Progress In Electromagnetics Research C, Vol. 23, 15–25, 2011

HIGH GAIN AXIAL-MODE HELICAL ANTENNA WITH CIRCULAR METAL DISK

S. Lin[1, 2, *], L.-N. Wang[2], W.-B. Zhang[2], C.-F. Zhou[2], X.-Q. Zhang[2], and J.-X. Wang[3]

[1]Electronic Science and Technology Post-doctoral Research Center, Harbin Institute of Technology, Harbin 150080, China

[2]School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150080, China

[3]Department of Microelectronics Science and Technology, Harbin Institute of Technology, Harbin 150080, China

Abstract—A method to improve the gain of axial-mode helical antenna is proposed. This method involves a parasitical circular metal disk, which is installed on the front of general axial-mode helical antenna and is apart from the helical line. A circular current whose phase lags behind that of helical line current appears, which brings a more concentrated radiation field. Consequently, the antenna gain is improved. Based on the simulation results, an antenna array model fed independently is proposed. This model gives an excellent explanation of the radiation characteristic of helical antenna. Both the simulation and experiment results show that for obtaining the same gain, the antenna length in this new method is only 71% of that in traditional helical antenna. The reduction of antenna length favors the miniaturization of antenna. In addition, this method has little effect on the bandwidth of antenna, so it can be widely used in the design of helical antenna element and array.

1. INTRODUCTION

Metal wires are generally used as the radiator of helical antenna. According to the different spiral winding shapes, the helical antenna can be divided into many types, such as cylinder helical, elliptical

Received 27 May 2011, Accepted 13 July 2011, Scheduled 23 July 2011
* Corresponding author: Shu Lin (linshu@hit.edu.cn).

cylinder helical, cone helical and sphere helical. As the main operating mode of these helical antennas, axial-mode can cause radiation along with helical direction. Moreover, the radiated electromagnetic-waves are circularly polarized waves. Therefore, the axial-mode helical antenna can be widely applied in satellite communications, and in recent years, with the development of mobile communications, this kind of antenna can be also used as base-station antennas to achieve wide and stable wireless network coverage. The input impedance of the helical antenna working in axial-mode approximates to a constant in broadband, $140\,\Omega$, which is the frequency range closed to $2:1$ theoretically and the wideband is obtained. Generally, helical antenna gain can be determined by the helical coil number, namely, the longer helical wire is, the higher gain of antenna is. However, when the number is too large, the improvement of gain is weak, and the fabrication of antenna becomes very complicated. Instead of that, the aligning array of antenna can be adopted to achieve high gain [1, 2], whose disadvantage is to require a more complex feed-network [3]. So, the arrays' application is constrained. Reference [4] proposed an axial-mode elliptical helical antenna with a variable pitch angle to improve antenna gain, and the simulation results show that under the condition of the same coil number, axial size and arm length, and the improvement of gain in certain frequency range is 1 dB comparing with a general elliptical helical antenna. Reference [5] proposed a circular polarized antenna with a big reflecting surface, which is fed by backward radiative helical antenna, and then, studied a paraboloid antenna with high gain and simple structure, this antenna has been applied in Chinese Chang'e satellites successfully.

Based on the design method of directing antenna, a cylinder axial-mode helical antenna with parasitic element is proposed in this paper. The parasitic element is constructed by a circular metal disk, which is apart from end of the helical wire within a very short distance. The dimensions of the disk and the distance between the disk and the end of the helical wire, which affect the antenna characteristics, are both simulated and optimized by CST Microwave Studio®. Finally, a high gain axial-mode helical antenna is obtained. It can be seen that the loading of parasitic element can effectively improve antenna gain, at the same time, the axial length of antenna doesn't increase. According to the simulation results, a dipole antenna array model fed independently is proposed. This model is equivalent to the radiation characteristic of the antenna and explains the radiated characteristic of axial-mode helical antennas.

2. ANTENNA STRUCTURE

Sketch of the proposed antenna structure is shown in Fig. 1. Antenna is made up with coaxial supply line, metal ground, helical line radiator whose coil number is few and a loaded metal disk which is apart from the helical line. It is remarkable where the inner conductor of the feeding coaxial-line is connected with the helical line, the inner conductor extends out a little part from the ground and then helically ascend with the pitch angle $\alpha = 11.3°$, which can ensure that the input impedance of the antenna is anamorphosis to achieve impedance matching in a large frequency range. The antenna structural parameters are shown in Table 1.

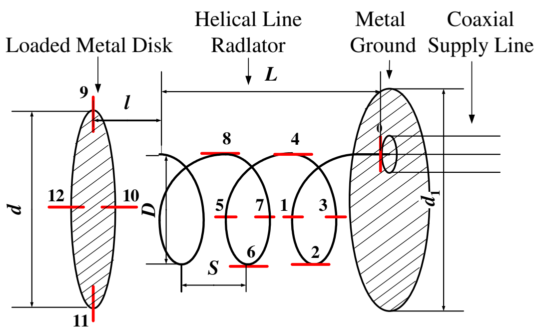

Figure 1. Sketch of the metal disk loaded helical antenna.

Table 1. Antenna structural parameters.

Parameter	Value
Diameter of metal ground plane d_1	100 mm
Helical pitch S	20 mm
Diameter of metal disk loaded d	48 mm
Diameter of helical line radiator D	32 mm
Coil number of helical line N	5 mm
Pitch angle α	11.3°
Helical axial length L	100 mm
Distance between metal disk and the end of the helical line l	12 mm

3. SIMULATION ANALYSIS

An antenna model is established by CST Microwave Studio®, and then a simulation is executed. In the simulation results, the amplitude and phase of current density on the first helical circle surface are presented in Fig. 2. As is shown, at a typical frequency 2.4 GHz, the length of the first circle helical line is 0.82λ. Calculated from the feeding point, the amplitude of the current density in the helical line fluctuate little and has no null point, while the phase of that is changing continuously (Fig. 2(b), the current phase is decreasing from Point 0 to 4, this indicates that the phase lags gradually), which approves that the current in the helical line is traveling-wave current at 2.4 GHz frequency point. Moreover, The simulation results concerning surface current density of the inner conductor of coaxial-line located at the feeding point show that the similar phenomena exist at an extreme wide frequency range (Fig. 3), this ensure the new kind of helical antenna a broad-band antenna. Fig. 3 demonstrates that the reflection loss of

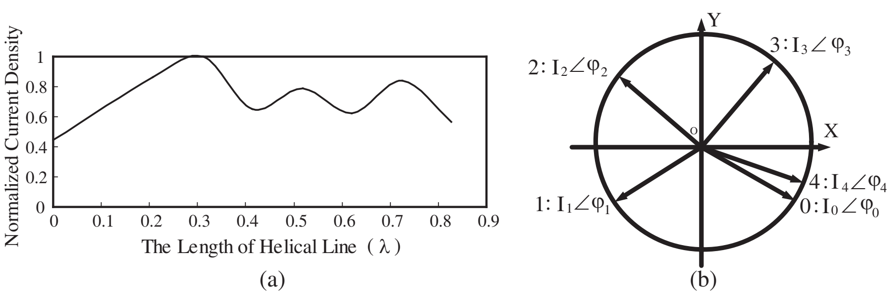

Figure 2. The amplitude and phase of the first circle surface current density. (a) The amplitude of the first circle surface current density. (b) The phase of the first circle surface current density.

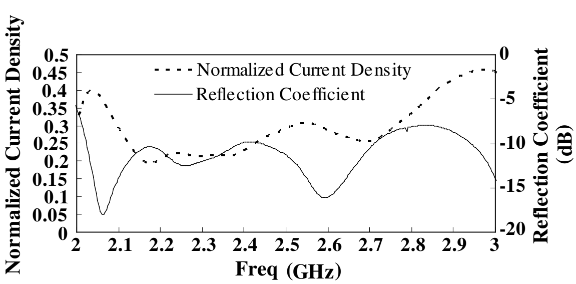

Figure 3. The simulation results concerning surface current density of the inner conductor of coaxial-line located at the feeding point.

the antenna is under −10 dB in the frequency range from 2.0 GHz to 2.4 GHz, and impedance bandwidth is 30%.

The simulation results also show that the phase of the surface current density in the first circle helical line is changing continuously. It is possible to find two points whose phase difference is 90° (for example Points 1 and 2, or Points 3 and 4). Meanwhile, the direction of current at these two points is perpendicular, so it is inevitable to form a circular polarized electromagnetic radiation. At 2.4 GHz frequency point, the length of one circle helical line is 0.82λ, which is close to 1λ, then current density amplitude and phase distribution on second circle surface is similar to that on the first circle surface, except that a small amplitude, and a null amplitude at the end of the helical line. The current in several circles of helical line superimposes in phase at far-zone field to produce the directed radiated characteristic.

The distribution of the surface current density in the loaded metal disk is displayed in Fig. 4. At 2.4 GHz, there is large amplitude of the current density in the edge of the metal disk. The simulation results concerning the amplitude and phase of the current density in the edge of the metal disk indicates that (Fig. 5), the current density in the edge

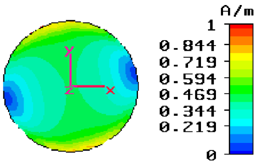

Figure 4. The distribution of the surface current density in the loaded metal disk.

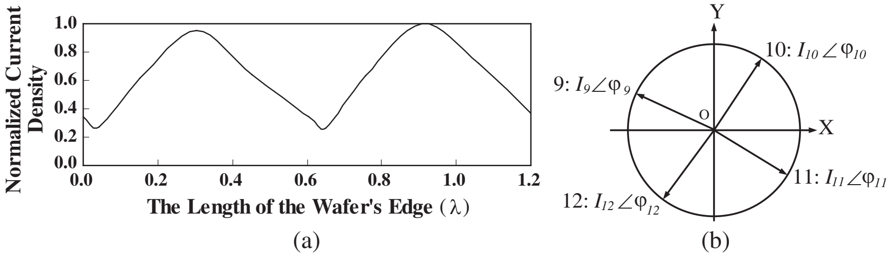

Figure 5. The simulation results concerning the amplitude and phase of the current density in the edge of the metal disk. (a) The simulated results of the amplitude of the current density in the edge of the metal disk. (b) The simulation results concerning the phase of the current density in the edge of the metal disk.

of the metal disk exists in standing wave form, meanwhile, there is a great phase difference of current density between edge of disk metal and the helical line. Fig. 5(b) demonstrates the phase of the current density at 2.4 GHz. Comparing the amplitude and phase of the current density at Points 2, 6 and 11 on helical antenna, the results show that the current density at Point 2 and 6 is in phase approximately, while that at Point 11 lags 66° behind from points 2 and 6 (Principal Value). This intensifies directional radiation of antenna, and consequently obtains a high gain.

In order to simplify the analysis, let coil numbers of the helical antenna (N) reduce to 2, the analysis method as above is still applied. The simulation results show that the surface currents of the first coil are also traveling wave currents at 2.0 GHz and the phase is continuously lagging, which can form the circular-polarized electromagnetic waves. However, currents on the loading metal disk are still standing wave currents. When $N = 2$, analyzing the current density of the positions 1 and 12 in Fig. 1. The magnitude and phase of the current density at these two points are shown in Fig. 6, which shows that the current at position 1 is 98.8° advancer than that at position 12 and the phase-shift between the two positions is 83.6°. Thus they contribute to form the directional radiation which is along the axial line. For the sake of explaining this process, we can observe the array which consists of two current vectors at positions 1 and 12. Space phase-shift between these two points is 83.6°, however, their current magnitudes and phases are the same as shown in Fig. 6, that is, at position 1: $J_1 = 1\angle - 45.2°$ and at position 12: $J_{12} = 0.19\angle 36°$. Furthermore, for this array, its array factor can be obtained from formula (1) and the final result is shown in formula (2).

To simplify the analysis, the coil number of helical line N is cut

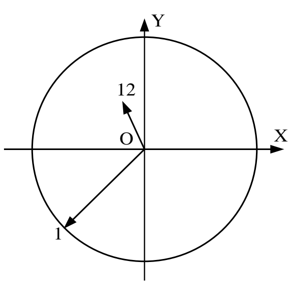

Figure 6. The amplitude and phase of the current density at points 1 and 12.

down to 2,

$$F(\delta) = \frac{\left[1 + m^2 + 2m\cos(kd\cos\delta + \xi)\right]^{\frac{1}{2}}}{1 + m} \qquad (1)$$

where $m = 0.19$, $kd = 83.6^\circ = 1.46\text{rad}$, $\xi = -98.8^\circ = -1.72\text{rad}$, so,

$$F(\delta) = [0.73 + 0.27\cos(1.46\cos\delta - 1.72)]^{\frac{1}{2}} \qquad (2)$$

Actually, formula (2) can be expressed as a normalized pattern in linear-polarized directional radiation field. Similarly, the normalized directional-function of current radiation field at positions 2 and 11 can be also obtained, as shown in formula (3). However, this linear-polarized radiation field is orthogonal with that of formula (2), and there exists 90° phase-difference between these two radiation field, as presented in Fig. 1 and Fig. 2(b). All this prove that the far-field of the helical antenna with metal disk loading is circular-polarized field.

$$F(\delta) = [0.60 + 0.40\cos(2.21\cos\delta - 1.36)]^{\frac{1}{2}} \qquad (3)$$

If the helical antenna has no metal disk loading, there would not exist the current whose phase is larger than that of the first ring in radiation direction. So, the forming directional radiation is only depended on the interaction between the two helical coils and the ground, which would weaken the effective of directional radiation. Consequently, comparing with the metal disk loaded helical antenna, antenna gain decreases.

Without the metal disk loaded, it is a only method to improve antenna gain that increasing the coil number of helical line and adjusting the coils' spacing to achieve the superposition in phase. In contrast, with the metal disk loaded which is apart from the helical line, induction current appears. Large additional phase shift and directional radiation can be obtained only by a short space distance. Thus it can be concluded that the metal disk loaded helical antenna just takes a shorter axial length (the length of the radiation direction) to obtain the same gain as that of the general helical antenna. Formula (4) can be used to evaluate the effect of the reduced axial length of the helical antenna.

$$K = G/L \qquad (4)$$

where G is the antenna gain (Linear Value) and L is axial length. This formula shows that the larger K value is, the shorter axial length is, so a better result can be obtained.

4. ANALYSIS OF SIMULATION RESULTS

According to the simulation results listed in Table 1, an antenna model has been made, as is shown in Fig. 7. By the VNA E8363B of Agilent

Corporation, the measurement of this antenna is executed in the microwave anechoic chamber, which including the reflection coefficient, directional diagram of circular polarization, antenna gain of circular polarization, and axial ratio. The results are demonstrated in Fig. 8 to Fig. 10. The measured results show that the reflection coefficient of the antenna lies under −10 dB at frequency range from 1.82 GHz to 2.94 GHz. Comparing with the simulated results, frequency range pans left for 200 MHz, with an error of 9%, which is because of the error of diameter of helical line radiator when produced. As the typical frequency (2.4 GHz) of the study is within both of the ranges, so the results can be accepted. In the aspect of circular polarization major lobe, there is little difference between measurement and simulation, however, in regard to side-lobe, a large difference exists. These results are due to the influence of measuring circumstance and holding devices. As a kind of directional antenna, this difference has no effect on application of the antenna. Besides, the feeder line and revolving stage also affect the measured results of gain and axial ratio.

The antenna proposed in this paper is compared with other helical antennas, and the relative results are shown as Table 2. The

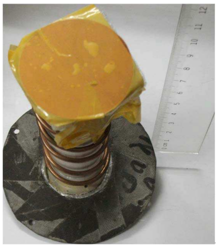

Figure 7. A picture of the antenna model.

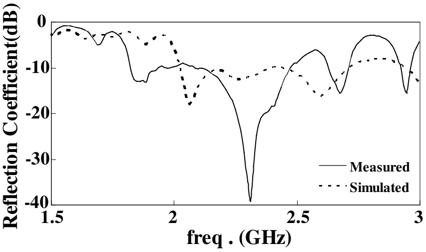

Figure 8. The result of antenna reflection coefficient.

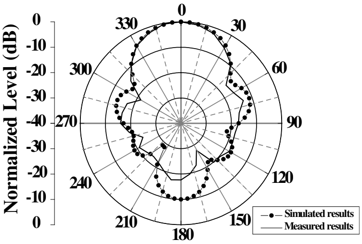

Figure 9. Radiation pattern of the antenna (@2.4 GHz).

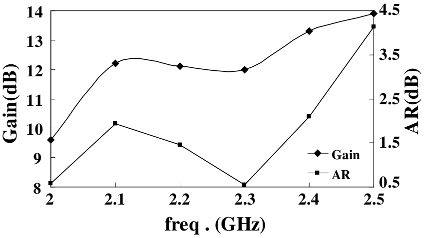

Figure 10. Antenna gain of circular polarization and axial ratio.

most important one of these parameters is the ratio of antenna gain (Linear Value) and axial length (Equation (4)), which is marked as K, representing the antenna gain produced by per unit length. The results of the comparison indicate that the under the condition of the same antenna dimension, the gain of mental disk loaded antenna is 2 dB larger than that of the general one at 2.4 GHz frequency point, and under the condition of the same antenna gain, the axial length of the former is only the 71% of that of the latter. While compared with the high-gain helical antenna proposed by Reference [4] (whose gain is 1 dB larger than the that of general helical antenna), the axial length is reduced greatly, which is helpful to minish the axial dimension of the antenna.

Compared with the general helical antenna, the improvement of antenna gain will influence the radiation pattern of the antenna, and the main lobe of the antenna will become more narrow. To prove this principle, the radiation patterns of the antenna with and without the metal disk are simulated specially, which are shown in Fig. 11. The simulation results show that both the main lobe and the minor lobe of the radiation pattern become more narrow, but neither of them change much. All of these indicate that the antenna gain improves.

Table 2. The comparison of different helical antenna.

Antenna Type	Gain(@2.4 GHz)	Axial Length	Value of K
Metal disk-loaded Helical Antenna	21.3 (13.3 dB)	112 mm	$0.190\,\text{mm}^{-1}$
General Helical Antenna	13.4 (11.3 dB)	100 mm	$0.134\,\text{mm}^{-1}$
The Helical Antenna Proposed in Reference [4]*	11.2 (10.5 dB)	65.5 mm*	$0.171\,\text{mm}^{-1}$*

*Notice: Axial length and K are calculated value based on the conclusion in Reference [4], and not the same value proposed in Reference [4].

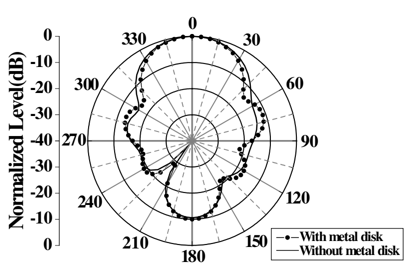

Figure 11. The normalized radiation pattern after and before adding the disk.

5. CONCLUSION

An axial-mode cylinder helical antenna with metal disk is proposed in this paper, and correlative simulation and experiment are executed. According to the simulation of surface current density, a current vector array model which is equivalent to the radiation characteristic of antenna is established, and this model provides a good explanation for both the circular polarized radiation characteristic and directed radiated characteristic. Both the simulated and measured results indicate that the ratio of antenna gain to axial length is large, which means that the antenna has smaller axial size, and this is helpful for lessening the antenna profile. The metal disk-loaded would not cause some negative effect on antenna impedance bandwidth and axial ratio characteristic. Therefore, it is a very effective method to improve gain of the axial-mode helical antenna.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to CST Ltd. Germany., for providing the CST Training Center (Northeast China Region) at our university with a free package of CST MWS software.

The authors would like to express their sincere gratitude to the funds supported by "the Fundamental Research Funds for the Central Universities" (Grant No. HIT.NSRIF.2010096) and the funds supported by "Heilongjiang post-doctorial financial assistance (LBH-Z09187)".

REFERENCES

1. Hui, H. T., E. K. N. Yung, C. L. Law, Y. S. Koh, and W. L. Koh, "Design of a small and low-profile 2×2 hemispherical helical antenna array for mobile satellite communications," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 1, 346–348, 2004.
2. Li, X.-Q., Q.-X. Liu, X.-J. Wu, L. Zhao, J.-Q. Zhang, and Z.-Q. Zhang, "A GW level high-power radial line helical array antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 9, 2943–2948, 2008.
3. Hassan, S. I. S., M. F. Ah, and A. R. Arief, "Four beams helical antenna array for mobile satellite application," *2004 RF and Microwave Conference*, 53–55, Subang, Selangor, Malaysia, 2004.
4. Yang, F., P. Zhang, C.-J. Guo, and J.-D. Xu, "Axial-mode

elliptical helical antenna with variable pitch angle," *Electronics Letters*, Vol. 44, No. 19, 1103–1104, 2008.

5. Sun, D. Y., "Design of reflector antenna fed by backfire helix," *Spacecraft Engineering*, Vol. 17, No. 2, 59–62, 2008 (in Chinese).