

Research Article

Design of an Edge Slotted Waveguide Antenna Array Based on T-Shaped Cross-Section Waveguide

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An edge slotted waveguide antenna array based on T-shaped cross-section radiating waveguide is proposed. The T-shaped waveguide is analyzed and designed to operate in dominant mode around the center frequency, which has a lower profile compared with the rectangular one. The radiating slots are etched and rotated alternatively on the broadened top plate without cutting into the adjacent walls. The metal fences are inserted between slots to reduce the mutual coupling and surface wave. Therefore, the sidelobe level in E -plane is well suppressed. A 2×8 antenna array working at Ka-band is designed and fabricated. The measured results agree well with simulations which demonstrate this novel waveguide structure.

1. Introduction

Slotted waveguide antenna array is a good candidate in the areas of radar and communication systems due to its attractive features, such as low power loss, low cross-polarization levels, low profile, high power capacity, high efficiency, and accurate control of amplitude and phase distributions. Some edge slot antenna arrays have been researched [1–6]. The edge slot waveguide antenna can be integrated with the other antennas for dual polarization applications [7–9]. The slots etched on the narrow wall of the waveguide are usually cut into the adjacent broad walls [1–3] or folded as Z-shaped [4–6] to achieve the resonance.

In this paper, a novel edge slotted waveguide antenna array is proposed based on the T-shaped cross-section waveguide. Owing to the top plate which is broadened, the radiating slots can be etched on the top without cutting into the adjacent walls or folded as Z-shaped. Furthermore, the waveguides with T-shaped cross-section can also reduce the profile compared with regular ones. The metal fences are inserted between slots to suppress mutual coupling and surface wave which are beneficial to improve the radiation performance. The effect of these fences on radiating slots is analyzed as well. A bend waveguide transition is invented to transform the waveguide from E -plane to H -plane. Finally, a

2×8 antenna array working at 35 GHz is designed by using full wave EM simulator and validated experimentally.

2. The Analysis of T-Shaped Waveguide

The rectangular waveguides are usually used as a radiating waveguide for the edge slotted waveguide antennas with the slots cutting into the broad walls for resonance. The novel T-shaped waveguide is firstly introduced as a radiating waveguide in [10] and the cross-section of the waveguide becomes T-shaped as shown in Figure 1(a). The port field in the dominant mode and the surface current on the top plate of the T-shaped waveguide are studied and they are depicted in Figure 1(b) compared with a rectangular one. It can be seen that the port field and surface current on the top plate of the two waveguides are similar to the TE dominant mode. Therefore, the inclined radiating slots etched on the top plate of the T-shaped waveguide can cut the surface current and be designed like the regular ones.

The higher order propagation mode may be introduced into the T-shaped waveguide such as TE_{01} mode owing to the broadened top plate. Therefore, the operating mode of the T-shaped waveguide should be analyzed and a rectangular waveguide with the same guide wavelength is proposed for comparison.

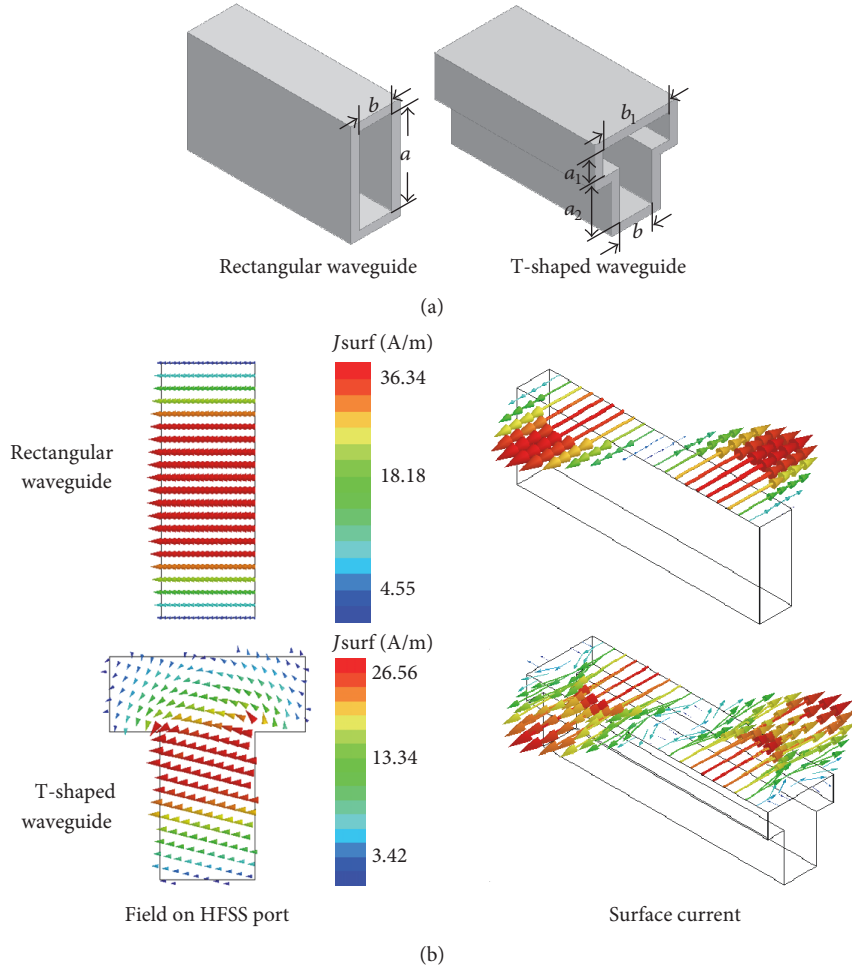


FIGURE 1: Geometry and field distributions of the rectangular and T-shaped waveguide. (a) Configuration. (b) Port field in dominant mode and surface current on the top plate.

The operating center frequency of antenna array is 35 GHz and the guide wavelength λ_g is set as 15.02 mm. The width b of the rectangular waveguide is set as 2 mm and the height $a = 5.21$ mm can be derived. For T-shaped waveguide, the dimensions are chosen as the following rules:

- The bottom width b is the same as the rectangular one.
- The top width a_1 should be wide enough to support the resonant slot and the higher order modes should be avoided over the working band. The length of the resonant radiating slot is around λ , where $\lambda = 8.57$ mm is the wavelength at the center frequency. Considering that the slot should be rotated at a certain angle, a_1 can be shorter than $\lambda/2$.
- The heights a_1 and a_2 should be chosen to achieve the demand guide wavelength.

Finally, $b_1 = 4.1$ mm, $a_1 = 1.5$ mm, and $a_2 = 2.94$ mm are decided. To reveal the operating mechanism of these dimensions, the parameter study is presented and the method is to sweep one parameter and fix the others. Figure 2 illustrates the propagation constant curves where β_R and β_T represent

the propagation constant of rectangular waveguide and T-shaped waveguide and the subscripts 1 and 2 represent the dominant mode and second higher mode. It can be found that the parameter b_1 takes the main effect on the second-order mode but a slight effect on dominant mode. Instead, the parameters a_1 and a_2 affect mostly the dominant mode. Compared with the rectangular waveguide, for the same β , the T-shaped waveguide shows a lower profile where $a_1 + a_2 < a$.

3. Design of 2×8 Antenna Array

3.1. Self-Admittance of Radiating Slot. As mentioned previously, the inclined radiating slots can be treated as the regular ones which can also be equivalent to shunt admittance in the resonant state. The inclined angle refers to the admittance and the length of the slot is used to achieve the resonance. The single slot model with period boundary condition (PBC) based on the T-shaped waveguide and normalized admittance curve are shown in Figure 3 where the thickness and the width of the slot are 0.5 mm and 0.6 mm, respectively. The admittance extractions are carried out by using S-parameter results [8]. These obtained curves referring to the resonant

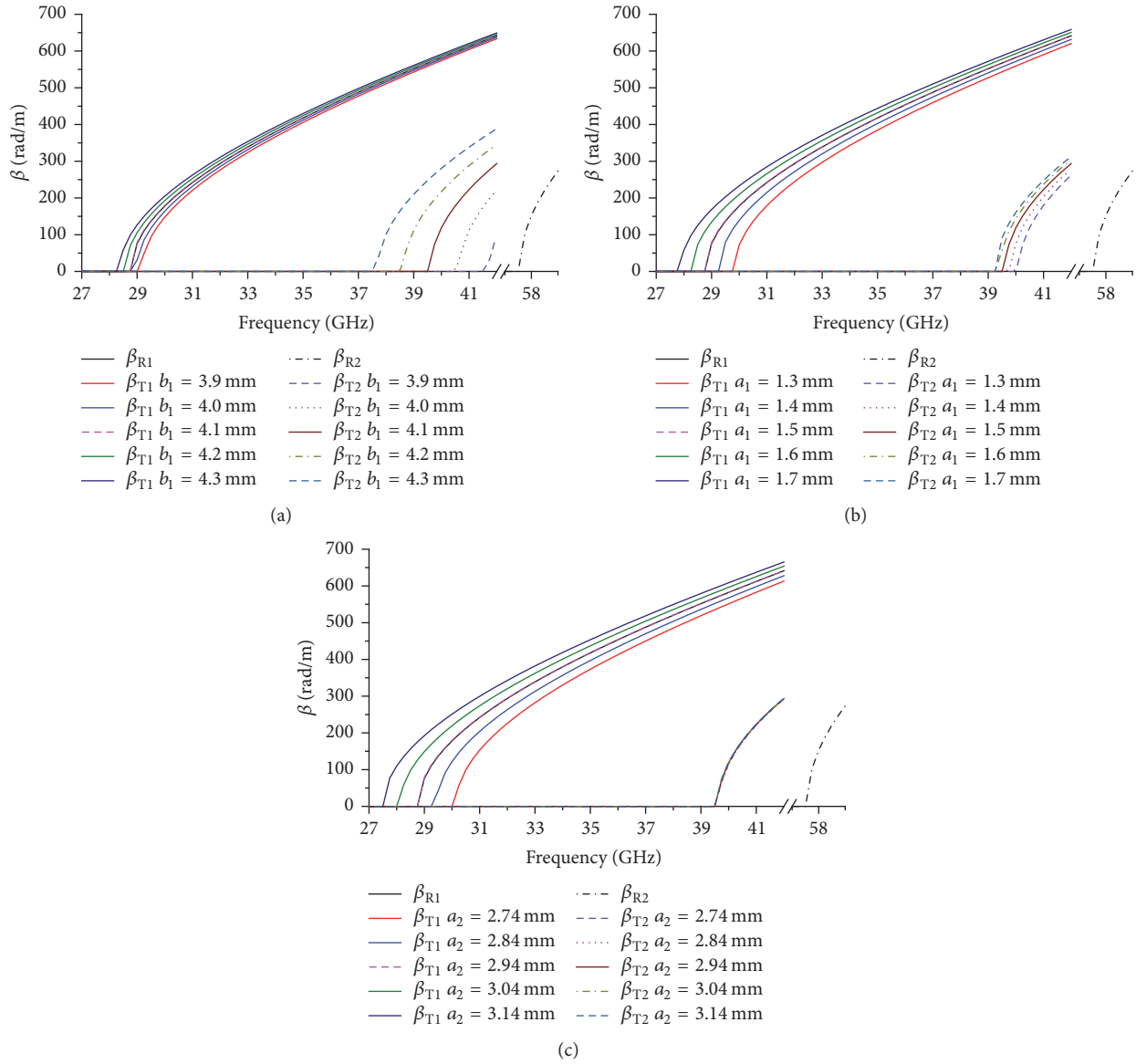


FIGURE 2: The propagation constant curves of rectangular waveguide and T-shaped waveguide versus frequency in dominant mode and second higher mode versus (a) b_1 , (b) a_1 , and (c) a_2 .

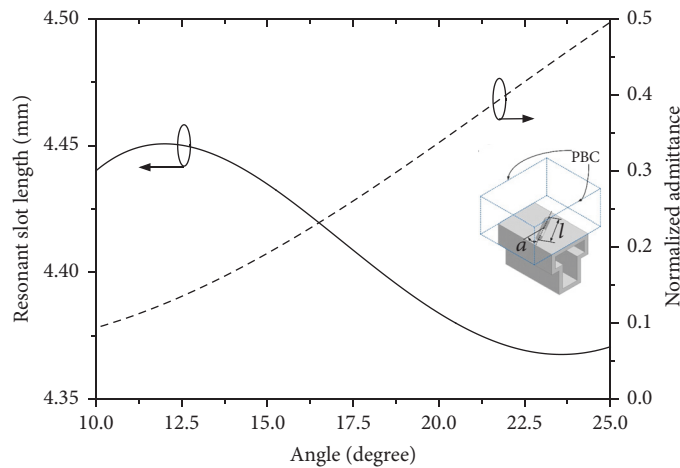


FIGURE 3: Normalized admittance and resonant length regarding the inclined angle.

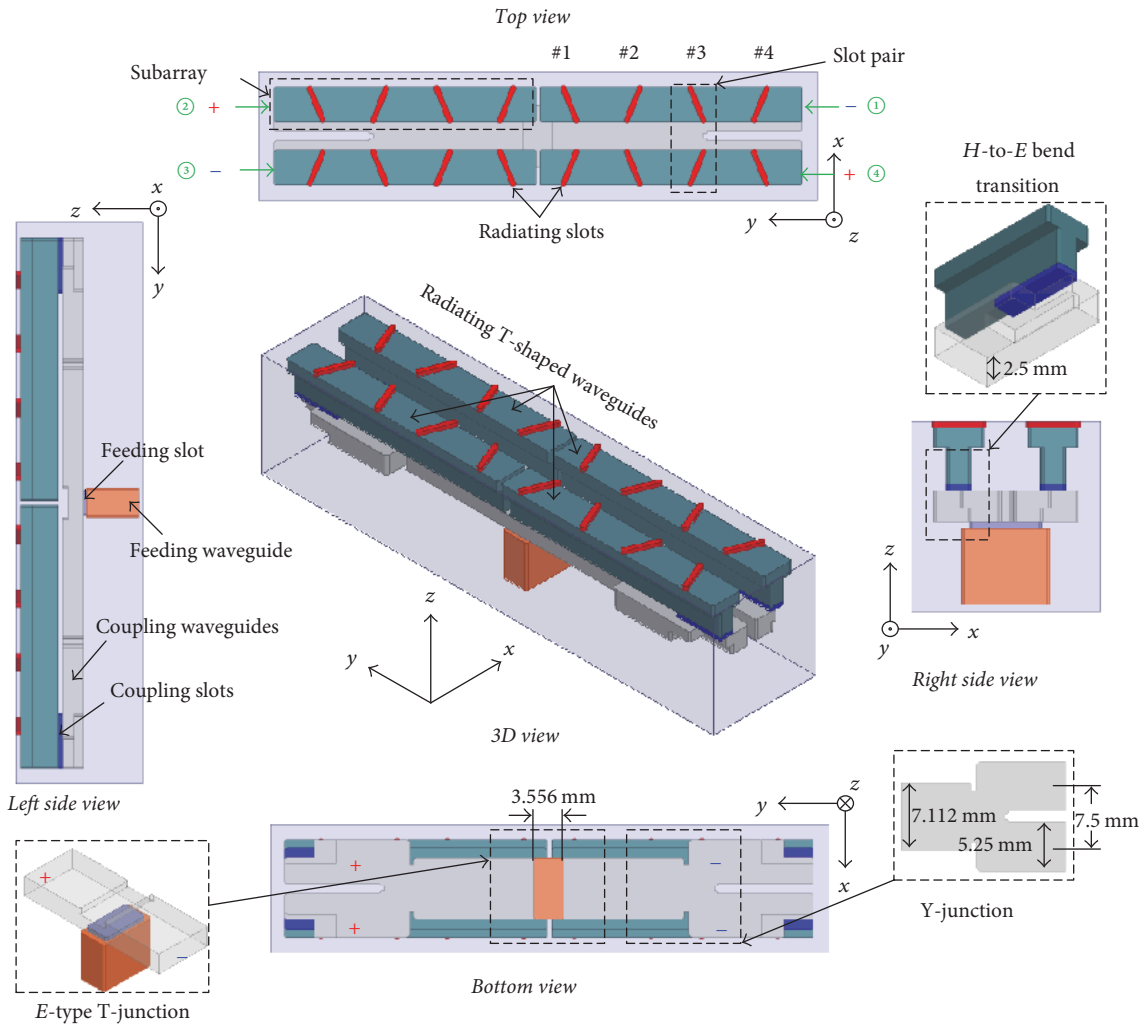


FIGURE 4: Structure of 2×8 antenna array.

admittance and the resonant length to angle variation are utilized to satisfy the input matching and the aperture field distributions. The PBC along waveguide direction is adopted for the purpose of accurate design which considers the mutual coupling between slots.

3.2. Antenna Array Structure. The slot pair consisting of two reverse inclined slots is introduced in the 2×8 antenna array to suppress the cross-polarization as depicted in Figure 4. Four subarrays are designed and fed from outside edge. The uniform distribution of aperture is desired and all slots have the same admittance of 0.25. The slot length and the inclined angle can be evaluated from Figure 3 by an interpolation method. However, the actual boundary conditions of the slots are different owing to the mutual coupling from the adjacent slots, the effect of short end from radiating waveguide, and feeding port. Therefore, the dimensions of slots are optimized individually and the final dimensions of slots from 1 to 4 are as follows: slot length = 4.42, 4.36, 4.36, and 4.43 (mm) and inclined angle = 17.6, 18.6, 20.35, and 20.15 (degree). The radiation amplitude ratio and phase difference of the four

slots are as follows: amplitude ratio is 1.01 : 0.988 : 0.988 : 1 and the phase difference is 0.79, -0.05 , -0.24 , and -0.98 (degree). Obviously, the uniform distribution of aperture is realized.

Due to the reversed slots of slot pair, the radiating waveguides in subarray 1 and subarray 4 and subarray 2 and subarray 3 should be fed out-of-phase. The symbols + and - in figures denote out-of-phase condition. Two Y-junctions and an E-type T-junction are designed for equal power splitting with in-phase and out-of-phase condition. Four H-to-E bend transitions are invented to connect the radiating waveguides and the coupling waveguides. According to the mirror symmetry, the coupling slots in subarrays 1 and 4 are placed in opposite direction to achieve the out-of-phase condition. The subarrays 2 and 3 have the same property. Finally, the out-of-phase conditions between the adjacent radiating waveguides are obtained and all slots are fed in-phase.

3.3. Simulation and Analysis. The simulated E-plane radiation patterns at the center frequency of antenna array are shown in Figure 5. As is known to all, the theoretical sidelobe

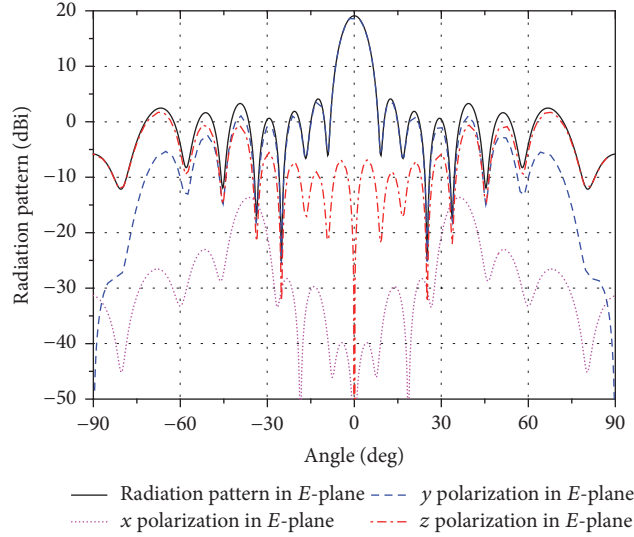


FIGURE 5: Simulated E -plane radiation patterns at 35 GHz.

level (SLL) of the uniform array is around -13.2 dB and then tapered from the first sidelobe to far-out sidelobe. The simulated gain is 19.1 dBi and the observed SLL is -15 dB with almost uniform value over a wide angle range which is different from the theoretical situation.

To figure out the reason, the radiation pattern in E -plane is separated into x , y , and z components as shown in Figure 5 which denote the corresponding polarization radiation pattern in E -plane. It can be seen that the y component is copolarization and the others are cross-polarizations. The x component is suppressed well by the slot pairs but the z component is intense at the far-out sidelobe. The z component is excited by radiating slots and then propagates as TM surface wave [11] to the edges of antenna array as depicted in Figure 6(a) which means the edge diffractions influence the radiation pattern.

To suppress the surface wave, the metal fences [12] are introduced between slots as shown in Figure 6(b). The height of fences is $f_h = \lambda/4$ and the width of the fences is $f_w = 2$ mm. Owing to the effect of fences, the dimensions of radiating slots should be modified. The optimal values from slot 1 to slot 4 are as follows: slot length = 4.65 , 4.65 , 4.65 , and 4.57 (mm) and inclined angle = 20.5 , 20.5 , 20.5 , and 20.5 (degree). It can be found that the differences between slots are decreased compared with the original one which demonstrate the mutual coupling suppression by the metal fences. The radiation amplitude ratio and phase difference of slots from 1 to slot 4 are also calculated: the amplitude ratio is $1:1:1.05:1.08$ and the phase difference is 0 , -0.65 , 0.66 , and -5.38 . Therefore, the uniform aperture excitation is realized.

The E -field distribution in the y - z plane is shown in Figure 6(c) for comparison. On the edge of the waveguide, the E -field of the original antenna is obviously stronger than the fenced one. As described previously, the edge diffractions may influence the radiation pattern and the power flow distribution is shown in Figure 6(d) for demonstration. The power flow direction on the edge of the original antenna is

about 45° which contributes to the far-out sidelobe. For the antenna with fences, most of the power flow is along the boresight.

To demonstrate the analysis of these structures, the radiation pattern of slotted waveguide antenna based on the regular waveguide and a T-shaped waveguide with/without fences are depicted in Figure 7. The spacings between slots of the three antenna arrays are all 7.5 mm. For the regular waveguide, the width and height are 2 mm and 5.21 mm, respectively, which can provide the same guide wavelength as the proposed one. It is clear that the gains of the proposed antenna arrays are much higher than the regular one due to the broad top wall which contributes larger aperture size. The first SLL of the antenna array with fences is 13.51 dB and the far-out sidelobe is well suppressed compared with the others. Furthermore, the fences between slots can correct the polarization and more energy is radiated in y -polarization which is benefit for the gain enhancement. The simulated gain is improved from the regular one of 16.22 dBi to the proposed one of 19.1 dBi and enhanced to 20.21 dBi by the fences.

4. Fabrication and Measurement Results

In order to demonstrate our design, the proposed 2×8 antenna array was fabricated and assembled by screws and alignment pins as shown in Figure 8. The return loss was measured by using Agilent E8363C vector network analyzer. Figure 9 shows the simulated and measured return loss. The measured locus is in good agreement with the simulation. The simulated and measured impedance bandwidths with a return loss better than 15 dB are from 33.85 GHz to 35.82 GHz (5.63%) and 33.96 GHz to 36.29 GHz (6.66%), respectively.

The simulated and measured radiation patterns at 35 GHz are shown in Figure 10. The measured copolarization radiation patterns in E -plane and H -plane are in good agreement with the simulations. The measured cross-polarization levels in E -plane and H -plane are both less than -25 dB.

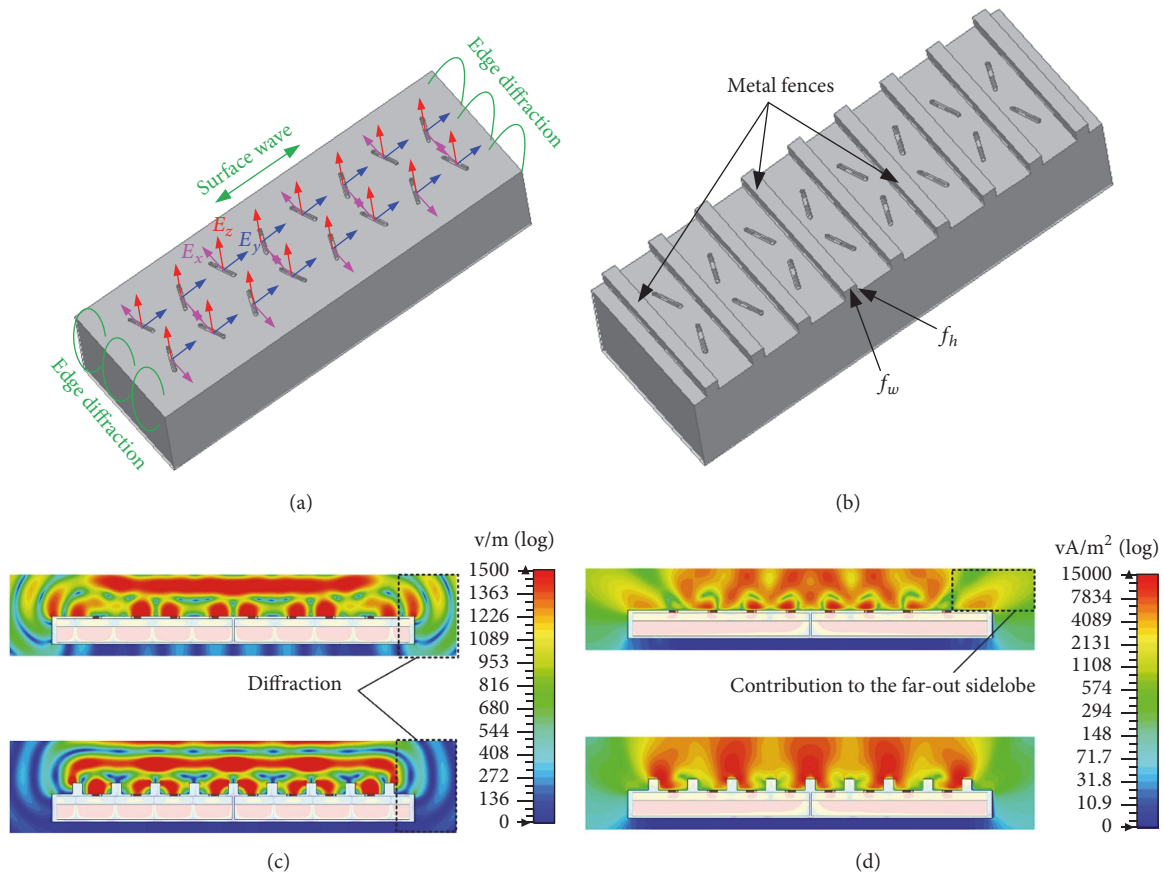


FIGURE 6: (a) Radiation analysis of antenna array. (b) Antenna array with metal fences. (c) E -field distribution. (d) Power flow distribution in the y - z plane at 35 GHz.

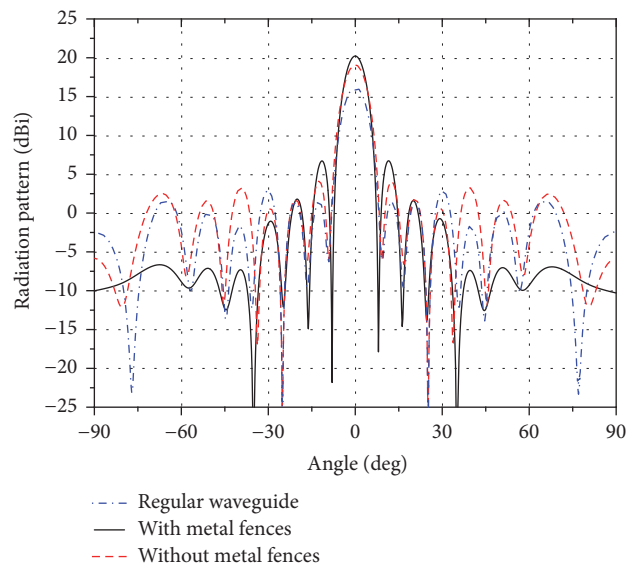


FIGURE 7: Radiation pattern of slot antenna based on the regular waveguide, the T-shaped waveguide with/without fences in E -plane at 35 GHz.

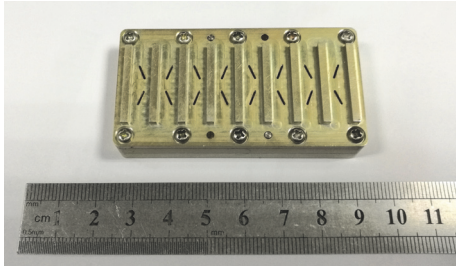


FIGURE 8: Photography of the fabricated 2×8 antenna array.

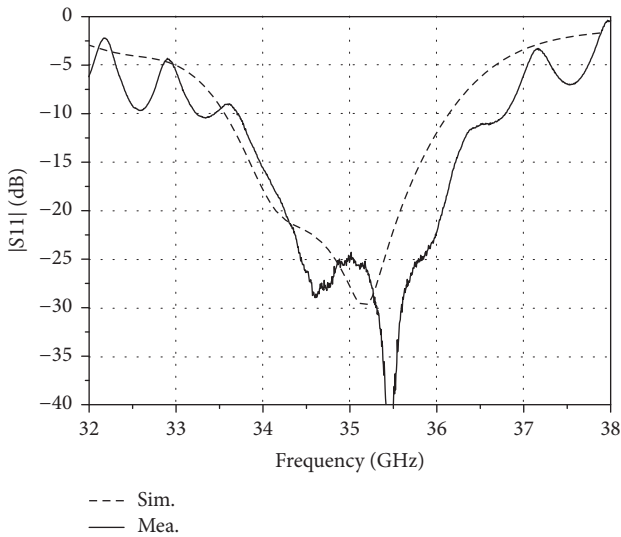


FIGURE 9: Simulated and measured return loss of 2×8 antenna array.

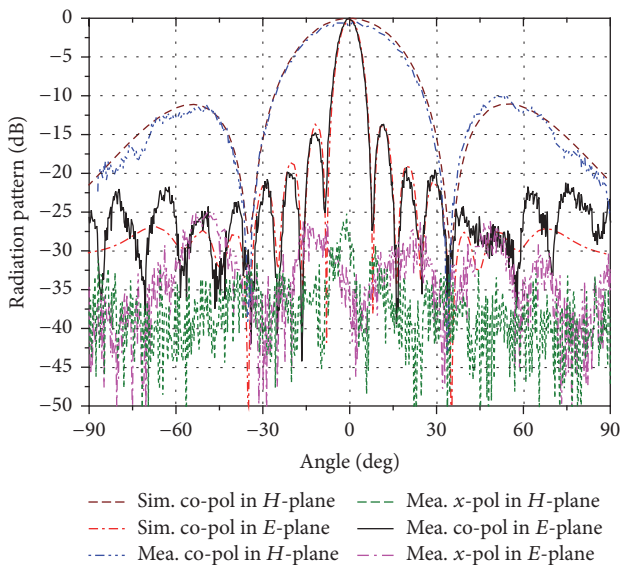


FIGURE 10: Simulated and measured normalized radiation pattern of the 2×8 antenna array at 35 GHz.

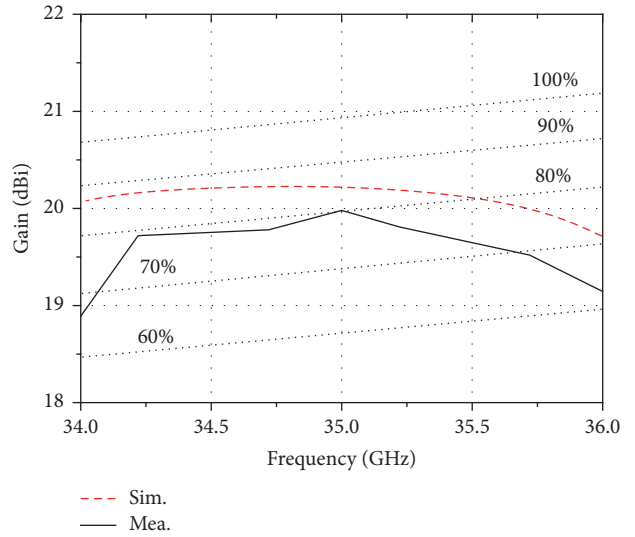


FIGURE 11: Gain and antenna efficiency of the proposed antenna array at 35 GHz.

The frequency characteristics of gain and antenna aperture efficiency are depicted in Figure 11. It can be found that the measured gains are a little less than the simulations owing to the conductor loss. The maximum gain of 19.98 dBi is measured at 35 GHz and the corresponding antenna aperture efficiency is 80.27%.

5. Conclusions

A 2×8 antenna array based on T-shaped cross-section waveguide working at Ka-band is proposed. The operating mode of the waveguide is analyzed and designed to operate in dominant mode over the working band. Compared with the rectangular waveguide, the T-shaped waveguide has a lower profile and the broadened top plates can support the resonant radiating slots without cutting into the adjacent broad walls. To suppress the surface wave, the metal fences are introduced between slots and the radiation performance is improved. The measured results agree well with the simulations which validate our design. This novel structure has great potential application in communication and radar systems.

Disclosure

An earlier version of this work was presented as a conference paper at iWAT, 2015.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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