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Conical Ground Helical Antenna with Feed-Through Insulator for High-Power Microwave Applications

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Abstract

In this paper, a novel helical antenna for high-power microwave is proposed. The proposed antenna is intended to demonstrate improved power handling capacity without any deterioration in matching characteristics, gain, and axial ratio. The proposed antenna with a long helix structure is investigated in order to achieve high gain and a relatively wide impedance bandwidth. By increasing the distance between the helix and the ground plane, an improved power handling capacity is obtained, and the impedance matching problem caused by the proposed method is addressed with the use of a feed-through insulator. In addition, a conical-shaped ground is used to compensate for the gain reduction by increasing the distance between the helix and the ground plane. As a result, the proposed antenna exhibits a gain exceeding 11 dBi and an axial ratio of less than 2 dB within the frequency range of 0.86–1.09 GHz. In addition, its power handling capacity exceeds 50 MW for a 0.7-ns input pulse length in air conditions.

Key Words: Circular Polarization, Helical Antenna, High-Power Microwaves.

I. INTRODUCTION

In recent years, there has been an increasing demand for high-power microwave (HPM) systems and antennas capable of transmitting gigawatt-level power. Various types of antennas for HPM systems, such as impulse radiating antenna (IRA) [1], radial line slot antenna [2], TEM horn antenna [3], and helical antenna [4–7], have been described in the literature. Helical antennas are widely used in HPM systems owing to their advantages, including their compact structure, simple radiating circularly polarized wave, and wide bandwidth. The most important consideration in designing an antenna suitable for HPM applications is its increased power handling capacity, which can be achieved in two ways. The first method aims to improve the critical electric field strength with the use of an SF6 gas or a vacuum pump [4–6]. The second method aims to reduce the maximum E-field on the antenna through the modification of the antenna structure [6, 7]. In [6], the E-field reduction method involving branching the helix radiator is proposed. However, such an antenna has a narrow impedance bandwidth due to the branched wire. In [7], in order to reduce the maximum E-field, the wire at the feed point is smoothly bent, and the diameter increases gradually. However, additional methods are needed to further reduce the maximum E-field in recently

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developed high power sources. In this paper, a design technique for improving the antenna power handling capacity based on the method described in [7] with additional modification of the feeding structure is proposed. To reduce the E-field on the helical antenna, the wire diameter is extremely increased, and the height of the connecting part is extended. Accordingly, this approach causes an impedance mismatch because the connecting part between the coax waveguide and the helix radiator cannot operate as an impedance transformer. Consequently, the matching method with a feed-through insulator is proposed for helical antennas with extremely large wire diameters. The proposed antenna is verified with respect to its gain and matching characteristics by performing low-power tests. Its power handling capacity is also investigated by performing high-power tests.

II. Antenna Design

1. *Power Handling Capacity of Conventional Helical Antenna*

The geometry of the conventional helical antenna is presented in Fig. 1(a). The configuration of the helical antenna can be divided into four sections. Section A consists of an RG-218 coaxial cable. Section B consists of a coaxial waveguide filled with a dielectric (PET-100, $\varepsilon_r = 2.9$). Section C consists of a horizontal wire conductor over the ground plane, which operates as a quarter-wave transformer with a characteristic impedance of 75 Ω. Section D consists of the helix defined by the pitch angle and diameter.

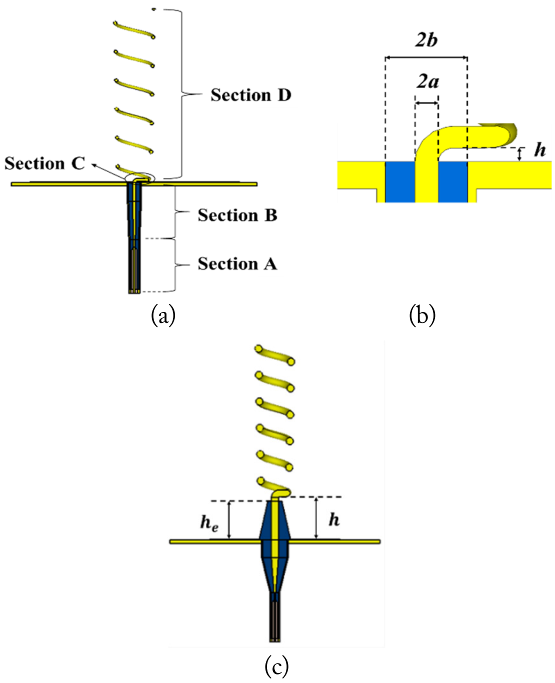


Fig. 1. Geometry of the helical antenna: (a) conventional helical antenna, (b) connecting part of the conventional helical antenna, and (c) proposed helical antenna with a feed-through insulator.

For HPM applications, the electric field strength should be taken into account to avoid electrical breakdown in each section. The E-field can be reduced if the wire of the helix is made of a thick copper tube [5]. However, as the wire diameter becomes thicker, the input impedance of the helical antenna decreases [8]. Thus, the wire diameter of a helical antenna designed for HPM applications is typically about 0.005–0.05λ [8]. The simulated maximum E-field of the conventional helical antenna for various wire diameters and distances (*h*) between the ground and the helix is presented in Fig. 2, for an input power of 0.5 W. As the wire diameter and the distance between the ground and the helix increases, the maximum E-field decreases, as shown in Fig. 2.

The relationship between the maximum E-field and the power handling capacity of the antenna is

$$P\ (W) = (E_b/E_{Max@0.5W})^2/2, \tag{1}$$

where, P is power handing capacity, E_b is critical peak electric field strength (3 MV/m for continuous wave), and $E_{Max@0.5W}$ is maximum E-field on antenna when the input power is 0.5 W. According to Eq. (1) and to the simulated maximum E-field in Fig. 2, the power handling capacity of the conventional helical antenna is improved by extending the distance between the ground and the helix.

The input impedance of the conventional helical antenna for various wire diameters is presented in Fig. 3. As the wire diameter increases, reducing the maximum E-field, the impedance bandwidth is restricted by the cutoff frequency of the coaxial waveguide in section B. Also, the horizontal wire conductor in section C can no longer operate as a quarter-wave transformer due to the enlarged dielectric of section B in order to maintain a 50-Ω characteristic impedance of the coaxial waveguide. Therefore, the wire diameter is chosen to be *2a* = 20 mm for a wide input impedance bandwidth and relatively low E-field intensity. The input impedance of the conventional helical antenna for different *h*, when *2a* = 20 mm, is presented in Fig. 4. As *h* increases, the reactance becomes capacitive, although the input

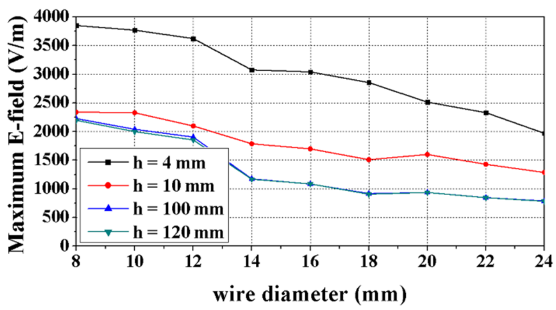
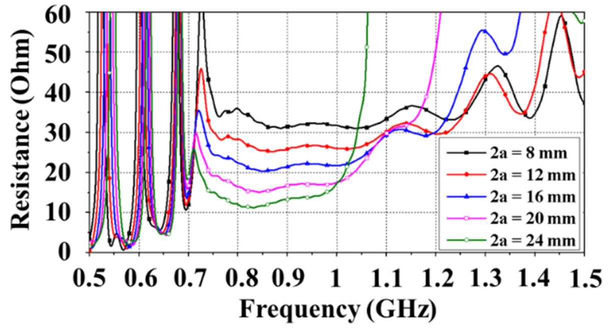
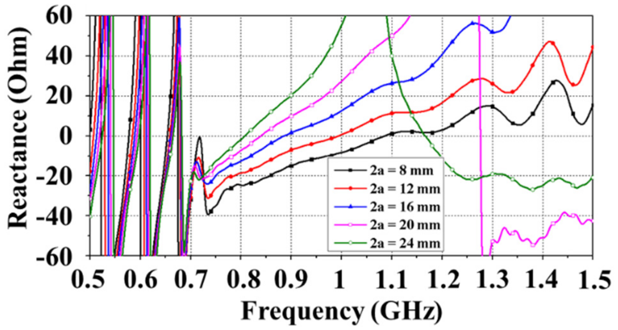


Fig. 2. Maximum E-field of the conventional helical antenna for different wire diameters (*2a*) and distances (*h*) between the ground and the helix.



(a)



(b)

Fig. 3. Input impedance of the conventional helical antenna for different wire diameters when $h = 4$ mm: (a) resistance and (b) reactance.

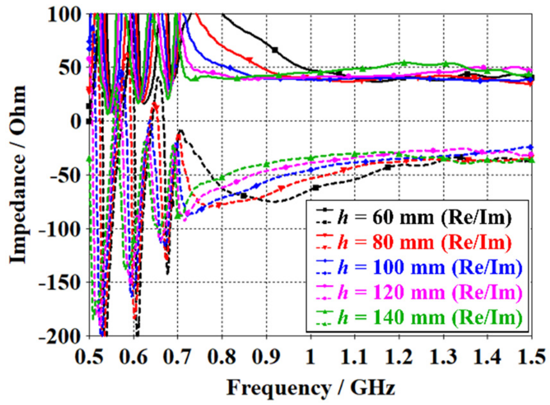


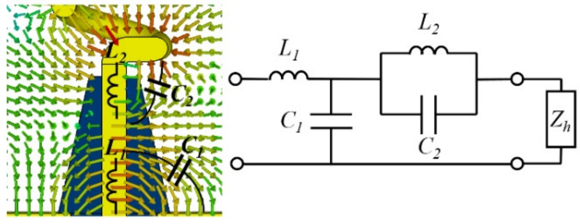
Fig. 4. Input impedance of the conventional helical antenna for different h values when $2a = 20$ mm.

resistance is saturated to 50 Ω.

Therefore, to provide better impedance matching to the helical antenna, the capacitive reactance must be compensated by modifying the feeding structure.

2. Helical Antenna with a Feed-Through Insulator

To compensate for the capacitive reactance of the helical antenna, a conical-shaped feed-through insulator (HAFI) is proposed, as shown in Fig. 1(c). The feed-through insulator is extended from the dielectric (PET-100) of the coaxial waveguide of section B, with a height of h_e. The E-field distribution and the equivalent circuit of the HAFI are presented in Fig. 5.



(a) (b)

Fig. 5. (a) E-field distribution and (b) equivalent circuit of the HAFI.

C_1 is the shunt capacitance between the vertical wire and the ground plane. C_2 is the parasitic capacitance between the vertical wire and the horizontal wire. L_1 and L_2 are the inductances corresponding to the length of the vertical wire. As the height of the insulator (h_e) increases, the shunt capacitance (C_1) and the parasitic capacitance (C_2) also increase. Similarly, the effective length of the vertical wire section increases.

The input impedance of the HAFI for different insulator heights (h_e) is presented in Fig. 6. The distance between the ground and the helix is 120 mm. As h_e increases, the input resistance decreases until $h_e = 50$ mm, because C_1 is the dominant parameter. Then, the input resistance increases due to the increase in C_2, as presented in Fig. 6. The input reactance also increases due to the increase in C_2 and due to the vertical wire electrical length. Therefore, the impedance bandwidth is enlarged to a lower frequency band, as presented in Fig. 7. The insulator height is set at 110 mm.

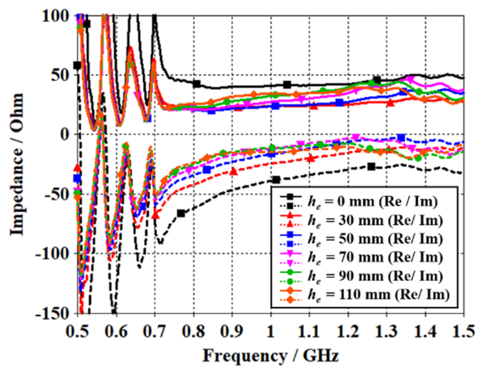


Fig. 6. Input impedance of the HAFI for different insulator heights.

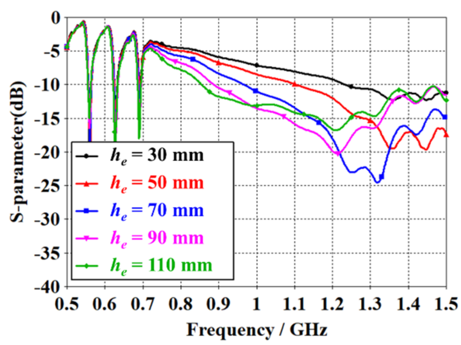


Fig. 7. S-parameter of the HAFI for different insulator heights.

The E-field distributions of the conventional helical antenna and of the HAFI are presented in Fig. 8. The maximum E-field occurs at the horizontal wire conductor, and the corresponding values are 2990 V/m and 942 V/m. Hence, in air conditions, the power handling capacity for each antenna type is calculated from the equation given in [6], that is, $(E_b/2990)^2 = 1$ MW and $(E_b/942)^2 = 10$ MW, respectively. Thus, the power handling capacity is improved by 10 times.

3. Gain Compensation with Ground Modification

Due to the increased height of the helix from the ground plane, a phase difference between the radiated field in the forward direction and the field reflected by the ground plane is generated. Therefore, the side-lobe level increases, and the gain of the HAFI is 1.4 dB lower than that of the conventional helical antenna, as shown in Fig. 9. To improve the gain of the HAFI, the ground plane is modified into a conical shape, as shown in Fig. 10(a). The slope of the conical ground is 45°, and its height is h_c. The gain of the HAFI with a conical ground for a different h_c is presented in Fig. 11, which shows that the gain increases with the increase in h_c. The maximum gain of the proposed antenna is 12.8 dBic for $h_c = 60$ mm, as presented in Fig. 9. The gain of the HAFI with a conical ground is enhanced by 3.2 dB compared with that of the HAFI. This is due to the reduction in the side-lobe level. Meanwhile, the simulated maximum E-field is 1253 V/m, which is higher than that of the HAFI with planar ground. This is because the E-field reflected by the conical ground is concentrated on the horizontal wire. The E-field distribution of the HAFI with a conical ground is presented in Fig. 12. Thus, the power handling capacity for air propagating a

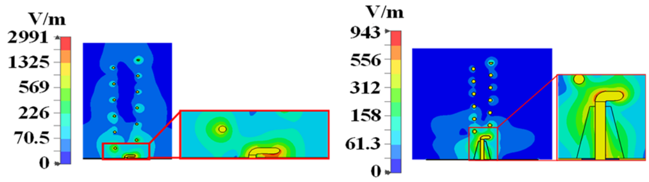


Fig. 8. E-field distribution: (a) conventional helical antenna and (b) HAFI.

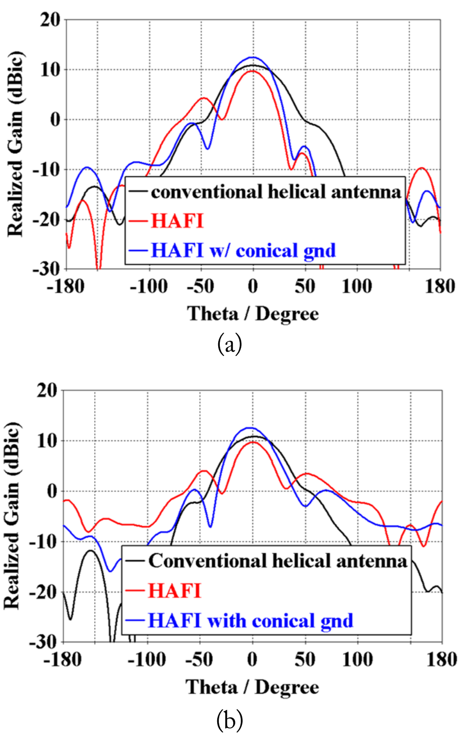


Fig. 9. Radiation pattern of helical antennas at 1 GHz: (a) $\phi = 0°$ and (b) $\phi = 90°$.

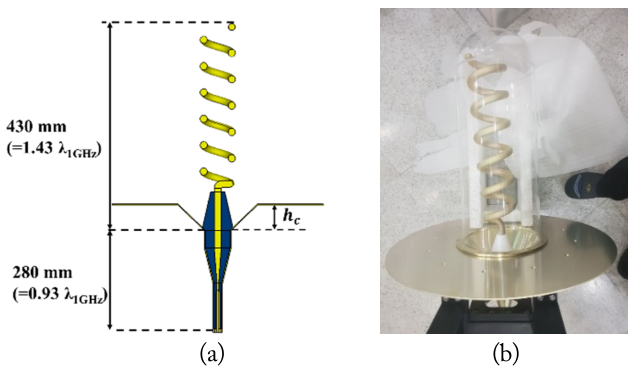


Fig. 10. Geometry of the proposed antenna: (a) HAFI with a conical ground and (b) the fabricated proposed antenna.

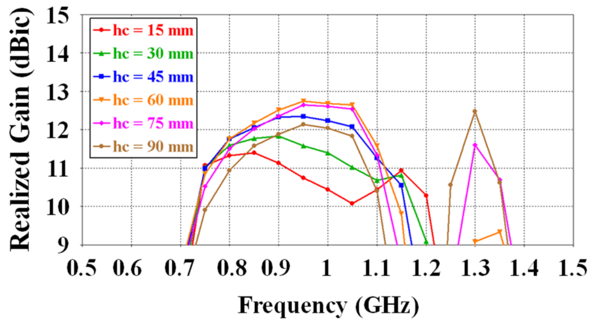


Fig. 11. Gain of the HAFI with a conical ground for different conical ground heights.

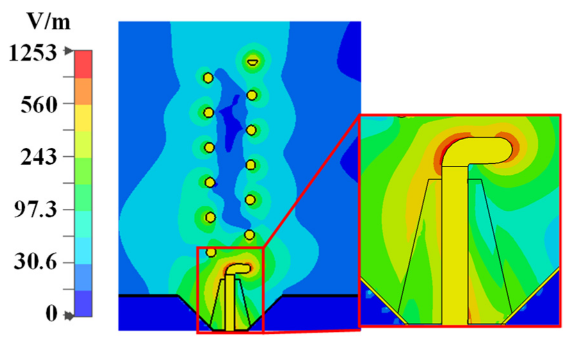


Fig. 12. E-field distribution of the HAFI with a conical ground.

continuous wave is $(E_b/1253)^2 = 5.74$ MW. This result shows that the power handling capacity is improved by 5.74 times compared with that of the conventional helical antenna and is higher than that reported in [6], which is 4.96 times that of the conventional antenna. Moreover, the antenna in [6] has a narrower impedance bandwidth (15.2%) than ours (0.86–1.09 GHz, approximately 23.5%), because the proposed method is applicable only to short helical antennas. In addition, the proposed antenna can be adapted for a longer helix, resulting in a high gain.

When the pulse generator is used as a source of high power, the power handling capacity can be determined by Eq. (1) and by the critical peak electric field strength. The critical peak electric field strength can be calculated from the equation in [9]:

$$E_{b,peak} = \sqrt{2}E_{b,RMS} = \sqrt{2}\times\ 22.4\times p\times\left(1+\frac{4\times10^{-2}}{p\ \tau_p}\right)^{3/16} \qquad (2)$$

where p is the ambient pressure (~10^5 Pa) and τ_p is the duration of the pulse. Given that the input pulse with a 0.7-ns pulse length is used to verify the power handling capacity of the proposed antenna, the critical peak electric field strength is 10.53 MV/m. Therefore, the recalculated power handling capacities of the conventional helical antenna and the proposed antenna are $(E_b/2990)^2 = (10.53 \times 10^6/2990)^2 = 12.4$ MW and $(E_b/1253)^2 = (10.53 \times 10^6/1253)^2 = 70$ MW, respectively.

III. Result

To verify the operation of the proposed antenna, experimental measurements were performed by conducting both low-power and high-power tests. The geometrical parameters of the fabricated proposed antenna are shown in Fig. 10(a).

1. Low-Power Test

The measurement results for the S-parameter of the proposed HAFI with a conical ground are presented in Fig. 13. The measured impedance bandwidth falls within the frequency range of 0.86–1.09 GHz. The gain and the axial ratio measured in an anechoic chamber are presented in Fig. 14. The measured gain exceeds 11 dBic within the frequency range of operation. The reduction of the measured gain is due to misalignment during the measurement. The measured axial ratio is less than 2 dB within the operating frequency range. Meanwhile, the proposed antenna radiates in near-circular polarization. Thus, the proposed antenna radiates in near-circular polarization.

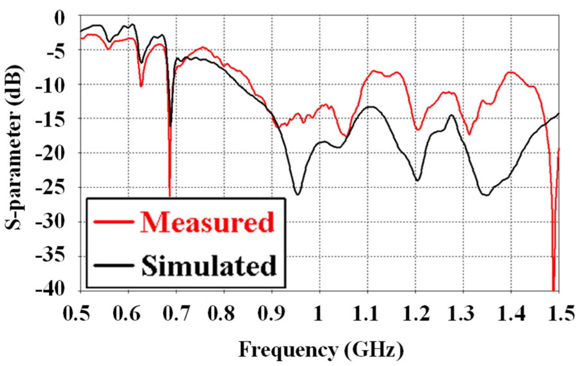


Fig. 13. Simulated and measured S-parameter of the proposed antenna.

2. High-Power Test

The power handling capacity of the proposed antenna is verified by a high-power test, the setup for which is presented in Fig. 15. An FPG-P pulse generator (FID GmbH, Burbach, Germany) is used to excite the proposed antenna. The waveform of the output pulse generated by the pulse generator is presented in Fig. 16. This pulse is used as the input pulse of the proposed antenna. The pulse radiated by the proposed helical antenna is measured by vertically and horizontally oriented D-dot sensors in the far-field region. The results, along with the simulation results, are shown in Fig. 16.

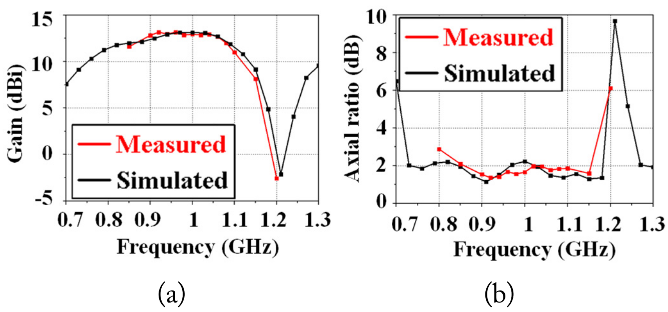


Fig. 14. Simulated and measured (a) gain and (b) axial ratio.

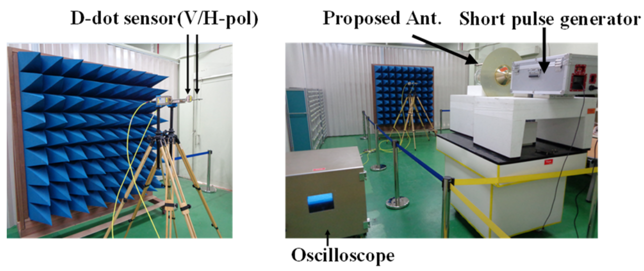


Fig. 15. High-power test setup.

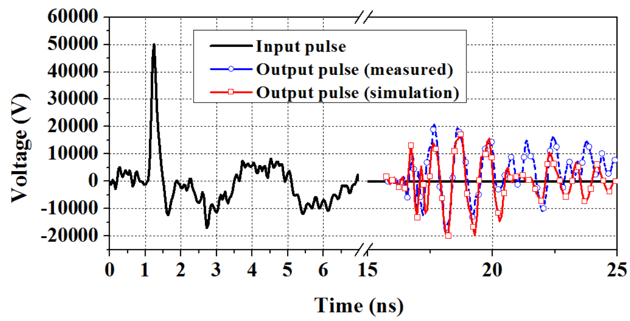


Fig. 16. Waveform of the input and output pulse.

The peak voltage of the input pulse is 50 kV, and the pulse length is 0.7 ns. Thus, the peak power of the input pulse is (V_p^2/R_{in}) = ((5 × 10^4)^2/50) = 50 MW. This input power is sufficient to verify the improvement in power handling capacity, given that this value is larger than the power handling capacity of the conventional helical antenna. The simulation and measured radiated pulses for a 0.7-ns pulse width are well matched, as shown in Fig. 16. Thus, the proposed helical antenna is capable of radiating a high-power short pulse without breaking down and without pulse shortening.

IV. CONCLUSION

A conical ground helical antenna with a feed-through insulator suitable for HPM application is proposed in this paper. The power handling capacity of the proposed antenna is improved by 5.7 times that of the conventional helical antenna. This is achieved by modifying the feeding section. Moreover, the gain of the proposed antenna is improved by modifying the ground plane structure. Additionally, the low- and high-power tests verified that the proposed antenna exhibits a higher power handling capacity and a higher gain than the conventional helical antenna. Therefore, it is suitable for HPM applications.

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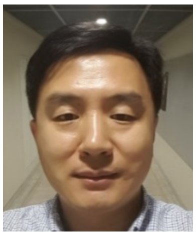

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