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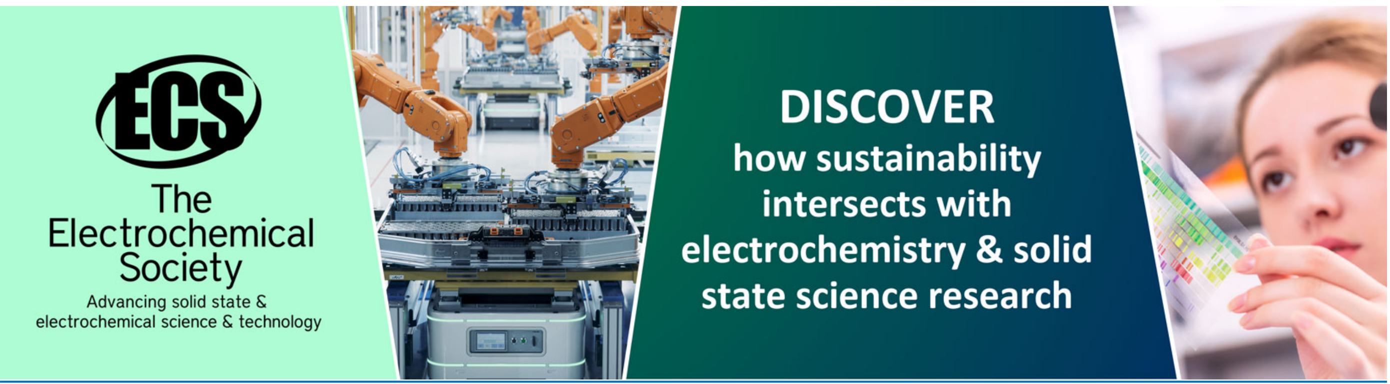

Design of a side-feed rectangular waveguide helical array antenna with fan-beam radiation characteristics

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Abstract. In the millimeter wave train-ground communication system of high-speed maglev train, train-mounted antennas are required to have the characteristics of miniaturization, wide band, circular polarization, and fan-beam radiation. A side-feed rectangular waveguide helical array antenna is designed to meet these requirements in this paper. Short axial-mode helical antenna which has compact structure and circularly polarized radiation characteristics is used as the unit antenna. To realize fan-beam radiation characteristics, this array is composed of 2×15 unit antennas. All elements are fed by a rectangular waveguide which is divided into two rectangular waveguides from the side direction of the antenna. By properly designing the length of the coupling probe in the feed system, an equal excitation amplitude distribution can be realized for all unit antennas. The radiation phase of the unit antenna can be adjusted by rotating the helix arounding its axis to realize in-phase radiation of all elements. An array antenna with a center frequency of 38.0 GHz was designed through simulation. Simulation results show that the antenna has a gain of 22.1dB, an axial ratio of 2.09dB, an elevation plane beam width of 4.4°, an azimuth plane beam width of 30.1° at 38.0GHz. In the band of 37.0-39.0GHz, the reflection coefficient of this antenna is less than -15dB, the antenna gain is greater than 21.5dB and the axial ratio is less than 2.0dB which meet the design requirements of train-mounted antenna in the millimeter wave train-ground communication system.

1. Introduction

Millimeter-wave wireless communication is the mainstream communication method for high-speed maglev trains, and train-mounted antennas are its key components. According to the requirements of the train-ground communication system, the antenna needs to have characteristics such as miniaturization, circular polarization and fan-beam radiation (i.e. small beam width on the elevation plane and wide beam width on the azimuth plane). At present, the beam-shaped reflector antenna technology is adopted in the communication system as described in [1]. The reflector antenna generates a fan-beam circularly polarized radiation with a beam width of 7.6º × 24.8º which meets the basic requirement of high-speed maglev trains millimeter wave communication. However, although this form of reflector antenna can meet the communication requirements to a certain extent, it has the disadvantages of that the antenna size is too large and the height is too high. The larger windward surface would increase the running resistance of the train, while the higher height would affect the appearance of the train, which is in serious contradiction with the image of advanced rail transit.

Compared with reflector antennas, helical array antennas have the advantages of compact structure, good axial ratio, etc., and have been successfully used in satellite communication [2-3] and high-power microwave radiation [4]. In lots of helical array antennas [4-5], radial line waveguide has been used as the antenna's feeding waveguide. As the radial line waveguide has the axisymmetric structure, an axisymmetric pencil beam will also be generated by these antennas. This characteristic makes them unsuitable to be applied to train-mounted antenna applications as it requires fan-beam radiation. Therefore, it is necessary to use a waveguide with large length-width ratio for feeding, among which rectangular waveguide is a good candidate. At present, there are few studies focus on the rectangular waveguide helical array antennas. A side-feed rectangular waveguide helical array is proposed in [6]. The antenna uses a side-feed waveguide structure as the feeding waveguide, but because one waveguide feeds three rows of units simultaneously, the coupling of each unit antenna is difficult to adjust, the internal structure of the antenna is complex, the accuracy is high, and the optimal output frequency band is narrow.

Based on the above background, a miniaturized rectangular waveguide helical array antenna is designed for millimeter-wave train-ground communication in this paper. The antenna is composed of 2×15 unit antennas, and all elements are fed by a rectangular waveguide which is divided into two rectangular waveguides from the side direction of the antenna. One column of unit antennas is fed by one rectangular waveguide. The lengths of the electric probes are reasonably designed, which solves the difficulty of adjusting the probe coupling amplitudes in the waveguide and makes the internal structure of the antenna simple.

2. Antenna structure and layout

According to the actual engineering needs, the main technical targets of the designed millimeter wave train-mounted antenna include: the antenna operating frequency band is 37.0-39.0GHz, the antenna gain is greater than 20dB, the standing wave ratio is less than 1.5, the elevation plane beam width is about 5º, and the azimuth plane beam width is about 30º. This antenna uses axial-mode short helical antenna as radiation element, which directly radiates circularly polarized waves required for communication. According to the fan-beam radiation requirement, the unit antennas are arranged in a rectangular array of 2×15, and the spacing between the unit antennas is 6.5mm≈0.82λ. The designed 30-element side-feed rectangular waveguide helical array antenna is shown in Figure 1. The feed system uses a BJ320 feeding waveguide as the input port, and feeds two rectangular waveguides with a cross-section size of 5.75mm×3.5mm, respectively. The amplitude of the unit antenna can be adjusted by optimizing the size of the electric probe, and the radiation phase of the unit antenna can be adjusted by rotating each helix around its axis [7]. In this way, equal amplitude and in-phase radiation for all the elements can be achieved and the axial ratio of the antenna can be improved by sequential rotation method.

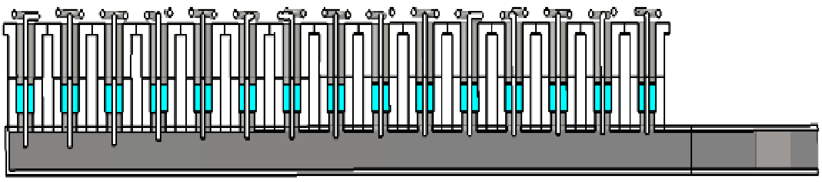


Figure 1. Front sectional view of the proposed array antenna.

3. Antenna component design

3.1. Design of the antenna

The short helical antenna [8] has the characteristics of few helical turns, small pitch angle, and can radiate circularly polarized waves. From the References [9] and [10], some experiences and theories of optimizing the helical elements can be obtained. The center frequency of the unit antenna is 38.0GHz, and the distance between the units is L=6.5mm. After optimization and simulation, the helical radius r_1 = 2.05 mm, the number of helical turns n=0.88, the pitch s = 0.35mm, and the height of the bend h_1= 0.35mm. The helical antenna model is shown in Figure 2, which is simulated using full-wave electromagnetic software. The simulated reflection coefficient of the unit antenna as a function of frequency is shown in Figure 3. The radiation pattern and axial ratio of the unit antenna in two orthogonal planes at 38.0GHz are shown in Figure 4. The simulation results show that the unit antenna gain is 9.4dB at 38.0GHz, and it radiates circularly polarized waves. The radiation pattern has good spatial axis symmetry. The reflection is less than -23dB in the 37.0-39.0GHz band.

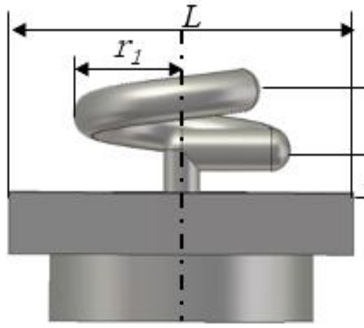


Figure 2. Helical antenna model.

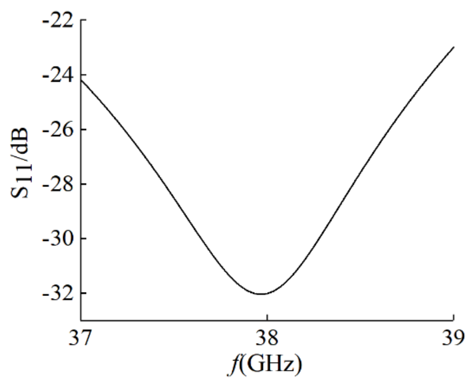


Figure 3. Reflection coefficient of the helical antenna.

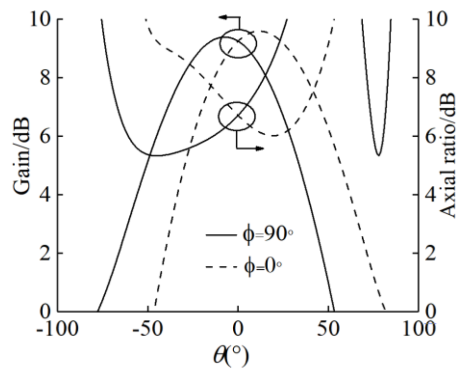
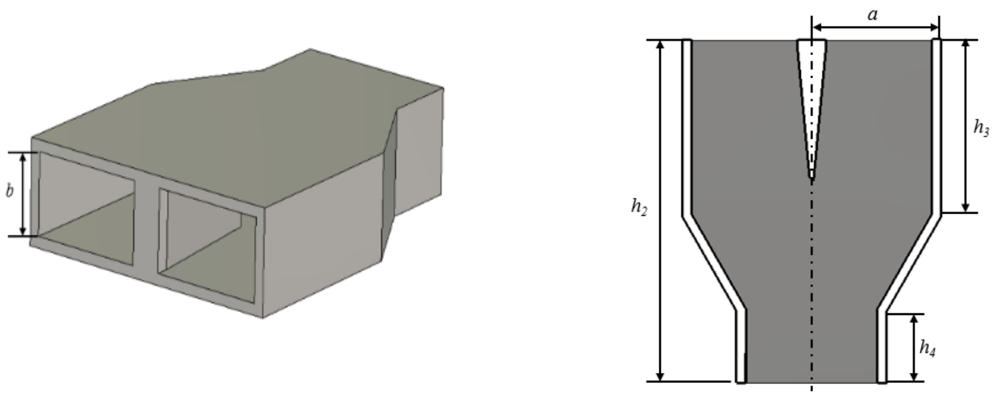


Figure 4. Radiation pattern and axial ratio of the helical antenna.



(a) (b)

Figure 5. Two-way power divider: (a) schematic diagram of a two-way power divider, (b) top sectional view of two-way power divider.

3.2. Design of two-way power divider

Figure 5 shows a two-way power divider using the BJ320 rectangular waveguide as the input port and two rectangular waveguides of 5.75mm (a) ×3.556mm (b) as the output ports. A gradual-changed waveguide section structure and a triangular pyramid structure inside the waveguide are used to realize good matching. Table 1 gives the optimized size of the two-way power divider. Using the full-wave electromagnetic simulation software, the S-parameter simulation results are simulated and shown in Figure 6. It can be seen that in the frequency band of 37.0-39.0GHz, the reflection coefficient of the power divider is less than 0.11, and the amplitudes of the two output rectangular waveguides are basically the same.

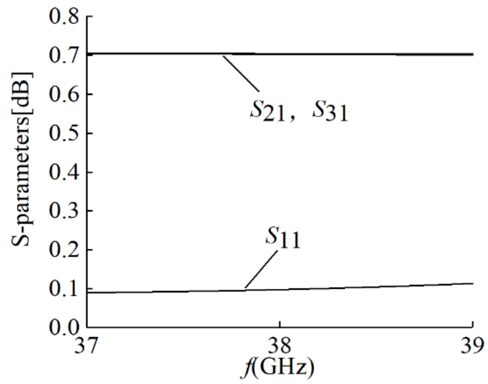


Figure 6. S-parameter of two-way power divider.

Table 1. Structural parameters of the power divider (mm).

Parameter	a	b	h_2	h_3	h_4
Value	5.75	3.556	18.5	9.5	3.85

3.3. Design of feed system

The output ports of the feed system are coaxial waveguides. According to the design principle of equal-amplitude excitation of the array antenna, it can be known that when the input power is 1, the coupling amplitude of each port in the 30-element feed system is 0.182. In the design of the 30-element array feed system, the probes at the symmetrical position are certainly have the same parameters, so these probes are grouped together, the top view and unit number of the feed system are shown in Figure 7. The size of the coupling probes of each port inserted into the waveguide is optimized by simulation, so that the coupling amplitude of each port is approximately 0.182, and the reflection of the feed system should not be too big. The reflection coefficient of the feed system calculated by simulation is shown in Figure 8, and the coupling amplitude curve of each port is shown in Figure 9 (assuming that the input power is 1). The coupling amplitude (I) and coupling phase (θ) of the output ports at 38.0 GHz are summarized in Table 2. From Figure 9 and Table 2, it can be seen that in the frequency band of 37.0-39.0GHz, the reflection coefficient of the feed system is less than -15dB, at the center frequency of 38.0GHz, the output coupling amplitudes of each ports of the feed system are approximately the same, which can realize equal amplitude feeding of 30 units, which is very helpful for improving the gain of the antenna.

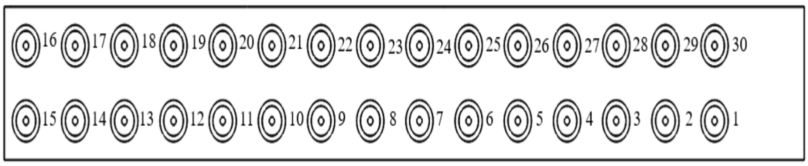


Figure 7. Top view of feed system and unit number.

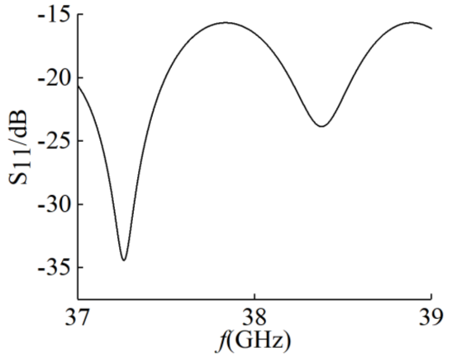


Figure 8. Reflection coefficient of the feed system.

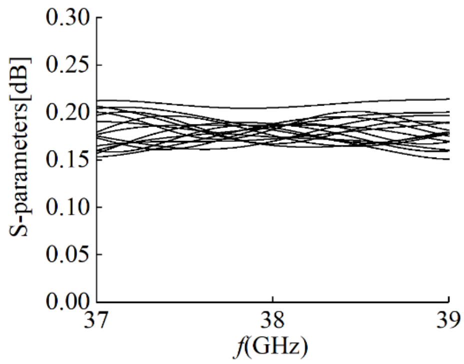


Figure 9. Coupling amplitude of each output port.

Table 2. Coupling result of the feed system.

Port	*I*	*θ*	Port	*I*	θ
1,30	0.18	-114	9,22	0.18	-76
2,29	0.18	31	10,21	0.18	61
3,28	0.18	171	11,20	0.18	-149
4,27	0.16	-51	12,19	0.17	5
5,26	0.17	85	13,18	0.17	114
6,25	0.18	-129	14,17	0.17	-137
7,24	0.18	16	15,16	0.2	6
8,23	0.16	155			

4. Antenna prototype and performance

The whole array antenna is fed by connecting the above-mentioned two-way rectangular waveguide power divider and the feed system. The unit element is excited by integrating the helical wire with the inner conductor of the coaxial output waveguide. Also, the unit antennas are rotated according to the coupling phases of each coaxial outputs to compensate the phases brought by the feed system [10-12]. A 30-element side-feed rectangular waveguide helical array antenna is then finalized as shown in Figure 10. The overall size of the antenna is 120mm (length)×13.25mm (width)×18mm (height). The array reflection coefficient is shown in Figure 11, and the radiation pattern and axial ratio of the two orthogonal planes at 38.0 GHz are shown in Figure 12 and Figure 13. Table 3 gives a summary of the radiation characteristics at the main frequencies. It can be seen from the simulation results that, at the center frequency of 38.0 GHz, the antenna gain is 22.1dB, the axial ratio is 2.09 dB, the elevation plane beam width is 4.4º and the azimuth plane beam width is 30.1º. In the band of 37.0-39.0 GHz, the reflection coefficient of this antenna is less than -15dB, the antenna gain is greater than 21.5dB and the axial ratio is less than 2.0dB.

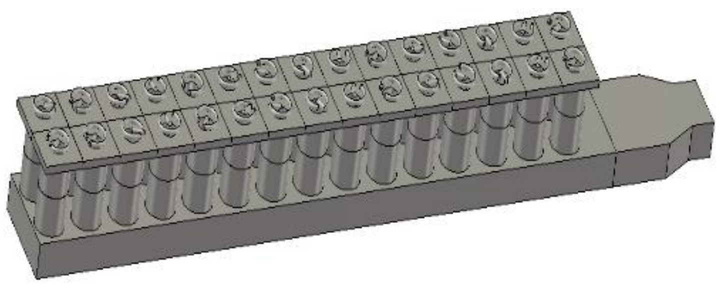


Figure 10. Side-feed rectangular waveguide helical array antenna.

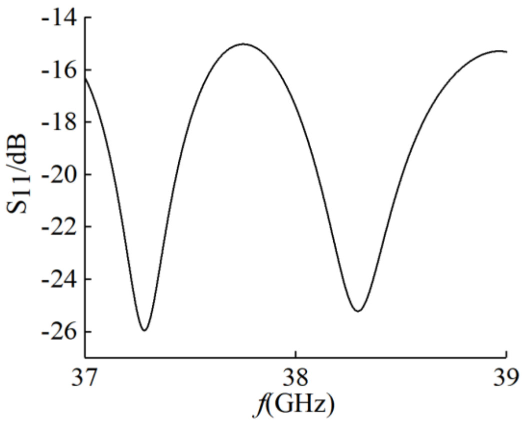


Figure 11. Antenna reflection coefficient.

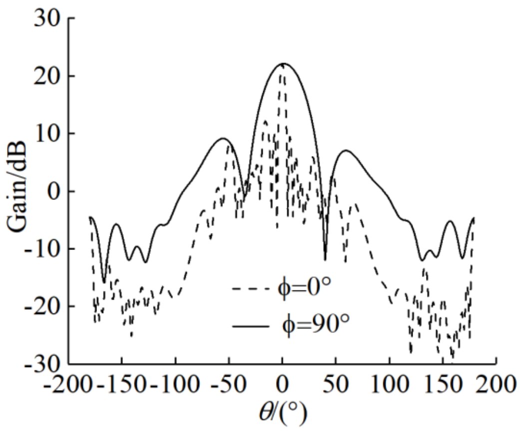


Figure 12. 38GHz radiation pattern.

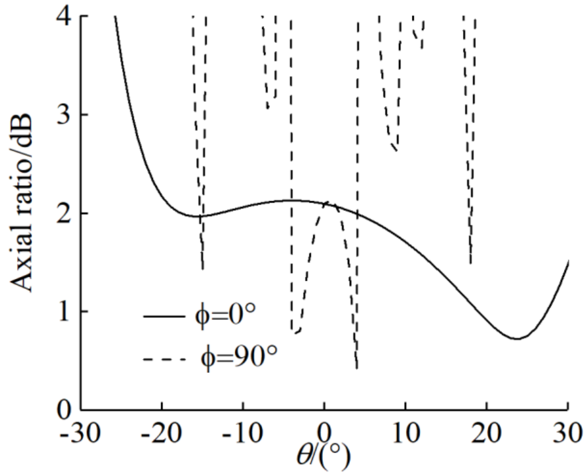


Figure 13. 38GHz antenna axial ratio diagram.

Table 3. Summary of radiation characteristics at main frequencies.

Frequency (GHz)	Gain (dB)	Axial Radio (dB)	φ=0° plane beam width (degree)	φ=90° plane beam width)degree)
37	21.5	1.7	4.6	31.2
38	22.1	2.09	4.4	30.1
39	22.1	1.5	4.3	30.3

5. Conclusions

A side-feed rectangular waveguide helical array antenna with fan-beam radiation characteristics for millimeter wave train-ground communication is designed in this paper. The antenna uses a BJ320 waveguide as the side-feed waveguide, and two rectangular waveguides are fed in parallel, which solves the problem that the probe coupling is difficult to adjust in the rectangular waveguide. Simulation results show that the antenna has high gain, low reflection, good axial ratio and miniaturized structure. Compared with the form of the reflector antenna, this antenna reduces the volume of the antenna, and compared with radial line helical array antennas, it has the characteristics of fan-beam radiation and wide working frequency band. This antenna meets the design requirements of train-mounted antenna in the millimeter wave train-ground communication system and provides certain reference value for the design of millimeter-wave train-mounted antennas.

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