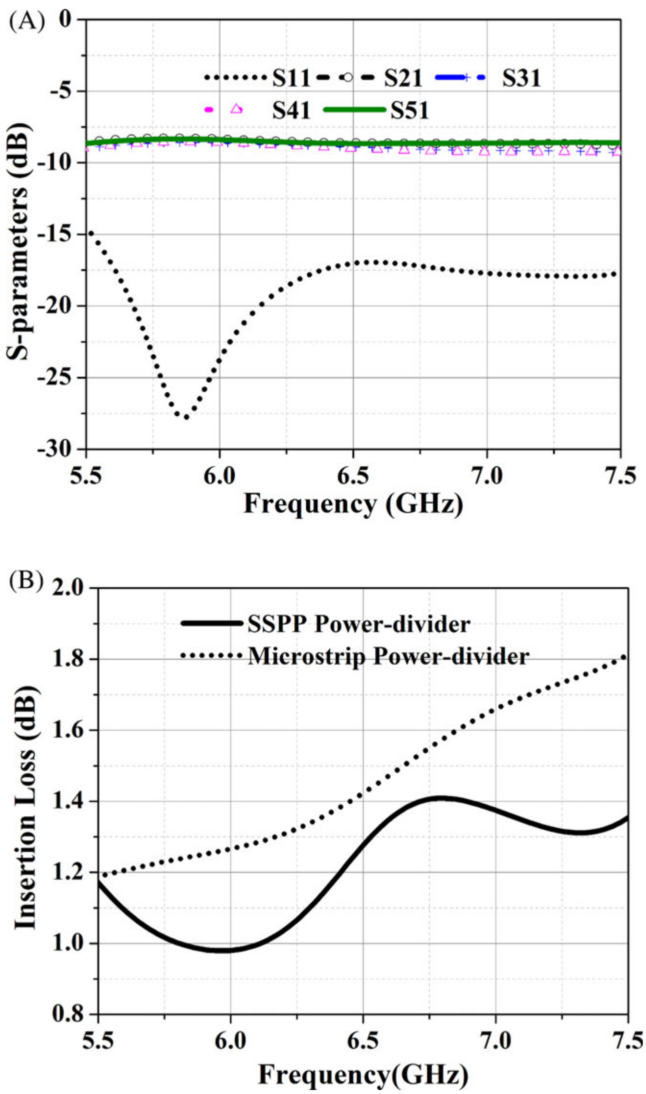

FIGURE 5 A, The simulated S-parameters of the SSPP power-divider (insertion losses from two CPW-SSPP transitions are included); B, the transmission loss comparison between SSPP power divider and microstrip power divider

$$\eta_{surf} = jX_s\left[1 + M\cos\left(\frac{2\pi z}{p}\right)\right] \quad (1)$$

in which *Xs* is the average surface reactance, *M* is the modulation depth, and *p* is the modulation period. The relationship between the wave vector (*k*) and the surface impedance (η_{surf}) can be expressed as:

$$k = k_0\sqrt{1 - \frac{\eta_{surf}^2(z)}{\eta_0^2}} \quad (2)$$

in which k_0, η_0 is the wave vector and the surface impedance in the free space respectively. From Equations 1 and 2, it can be seen that the surface impedance can be modulated by adjusting the wavenumber of the SSPP with varied $g_{i\ (i\,=\,1,\ ..\ ,\ N)}$ in Figure 1, as shown in Figure 2.

Generally, infinite space harmonics can be generated by varied wavenumber:

$$k_N p = nk_0 p + 2N\pi, N = 0, \pm 1, \pm 2, \ldots \quad (3)$$

in which *n* is an effective surface refractive index. From (3), if $N < 0$, the k_N is smaller than k_0, and the corresponding space harmonics is a fast wave and can be used as a radiated wave with a modulation period *p*. Base on above analysis, the proposed SSPP radiation unit is modulated for the radiation element of the leaky-wave antenna.

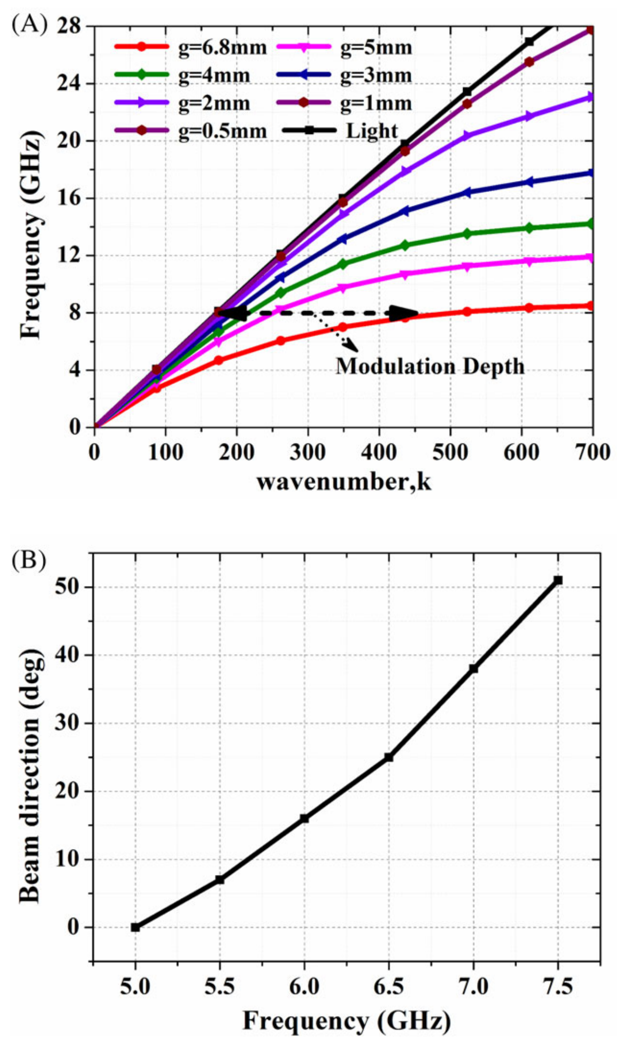

FIGURE 6 A, The dispersion curve of SSPP unit with varied *g*. B, The radiation beam scanning range

TABLE 2 Geometries of the transition (in millimeters)

w_1	w_2	l_1	l_2	l_3	r	w_c
1.82	0.61	2.9	4.0	1.88	4.0	2.0
H_1	g_1	g_2	g_3	g_4	g_5	p
4.0	6.8	6.0	4.5	2.8	1.0	4.0

In order to realize a leaky-wave antenna with less radiation element and a wide beam-scanning range, a larger modulation depth or smaller wavenumber is desired in the design. To this end, the radiation performance or the wavenumber is investigated by using the proposed SSPP unit shown in Figure 2A. In this investigation, the geometries of SSPP unit are: H = 7 mm, P = 4 mm, a = 1 mm, and $g = (2H - h)/2$ is the modulated groove. The larger *H* used in this investigation ensures that a larger modulation depth can be obtained for adjusting the wavenumber in the design of the leaky-wave antenna.[18] Figure 6A shows the extracted wavenumbers of SSPP unit with different *g*. As the *g* increasing, a smaller wavenumber is obtained, which results in more electromagnetic waves are radiated into the space.

The beam-scanning performance of the SSPP unit can be evaluated with Equation 4:

$$\cos\theta = \frac{k}{k_0} - \frac{\lambda_0}{p} \quad (4)$$

where, θ is the radiation beam direction, k is the wavenumber, k_0 is the wavenumber in free space, $\lambda_0$is the wavelength in free space, and *p* is the modulation period. Figure 6B shows the simulated radiation beam scanning range of the proposed SSPP unit. From 5 to 7.5GHz, the radiation beam can scan from 0° to 51°. Since the wavenumber *k* of the case H = 7 mm is much larger than that of H = 4 mm, the confined waves in the SSPP powerdivider can be converted as the radiation waves with a large beam scanning range.

2.3 | The leaky-wave SSPP array antenna

A SSPP leaky-wave antenna shown in Figure 1 is designed based above analysis. The width and gap of the CPW is w_c = 2 mm and g_c = 0.2 mm, which are used to achieve a 50-Ω input impedance. The ground of CPW is flared by the exponential function $y = r * \ln(x + 1)$ for realizing mode matching.[14] The SSPP radiation unit consists of

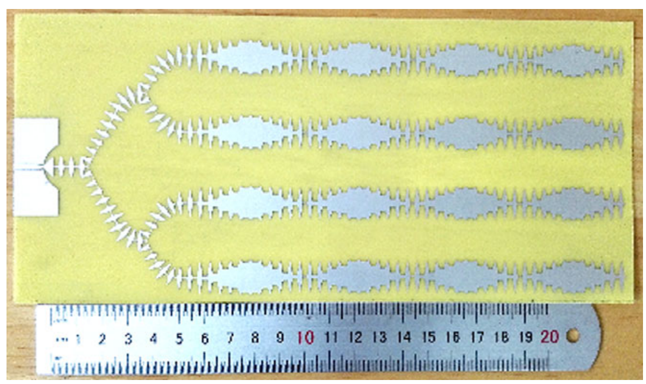

FIGURE 7 Photograph of the fabricated prototype

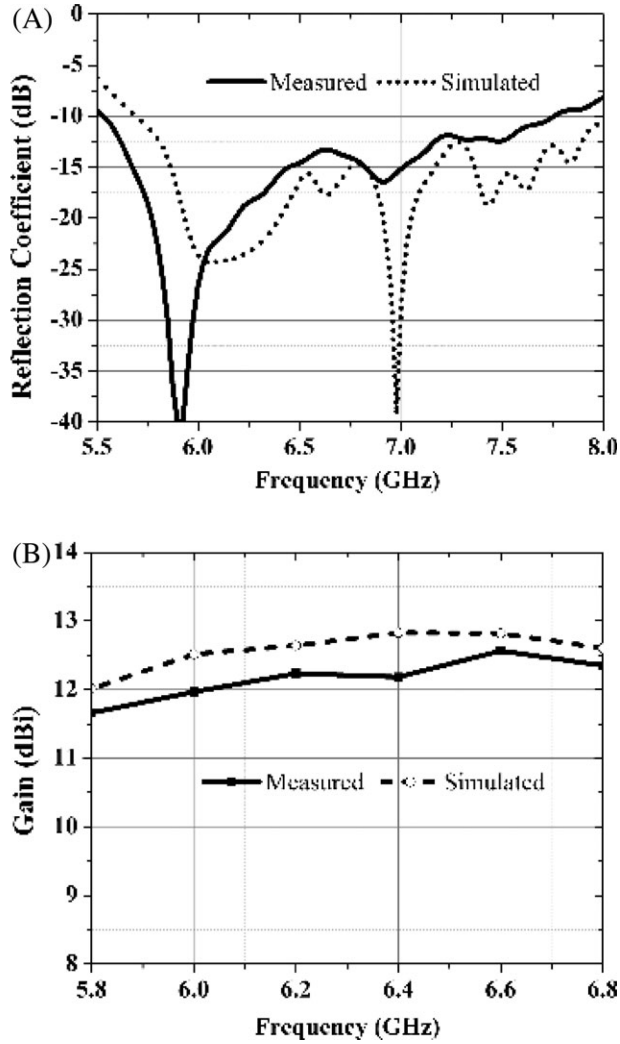

FIGURE 8 A, Measured and simulated S11; B, measured and simulated radiation gain

11 diamond SSPP units. As shown in Figure 1, the SSPP radiation unit has a symmetrical structure, in which the diamond SSPP units are modulated gradually for obtaining a good in-band matching. The full-wave simulator HFSS is adopted to finalized the design and the final geometries are listed in Table 2. Since the diamond SSPP unit can be modulated to have a much small wavenumber, the SSPP waves of the SSPP radiation unit can be radiated as much as possible. As a result, a compact footprint can be achieved by only using a small number SSPP radiation elements.

3 | EXPERIMENTS AND DISCUSSION

A prototype of the designed SSPP leaky-wave antenna has been fabricated by using the low cost printed-circuit-board technology. Figure 7 illustrates the photograph of the fabricated SSPP antenna. The key sight vector network analyzer (VNA) has been used to measure the reflection coefficient of the fabricated prototype. The measured and simulated reflection coefficients are presented in Figure 8, where a good agreement can be found. Unlike traditional leaky-wave antennas, the measured prototype has a S11 smaller than −10 dB from 5.5 to

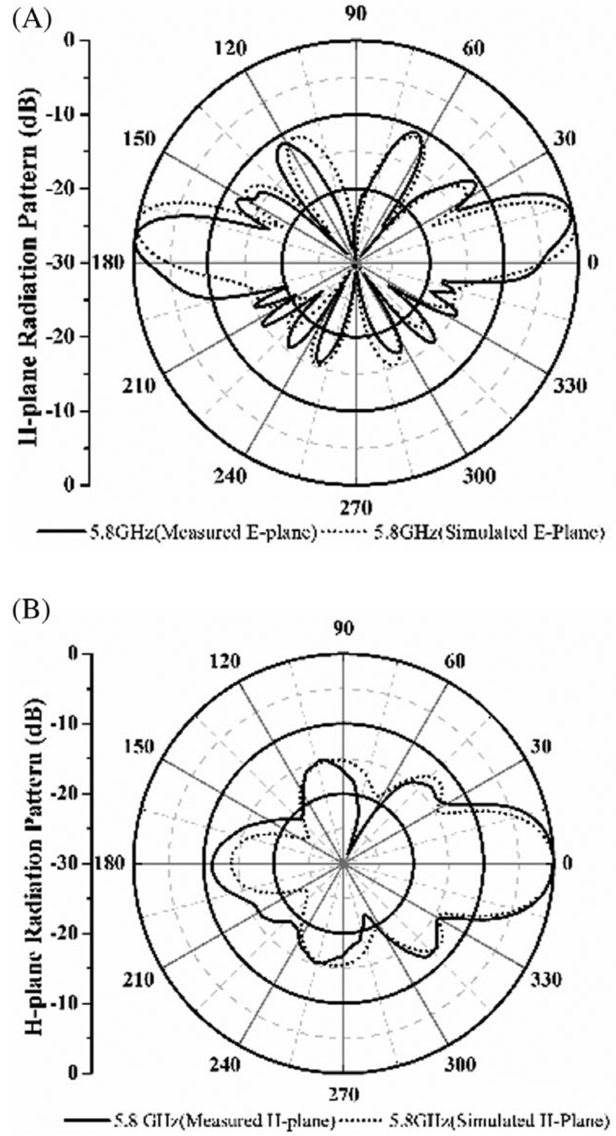

FIGURE 9 Measured 5.8 GHz radiation patterns. A, E-plane; B, H-plane

7.5 GHz without using any terminators, which indicates most of the electromagnetic waves are radiated by the SSPP antenna. The radiation performance of the fabricated prototype has been measured in a microwave chamber. The measured radiation gain of the fabricated prototype is larger than 11.5 dBi from 5.8 to 6.8 GHz, and the maximum measured radiation gain is 12.5 dBi at 6.6 GHz. Compared with the simulation results, a small discrepancy around 0.3 dB can be found between the simulated and measured radiation gains in Figure 8. That may due to the imperfect copper used in the fabrication process and the addition loss from the SMA connector.

Figures 9 and 10 show the measured radiation patterns of the fabricated prototype at 5.8 and 6.8 GHz. In the H-plane, the radiation direction always keeps in the boresight direction. In the E-plane, it scans from 12 to 30°. Generally, the measured results are in good agreement with the simulated ones. A small discrepancy can be found between the radiation directions of the simulation and measurement. This is mainly due to the dielectric constant tolerance of the FR-4 substrate.

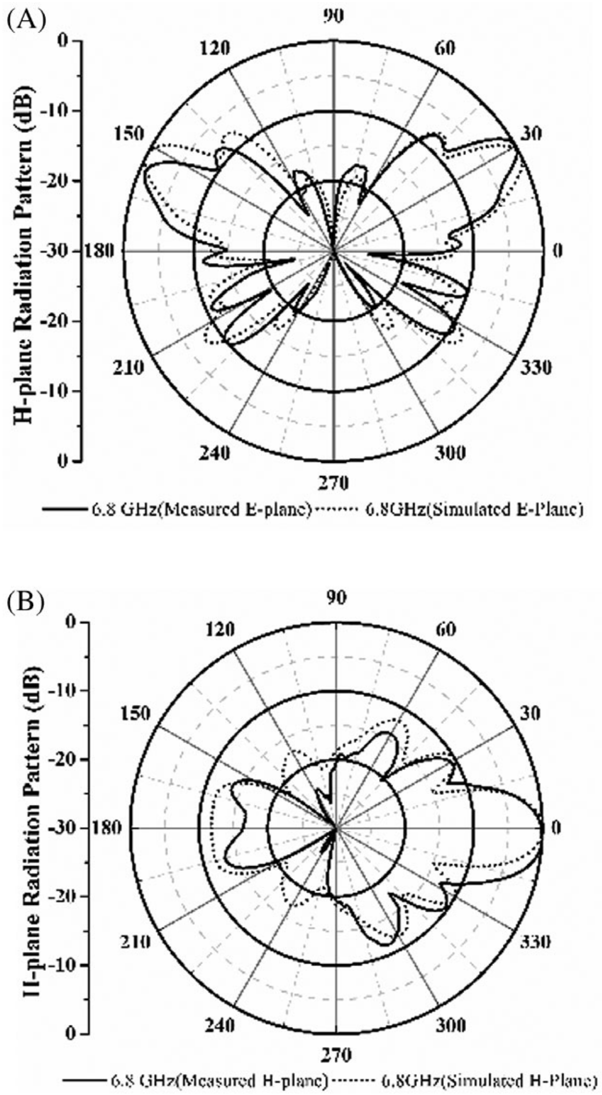

FIGURE 10 Measured 6.8 GHz radiation patterns. A, E-plane; B, H-plane

4 | CONCLUSION

A SSPP leaky-wave array antenna is presented in this article, which has a compact footprint and a good radiation performance. By properly design the SSPP units and its modulation, the SSPP waves can be switched from the confinement mode to the radiation mode with large radiation efficiency. A 4 by 4 prototype has been fabricated by using the SSPP feeding network and radiation units. Experiments verify the design. The proposed antenna shows the possibility of the SSPP technique for designing high performance leaky-wave antennas in the microwave frequency.

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China under Grant No. 61471118 and in part by the Research Program of 2017-JCJQ-ZD-041-05.

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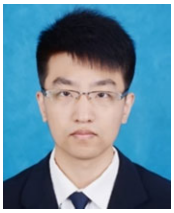

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How to cite this article: Hao Z-C, Zhang J, Zhao L. A compact leaky-wave antenna using a planar spoof surface plasmon polariton structure. *Int J RF Microw Comput Aided Eng*. 2019; e21617. https://doi.org/10.1002/mmce.21617