Received March 10, 2019, accepted April 2, 2019, date of publication April 11, 2019, date of current version May 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2910211

Design of Ultra-Wide Band Metal-Mountable Antenna for UHF Partial Discharge Detection

YANG QI[1], YANG FAN [1], (Member, IEEE), GAO BING[1], RAN JIA[1], WANG SEN [2], SHEN WEI[2], AND AMMAD JADOON[1]

[1]State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China
[2]Electric Power Research Institute, Shaanxi Electric Power Company, Xi'an 710054, China

Corresponding authors: Yang Qi (20151101012@cqu.edu.cn), Yang Fan (yangfancqu@gmail.com), and Gao Bing (gbcqu425@cqu.edu.cn)

This work was supported in part by the National Key Research Project of China under Grant 2017YFB0902703, and in part by State Grid under Grant SGJSCZ00FZJS1802179.

ABSTRACT This paper presents an ultra-wideband metal-mountable antenna used in the ultra-high-frequency (UHF) partial discharge (PD) detection. The designed antenna combines a coplanar waveguide antenna and multilayer substrates to effectively broaden its bandwidth when mounted on a conductive surface. These substrates consist of two layers of FR-4 dielectric substrates and two layers of the absorbing gasket, which is adapted to absorb the reflected electromagnetic signals. The parametric study is conducted to optimize antenna performance. A prototype is fabricated to confirm the design, and the measurement results show good agreement with the simulation. When mounted on the metal plate, the proposed antenna covers the UHF bandwidth of 400 MHz–3 GHz for $S_{11} < -10$ dB with a compact size (282 mm × 242 mm × 8.75 mm). As the thickness of the antenna is only 8.75 mm, the safety distance of electric insulation in electrical equipment will not be affected. A PD experiment has been carried out, and a reference antenna is used in the experiment for comparison. Compared with the conventional antenna, the proposed antenna has a better performance when mounted on the metal plate. It is shown that the designed antenna is a very good candidate for UHF PD detection inside of high-voltage equipment.

INDEX TERMS Metal-mountable antenna, partial discharge, ultra-wide band, UHF detection.

I. INTRODUCTION

High-voltage electrical equipment is the fundamental facility in electric power system, of which insulation level directly determines the power reliability. PD as the potential threat directly affects the insulation safety of high-voltage electrical equipment and power system [1], [2]. The detection of PD is of great significance to evaluate the insulation condition of electrical equipment [3]. When PD occurs in power equipment, it generates pulse current, electromagnetic emission, heat and so on. For these physical phenomena, scholars have proposed methods such as temperature detection, pulse current detection, and ultra-high frequency(UHF) detection to measure the PD [4], [5]. As its advantages in anti-interference ability and high sensitivity, the UHF detection has become a common method to judge the insulation condition of electrical equipment [6]–[8].

For UHF PD detection method, the sensitivity of antenna directly affects the performance of the detection system. Thus various types of UHF antennas have been designed for PD detection and those UHF antennas are mainly classified into two types: external antenna and internal antenna [3], [9]–[11]. External antennas are mainly used for external insulation detection and built-in antennas are installed inside of the electrical equipment such as GIS, transformer and switchgear for PD detection. Due to the small internal space and safety distance for insulation requirement in electrical equipment, most UHF built-in antennas are designed as planar antennas to reduce their height. Simultaneously, these UHF antennas are mounted on the grounded metal surface of electrical equipment. While in the past design for internal antenna in PD detection, the influence of conductive surface on antenna is neglected. When these antennas are placed in the proximity of metal, its image current can reduce bandwidth, change the output impedance and deteriorate the radiation efficiency significantly [12]. Therefore, these designed antennas cannot meet the requirements for ultra-wide band detection when mounted on metallic plane.

The associate editor coordinating the review of this manuscript and approving it for publication was Yejun He.

For the design of metal-mountable antenna, scholars mainly focus on the design of RFID antennas in the past decades. Gao et al. proposed to use the electromagnetic band gap (EBG) material for metallic objects tracking in Passive RFID [13]. Kim et al. used artificial magnetic conductor (AMC) loaded long-range passive RFID tag antenna mountable on metallic objects [14]. Inserting a high-dielectric polymer-ceramic composite substrate between the dipolar tag and metallic object has been employed to improve the radiation performance [15]. In recent years, the microstrip patch antenna, planar inverted-F antenna (PIFA), and planar inverted-L antenna (PILA) have been used for isolating the tag antennas from their backing metal [16]–[19]. Usually, the bandwidths of these designed metal-mountable antennas are often in the range of tens of megahertz or few hundred megahertz [20]–[23]. Owing to this limitation, these antennas cannot cover the bandwidth of PD signal. Therefore, there is an urgent need to design a wideband UHF metal-mountable antenna for PD detection in power equipment.

In this paper, a monopole coplanar waveguide ultra-wideband antenna, which is designed by combining FR-4 dielectric layer and absorbing gasket layer, is proposed to cover the UHF bandwidth of 400MHz to 3GHz for PD detection. Among these dielectric medium, two layers of absorber material are used to absorb the reflection of electromagnetic waves from the conductive surface. In comparison with the conventional antenna, the proposed antenna shows a better performance in PD detection when mounted on metallic objects. Owing to the simple structure of the monopole coplanar waveguide antenna, it can be easily fabricated. Since the thickness of the antenna is only 8.75mm, the proposed antenna would be a promising candidate for UHF PD detection when mounted on metallic plane of electrical equipment.

The paper is organized as follows: firstly, the geometry, design considerations and optimized design of the proposed antenna is described in Section II. The simulated, measured results and the discussions are detailed in Section III. Then a PD test platform is built in the laboratory to verify the PD detection performance in Section IV. Finally, a conclusion is given in Section V.

II. ANTENNA DESIGN AND ANALYSIS

A. DESIGN CRITERIA OF ANTENNA FOR PD DETECTION

For PD detection, the performance of the built-in UHF antenna in electrical equipment directly determines the sensitivity of the entire detection system [24]. As the internal space of the electrical equipment is narrow, these designed antennas are needed installed on the metallic plane of electric equipment. Therefore, the design of internal antenna for PD detection needs to consider the following criteria:

1) The frequency of the electromagnetic interference signal in electrical equipment is below 400MHz [25]. In addition, the discharge signal band covers the entire UHF range. Therefore, the bandwidth of the antenna requires a high cutoff frequency and wide bandwidth.

2) Since the built-in antenna is mounted on the inner surface of the metal casing in the high-voltage electrical equipment, the on-metal antenna should not be affected by the metal surface.

3) Due to the small internal space and the safety distance of electric insulation in electrical equipment, the inner antenna should also have a suitable size and shape, and its installation should not affect the insulation performance inside the power equipment.

B. ANTENNA DESIGN

Based on the design criteria and previous monopole coplanar waveguide antenna in literature [26], an improved structure of metal-mountable ultra-wideband antenna which is incorporated with FR-4 substrate and absorbing gasket is proposed for the first time. Fig. 1 shows the top view of the improved configuration for the proposed monopole coplanar waveguide antenna with dimensions of $L \times W$ (282mm×242mm). It is made by depositing a thin layer of copper onto the surface FR-4 substrate, which has a relative permittivity $\varepsilon_r = 4.4 \sim 4.5$, and a dielectric loss tangent $0.12 \sim 0.24$ in the UHF range. The top radiation patch consists of an elliptical patch with dimensions of $a \times b$, which is fed through a gradient feeder. At the intersection of the ellipse patch and the feeder, a circular patch with dimension r is used for the smooth transition. At both ends of the feeder are ground layers. In order to increase the current path length, the outer edge of the ground plate is adopted a curved structure.

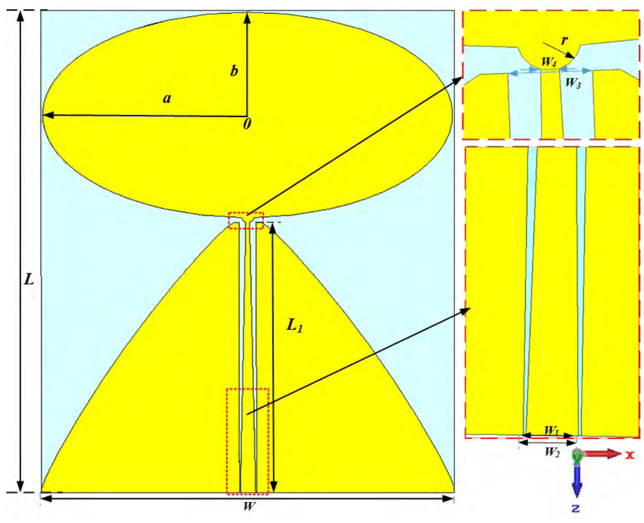


FIGURE 1. Top view of the proposed monopole coplanar waveguide antenna.

A breakdown diagram of the proposed monopole coplanar waveguide antenna integrated with various components is shown in Fig. 2. The up layer is fabricated with 1 oz copper (35 μm thick). As is shown in the figure, the antenna consists of five substrate layers. Behind the substrate of FR-4 is a layer of absorbing gasket. The absorbing material adopted is ECCOSORB MCS, of which characteristic impedance is

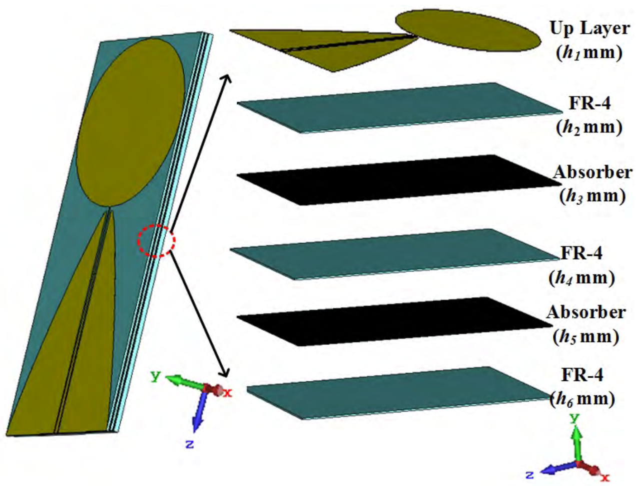


FIGURE 2. **Breakdown diagram of the proposed antenna with various components.**

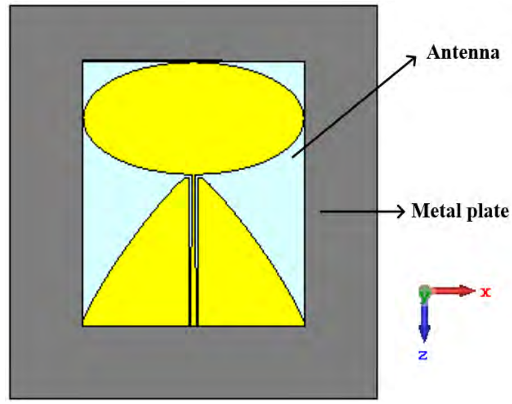


FIGURE 3. **Simulation model of the antenna with metal plate.**

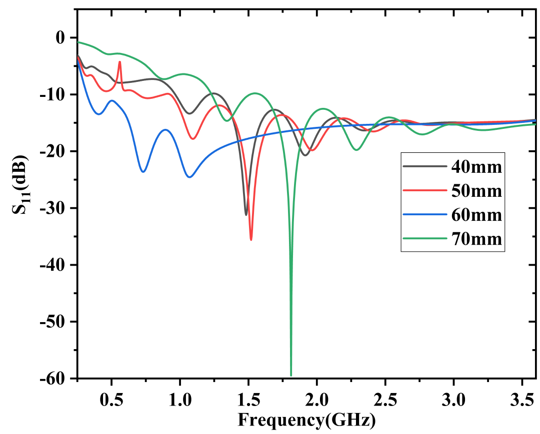


FIGURE 4. **Simulated S_{11} with different values of *b*.**

367.73Ω throughout the calculated frequency band. Simultaneously, the imaginary part of the relative dielectric constant and the imaginary part of the relative magnetic permeability have a large value in the UHF range, which can achieve the electromagnetic wave absorption. Since the characteristic impedance is close to the characteristic impedance(120π) of the free space, the electromagnetic wave transmitted through the FR-4 substrate into the absorber can simulate the propagation in free space, which significantly reduce the reflection and absorb the transmitted electromagnetic wave.

C. PARAMETRIC OPTIMIZATION

When the proposed antenna is mounted on metallic objects, many parameters influence the performance of the antenna. Despite the proposed antenna has a multilayer structure, the design theory is still based on the planar monopole antenna [27]. Thus, the size of the antenna is determined by the low frequency band, of which is mainly affected by the size of the radiation patch.

To investigate the effects of these parts, parametric optimizations are performed with the CST MWS tools. One parameter is changed at a time to observe its effects on the performance while other parameters are kept constant. The proposed antenna placed on the metal plate in simulation is shown in Fig. 3.

1) OPTIMIZATION OF SHORT AXE (*b*)

For coplanar waveguide monopole antenna, the lower cutoff frequency is mainly determined by the long axe (*a*) and short axe(*b*) of the radiation patch. To investigate the effects of the short axis, the simulated S_{11}(dB) with different values of *b* are plotted in Fig. 4. It can be seen that when *b* varies from 40mm to 60mm, the cutoff frequency gradually decreases. Once it exceeds 60mm, S_{11} rises rapidly. Considering that fluctuations of transmission coefficient in the designed frequency band are more stable at 60mm, *b* is designed to be 60mm.

2) OPTIMIZATION OF LONG AXE (*a*)

For the long axis (*a*) of the radiation patch, it also influences the lower cutoff frequency. To investigate the effects of *a*, the simulated S_{11} with different values of *a* are plotted in Fig. 5.

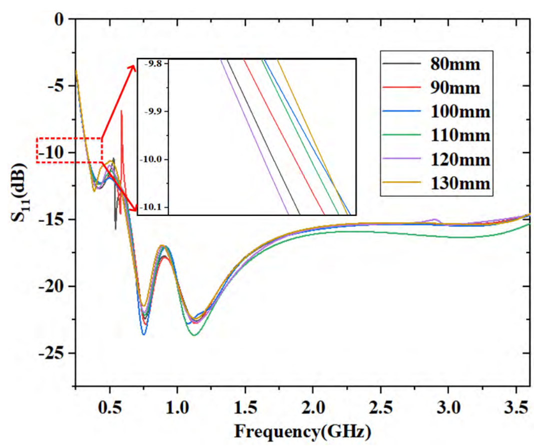


FIGURE 5. **Simulated S_{11} with different values of *a*.**

when *a* increases from 80mm to 100mm, the low cutoff frequency shows an upward trend. Once it exceeds 100mm, the cutoff frequency begins to drop. When a exceeds 120mm, the low cutoff frequency rises significantly again. Considering a is 120mm, the antenna covers the UHE bandwidth of 400 MHz to 3GHz band for $S_{11} < -10$dB and the S-parameter fluctuates much more smoothly throughout the passband. Therefore, a is set as 120mm.

3) OPTIMIZATION OF FEEDING POINT

Due to the gradual structure of the feeder, the current density is too high at the intersection of the radiation patch and the feeder. In the design of the antenna, the circular feed point (r) is used to increase the current flow path. Subsequently, parametric study is conducted to analyses the effects of the crucial radius of the feeding point. Fig. 6 shows simulated S-parameters versus frequency at different radius.

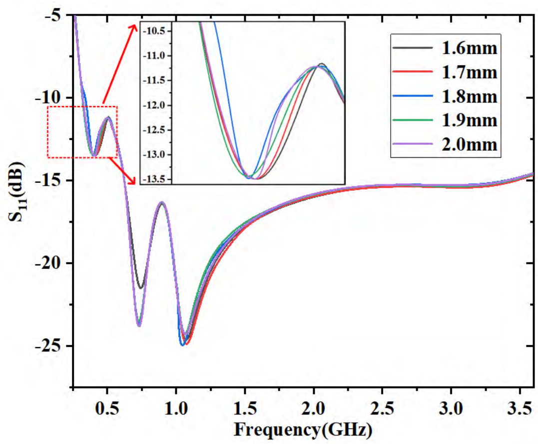


FIGURE 6. Simulated S_{11} with different values of r.

It can be seen that when the radius of the feed point ranges from 1.8mm to 1.9mm, the parameters of S_{11} in the whole designed passband are less than -10dB. Therefore, considering the fluctuation in the whole passband, the radius of the feed point is designed to be 1.9mm. Based on these parametric results, the optimal geometrical parameters of the proposed antenna are summarized in Table 1.

TABLE 1. Optimal geometrical parameters of the proposed antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L	282	L_1	159
W	242	W_1	7.16
a	120	W_2	10
b	60	h_1	0.35
r	1.9	h_2	1.6
W_4	2.63	h_3	1
W_3	10	h_4	1.6
h_5	1	h_6	3.2

D. EFFECT OF METAL CONDUCTOR ON ANTENNA

To further demonstrate that the combination of a coplanar waveguide antenna and multilayer substrates effectively broaden bandwidth of the antenna when mounted on metal conductor. Simulations for coplanar waveguide antenna and the proposed antenna are conducted and Fig. 7 shows simulated S-parameters versus frequency for two antennas.

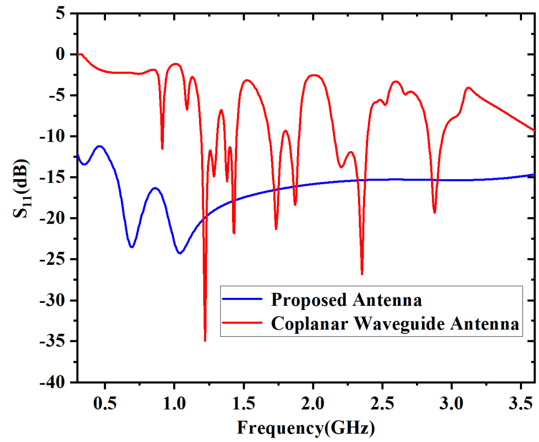


FIGURE 7. Comparison of S_{11} between designed antenna and coplanar waveguide antenna.

It can be seen that due to the influence of the metal conductor, the coplanar waveguide antenna has multiple narrow resonant bands and S_{11} is greater than -10dB in most of the UHF band. The coplanar waveguide antenna cannot meet the requirement for built-in detection. This is mainly due to the superposition of reflected electromagnetic wave and incident electromagnetic wave to form standing wave on the surface of the metal, and this leads to the resonance phenomenon only at some points in the UHF range. Because of the high dielectric loss and hysteresis loss of the absorbing material in the multilayer substrates, the electromagnetic wave is absorbed in the multilayer substrates and the proposed antenna shows a better performance with $S_{11} < -10$dB in the designed bandwidth.

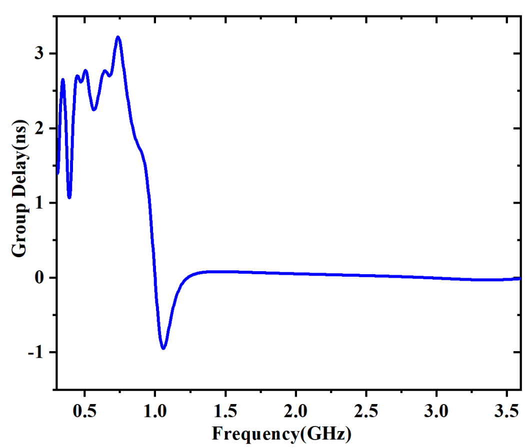
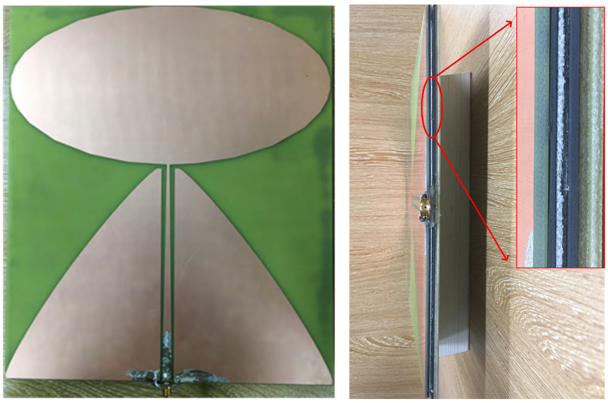


FIGURE 8. Group delay of the proposed antenna.

Figure 8 shows the simulation curves of group delay for the designed antenna. The group delay of the antenna is only about 2.5 ns in the low frequency band, while the group delay response of the antenna is relatively flat in high frequency range. Therefore, it can be obtained that when the detected PD signal transmits through the antenna, the waveform will not be seriously distorted.

III. FABRICATION AND MEASURED RESULTS

To verify the design, the antenna is fabricated based on the previous simulation parameters. The prototype of the proposed antenna is shown in Fig. 9. The S_{11} of the antenna placed on the metal plate with dimensions 400mm×400×5mm has been measured in the laboratory using a network vector analyzer.



(a) (b)

FIGURE 9. Prototype of the proposed antenna. (a) Top view. (b) Side view.

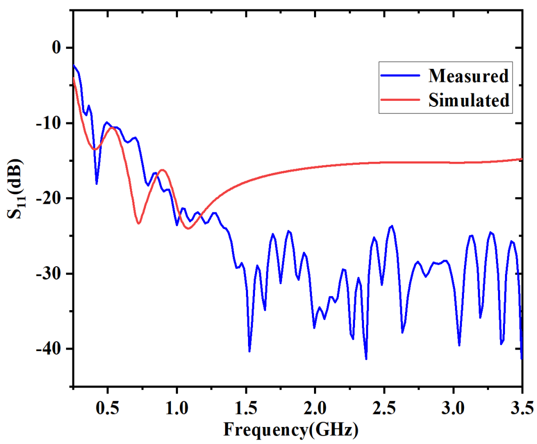


FIGURE 10. Simulated and measured s_{11} versus frequency of the proposed antenna.

Fig. 10 depicts the simulated and measured S-parameters (S_{11}) of the proposed antenna. It is evident that the proposed antenna can satisfy the designed frequency band (400MHz ~3GHz) for $S_{11} < -10$dB when mounted on metal plate. Compared with the simulated curve, it can be observed that the measured value has some discrepancies between the measured values and the simulated values. In low frequency band, the difference between the measured and the simulated mainly comes from numerical errors. For high frequency range, this is mainly due to the set of ideal parameters for ECCOSORB MCS in simulation. With the increase of frequency, the difference between simulation and test results becomes more obvious.

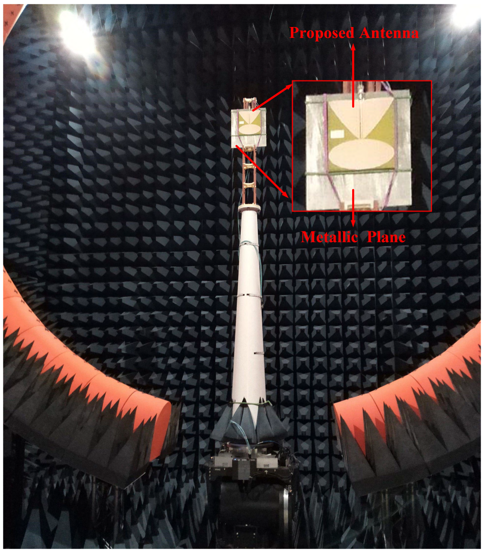


FIGURE 11. Photograph of the proposed antenna in darkroom for directional pattern measurement.

Fig. 11 shows the directional pattern measurement in a darkroom for the proposed antenna when mounted on a metal conductor. The simulated and measured results are compared in terms of gain and radiation pattern in E-plane as shown in Figs 12-13. The discrepancies between measured and simulated gain vs frequency of the antenna are mainly caused by the material difference and fabrication error. It can also be obtained from Fig. 13 that the antenna has good omnidirectional characteristics in the upper space above metal surface(0~180°).

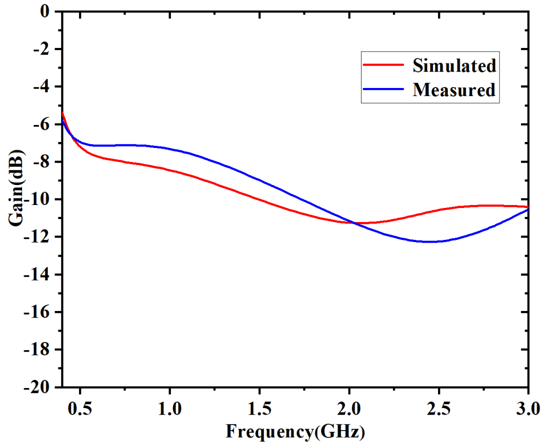


FIGURE 12. Measured and simulated gain vs frequency of the proposed antenna.

IV. PD EXPERIMENTS AND RESULTS

The proposed antenna is also tested on a PD platform when mounted on a metal plate. Fig. 14 shows the schematic of the

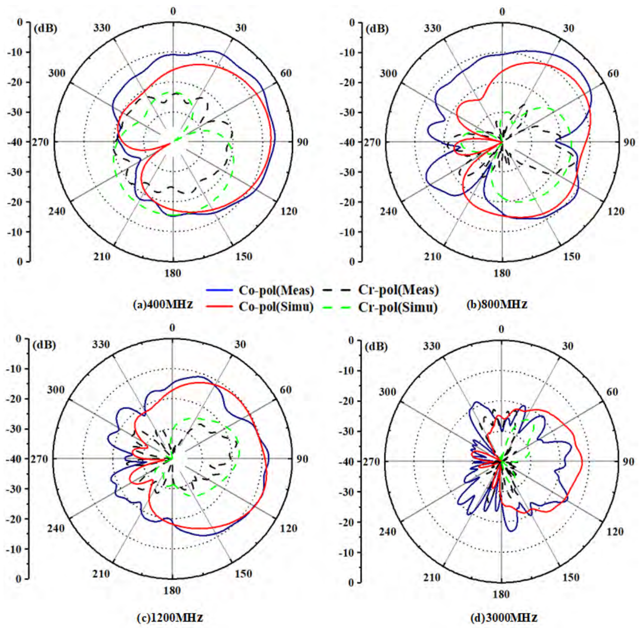


FIGURE 13. Simulated and measured 2-D radiation patterns of the proposed antenna in E- plane at: (a) 400MHz, (b) 800MHz, (c) 1200MHz, (d) 3000MHz.

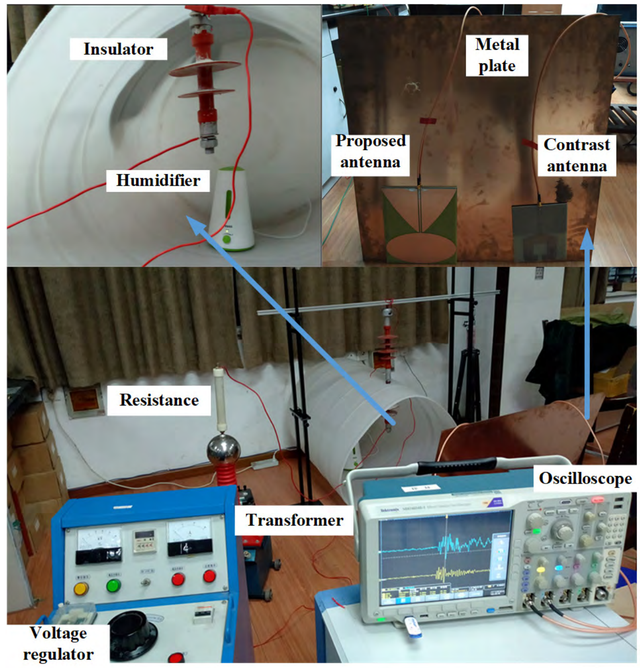


FIGURE 15. PD set-up for antenna test in laboratory.

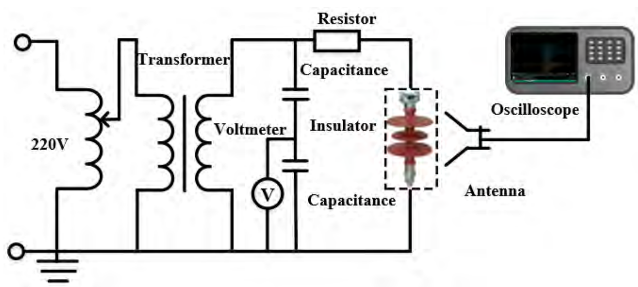


FIGURE 14. Schematic of test platform for PD.

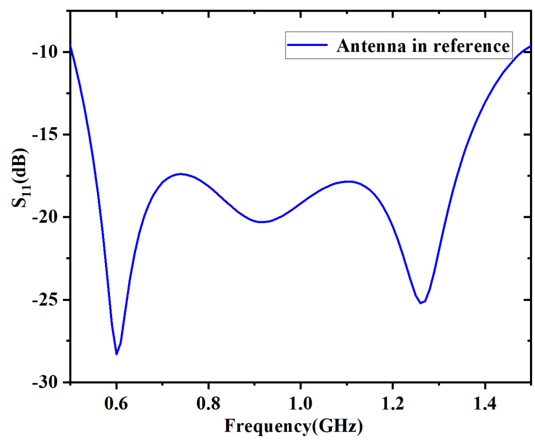


FIGURE 16. S_{11} of the reference antenna.

test platform. The output of the single-phase transformer is controlled by a voltage regulator and the protection resistor is used to limit the overcurrent to protect the system. The PD occurs on the surface of contaminated insulator which is the mixture of diatomite and sodium chloride to simulate industrial pollution, and the antenna is connected to the oscilloscope via a coaxial line to record the waveforms of PD signal.

Fig. 15 shows the PD set-up for antenna in laboratory. In order to increase the PD probability of the contaminated insulator, a humidifier is used to increase the air humidity. To simulate a metallic environment in a high voltage switchgear, a copper plate of 800mm × 800mm × 3mm was placed on the back of the antenna.

For comparison of the receiving performance of the proposed antenna, an antenna in [24] is used to detect the PD signal at the same time. The operating frequency band range of the reference antenna is 0.5-1.5GHz as is shown the S_{11} curve in Fig. 16. Owing to the randomness of the PD, two antennas are mounted on the metal surface at a horizontal distance of 940mm to the PD source.

Fig. 17 and Fig. 18 show the time-domain waveforms and spectrum waveforms of PD signals received by two antennas at 5kV and 7.5kV, respectively. It can be seen from Fig. 17(a) and Fig. 18(a), that the maximum amplitude of the PD signal detected by the designed antenna exceeds 65mV, while the antenna in literature detects a PD signal with a maximum of 48mV. It also can be obtained from Fig. 17(b) and Fig. 18(b) that the energy of PD is mainly at the range form 400MHz to 800MHz. At the same time, it can be found that the spectral amplitude of the reference antenna shows a significant drop from 450MHz to 550MHz while the proposed antenna shows much more stable fluctuation in the main frequency band of PD. This is due to the fact that

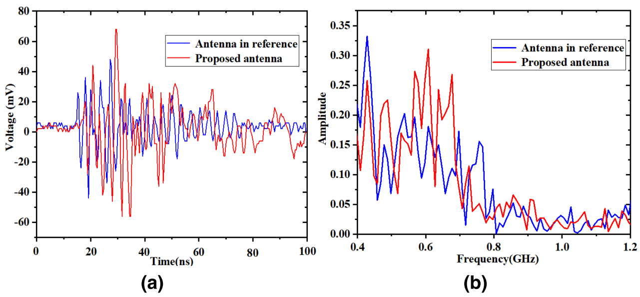


FIGURE 17. **Waveforms of PD signal detected by two different antennas at 5 kV. (a) Time-domain waveform. (b) Frequency spectrum.**

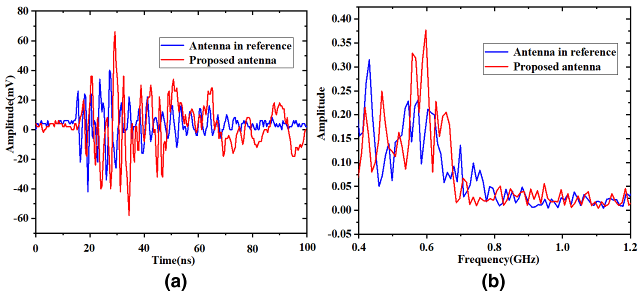


FIGURE 18. **Waveforms of PD signal detected by two different antennas at 7.5 kV. (a) Time-domain waveform. (b) Frequency spectrum.**

the designed antenna can avoid electromagnetic reflection from the metal plane, making the detected signal spectrum more stable in the entire frequency band, which demonstrates that the designed antenna has better performance than the reference antenna.

V. CONCLUSIONS

In this paper, an ultra-wide band metal-mountable antenna for UHF PD detection in high voltage equipment has been proposed. By parametric study, the effects of various parameters on the antenna performance have been carefully examined. The proposed antenna consists of a coplanar waveguide antenna and multilayer substrates, which contains 2 absorbing layers and 2 FR-4 layers. The bandwidth performance of the proposed antenna has been investigated, which demonstrates that the proposed antenna mounted on a metal plate can cover the UHF bandwidth of 400MHz to 3GHz. As the thickness of the antenna is 8.75mm it can ensure that the safety distance of electric insulation will not be affected inside of electrical equipment.

A good agreement is obtained between the simulation and the measurement results. Moreover, a PD experiment was carried out to verify the performance of the proposed antenna. In contrast with the reference Antenna, the proposed antenna has wider band and sensitivity when mounted on metal background. The research is valuable for the antenna development and the proposed antenna can be a very promising candidate for UHF PD detection inside electrical equipment.

REFERENCES

[1] L. Luo, B. Han, J. Chen, G. Sheng, and X. Jiang, "Partial discharge detection and recognition in random matrix theory paradigm," *IEEE Access*, vol. 5, pp. 8213–8250, Jun. 2016.

[2] X. Chen, Y. Qian, Y. Xu, G. Sheng, and X. Jiang, "Energy estimation of partial discharge pulse signals based on noise parameters," *IEEE Access*, vol. 4, pp. 10270–10279, Jan. 2017.

[3] P. Li, W. Zhou, S. Yang, Y. Liu, Y. Tian, and Y. Wang, "Method for partial discharge localisation in air-insulated substations," *IET Sci., Meas. Technol.*, vol. 11, no. 3, pp. 331–338, Jan. 2017.

[4] K. Xu *et al.*, "High-voltage circuit-breaker insulation fault diagnosis in synthetic test based on noninvasive switching electric-field pulses measurement," *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 1168–1175, Jun. 2016.

[5] C. Pintassilgo, V. Guerra, O. Guaitella, and A. Rousseau, "Study of gas heating mechanisms in millisecond pulsed discharges and afterglows in air at low pressures," *Plasma Sources Sci. Technol.*, vol. 23, no. 2, Jan. 2014, Art. no. 025006.

[6] J. Li, X. Han, Z. Liu, and X. Yao, "A novel GIS partial discharge detection sensor with integrated optical and UHF methods," *IEEE Trans. Power Del.*, vol. 33, no. 4, pp. 2047–2049, Aug. 2016.

[7] X.-J. Shao, W.-L. He, J.-L. Xu, M.-X. Zhu, and G.-J. Zhang, "Partial discharge detection by extracting UHF signal from inner grading electrode of insulating spacer in GIS," *IET Sci., Meas. Technol.*, vol. 12, no. 1, pp. 90–97, Oct. 2017.

[8] X. Li, X. Wang, D. Xie, X. Wang, A. Yang, and M. Rong, "Time–frequency analysis of PD-induced UHF signal in GIS and feature extraction using invariant moments," *IET Sci., Meas. Technol.*, vol. 12, no. 1, pp. 169–175, Oct. 2017.

[9] B. A. Castro *et al.*, "A low cost system for acoustic monitoring of partial discharge in power transformer by Piezoelectric Sensor," *IEEE Latin Amer. Trans.*, vol. 14, no. 7, pp. 3225–3231, Jul. 2017.

[10] X. Zhang, Z. Cheng, and Y. G. Gui, "Design of a new built-in UHF multi-frequency antenna sensor for partial discharge detection in high-voltage switchgears," *Sensors*, vol. 16, no. 8, pp. 1170–1185, Jul. 2016.

[11] K. Gülnihar, S. Cekli, C. P. Uzunoğlu, and M. Uğur, "Location estimation of partial discharge-based electromagnetic source using multilateration with time difference of arrival method," *Elect. Eng.*, vol. 100, no. 2, pp. 839–847, May 2018.

[12] Y. H. Lee, E. H. Lim, and F. L. Bong, "Compact folded C-shaped antenna for metal-mountable UHF RFID applications," *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 765–773, Feb. 2019.

[13] B. Gao and M. M. F. Yuen, "Passive UHF RFID packaging with electromagnetic band gap (EBG) material for metallic objects tracking," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 1, no. 8, pp. 1140–1146, Aug. 2011.

[14] I.-Y. Park and D. Kim, "Artificial magnetic conductor loaded long-range passive RFID tag antenna mountable on metallic objects," *Electron. Lett.*, vol. 50, no. 5, pp. 335–336, Feb. 2014.

[15] A. A. Babar, T. Björninen, V. A. Bhagavati, L. Sydänheimo, P. Kallio, and L. Ukkonen, "Small and flexible metal mountable passive UHF RFID tag on high-dielectric polymer-ceramic composite substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1319–1322, 2012.

[16] M. Hirvonen, P. Pursula, K. Jaakkola, and K. Laukkanen, "Planar inverted-F antenna for radio frequency identification," *Electron. Lett.*, vol. 40, no. 14, pp. 848–850, Jul. 2004.

[17] S.-L. Chen, "A miniature RFID tag antenna design for metallic objects application," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1043–1045, 2009.

[18] H.-D. Chen and Y.-H. Tsao, "Low-profile PIFA array antennas for UHF band RFID tags mountable on metallic objects," *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1087–1092, Apr. 2010.

[19] S. S. Alja'afreh, Y. Huang, L. Xing, Q. Xu, and X. Zhu, "A low-profile and wideband PILA-based antenna for handset diversity applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 923–926, Apr. 2015.

[20] E.-S. Yang and H.-W. Son, "Dual-polarised metal-mountable UHF RFID tag antenna for polarisation diversity," *Electron. Lett.*, vol. 52, no. 7, pp. 496–498, Apr. 2016.

[21] Y. D. J. Ternera, J. C. Velez, M. Calle, and L. A. Torres, "Algorithm for detection of unwanted tag reads in passive UHF RFID systems for static metallic objects," *IEEE Latin Amer. Trans.*, vol. 15, no. 11, pp. 2084–2089, Nov. 2017.

[22] Y. Zhao, K. Liu, Y. Ma, Z. Gao, Y. Zang, and J. Teng, "Similarity analysis-based indoor localization algorithm with backscatter information of passive UHF RFID tags," *IEEE Sensors J.*, vol. 17, no. 1, pp. 185–193, Jan. 2017.
[23] S. Zuffanelli, G. Zamora, F. Paredes, P. Aguila, F. Martin, and J. Bonache, "On-metal UHF-RFID passive tags based on complementary split-ring resonators," *IET Microw., Antennas Propag.*, vol. 11, no. 7, pp. 1040–1044, Jun. 2017.
[24] F. Yang, C. Peng, Q. Yang, H. Luo, I. Ullah, and Y. Yang, "An UWB printed antenna for partial discharge UHF detection in high voltage switchgears," *Prog. Electromagn. Res.*, vol. 69, pp. 105–114, Nov. 2016.
[25] C. Yao, C. Pan, C. Huang, Y. Chen, and P. Qiao, "Study on the application of an ultra-high-frequency fractal antenna to partial discharge detection in switchgears," *Sensors*, vol. 13, no. 12, pp. 17362–17378, Dec. 2013.
[26] S. Zhong, X. Liang, L. Zhang, and W. Wei, "Printed monopole antenna with impedance bandwidth exceeding 21:1," *J. Shanghai Univ. (Natural Sci.)*, vol. 13, no. 4, pp. 337–343, Aug. 2007.
[27] Z. Hou, *Planar Antenna Fed by Coplanar Waveguide*. Xi'an, China: Xidian Univ. Press, 2014, pp. 62–63.

YANG QI was born in Sichuan, China, in 1990. He received the B.S. degrees in electrical engineering and automation from the Shenyang University of Technology, Shenyang, China, in 2014. He is currently pursuing the Ph.D. degree in electrical engineering with the School of Electrical Engineering, Chongqing University, China.

His current research interests include partial discharge detection and insulation state evaluation of electrical equipment.

YANG FAN received the Ph.D. degree from Chongqing University, Chongqing, China, in 2008. He joined the Department of Electrical Engineering, Chongqing University, in 2008, as a Lecturer. Two years later, he became an Associate Professor at Chongqing University. From 2013 to 2014, he was a Postdoctoral Research Fellow with Oklahoma State University, Stillwater, OK, USA. He is currently a Professor and the Vice Dean of the Department of Electrical Engineering, Chongqing University. He has been conducting research in the areas of electromagnetic-thermal coupled field calculation, fault diagnosis of high-voltage equipment, and terahertz imaging research. He is a member of the International Electromagnetic Field Computing Society.

GAO BING received the Ph.D. degree from the School of Electrical Engineering, Chongqing University, Chongqing, China, in 2016, where he is currently a Lecturer. His research interests include the reliability of power modules, the multi-physics coupling field calculation for power electronics, and the development of condition monitoring methods for power electronic converters.

RAN JIA received the bachelor's degree in physics and the Ph.D. degree in condensed matter physics from Tongji University, China, in 2012 and 2017, respectively. She was with the Queen Mary University of London as a Research Associate, from 2015 to 2016, and Chongqing University as a Postdoctoral Research Assistant, from 2017 to 2019. Her research interests mainly include microwave metamaterials, terahertz metal surface, and terahertz imaging.

WANG SEN was born in 1984. He is currently with the Electric Power Research Institute, Shaanxi Electric Power Company, Xi'an, China. His main research interests include high-voltage electrical equipment discharge detection, and UHV converter station control and protection.

SHEN WEI was born in 1983. He is currently with the Electric Power Research Institute, Shaanxi Electric Power Company, Xi'an, China. He is mainly engaged in the investigation and diagnosis of electrical equipment and the evaluation of insulation status.

AMMAD JADOON received the master's degree from the School of Electrical Engineering, Chongqing University, Chongqing, China, in 2016. He is currently pursuing the Ph.D. degree in electrical engineering with Chongqing University. His current research interest includes high-voltage direct current interference with underground gas pipelines.