A New Printed Quasi-Landstorfer Antenna

Masud A. Aziz, Sayan Roy, and Benjamin D. Braaten

***Abstract*—A recently developed compact planar Quasi-Landstorfer antenna is presented here. For this design, the reflector element was removed from the original Landstorfer antenna and the ground plane was modified to have the same behavior as the removed reflector element. By using the ground plane as a reflector, the overall size of the planar Landstorfer antenna was reduced by 44%. The smaller prototype Quasi-Landstorfer antenna presented here had a measured return loss of -42.7 dBi and measured gain of 6.6 dBi at the resonant frequency of 2.44 GHz. Furthermore, a Quasi-Landstorfer antenna design with an extended ground plane was also investigated and is presented. Simulations and measurements of a prototype antenna have shown that by adding conducting strips to the end of the ground plane, approximately 1 dBi of gain could be added without changing the overall dimensions. Throughout this work, it is shown that the measured values agree well with simulations.**

***Index Terms*—Dipole antennas, Landstorfer antenna and Quasi-Yagi antenna, printed antennas.**

I. Introduction

Modern wireless systems have been deployed in many areas including personal communications, sensor systems, entertainment, security and the automobile industry. These applications require printed antennas that are small in size, light weight and cost-effective. Recently, researchers have shown that various forms of the printed Yagi-Uda antenna can be used successfully in wireless systems [1]–[7]. The planar Quasi-Yagi antenna that uses the ground plane as a reflector [5] was a significant development from these efforts. The use of the ground plane eliminates the need of a dipole as a reflector and thus reduces the overall size. However, the size reduction of the overall structure comes at the cost of gain. Another type of modified Yagi-Uda antenna is the Landstorfer antenna that has a higher gain than the traditional Yagi-Uda antenna [8]. In the Landstorfer antenna configuration, the antenna consists of dipole elements that are electrically large. These elements are designed in a sweeping manner to reduce the overall size and because of the electrical length of the each dipole this antenna has a sizable gain. Based on the Landstorfer antenna in [8], a planar reconfigurable Landstorfer 3-element array was recently presented in [9]. This design has been shown to have a high gain and is very useful for many wireless applications.

In this communication, a compact printed Quasi-Landstorfer antenna is presented. The layout of this new design is shown in Fig. 1. The reflector element was removed from the planar Landstorfer antenna design and the ground plane was redesigned to perform the role of the reflector and allow for a much more simple feed-network. The result of this effort is an antenna design that has a high gain and is 44% smaller than the reconfigurable printed Landstorfer antenna presented in [9] (with the same substrate). Finally, it is shown that by extending the ground plane in the y-direction with conducting strips, the gain of the Quasi-Landstorfer antenna can be further improved.

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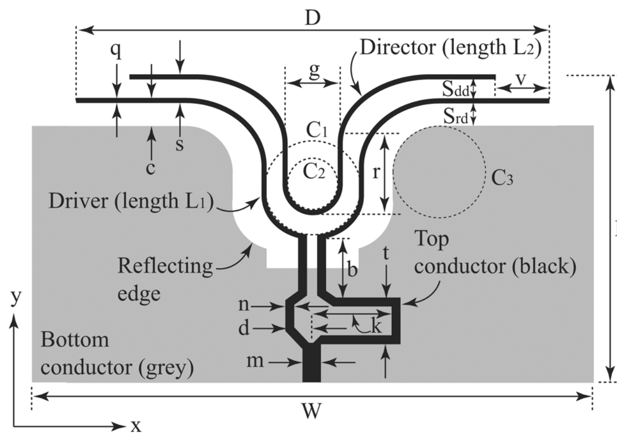


Fig. 1. The layout of the proposed Quasi-Landstorfer antenna.

II. Layout and Design of the Quasi-Landstorfer Antenna

The overall design in Fig. 1 comprises of a printed transmission line that feeds the antenna, a driven element, a director element and a ground plane. The top layer consists of the transmission line and the radiating elements while the bottom layer consists of the ground plane. The dotted circles denoted as C_1, C_2 and C_3 have radius values r_1, r_2 and r_3, respectively. These circles are to be used for reference to assist designers with the layout of the antenna. The two arms of the microstrip line form a balun to transition power from the microstrip line to the coplanar stripline (CPS) at the edge of the ground plane [5]. The guided wavelength of the balun λ_g was calculated with the aid of the commercial software package AppCAD (Applications Computer Aided Design Program) by Agilent Technologies [10].

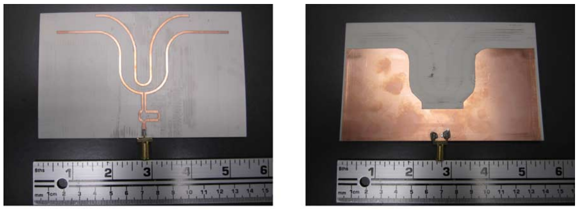
The radiating elements consist of two sweeping printed conductors, of which the larger element is the driven element fed by the CPS and the shorter element is the director. It has been shown that by choosing the length of the driver to be $L_1 \approx 3\lambda_0/2$, where λ_0 is the free-space wavelength at resonance and modifying the shape to a more swept form, the overall gain of the driver element can be increased [9]. The director or parasitic element guides electromagnetic energy in the y-direction and is used for matching [11]–[13]. The ground plane is truncated in parallel to the driven element to behave as a reflector in the y-direction. Moreover, the truncated ground plane also serves as the ground for the microstrip feed line of the antenna [5].

The design of the Quasi-Landstorfer antenna was simulated in both ADS using Momentum [14], which is based on the Moment Method technique, and HFSS [15], which is based on the Finite Element Method. The antenna was designed to operate in the S-band on a 0.5 mm thick Rogers 4003 substrate ($\varepsilon_r = 3.38$). A picture of the manufactured prototype antenna and dimensions are shown in Fig. 2. The antenna was manufactured on a substrate with dimensions of 133 mm × 82 mm × 0.5 mm.

III. Simulation and Measurement Results

A. S-Parameters

The simulated and measured S-parameters of the prototype antenna are shown in Fig. 3. It is shown that the antenna has a measured return loss of -42.7 dBi at 2.44 GHz. The measurements were taken in an anechoic chamber (Fig. 4) using an 8.5 GHz Agilent 8057 ENA series



a) b)

Fig. 2. (a) A photograph (top view) of the manufactured prototype Quasi-Landstorfer antenna ($\mathrm{b} = 10.69$ mm, $\mathrm{c} = 6.5$ mm, $\mathrm{d} = 3.66$ mm, $\mathrm{g} = 9.0$ mm, $\mathrm{k} = 10.2$ mm, $\mathrm{m} = 2.4$ mm, $\mathrm{n} = 1.2$ mm, $\mathrm{q} = 1.5$ mm, $\mathrm{r} = 20.74$ mm, $\mathrm{s} = 12.8$ mm, $\mathrm{t} = 7.2$ mm, $\mathrm{v} = 26.3$ mm, $r_1 = 14.19$ mm, $r_2 = 4.0$ mm, $r_3 = 9.65$ mm, $L_1 = 170$ mm, $L_2 = 130$ mm, $S_{rd} = 5.0$ mm, $S_{dd} = 9.66$ mm, $\mathrm{D} = 114.35$ mm, $\mathrm{H} = 82.0$ mm and $\mathrm{W} = 132.67$ mm) and (b) a photograph (bottom view) of the ground plane on the prototype Quasi-Landstorfer antenna.

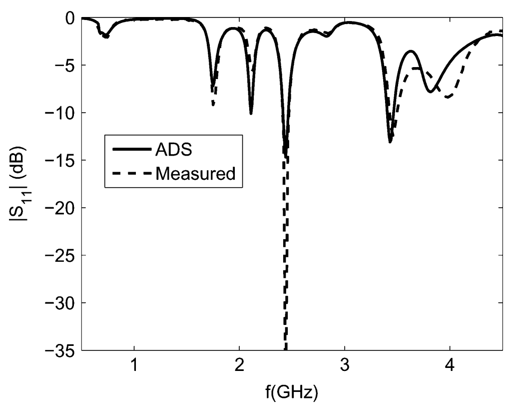


Fig. 3. Measured and simulated S-parameters of the Quasi-Landstorfer antenna.

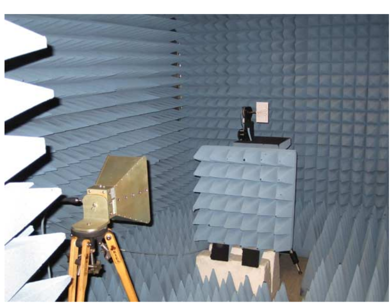


Fig. 4. Measurement of the prototype Quasi-Landstorfer antenna in the anechoic chamber.

network analyzer. The measured results are shown to be in good agreement with the values computed by ADS. The 10 dBi bandwidth of the antenna was measured to be 60 MHz. It should also be mentioned that similar agreement between the S-parameters shown in Fig. 3 and the values computed by HFSS was also observed.

B. Radiation Pattern

Next, the radiation pattern of the antenna was measured in the x-z and y-z planes at 2.44 GHz. The values are shown to agree well with the simulations from both ADS and HFSS in Figs. 5 and 6 for both planes. Both of the simulated and measured results in Figs. 5 and 6 confirm that the antenna is radiating in the y-direction. In the y-z plane, the measurements were conducted twice from 0° to $\pm 180^\circ$ to get the

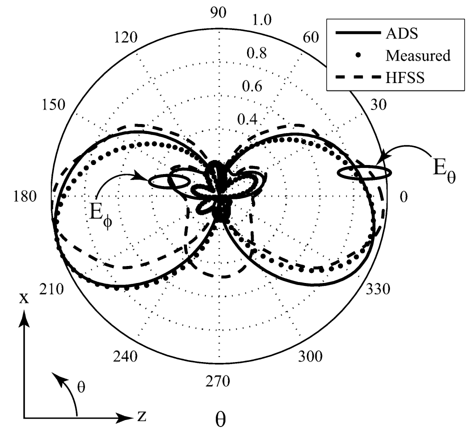


Fig. 5. Measured and simulated radiation pattern in the x-z plane at 2.44 GHz.

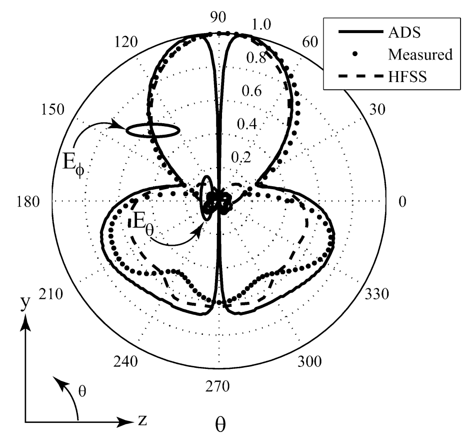


Fig. 6. Measured and simulated radiation pattern in the y-z plane at 2.44 GHz.

360° pattern. Therefore, there is an overlapping of the measured data in the y-z plane at $\theta = 0^\circ$ and 180°. It is believed that the differences between the simulation results in Figs. 5 and 6 are a result of the substrate dimensions and the accuracy of the numerical methods used by each tool. For example, an infinite substrate is assumed in ADS and a finite substrate is defined in HFSS.

C. Gain

The gain of the Quasi-Landstorfer antenna was measured and compared to simulations next. The results from this comparison are shown to agree well in Fig. 7. The maximum simulated gain of the antenna was found to be 7.1 dBi and the max measured gain was found to be 6.6 dBi over the 10 dBi bandwidth of the antenna. Also, the simulated efficiency over the 10 dB BW was comparable to the efficiency reported in [9].

D. Surface Currents

Next, the surface currents on the antenna were computed at 2.44 GHz using ADS. The magnitude and direction of these currents are shown in Fig. 8. Closer observation of the x-directed currents on the driver and ground plane show that they are in the opposite direction. This 180° phase difference between the reflector and driven elements is observed in the traditional Yagi-Uda antenna designs [16] thus showing that the ground plane is performing the role of a reflector. From array theory, the result of this phase difference is a strong radiation in the y-direction (in the direction of the director). Also, the radiating currents on the driver and director are in the same direction; which contributes to the

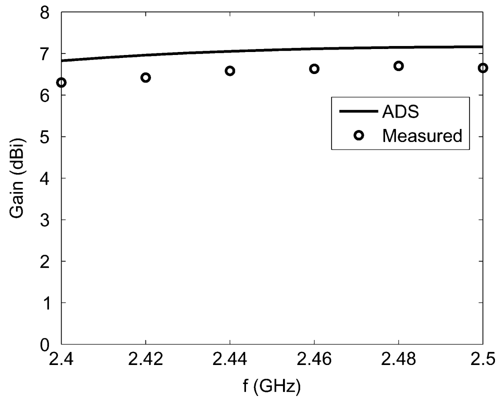


Fig. 7. Measured and simulated gain of the Quasi-Landstorfer antenna.

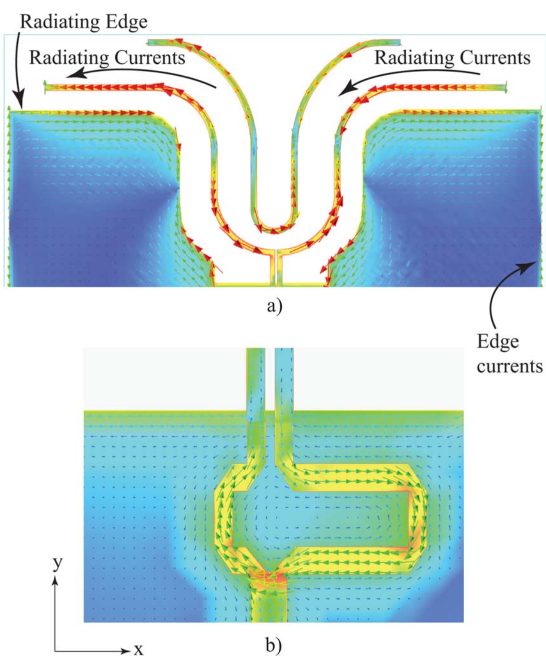


Fig. 8. (a) Simulated current distribution on the Quasi-Landstorfer antenna elements and ground plane at 2.44 GHz and (b) a closer image of the simulated currents on the printed balun at 2.44 GHz.

high gain of the antenna. The S-parameters in Fig. 3 show a second resonant point at 3.45 GHz. At this frequency, the driver element length L_1 is approaching twice the wavelength of the 3.45 GHz source; however, the currents on the driver at this operating frequency are in opposite directions which results in a reduced gain of 1.6 dBi. Only the desired operating bands and corresponding gains are reported here. Furthermore, the currents on the two printed transmission lines in Fig. 8(b) are also in opposite direction. This shows that a differential voltage is provided at the end of the ground plane and that far-fields radiated from the feed network are minimized.

IV. Discussion and Design Guidelines

Further simulations were performed to understand the radiation and matching characteristics for different values of S_{dd}, L_1, L_2 and S_{rd}. The results from these simulations are shown in Figs. 9–14. The following noteworthy comments can be made about these results:

1) The results in Figs. 9 and 11 show that the gain of the Quasi-Landstorfer antenna can be optimized with appropriate values of S_{dd} and L_2.

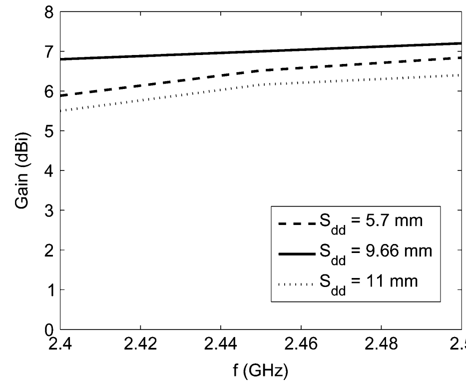


Fig. 9. Simulated gain of the Quasi-Landstorfer antenna for various values of S_{dd}.

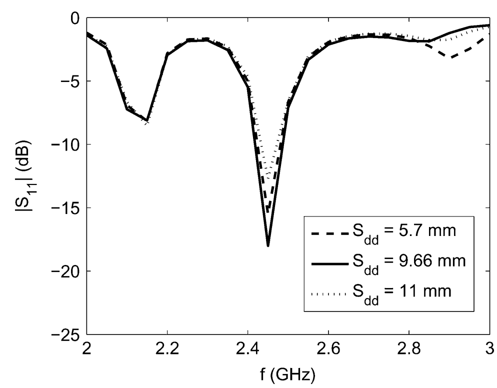


Fig. 10. Simulated S-parameters of the Quasi-Landstorfer antenna for various values of S_{dd}.

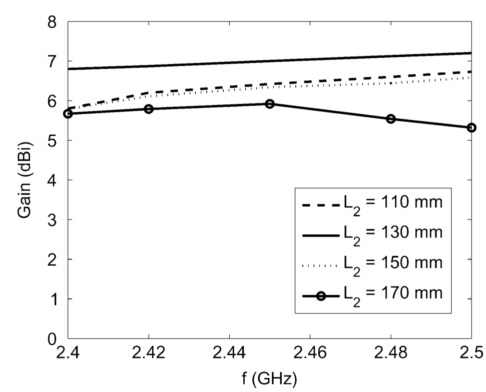


Fig. 11. Simulated gain of the Quasi-Landstorfer antenna for various values of L_2.

2) In Figs. 10 and 12, it is shown how the length and spacing between the driven and director elements can be used to control the $|S_{11}|$ values of the Quasi-Landstorfer antenna.

3) The results in Fig. 13 show how the resonant frequency can be controlled with the length of the driver element. Furthermore, the results in Fig. 14 show how the resonant frequency of the antenna can be significantly altered with different values of S_{rd}.

V. Extended Ground Plane Design

Next, the ground plane of the Quasi-Landstorfer antenna was extended using two conducting strips. The layout of the extended ground

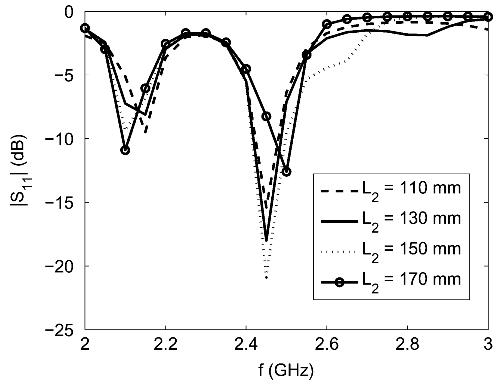


Fig. 12. Simulated S-parameters of the Quasi-Landstorfer antenna for various values of L_2.

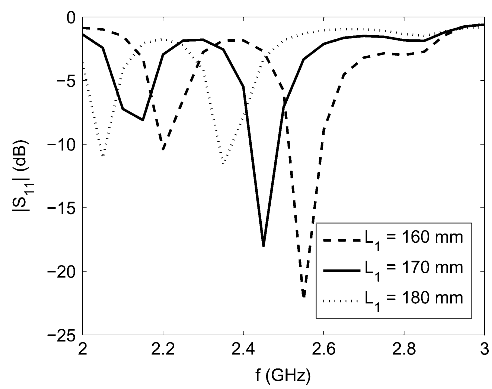


Fig. 13. Simulated S-parameters of the Quasi-Landstorfer antenna for various values of L_1.

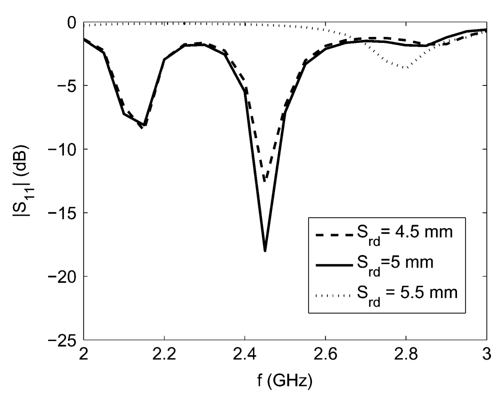


Fig. 14. Simulated S-parameters of the Quasi-Landstorfer antenna for various values of S_{rd}.

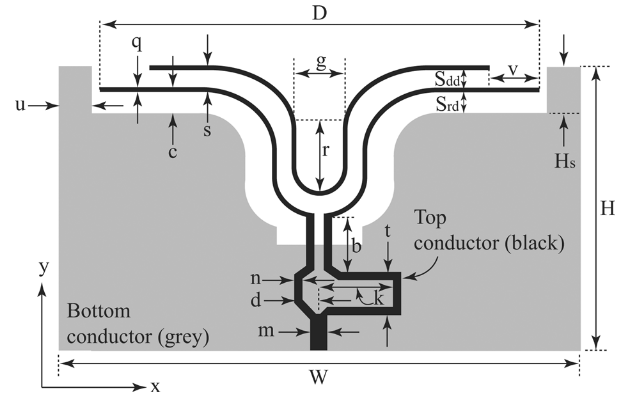


Fig. 15. The layout of the Quasi-Landstorfer antenna with the extended ground plane.

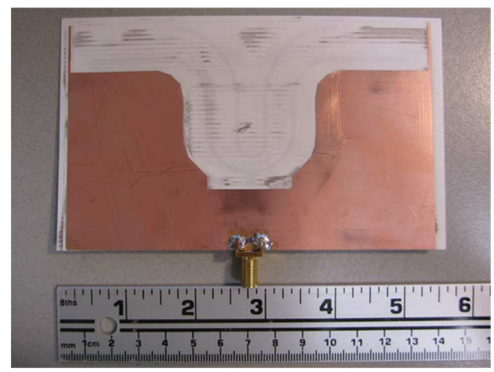


Fig. 16. A photograph of the manufactured prototype Quasi-Landstorfer antenna with the extended ground plane (b = 10.69 mm, c = 6.5 mm, d = 3.66 mm, g = 9.0 mm, k = 10.2 mm, m = 2.4 mm, n = 1.2 mm, q = 1.5 mm, r = 20.74 mm, s = 12.8 mm, t = 7.2 mm, v = 26.3 mm, $r_1 = 14.19$ mm, $r_2 = 4.0$ mm, $r_3 = 9.65$ mm, $L_1 = 170$ mm, $L_2 = 130$ mm, $S_{rd} = 5.0$ mm, $S_{dd} = 9.66$ mm, D = 114.35 mm, H = 82.0 mm, W = 132.67 mm, Hs = 17.5 mm and u = 1 mm).

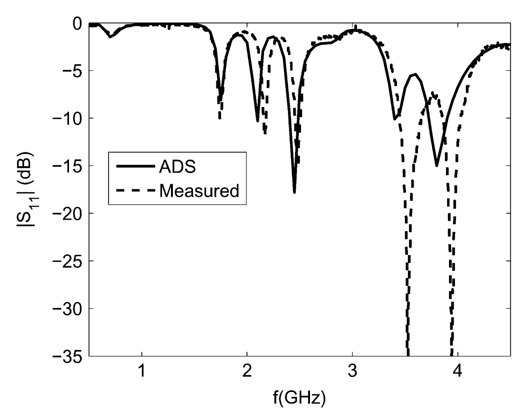


Fig. 17. Measured and simulated S-parameters of the Quasi-Landstorfer antenna with the extended ground plane.

plane design is shown in Fig. 15 and the ground plane of the manufactured prototype is shown in Fig. 16. The overall dimensions of the design in Fig. 15 are are the same as the design in Fig. 2.

A. S-Parameters

The simulated and measured S-parameters of the Quasi-Landstorfer antenna with the extended ground plane are shown to be in good agreement in Fig. 17. The measured resonant frequency of the antenna was 2.48 GHz with a return loss of -15.1 dB. Again, the S-parameters computed using HFSS agreed well with the results in Fig. 17.

B. Radiation Pattern

Next, the simulated and measured radiation pattern of the antenna with the extended ground plane was compared and is shown in Figs. 18 and 19 for x-z and y-z planes, respectively. It can be seen that the antenna is radiating in the y-direction and that the ϕ-component of the electric field is more appreciable in the x-z plane.

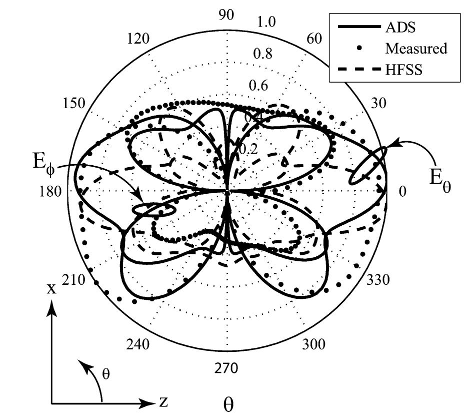


Fig. 18. Measured and simulated radiation pattern in the x-z plane at 2.48 GHz of the Quasi-Landstorfer antenna with the extended ground plane.

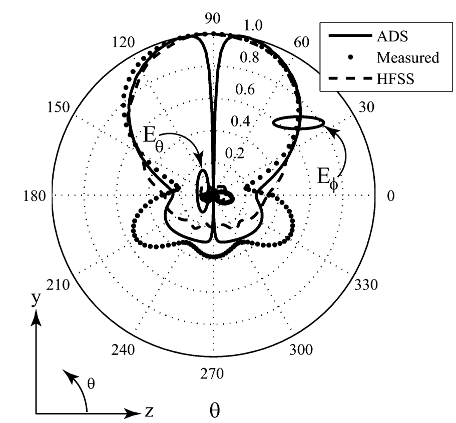


Fig. 19. Measured and simulated radiation pattern in the y-z plane at 2.48 GHz of the Quasi-Landstorfer antenna with the extended ground plane.

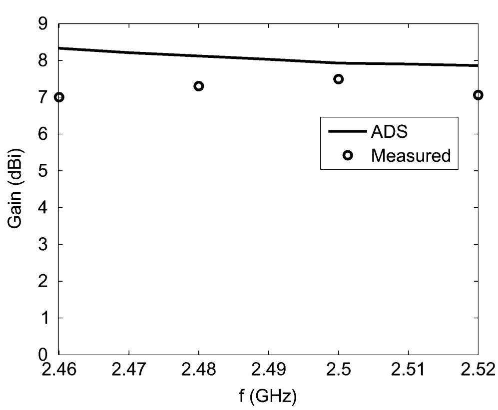


Fig. 20. Measured and simulated gain of the Quasi-Landstorfer antenna with the extended ground plane.

C. Gain

The simulated and measured gain of the antenna is shown in Fig. 20. It is shown that the gain of the antenna increases by 1 dBi (from approximately 7 dBi to 8 dBi) by extending the ground plane. This ground plane extension is particularly useful because this increase in gain is achieved without an increase in overall size of the printed antenna.

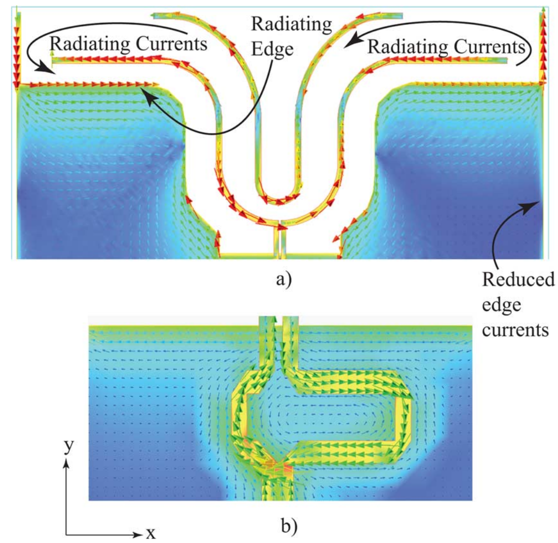


Fig. 21. (a) Simulated current distribution on the Quasi-Landstorfer antenna elements and the extended ground plane at 2.48 GHz and (b) a closer image of the simulated currents on the printed balun at 2.48 GHz.

D. Surface Currents

Finally, the surface currents on the antenna were simulated at 2.48 GHz in ADS. The surface currents are shown in Fig. 21. The two main differences between the surface currents in Figs. 8 and 21 are 1) the currents on the edge of the extended ground plane in the y-direction are reduced and 2) more current is supported on the radiating edge of the extended ground plane. Since the edge currents are reduced in the extended ground plane design, less power is radiated from the edge of the substrate. Furthermore, by supporting more x-directed currents on the radiating edge of the ground plane, the directivity is improved in the y-direction, which improves the gain of the antenna. Also, the current on the printed conductors extending the ground plane is in the y-direction and contribute more to the electric fields in the x-z plane. This can be observed by comparing the fields in Figs. 5 and 18.

The S-parameters in Fig. 17 also show the multi-resonant nature of the antenna. As with the Landstorfer antenna design presented in the previous section, at these other resonant frequencies the surface currents on the director, driven element and ground plane are either reduced or in opposite directions when compared to the currents at 2.48 GHz. Because of this, the gain of the Landstorfer antenna design with the extended ground plane is reduced to 4–5 dBi. Once more, the design with the maximum gain is reported here.

VI. Conclusion

In this communication, the design, simulation and measurements of a new compact planar Quasi-Landstorfer antenna was presented and discussed. In particular, the reflector element was removed from the original Landstorfer antenna and the ground plane was modified to have the same behavior as the removed reflector element. By using the ground plane as a reflector, the size of a planar Landstorfer antenna was reduced by 44%. The prototype Quasi-Landstorfer antenna presented here had a measured return loss of -42.7 dBi and a measured gain of 6.6 dBi at the resonant frequency of 2.44 GHz. Finally, a Quasi-Landstorfer design with an extended ground plane was investigated and presented. Measurements and simulations have shown that by extending the ground plane with conducting strips, approximately 1 dBi of gain could be added without changing the overall dimensions or operating frequency.

References

[1] D.-C. Chang, C.-B. Chang, and J.-C. Liu, “Modified planar Quasi-Yagi antenna for WLAN dual-band operations,” *Microw. Optical Tech. Lett.*, vol. 46, no. 5, pp. 443–446, 2005.

[2] P.-Y. Qin, A. R. Weily, Y. J. Guo, T. S. Bird, and C.-H. Liang, “Frequency reconfigurable Quasi-Yagi folded dipole antenna,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 8, pp. 2742–2747, 2010.

[3] J. M. Steyn, J. W. Odendaal, and J. Joubert, “Double dipole antenna for dual-band wireless local area networks applications,” *Microw. Optical Tech. Lett.*, vol. 51, no. 9, pp. 2034–2038, 2009.

[4] J. Huang and A. C. Densmore, “Microstrip Yagi array antenna for mobile satellite vehicle application,” *IEEE Trans. Antennas Propag.*, vol. 39, no. 7, pp. 1024–1030, 1991.

[5] W. R. Deal, N. Kaneda, J. Sor, Y. Qian, and T. Itoh, “A new Quasi-Yagi antenna for planar active antenna arrays,” *IEEE Trans. Microw. Theory Tech.*, vol. 48, no. 6, pp. 910–918, 2000.

[6] N. Kaneda, W. R. Deal, J. Sor, Y. Qian, and T. Itoh, “A broadband planar Quasi-Yagi antenna,” *IEEE Trans. Antennas Propag.*, vol. 50, no. 8, pp. 1158–1160, 2002.

[7] T.-G. Ma, C.-W. Wang, R.-C. Hua, and J.-W. Tsai, “A modified Quasi-Yagi antenna with a new compact microstrip-to-coplanar strip transition using artificial transmission lines,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 8, pp. 2469–2474, 2009.

[8] F. Landstorfer, “A new type of directional antenna,” in *Proc. IEEE Antennas Propag. Soc. Symp.*, Oct. 1976, pp. 169–172.

[9] A. C. K. Mak, C. R. Rowell, and R. D. Murch, “Low cost reconfigurable Landstorfer planar antenna array,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3051–3061, 2009.

[10] *Applications Computer Aided Design Program-AppCAD 2010*, , Agilent Technologies, Inc..

[11] N. Kaneda, Y. Qian, and T. Itoh, “A broadband microstrip-to waveguide transition using Quasi-Yagi antenna,” *IEEE Trans. Microw. Theory and Tech.*, vol. 47, no. 12, pp. 2562–2567, 1999.

[12] C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed. Hoboken, NJ: Wiley, 2005, ch. 10.

[13] W. Nannan, Q. Jinghui, L. Shu, and D. Weibo, “Research on wide beamwidth and high gain Quasi-Yagi antenna,” in *Proc. 8th Int. Symp. Antennas, Propag. and EM Theory*, Kunming, China, Nov. 2008, pp. 302–305.

[14] *Advanced Design System—ADS 2009* Agilent Technologies.

[15] *High Frequency Structure Simulator—HFSS 2009* Version 11.2, Ansoft, LLC.

[16] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*, 2nd ed. New York: Wiley, 1998.

Optimization of UHF Hilbert Antenna for Partial Discharge Detection of Transformers

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***Abstract*—Partial discharge (PD) online monitoring is an effective tool of inspecting insulation defects and identifying potential faults in power transformers. Ultra-high-frequency (UHF) approaches have caught increasing attention recently and been considered as a promising technology for online monitoring PD signals. The size of a UHF sensor for PD online monitoring of transformer is a critical factor for practical installation inside transformer. This communication presents a compact fourth order UHF Hilbert fractal antenna with desired performance and suitable size for easy installation. Actual PD experiments were carried out for four typical artificial insulation defect models while the antenna was used for PD measurements. The experimental results show that the proposed Hilbert fractal antenna is suitable and effective for UHF online monitoring of PDs in transformers.**

***Index Terms*—Hilbert fractal antenna, partial discharge, transformer, ultra-high-frequency detection.**

I. Introduction

Power transformers are very important equipment in power systems. A large portion of power transformers failures are caused by faults of oil-paper insulation, which often start with partial discharges (PDs). PDs generate electromagnetic emissions which can be detected by ultra-high-frequency (UHF) antennas in the frequency band greater than 300 MHz [1]. Radio frequency interferences (RFIs) from power line communication and corona discharges on high voltage terminals near transformers can propagate into transformers through high voltage bushings of the transformers and reduce accuracy of PD online monitoring based on principles of traditional PD detection, of which frequency bands are between several tens kHz and several MHz [2]. The frequency bands of RFIs are between a few hundreds kHz and a few tens MHz and the upper frequency limits of the corona discharges do not exceed 300 MHz. The UHF PD detection thus takes advantages of strong anti-interference ability over traditional detection approaches.

The performance of UHF antenna determines the ability of PD online detection systems of high voltage equipment. Currently, various UHF antennas have been used for PD detection. Publication [3] introduced a two-wire Archimedean planar spiral antenna and its application in PD detection. An inverted cone antenna was presented in [4] to measure PD signals in transformer oils. A circular plate antennas and a circular ring antenna were used for PD detection of sulfur hexafluoride

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