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Cavity-backed Two-arm Spiral Antenna with a Ring-shaped Absorber for Partial Discharge Diagnosis

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Abstract – A cavity-backed two-arm spiral antenna for partial discharge diagnosis is presented. The proposed antenna consists of a two-arm Archimedean spiral, a tapered microstrip balun as spiral antenna feed, and a ring-shaped absorber-loaded cavity. The Archimedean spiral antenna is designed for the operating frequency band of 0.3 GHz to 1.5 GHz and fed by the tapered microstrip balun. The cavity is utilized to transform the bidirectional beam into a unidirectional beam, thereby enhancing gain. The ring-shaped absorber is stacked in the cavity to reduce the reflected waves from the cavity wall. The proposed antenna is designed and simulated using CST Microwave Studio. A prototype of the proposed antenna is likewise fabricated and tested. The measured radiation patterns are directional to the positive z-axis, and the measured peak gain is 8.13 dBi at a frequency of 1.1 GHz.

Keywords: Archimedean spiral, Cavity-backed antenna, Microstrip balun, Partial discharge diagnosis, Two-arm spiral antenna

1. Introduction

Planar antennas have been widely used for various applications for their low-profile, light weight, and ease of integration with active devices. Some examples of antennas are global positioning systems (GPS) [1], partial discharge diagnosis systems [2], and radio frequency identification (RFID) tags [3]. One of the most attractive planar antennas is the planar spiral antenna, which is characterized by broad bandwidth, circular polarization, and small physical size. According to Babinet's principle, a self-complementary spiral antenna is a popular frequency-independent antenna with stable input impedance and radiation characteristics [4-6]. However, the spiral antenna usually produces a bidirectional beam pattern, which is symmetric with respect to the antenna plane. However, the spiral antenna is required to have a unidirectional beam for most applications. Therefore, the transformation of the bidirectional beam into a unidirectional beam is necessary. This transformation can be achieved by approximately backing the spiral antenna on one side with a reflector, a cavity, or an electromagnetic bandgap (EBG) ground plane. The spiral antenna is backed by a conducting plane as a reflector, which is placed at the distance of one-quarter wavelength from the antenna plane [7]. The spiral antennas backed by a cavity are presented, namely, the two-arm equiangular spiral antenna [8] and the two-arm Archimedean spiral antenna [9]. The transformation of the bidirectional beam into a unidirectional beam is successfully realized by utilizing the cavity located behind the spiral antenna. However, the wideband characteristics deteriorate because the reflected waves from the cavity wall impinge on the spiral. This problem is solved by inserting an absorbing strip (ABS) into the cavity to absorb the reflected waves to restore the wideband characteristics of the spiral antenna. The design of a low-profile Archimedean spiral antenna using an EBG ground plane is another development [10]. Instead of using a perfectly electric conducting (PEC) ground plane or cavity, the spiral antenna is placed above an EBG structure to obtain the unidirectional beam and maintain the wideband characteristics. In addition, antenna height is reduced.

In this paper, an absorber-loaded, cavity-backed, two-arm Archimedean spiral antenna for a partial discharge diagnosis receiver is proposed. A receiver antenna usually requires a reflection coefficient level of less than -5 dB, whereas Rx/Tx operations require a -10 dB reflection coefficient. Therefore, a two-arm Archimedean spiral antenna with -5 dB reflection coefficient bandwidth from 0.3 GHz to 1.5 GHz is designed to develop a UHF (ultra-high frequency) band receiver antenna. The spiral antenna is fed by a tapered microstrip balun to match the unbalanced mode to the balanced mode. To obtain the unidirectional beam and enhance gain, the proposed spiral antenna is backed by a cavity. A ring-shaped absorber is applied and stacked in the cavity to restore the wideband characteristics. Details of the proposed antenna design and measurement results are presented and discussed in the following sections.

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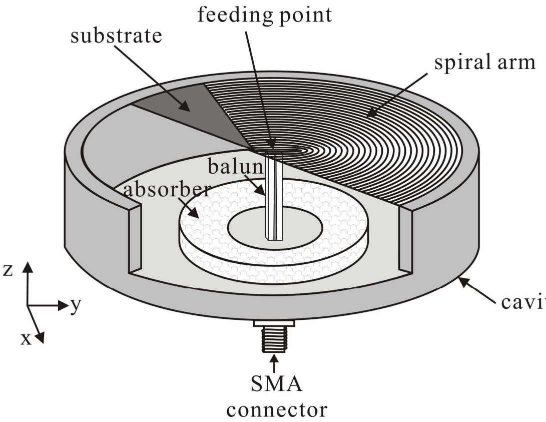

Fig. 1. Perspective view of the proposed spiral antenna.

2. Antenna Design

Fig. 1 shows a perspective view of the proposed absorber-loaded, cavity-backed two-arm Archimedean spiral antenna with a coordinate system. A two-arm Archimedean spiral pattern is printed on a TLY-5A substrate with the following measurements: dielectric constant of 2.17; loss tangent of 0.0009; and thickness of 1.1 mm. A tapered microstrip balun is located vertically to match the impedance between the input port and the Archimedean spiral. A cavity is positioned at the back side of the proposed spiral antenna to transform the bidirectional radiation into a unidirectional radiation and enhance antenna gain. A ring-shaped absorber is stacked in the cavity to prevent the reflected waves from the cavity wall from impinging on the spiral. Detailed descriptions of the structures composed of the Archimedean spiral pattern, the tapered microstrip balun, and the absorber-loaded cavity are presented in the following sections.

2.1 Two-arm Archimedean spiral antenna

Fig. 2 illustrates the top view of a spiral antenna and the geometry of a self-complementary, two-arm Archimedean spiral. For the design of a self-complementary spiral structure, the spacing s is equal to width w and can be obtained using the following equation:

$$s = \mathrm{w} = \frac{r_2 - r_1}{4N} \tag{1}$$

where r_1 and r_2 are the inner and outer radii of the spiral, respectively; and N denotes the number of turns of the arm pattern. The inner radius r_1 and outer radius r_2 are determined by the lowest and highest operating frequencies of spiral antenna, respectively, as follows:

$$r_1 \le \frac{c}{2\pi f_{high}} \tag{2}$$

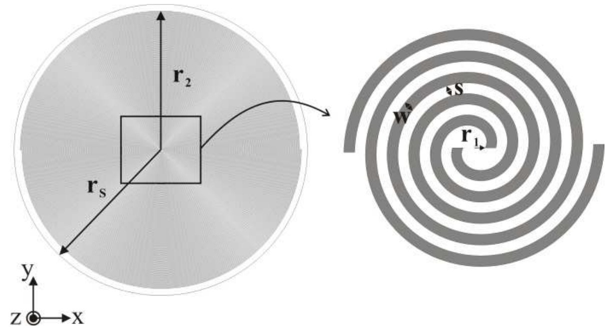

Fig. 2. The spiral antenna with a two-arm Archimedean pattern.

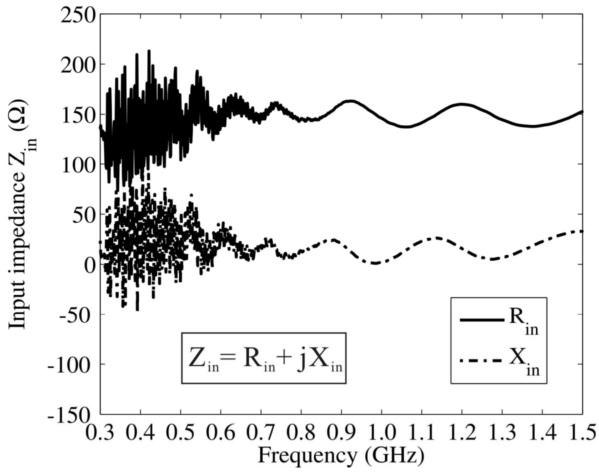

Fig. 3. Simulated input impedance of the spiral antenna.

$$r_2 \ge \frac{c}{2\pi f_{low}} \tag{3}$$

where c is the speed of light; and f_{high} and f_{low} are the highest and lowest operating frequencies, respectively. In this work, the Archimedean spiral antenna is designed for the operating frequency band from 0.3 GHz to 1.5 GHz. To satisfy Eqs. (2) and (3), the values of r_1 and r_2 are set as 1 and 160 mm, respectively. The spacing s and width w are set as 1 mm to satisfy (1), and number of turns $N = 40$. The substrate radius r_s is set as 172 mm to cover the range of the outer radius r_2 in the spiral pattern.

Fig. 3 shows the simulated input impedance of the two-arm Archimedean spiral antenna fed by the lumped port. The results show that the real component of the input impedance ranges from 73 Ω to 213 Ω, and the average value is 143 Ω. Meanwhile, the imaginary component varies from -50 Ω to 100 Ω. The input impedance oscillates at a lower frequency band because of the reflected waves from the end of the spiral arm.

2.2 Balun transmission line for spiral antenna feed

Fig. 4 shows a wideband tapered microstrip balun used

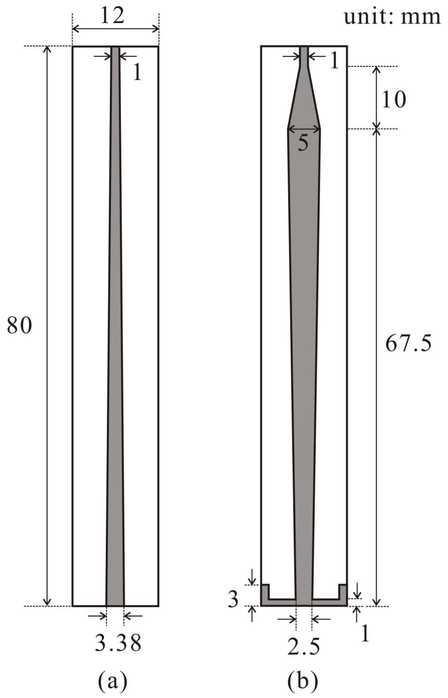

Fig. 4. The tapered microstrip balun: (a) front view and (b) back view.

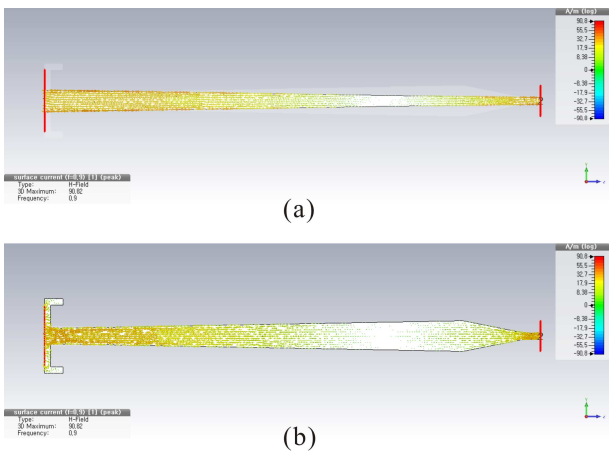

Fig. 5. Simulated surface currents on (a) the top and (b) the bottom surfaces of the balun.

to feed the Archimedean spiral antenna. The balun transforms the unbalanced mode (coaxial connector) into the balanced mode (parallel microstrip line). The parameters of the balun are designed to achieve good impedance matching between 50 Ω of the coaxial connector and 143 Ω of the spiral antenna based on the tapered transition configuration. Over the entire simulated frequency band, the reflection coefficient of the balun is below -13.4 dB. The tapered microstrip balun is designed on a Taconic RF-35 dielectric substrate with a dielectric constant of 3.5, loss tangent of 0.0018, and thickness of 1.52 mm. Fig. 4 shows the optimized design parameters of

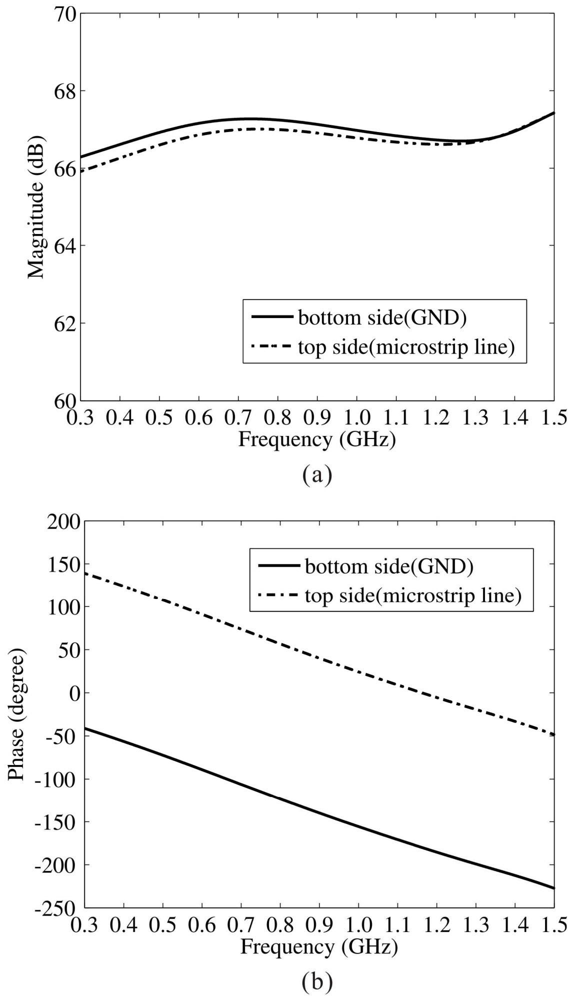

Fig. 6. Simulated: (a) amplitude and (b) phase characteristics of the proposed balun.

the balun.

Fig. 5 illustrates the surface currents on the bottom and top surfaces of the balun. Balanced currents are generated by the proposed compact balun. Fig. 6 shows the simulated amplitude and phase characteristics of the proposed balun. In the entire frequency band, the amplitude and phase imbalance measurements are less than 0.37 dB and 1.2°, respectively.

The spiral antennas with and without balun are simulated to investigate the effect of the balun. Figs. 7 and 8 show the simulated reflection coefficient and gain, respectively. As shown in Fig. 7, the reflection coefficient level is below -9.6 dB and significantly oscillates at lower frequency band when the spiral antenna is fed by an ideal lumped port (without balun). This result corresponds to the simulated impedance shown in Fig. 3. However, when the spiral antenna is fed by the tapered microstrip balun, the oscillation in the reflection coefficient at a lower frequency band is reduced because of the balanced mode obtained from the balun. In addition, the degradation of matching characteristics is observed at the high frequency region

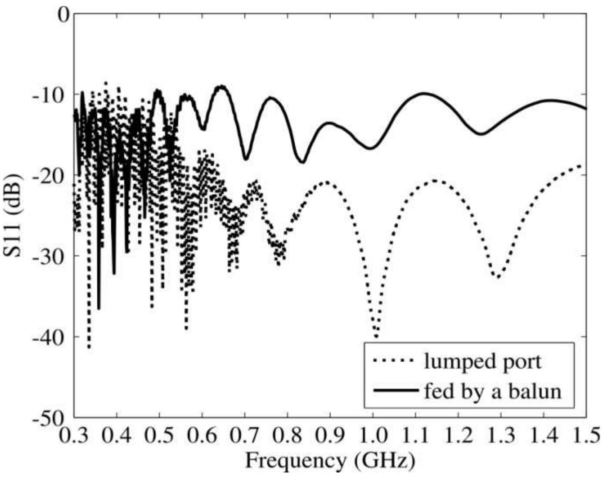

Fig. 7. Simulated reflection coefficients of the spiral antenna with and without balun.

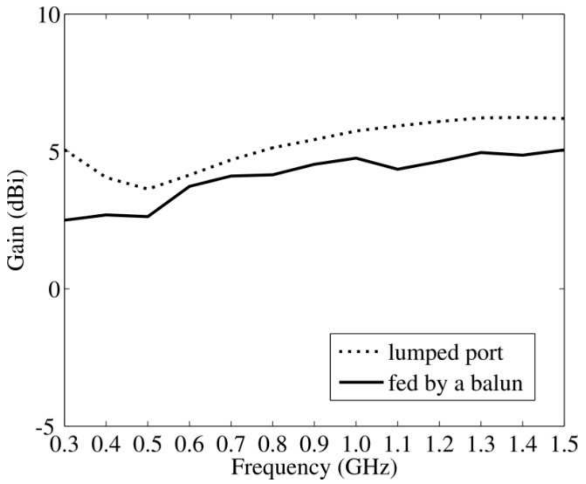

Fig. 8. Simulated antenna gains of the spiral antenna with and without balun.

because of the small imbalance between the outputs of the balun. Fig. 8 shows that the simulated gain of the spiral antenna fed by the lumped port is from 3.63 dBi to 6.24 dBi, whereas the simulated gain of the spiral antenna fed by balun ranges from 2.5 dBi to 5.06 dBi. The realized gain of the antenna with balun feed slightly decreased compared with the antenna without balun because of the transmission loss of the tapered microstrip balun shown in Fig. 4.

2.3 The Effects of Cavity and Absorber

Fig. 9 shows a side view of the proposed absorber-loaded, cavity-backed, two-arm Archimedean spiral antenna. The cavity has a height of 80 mm corresponding to one-quarter wavelength of the center frequency of 0.94 GHz. This cavity is used to transform the bidirectional beam into a unidirectional beam. The radiating wave from the spiral antenna in the backward direction impinging to the bottom of cavity is reflected back to the forward

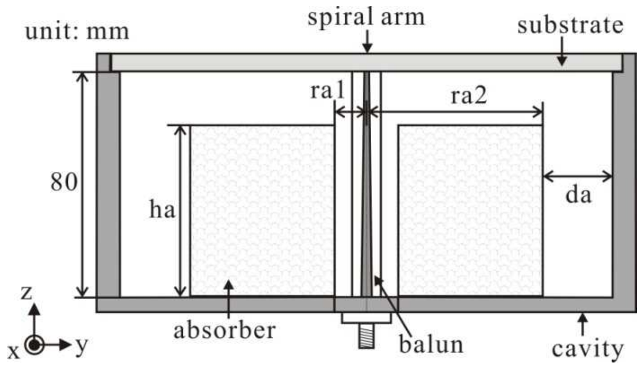

Fig. 9. The side view of the proposed Archimedean spiral antenna.

direction. Therefore, one complete cycle is equal to the total round trip phase shift from the antenna to the cavity (including 90° of phase shift attributed to travelling and 180° of phase shift attributed to reflection) and back to the antenna (90° of phase shift attributed to travelling). Moreover, the waves add up constructively. The use of cavity degrades both antenna gain and reflection coefficient at low operating frequency, but is essential to obtain the unidirectional beam. Thus, the microwave absorber was used to improve the reflection and gain characteristics of the antenna. The absorber is stacked in the cavity at the spacing of *da* from the wall of the cavity. Both cavity and absorber shapes are concentric hollow cylinders. The tapered microstrip balun is located vertically at the center of the cavity.

The genetic algorithm (GA) was also applied to optimize the performance of the absorber. The parameters for optimization include inner radius *ra1*, outer radius *ra2*, height of the absorber *ha*, and the spacing between the cavity and absorber *da*. The goal of optimization is to achieve high gain exceeding 0 dBi at 0.3 GHz. Table 1 summarizes the final optimized parameters after 30 iterative evolutions. Simulation and measurement of cases with and without absorber are discussed in Section 3.

3. Measurement

Fig. 10 shows a photograph of the fabricated absorber-loaded, cavity-backed, two-arm Archimedean spiral antenna. The self-complementary, two-arm Archimedean spiral antenna with number of turns $N = 40$ was fabricated on a TLY-5A substrate. The cavity was made of aluminum alloy with thickness of 10 mm. The absorber with optimized parameters was stacked in the cavity, as shown in Fig. 10.

Figs. 11 and 12 show the simulated and measured reflection coefficient and antenna gain versus frequency. The effect of the absorber is investigated through the simulation of the proposed antenna with and without absorber. Fig. 11 indicates that the reflection coefficient of

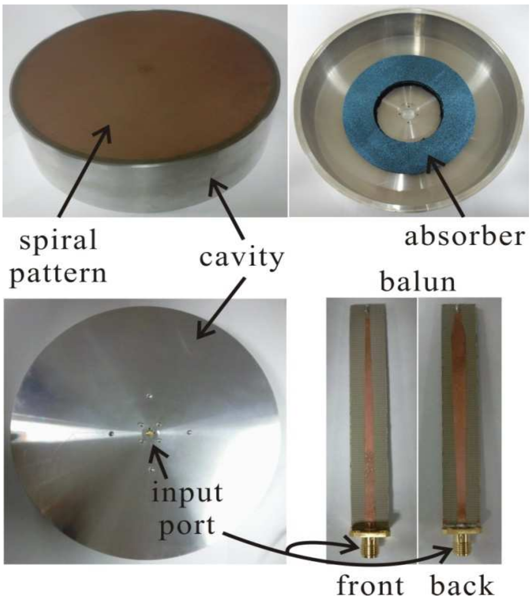

Fig. 10. The photograph of the fabricated antenna.

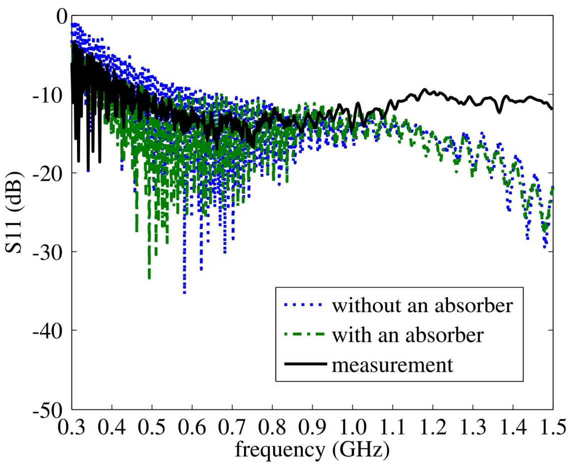

Fig. 11. Simulated and measured reflection coefficients for the cavity-backed spiral antenna.

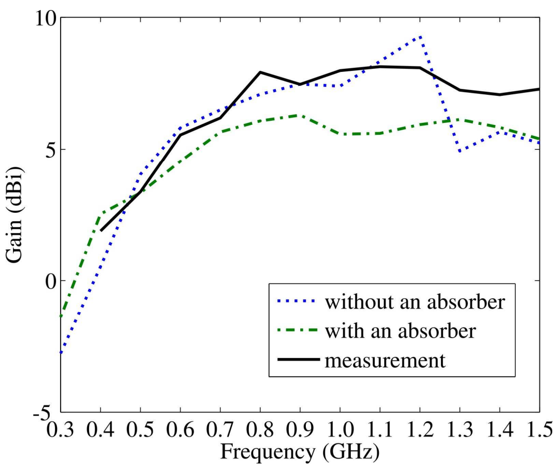

Fig. 12. Simulated and measured antenna gains for the cavity-backed spiral antenna.

the proposed spiral antenna without absorber oscillates and degrades because of the effect of the reflected waves from the cavity wall. As mentioned in the previous section, the absorber was optimized to reduce the reflected waves from the cavity wall and restore the wideband characteristics of the antenna. The proposed antenna with the optimized absorber exhibits improved reflection coefficient in the lower frequency band adequate for use by the receiving antenna. The measured reflection coefficient level is below -9.5 dB in the frequency band over 0.5 GHz. Fig. 12 shows that the simulated peak gain of the proposed antenna with absorber is lower than that of the antenna without absorber. However, a stable gain level is achieved, which indicates that the use of the absorber increases gain at lower frequency band but reduces gain at higher frequency band. The measured gain ranges from 1.88 dBi to 8.13 dBi, and

Table 1. Optimized parameters of the absorber.

Optimization parameter	In terms of millimeter (mm)	
	Range	Optimized value
ra1	30-70	57.3
ra2	–	108.9
da	0-80	53.1
ha	10-50	27.7

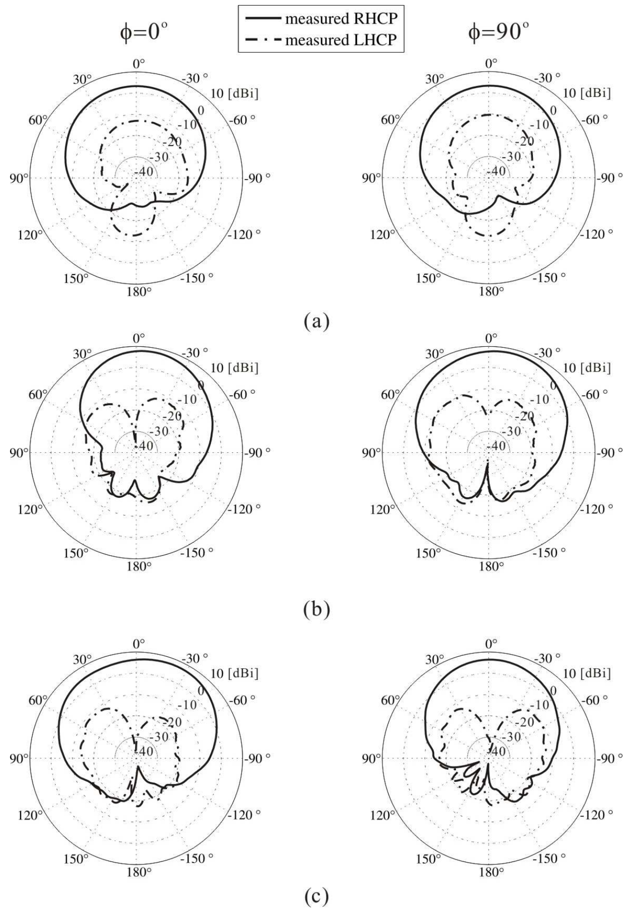

Fig. 13. Measured radiation patterns at (a) 0.5 GHz, (b) 1.0 GHz, and (c) 1.5 GHz.

the peak gain of 8.13 dBi is achieved at 1.1 GHz.

Fig. 13 illustrates the measured radiation patterns of the proposed antenna along two elevation cuts (on the *xz* and *yz* planes) at 0.5, 1.0, and 1.5 GHz. The co-polarization (RHCP) to cross-polarization (LHCP) levels in the broadside direction ($\theta = 0°$) are 13.7 dB at 0.5 GHz, 30 dB at 1.0 GHz, and 36.9 dB at 1.5 GHz. Employment of the cavity successfully suppressed the backward radiation.

5. Conclusion

In this paper, an absorber-loaded, cavity-backed, two-arm Archimedean spiral antenna was developed for partial discharge diagnosis. The proposed spiral antenna consists of a two-arm Archimedean spiral, a tapered microstrip balun, and an absorber-loaded cavity. A prototype antenna was analyzed, fabricated, and measured to prove the suitability of the proposed antenna. The experimental results demonstrate that the antenna achieves reasonable realized gain in the entire measured frequency range from 0.3 GHz to 1.5 GHz. Therefore, the proposed antenna can be feasibly applied to partial discharge diagnosis systems.

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References

[1] S. Hamedi-Hagh, J. Chung, S. Oh, J.-U. Jo, N.-J. Park, and D.-H. Park, "Design of a high performance patch antenna for GPS communication systems," *Journal of Electrical Engineering & Technology,* Vol. 4, No. 2, pp. 282-286, 2009.

[2] K.-S. Lwin, K.-J. Lim, N.-J. Park, and D.-H. Park, "PD diagnosis on 22.9kV XLPE underground cable using ultra-wideband sensor," *Journal of Electrical Engineering & Technology,* Vol. 3, No. 3, pp. 422-429, 2008.

[3] E.-S. Choi, H.-Y. Lee, J.-S. Lee, K. Lee, S.-W. Lee, and Y.-H. Lee, "Design of the Crab label tag with a loop matching feed and a modified dipole structure at 900 MHz," *Journal of Electrical Engineering & Technology,* Vol. 6, No. 4, pp. 551-555, 2011.

[4] Y. Mushiake, "Self-complementary antennas," *IEEE Antennas Propag. Mag.,* Vol. 34, No. 6, pp. 23-29, Dec. 1992.

[5] V. H. Rumsey, "Frequency independent antennas," *IRE International Convention Record,* Vol. 5, pp. 114-118, Mar. 1957.

[6] R. Bawer and J. J. Wolfe, "The spiral antenna," *IRE International Convention Record*, Vol. 8, pp. 84-95, Mar. 1960.

[7] H. Nakano, K. Nogami, S. Arai, H. Mimaki, and J. Yamauchi, "A spiral antenna backed by a conducting plane reflector," *IEEE Trans. Antennas Propag.*, Vol. 34, No. 6, pp. 791-796, Jun. 1986.

[8] H. Nakano, K. Kikkawa, and J. Yamauchi, "A low-profile equiangular spiral antenna backed by a cavity with an absorbing strip," *in Proceedings of EuCAP 2006*, Nov. 2006.

[9] H. Nakano, S. Sasaki, H. Oyanagi, and J. Yamauchi, "Cavity-backed Archimedean spiral antenna with strip absorber," *IET Proc. Microw. Antennas Propag.*, Vol. 2, No. 7, pp. 725-730, Oct. 2008.

[10] J. M. Bell and M. F. Iskander, "A low-profile Archimedean spiral antenna using an EBG ground plane," *IEEE Antennas Wireless. Propag. Lett.*, Vol. 3, pp. 223-226, 2004.

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