where the center pin is in contact with the hot electrode of the CPW line and the four grounding pins are soldered to the ground-planes of this transmission line. The purpose of the small square slot at the center of the antenna (see Fig. 1 or Fig. 2) is help provide isolation between the hot electrode of the CPW transmission line and the surrounding ground-plane. In our original concept for the developed radiator, we were going to attempt to 'edge' feed the antenna from the center, however subsequently we were unable to source an interface small enough to accommodate the space required for the transition.

III. Results

The predicted and measured return loss performance of the proposed small, uni-planar antenna is shown in Fig. 3. As can be seen from this plot, very good agreement between theory and experiment was achieved. The measured 10 dB return loss bandwidth for the radiator is 25 MHz compared to a predicted bandwidth of 35 MHz, however the minimum return loss for the measured case is better by almost 2 dB. The reasonable bandwidth, in excess of 5.5%, is due to the bandwidth of the slot primary radiating element, which inherently has more bandwidth than a patch antenna. The predicted and measured principal plane radiation patterns [XZ plane, $\phi = 0^\circ$ and YZ plane, $\phi = 90^\circ$ where ϕ is defined in Fig. 1 and θ is the angle from the Z axis (out of the paper)] are shown in Fig. 4. Co-polar patterns are defined as radiation patterns with the linear polarization source antenna (a Yagi–Uda antenna) in the appropriate orientation and cross-polar patterns are taken with the source and antenna under test in orthogonal planes. The measurements were carried out at an outdoor antenna range. As can be seen from these results the patterns are in reasonable agreement, with higher cross-polarization levels, particularly towards endfire ($\theta = \pm 90^\circ$), and scalping of the co-polar patterns in the measured patterns compared to the predicted results. These are characteristics that are typically observed for small antennas with truncated ground-planes. The measured gain was approximately 0 dBi, with an uncertainty of 2 dB. All cables used to make the measurement were covered with RF absorber to minimize their impact on the measured radiation patterns. The calculated efficiency of the antenna was approximately 75%.

IV. Conclusion

In this paper we have presented a new small, uni-planar printed antenna that has near omnidirectional radiation patterns. The antenna can be classified as a uni-planar version of a shorted spiral-like patch antenna, where in this case the primary radiator is a printed slot. The antenna is useful for wireless applications requiring thin, small radiators. Good agreement between the predicted and measured performance of the antenna has been achieved.

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A Horizontally Polarized Omnidirectional Printed Antenna for WLAN Applications

C.-C. Lin, L.-C. Kuo, and H.-R. Chuang

***Abstract*—The design simulation, fabrication, and measurement of a 2.4-GHz horizontally polarized omnidirectional planar printed antenna for WLAN applications is presented. The antenna adopts the printed Alford-loop-type structure. The three-dimensional (3-D) EM simulator HFSS is used for design simulation. The designed antenna is fabricated on an FR-4 printed-circuit-board substrate. The measured input standing-wave-ratio (SWR) is less than three from 2.40 to 2.483 GHz. As desired, the horizontal-polarization H-plane pattern is quite omnidirectional and the E-plane pattern is also very close to that of an ideal dipole antenna. Also a comparison with the popular printed inverted-F antenna (PIFA) has been conducted, the measured H-plane pattern of the Alford-loop-structure antenna is better than that of the PIFA when the omnidirectional pattern is desired. Further more, the study of the antenna printed on a simulated PCMCIA card and that inserted inside a laptop PC are also conducted. The HFSS model of a laptop PC housing, consisting of the display, the screen, and the metallic box with the keyboard, is constructed. The effect of the laptop PC housing with different angle between the display and keyboard on the antenna is also investigated. It is found that there is about 15 dB attenuation of the gain pattern (horizontal-polarization field) in the opposite direction of the PCMCIA slot on the laptop PC. Hence, the effect of the large ground plane of the PCMCIA card and the attenuation effect of the laptop PC housing should be taken into consideration for the antenna design for WLAN applications. For the proposed antenna, in addition to be used alone for a horizontally polarized antenna, it can be also a part of a diversity antenna.**

***Index Terms*—Alford loop, HFSS, horizontal polarization, laptop PC, omnidirectional, printed antenna, printed inverted-F antenna (PIFA), WLAN.**

I. Introduction

Recently, with the rapid progress in the wireless communication technology, the demands of using the laptop and other portable computers with wireless modems as the terminals increase vastly in the wireless local area network (WLAN) applications. Given the antennas designed for the laptop PC, they can be simply classified into two categories: one is the built-in type and the other is integrated into an external interface card, such as the personal computer memory card international association (PCMCIA) card. Several kinds of the built-in antennas designed for the laptop PC have been introduced and studied [1]–[3]. It is noted that these built-in antennas can be integrated into the display panel or the chassis of the laptop PC. However in many current practical applications, as shown in Fig. 1, an external WLAN interface card (PCMCIA card) is normally plugged horizontally into a horizontal slot of the laptop PC. Also in the near future, the WLAN card may be built in with the laptop PC motherboard. In both situations, the printed antenna on the WLAN card is probably still situated in the horizontal plane and hence the antenna polarization may be dominant by the horizontally-polarized field. For example, a popularly used printed inverted-F antenna (PIFA) [4], in which it is reported that the dominant antenna pattern is basically in horizontal polarization but is not quite omnidirectional as desired in the H-plane.

In the urban or indoor wireless environment, after complicated multiple reflections or scatterings, the polarization of the propagating radio

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Color versions of Figs. 1–13 are available online at http://ieeexplore.ieee.org.
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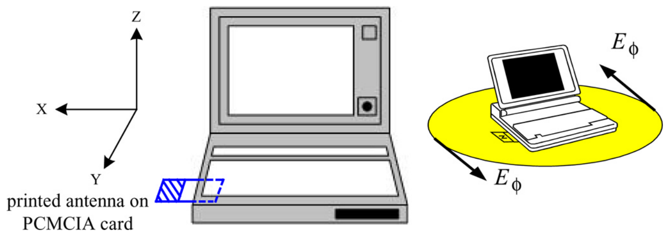


Fig. 1. (left) Illustration of the printed antenna on a PCMCIA card inserted inside a laptop PC for WLAN application and (right) a desired horizontally polarized omnidirectional pattern.

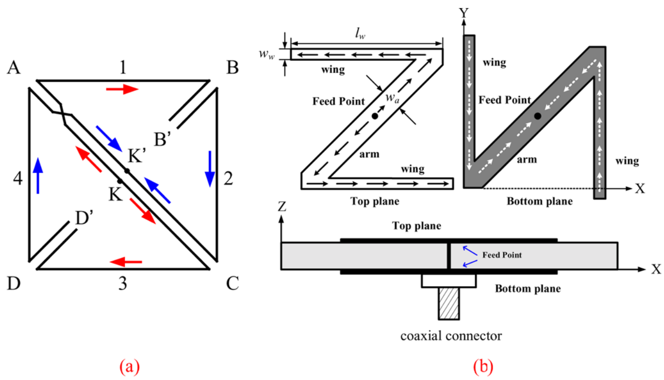


Fig. 2. Geometry of (a) original wire-structure Alford loop antenna presented in [6], and (b) a printed Alford-loop-structure antenna.

wave may change significantly. As reported in [4], [5], although many current wireless system are vertically polarized, it has been predicted that using horizontally polarized antenna at both the transmitter and receiver will result in 10 dB more power, as compared to the power received by using vertically polarized antennas at both end of the link. Hence, it seems that a horizontally polarized printed antenna with an omnidirectional pattern may be most suitable for the WLAN card application. Moreover, the effects of the laptop PC housing, including the location of the PCMCIA card, the tilted angle of the display screen, and the housing materials, will all affect the performances of the WLAN antenna and should be investigated in detail to obtain the final antenna patterns in the practical using condition.

In order to achieve the horizontally polarized radiation pattern, a loop antenna is a suitable choice. A small loop antenna with an uniform current distribution will have an omnidirectional pattern. However, a small loop antenna will have a very small radiation resistance and a high reactance. This will cause difficult impedance matching problem. A large loop antenna will have a reasonable radiation resistance. But the antenna current distribution along the loop becomes nonuniform and hence could not yield a desired omnidirectional pattern. To design a loop antenna with an omnidirectional pattern and an acceptable input impedance matching becomes a design challenge.

The wire-structure Alford loop antenna [Fig. 2(a)] to achieve an omnidirectional horizontally polarized waves was first reported in [6]. As shown in Fig. 2(a), the Alford loop antenna is fed at the terminal (K, K') and due to the symmetric structure the current distribution on the conductors 1, 2, 3, and 4 will have the same magnitude and 180-degree phase difference. Also, since the conductors of *BB'*, *DD'*, and *AC* are very close to each other and the current flowing direction are opposite, the radiation of these current distribution will cancel by each other. Hence, the antenna currents on the Alford loop conductors 1, 2, 3, and 4 form a square-"loop" type current distribution, and a horizontally-polarized omnidirectional pattern can be achieved.

For the printed antenna purpose, a more convenient feeding mechanism and planar Alford-loop-structure antenna was adopted to design a 900-MHz planar printed omnidirectional horizontally polarized antenna [7]. In this paper, a 2.4-GHz printed WLAN antenna which adopts the printed structure of the Alford loop antenna is presented. Except designing an independent printed Alford loop antenna, the designed antenna printed on a simulated PCMCIA card and that inserted inside a laptop PC housing are also studied. The Ansoft HFSS three-dimension (3-D) EM simulator is utilized for antenna design simulation. The HFSS model of a laptop PC housing, consisting of the display, the screen, and the metallic box with the keyboard, is constructed. The effect of the laptop PC housing with different angle between the display and keyboard on the antenna is also investigated. For the proposed antenna, in addition to be used alone for a horizontally polarized antenna, it can be also a part of a diversity antenna.

II. Antenna Design

As shown in Fig. 2, the printed Alford-loop-structure antenna consists of two Z-shaped strips printed on the top and bottom plane of the printed-circuit board (PCB). The bottom strip is arranged in such a manner that the "arm" is mapped to that of top strip through the PCB substrate. A coaxial connector is used to connect the central feed point of the top and bottom strips. The "wing" length of the Alford loop is of the order of a quarter of wavelength. Due to structure symmetry, the antenna current distribution on the two strips will have the same magnitude and 180-degree phase difference, as illustrated in Fig. 2(b). Since the PCB substrate thickness is very small, the radiation of the antenna current along the "arm" will cancel by each other. The antenna currents on the two "wings" of each "Z" strip establish a square-"loop"-type current distribution. This "loop"-type current distribution will radiate a horizontally polarized field and is expected to have an omnidirectional pattern.

A. Stand-Alone Antenna

In designing the printed Alford-loop-structure antenna, the dimensions of the Z-shaped strips including the length and width of the "arm" and the "wing" should be considered carefully for a good impedance matching. The length of the "wing" is approximately a quarter-wavelength. It is noted that from the study in [8], since the metal strip on the FR-4 substrate is without the ground plane, the metal strip does not belong to the microstrip line (which has a ground plane). Hence, unlike the wavelength associated with the effective dielectric constant used in the microstrip line, it is treated that the wavelength is approximated as that in a medium with a dielectric constant equivalent to the average of that in free space and the substrate (ε_r), which is $(1+\varepsilon_r)/2$. Hence the length of the "wing" (quarter-wavelength), l_w, is expressed as

$$l_w = 0.25 \times [\lambda_e] = 0.25 \times [\lambda_0/\sqrt{(1+\varepsilon_r)/2}]. \tag{1}$$

At 2.45 GHz l_w is approximately equal to 18 mm for FR-4 substrate $(\varepsilon_r = 4.7)$. However, the accurate length and width has to be fine-tuned by HFSS 3-D EM simulation. After the HFSS fine-tuning, l_w is set to be 17.8 mm. Table I shows the dimensions of a designed 2.4-GHz printed Alford-Loop-structure antenna on an FR-4 substrate.

Fig. 3 shows the simulated surface current distributions of a designed 2.4-GHz Alford-loop-structure antenna. The symmetrical current distribution on the top and bottom strips is observed. Fig. 4 shows the photograph of a realized printed Alford-loop-structure antenna on an FR-4 PCB substrate and the measured input standing-wave-ratio (SWR). It can be observed that the measured input SWR is less than 3 from 2.40 to 2.483 GHz. Fig. 5 shows the measured antenna patterns of the horizontal- and vertical-polarization field in the H-plane (*xy*-plane, $\theta = 90^\circ$) and E-plane (xz-plane, $\phi = 0^\circ$). As expected, instead of the vertical-polarization field, the horizontal-polarization H-plane pattern is quite omnidirectional and the E-plane pattern is also very close to that of an ideal dipole antenna.

Comparison With the Printed Inverted-F Antenna (PIFA): For comparison with the PIFA [9]–[12], a 2.4-GHz PIFA is realized on an FR-4

TABLE I
DIMENSIONS OF A PLANAR PRINTED ALFORD-LOOP-STRUCTURE ANTENNA ON AN FR-4 SUBSTRATE

Parameters	Dimensions (mm)
Length of wing (l_w)	17.8
Width of wing (w_w)	1.5
Width of arm (w_a)	6.36
PCB substrate thickness (t)	1

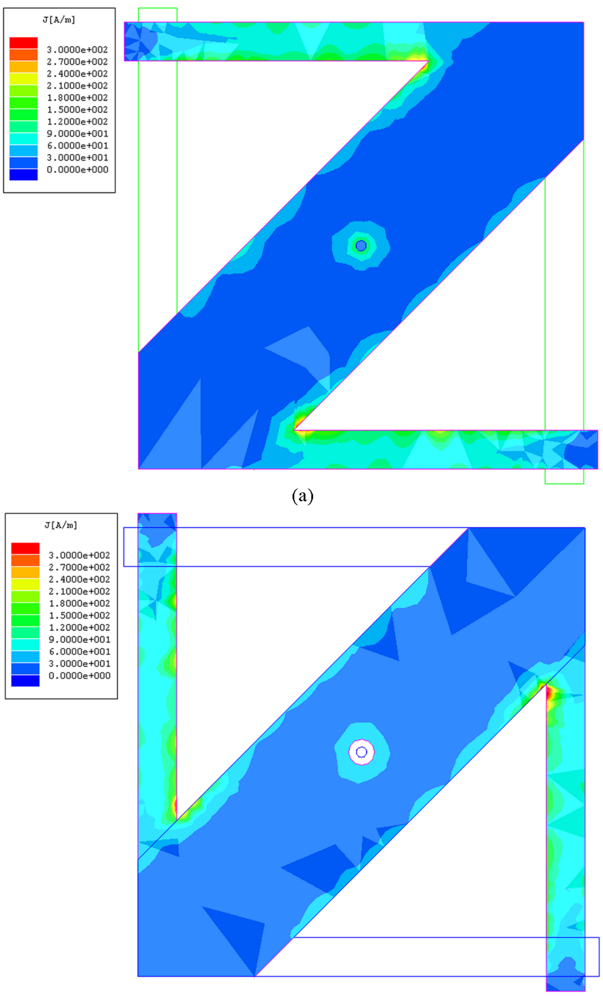


Fig. 3. The simulated current distributions of the printed Alford-loop-structure antenna. (a) On the top metal. (b) On the bottom metal.

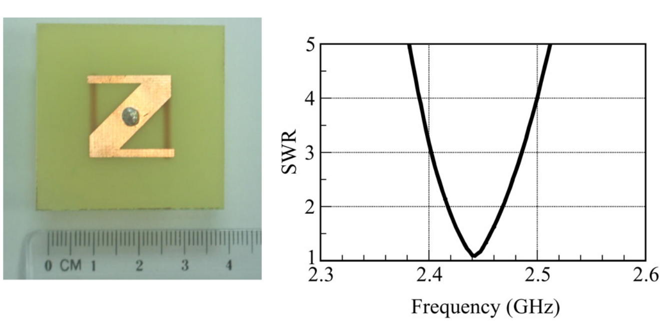


Fig. 4. Photograph of a realized printed Alford-loop-structure antenna on an FR-4 PCB substrate and the measured input SWR.

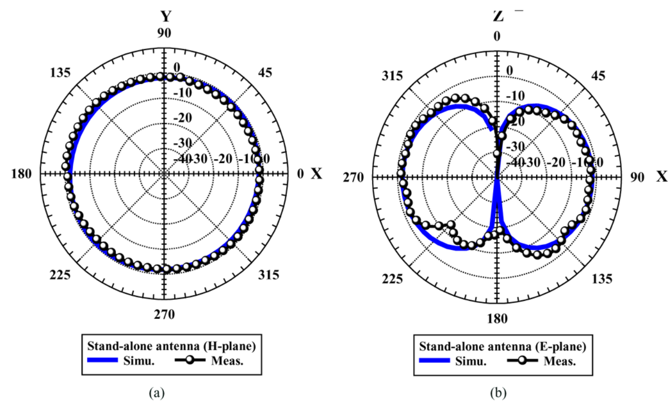


Fig. 5. Simulated and measured radiation patterns of the horizontal-polarization field of a 2.4-GHz printed Alford-loop-structure antenna. (a) In the H-plane. (b) In the E-plane.

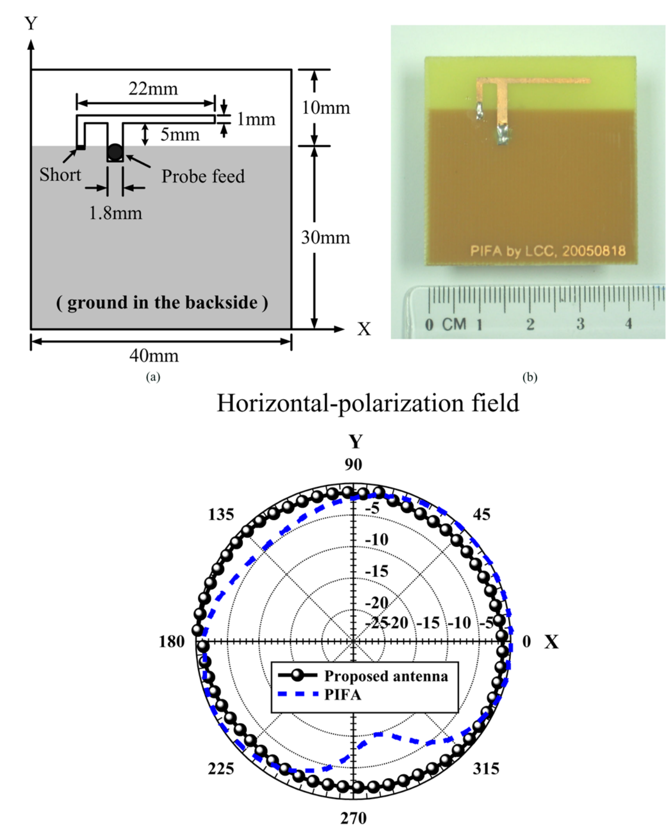
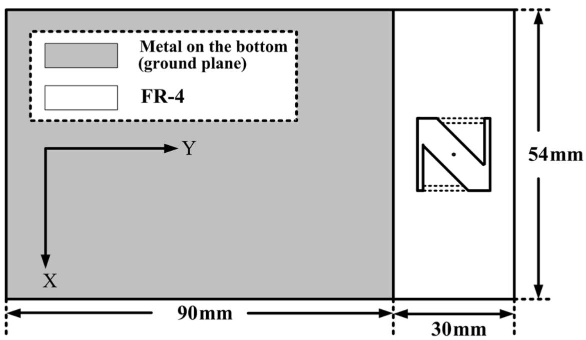


Fig. 6. (a) Schematic of a 2.4-GHz PIFA, (b) photograph of a realized 2.4-GHz PIFA on an FR-4 substrate, (c) comparisons of the measured H-plane patterns.

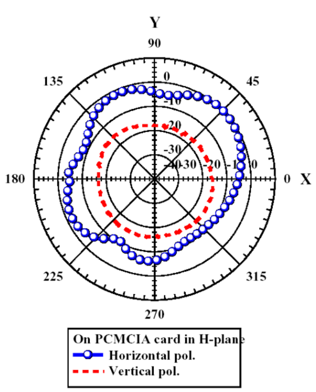
substrate of which the dimension is the same as that of the Alford-loop-structure antenna. As shown in Fig. 6(a) and (b), the PIFA is fed with the coaxial probe and the dimension of ground plane in the backside is 40×30 mm^2. As shown in Fig. 6(c), the H-plane pattern of the Alford-loop-structure antenna is better than that of the PIFA when the omnidirectional pattern is desired.



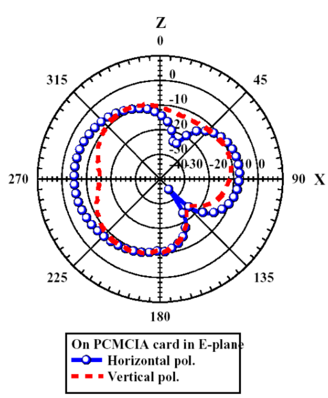
(a)

(b)

Fig. 7. (a) Geometry and (b) photograph of a fabricated Alford-loop-structure antenna on a simulated PCMCIA card.



(a)



(b)

Fig. 8. Measured radiation patterns of the horizontal-polarization field for the Alford-loop-structure antenna printed on a simulated PCMCIA card in: (a) H-plane. (b) E-plane.

B. Antenna Printed on a Simulated PCMCIA Card

Fig. 7 shows the geometry and the photograph of an Alford-loop-structure-type antenna printed on an FR-4 PCB board (120×54 mm^2) which has the same dimension as a practical WLAN PCMCIA card. The metallic plane (90×54 mm^2) on the bottom is to simulate the ground plane of the PCMCIA card. Fig. 8 shows the measured radiation patterns of the horizontal-polarization field. Due to the large ground plane effect, the pattern is distorted from the omnidirectional pattern and the measured average antenna gain in the H-plane is -5.3 dBi. Here, the H-plane average gain, $G_{\rm avg}$, is the average of gain values of the associated N points in the H-plane which can be formulated as

$$G_{\rm avg} = \frac{1}{N}\sum_{i=1}^{N} G_p\left(\theta = \frac{\pi}{2}, \phi_i\right) \quad \phi_i = i \times \frac{2\pi}{N} \tag{2}$$

where G_p is the value of the antenna gain at each specified position. In this paper, we measure 180 points for the antenna gain (pattern) in the H-plane (2-degree per point). The average gain is the average of gain values of the associated 180 points.

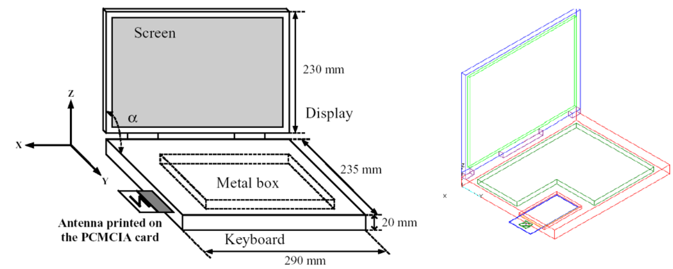


Fig. 9. The geometry and dimensions of a simulated laptop PC housing model (left) and the HFSS simulation schematics (right).

As shown in Table III, it is noted that the average gain of the vertical-polarization field is about 11 dB less than that of the horizontal-polarization field. The effects due to the large ground plane of the PCMCIA card, such as attenuations of the antenna patterns, should be taken into considerations for the antenna design in WLAN card.

C. Antenna Printed on Simulated PCMCIA Card Inserted to a Laptop PC

To simulate the effects of the laptop PC housing on the printed Alford-loop-structure antenna on a PCMCIA card, a laptop PC model, which consists of the display, the screen (inside the display), and the keyboard (including a metallic box inside), is constructed as shown in Fig. 9 (left). Table II lists the details of the materials: the display is polyethylene ($\varepsilon_{\rm r} = 2.25$) covered by a perfect electrical conductor (PEC), the screen is glass ($\varepsilon_{\rm r} = 5.5, \sigma = 10^{-12}$ S/m), and the keyboard is polyethylene with a metallic box inside. The angle between the display and keyboard is defined as α. The effect of the laptop PC housing with different angle between the display and keyboard on the antenna is also investigated. The HFSS simulation schematic is also shown in the figure (right).

Fig. 10 shows the HFSS simulated E-field distribution around the laptop PC housing. Fig. 11 presents the HFSS simulated antenna patterns of the horizontal-polarization field in the H-plane with the angles of $\alpha = 90^\circ, 120^\circ$, and 135° that are usually used in practical cases. It is found that the differences are not obvious. In the following cases, the angle of α will be set as 90-degree.

Fig. 12 shows a photograph of the pattern measurement of the antenna (printed on a PCMCIA card) inserted inside a laptop PC in an anechoic chamber. Fig. 13 presents the measured antenna patterns in the H-plane for the three aforementioned cases: the stand-alone Alford-loop-structure antenna, the antenna printed on a simulated PCMCIA card, and that inserted inside the laptop PC. For the case of the antenna printed on the PCMCIA card inside a laptop PC, it can be observed that there is about more than 15 dB attenuation of the gain pattern in the opposite direction of the PCMCIA slot of a laptop PC. The measured average H-plane antenna gain of the E_ϕ field is about -8.0 dBi. More detailed comparisons of the measured antenna gains are listed in Table III. It is noted that the maximum E_θ-field (-7.0 dBi) of the antenna on the PCMCIA card inserted inside the laptop is higher than that (-15.3 dBi) of the antenna on the PCMCIA card (in free space). It can be explained that, for a horizontally-polarized antenna, E_θ is a cross-polarized field and hence the laptop housing effect could be possible to induce a high level of cross-polarization when the PCMCIA card (with the printed antenna) inserted inside it. This information will be useful for analyzing characteristics of antennas used for WLAN applications. Furthermore, how to reduce the attenuation effect of the laptop PC housing and maintain the desired performance of antennas is needed for more advanced study.

TABLE II
LAPTOP HOUSING COMPONENTS AND MATERIALS FOR HFSS SIMULATION

Laptop Housing Component	Material
Display	PEC-covered polyethylene ($\varepsilon_r = 2.25$)
Screen	Glass ($\varepsilon_r = 5.5$, $\sigma = 10^{-12}$ S/m)
Keyboard	Polyethylene (a metallic box inside)

TABLE III
COMPARISONS OF MEASURED ANTENNA GAINS IN THE H-PLANE

2.4-GHz printed Alford-Loop Antenna	E_θ (vertical pol.) (dBi)			E_ϕ (horizontal pol.) (dBi)		
	Max.	*Min.*	*Avg*	*Max.*	*Min.*	*Avg*
On PCMCIA card	-15.3	-18.3	-16.6	0.1	-11.2	-5.3
On PCMCIA card inserted inside laptop PC (α=90°)	-7.0	-36.0	-15.0	-1.9	-29.3	-8.0

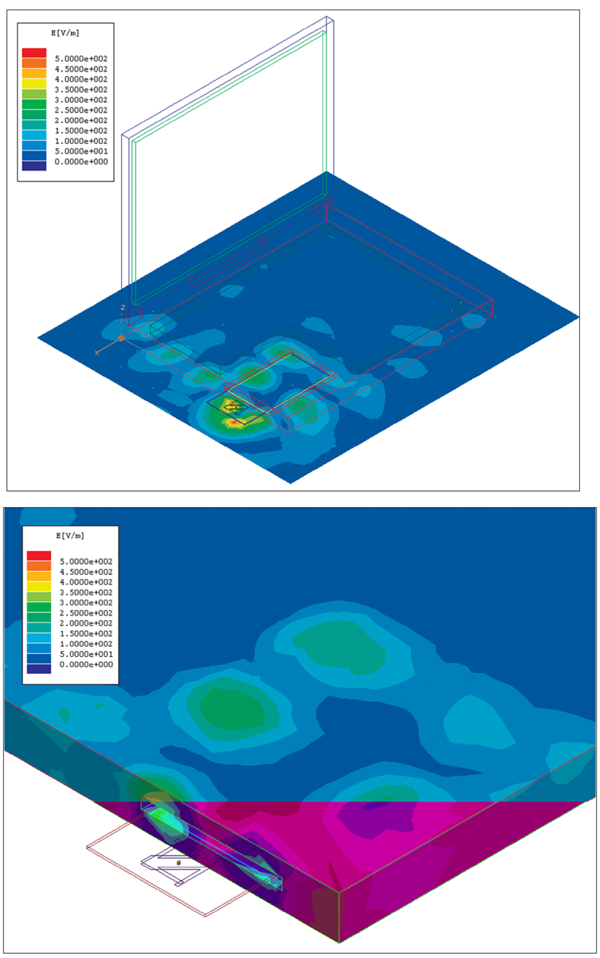


Fig. 10. HFSS simulated E-field distribution around the laptop PC housing.

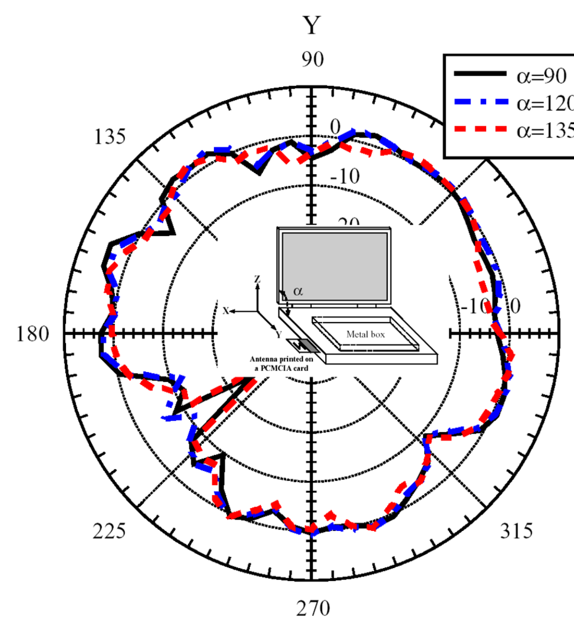


Fig. 11. Simulated antenna patterns of the horizontal-polarization field in the H-plane for the Alford-loop-structure antenna printed on a simulated PCMCIA card inside the laptop PC with angles of $\alpha = 90°$, 120°, and 135°.

Fig. 12. Photograph of the pattern measurement of the antenna (printed on a PCMCIA card) inserted inside a laptop PC in an anechoic chamber.

III. CONCLUSION

A 2.4-GHz omnidirectional horizontally polarized planar-printed antenna which adopts the Alford-loop-type structure has been designed, fabricated on an FR-4 PCB board. The measured input SWR of the antenna is less than three from 2.40 to 2.483 GHz. The horizontal-polarization H-plane pattern is quite omnidirectional and the

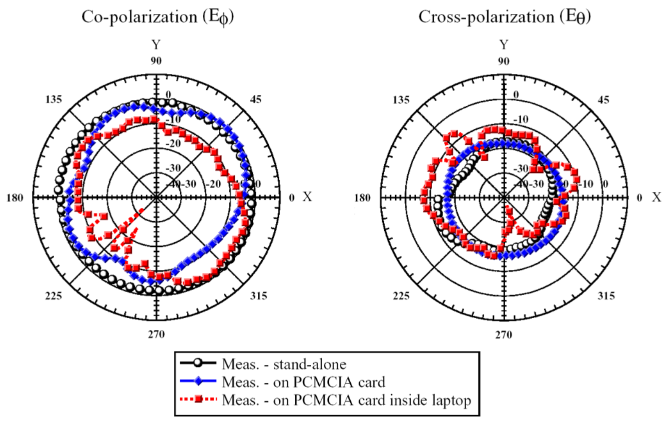


Fig. 13. Measured antenna patterns in the H-plane for the three cases: a stand-alone Alford-loop-structure antenna, the antenna printed on a simulated PCMCIA card, and that inserted inside a laptop PC.

E-plane pattern is also very close to that of an ideal dipole antenna. For comparison with the PIFA, a 2.4-GHz PIFA is realized on an FR-4 substrate. The measured H-plane pattern of the Alford-loop-structure antenna is better than that of the PIFA when the omnidirectional pattern is desired. Further more, study of the antenna printed on a simulated PCMCIA card and that inserted inside a laptop PC are also conducted. The antenna printed on a simulated PCMCIA card has an average antenna gain (horizontal-polarization field) of -5.3 dBi. The HFSS model of a laptop PC housing, consisting of the display, the screen, and the metallic box with the keyboard, is constructed to investigate the effects of the antenna printed on a PCMCIA card and that inserted inside the laptop PC. The display is polyethylene ($\varepsilon_{\rm r} = 2.25$) covered by the a perfect electrical conductor (PEC), the screen is the glass ($\varepsilon_{\rm r} = 5.5, \sigma = 10^{-12}$ S/m), and keyboard is polyethylene with a metallic box inside. The effect of the laptop PC housing with different angle (α) between the display and keyboard on the antenna pattern is also investigated. It is found that the effect of the different display-keyboard angle ($\alpha = 90^\circ$, 120°, and 135°) on the antenna pattern is not significant. For the case of the antenna printed on a PCMCIA card inserted inside the laptop PC, more than 15 dB attenuation of the gain pattern (horizontal-polarization field) is found in the opposite direction of the PCMCIA slot on the laptop PC, and the average antenna gain is -8.0 dBi in the H-plane. It is suggested that the effect of the large ground plane of the PCMCIA card and the attenuation due to the laptop PC housing should be taken into considerations in designing the antennas for WLAN applications. Also, in addition to be used alone for a horizontally polarized antenna, the proposed antenna can also be used as a part of a diversity antenna.

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Aperture Antennas on Probe-Fed Hemispherical Metallic Cavities

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***Abstract*—Aperture antennas cut onto probe-fed hemispherical cavities are investigated theoretically and experimentally. The result is valid for any aperture position and width. The operating frequencies of the antennas are primarily controlled by the resonant modes of the hemispherical cavity, with the input impedances easily matched by changing the probe length and/or aperture size. When the probe length and aperture size are designed properly, a very wide bandwidth of ∼45% can be obtained. This bandwidth is nearly twice that of a bare monopole. The calculations are verified by measurements.**

***Index Terms*—Coaxial probe, method of moments (MoM), resonant cavity, slot antenna.**

I. INTRODUCTION

The slot antenna has been an important subject for many years, and both the open and cavity-backed slot antennas have been studied extensively, e.g., [1]–[4]. The slot antenna has a number of advantages including its conformability, lightweight, ease of fabrication, and high power capability. The slot antenna can be fabricated on a spherical body, such as a sphere-like satellite and the nose of a plane. In land mobile satellite systems, a spherical antenna array can overcome the scanning problems that are found in planar arrays at low elevation angles [5].

The slot antenna on a spherical body was studied extensively [6]–[11]. The simplest spherical antenna is the zonal slot located in the

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