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NOVEL UNIDIRECTIONAL SLOT ANTENNA WITH A VERTICAL WALL

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Abstract—A novel slot antenna that consists of an H-shaped slot encompassed by a rectangular metallic wall and a pair of C-shaped slots outside the wall is proposed. It features a unidirectional pattern, small electrical dimensions and medium gain. The H-shaped slot radiates as an inductively loaded magnetic dipole while the induced electric currents on the vertical wall radiates as electric dipoles. The front-to-back ratio (FBR) of the antenna can be controlled by proper constructive and destructive interferences of radiating fields of the magnetic and electric dipoles. The size of the ground plane can be reduced by the use of the C-shaped slots that confine the currents to the proximity of the metallic wall. Two prototype antennas operating at 2.4 GHz were designed. By adjusting the structure parameters, the front-to-back ratio of the antenna can be conveniently altered. The first prototype has an impedance bandwidth (BW) of 3.8% for SWR ≤ 2, a 4.6 dBi gain, a 10-dB FBR and a ground size of $0.84\lambda_0 \times 0.64\lambda_0$ where λ_0 is the free-space wavelength at the center frequency. The corresponding figures of the second prototype are 1.83%, 4.1 dBi, over 20 dB and $0.64\lambda_0 \times 0.64\lambda_0$. Both antennas have a height of $0.128\lambda_0$.

1. INTRODUCTION

In many applications, e.g., aircrafts, satellites and missiles, where size, weight, cost, performance, ease of installation, and aerodynamic profile are constrained, antennas with unidirectional pattern and small size are often required. In spite of their large bandwidth, horn antenna, logarithm periodic antenna, Yagi-Uda antenna and tapered slot antenna [1–4] are limited by their electrical large sizes for these applications. On the other hand, microstrip patch antennas (MPAs) [5] are an appropriate candidate due to their low cost and profile, compactness, and conformity to planar and nonplanar surfaces. Various shapes of the MPA element were extensively studied, such as rectangular [6–10], U-slot [11, 12], H-shaped [13], fractal [14], annual ring [15], polygonal [16], star-shaped [17] patch antennas and so on, and have a lot of applications, for example in the RF front-end [18]. But their impedance bandwidths are often a few percents.

Another important aspect of the unidirectional radiation pattern is the front-to-back ratio (FBR). The FBR of the MPA is usually enhanced by using a large ground plane [6–8] or adding a reflecting strip [9, 10], which either increases the antenna sizes or complicates the antenna design procedure.

As we know, a narrow slot radiator, corresponding to a complementary counterpart of an electric dipole, can be fabricated on a supporting substrate and fed by a microstrip line or a coplanar waveguide (CPW). Its electrical size can be reduced by the terminal loading method, such as antennas with H-shaped or spiral lines loading slots [19, 20]. However, the slot antenna has a bi-directional pattern and is not suitable for many applications that require unidirectional radiation patterns. Common methods to alleviate this problem are to put a reflecting plane one-quarter wavelength away from the antenna or back the antenna with a cavity [21].

In this paper, an alternative approach for achieving unidirectional slot antenna is proposed. It is based on the notion that electric and magnetic dipoles, when placed on the same plane orthogonally to each other, will constructively interfered in one half space and destructively interfered in the other [22]. In this paper, an H-shaped slot, equivalence of an inductively loaded magnetic dipole, is encompassed by a thin rectangular metallic wall. Currents induced on the wall will radiate as electric dipoles. To confine the induced currents to the proximity of the wall, two C-shaped slots are symmetrically placed close to the radiating edges of the wall. As such, the size of the ground plane can be reduced and the FBR can also be enhanced.

Two prototypes of the proposed design operating at 2.4 GHz were constructed. The first prototype shows an impedance bandwidth (BW) of 3.8% for SWR ≤ 2, a 4.6 dBi gain, a 10-dB FBR and a total area (including the ground plane) of $0.84\lambda_0 \times 0.64\lambda_0$ where λ_0 is the free-space wavelength at 2.4 GHz. By adjusting some key structure parameters, we can improve the FBR albeit reduction of bandwidth. A second prototype was designed to have a larger FBR and the corresponding performance figures are 1.83%, 4.1 dBi, over 20 dB and $0.64\lambda_0 \times 0.64\lambda_0$. Both antennas have a height of $0.128\lambda_0$. Simulated and measured return losses and radiation patterns show good agreements.

2. GEOMETRY AND ANALYSIS OF THE SLOT ANTENNA

2.1. Geometry of the Proposed Antenna

Figure 1 shows the configuration of the proposed slot antenna which was fabricated on a substrate with a relative dielectric constant of 2.33 and thickness of 0.787 mm. On one side of the substrate, an H-shaped slot was etched at the center of a $G_W \times G_L$ ground plane and its size is determined by S_L, S_W, V_L and V_W, respectively (see Fig. 1(a)). A microstrip line with a two-stage impedance transformer on the other side of the substrate is utilized to feed the slot. There

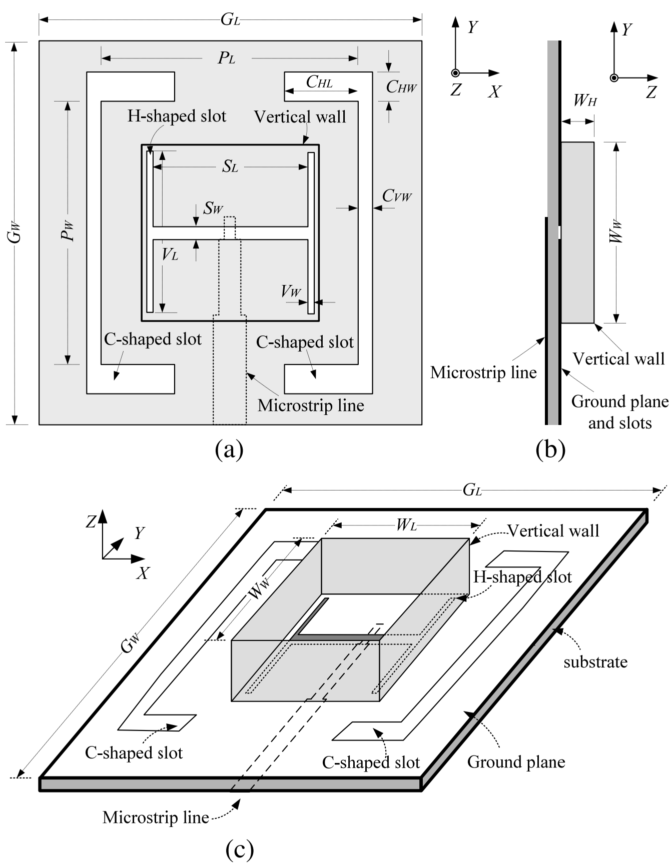

Figure 1. Geometries of the proposed slot antenna, (a) Top view, (b) Side view, (c) 3-D view.

is a vertical metallic wall soldered on the ground, forming an open frame enclosing the H-shaped slot. The dimensions of the rectangular wall are denoted by W_W (width), W_L (length) and W_H (height) (see Figs. 1(b) and (c)). Two C-shaped slots, in a mirror reflection fashion, are also etched on the ground plane and symmetrical along the central line of the microstrip line. The parameters of the C-shaped slots are illustrated in Fig. 1 (a), which are C_{HL}, C_{HW}, P_L, P_W and C_{VW}.

2.2. Analysis of the Antenna

First of all, the electric current on the vertical wall can be simply denoted by the solid line in Figs. 2(a) and (b). (The simulated electric current distribution on the vertical wall is given in Fig. 3(a) to verify the simplified electric current denotation and to show that radiating edges are mainly along AB and CD.) It is symmetrical along the y-z plane due to the symmetry of the structure, acting as two electric dipoles. The electric currents on AB and CD edges of the wall are dominant due to their larger intensity and identical directions. In contrast, electric currents on AC and BD edges are out of phase, thus their far fields cancel each other along the y-z and x-z planes. The electric field distribution in the H-shaped slot is given in Fig. 3(b). According to the equivalence theorem [23], the H-shaped slot is equivalent to a shortened magnetic dipole with inductive loading [19], which is along the x-direction, depicted as the dashed line in Fig. 2(a). Fig. 2(c) shows the interaction between the electric

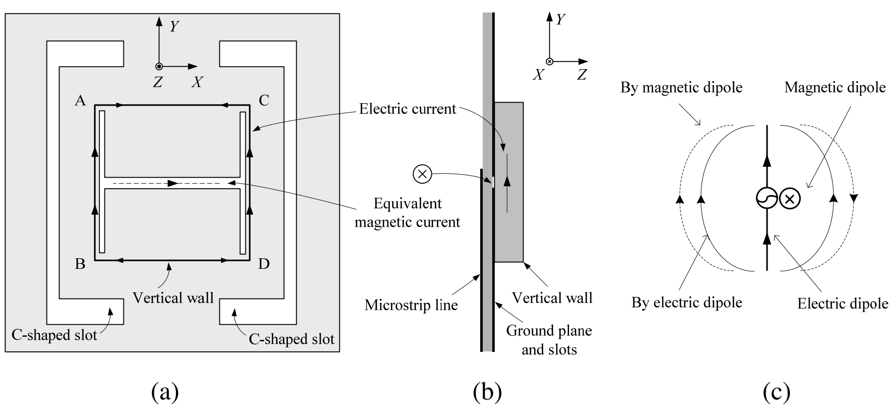

Figure 2. The proposed antenna is equivalent to the combination of a magnetic dipole and two electric dipoles, (a) Top view, (b) Side view, (c) Combination of a magnetic dipole and an electric dipole.

fields of the equivalent magnetic dipole and the electric dipoles, which are denoted by the dashed and solid lines, respectively. In the right-hand side, the electric fields corresponding to the magnetic and electric dipoles destructively interfere as they are out of phase. In contrast, the fields in the left-hand side are in phase and they constructively interfere. When the respective fields generated by the magnetic and electric dipoles hold approximately equal amplitude, a good FBR is achieved. Thus, the ground size plays a lesser role in the FBR and can be relatively small, in contrast to the large ground size of MPAs that is critical to obtain a large FBR. The two C-shaped slots confine the induced current on the ground plane in the proximity of the wall, as shown in Fig. 3(b), which also indicates that the large ground plane is unnecessary for the proposed antenna.

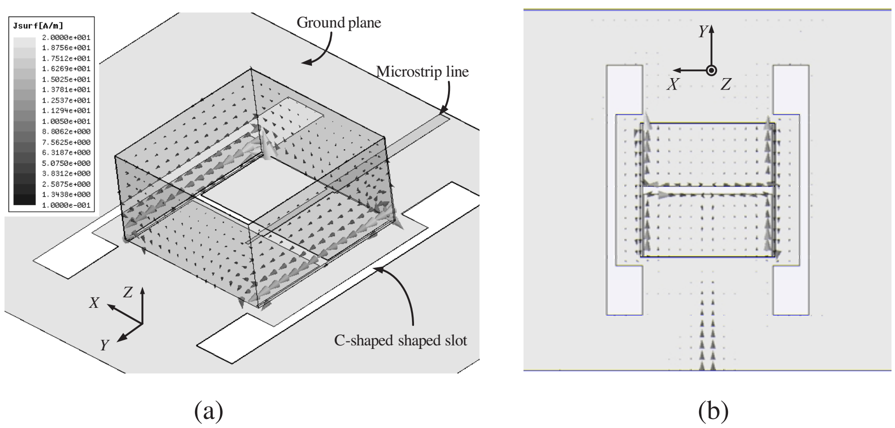

Figure 3. Simulated electric current distributions of the proposed antenna, (a) Electric current on the vertical wall, (b) Electric current on the ground plane.

3. NUMERICAL AND EXPERIMENTAL RESULTS

3.1. Sensitivity Analysis

In this section, we investigate structure parameters that are sensitive to the antenna performances. All the simulations were performed by Ansoft High Frequency Structure Simulator (HFSS$^{\mathrm{TM}}$) and the main antenna structure parameters and their effects will be summarized in reference to the geometry shown in Fig. 1. The operating principles of the proposed antenna and key performance indicators of the resonant

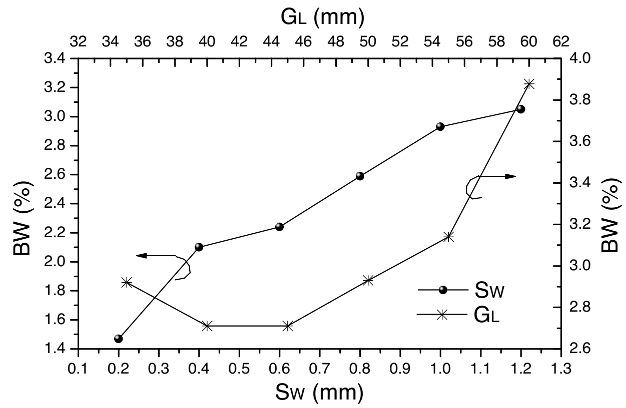

Figure 4. Simulated BW of the proposed antenna versus S_W and G_L. For S_w studies: $S_L = 14$, $V_W = 0.25$, $V_L = 13.5$, $P_L = 28$, $P_W = 16$, $C_{HL} = 3$, $C_{HW} = 5$, $C_{VW} = 2$, $W_H = 8$, $G_W = 50$, $G_L = 50$, $W_W = 14$, $W_L = 15$ (in millimeter). For G_L studies: $S_W = 1$, and the others are same to those of the former.

frequency, impedance BW and FBR can be further understood by these parametric studies.

First of all, the BW is mainly determined by two parameters G_L and S_W, as shown in Fig. 4. It increases along with S_W, denoting the width of the horizontal part of the H-shaped slot, which is similar to the ordinary slot antenna [24]. Increase in the size of the ground plane in the x-direction G_L has positive influence on the BW. However, the FBR decreases by 2 dB when G_L increases from 35 to 60 mm. Secondly, the center frequency is mainly influenced by the parameters of the H-shaped slot, especially S_W and V_L, the width of the horizontal and the length of the vertical portion of the slot, respectively. As shown in Fig. 5, the value of inductive loading of the slot increases with V_L and consequently, the center frequency decreases [19]. The center frequency increases along with S_W, similar to the characteristics of the ordinary slot antenna. Thirdly, the FBR is mainly determined by W_H and P_L. W_H is the height of the wall and P_L determines the distance between the two C-shaped slots. As shown in Fig. 6, the FBR increases rapidly from 4.6 to 18.3 dB as W_H increases from 4 to 12 mm. From the figure, it can be seen that the larger the distance P_L, the worse is the FBR. According to our simulations, ± 0.2 mm misalignments of the vertical wall along either x or y direction cause only 0.4% shift of the center frequency, and thus the antenna resonance is insensitive to wall misalignment.

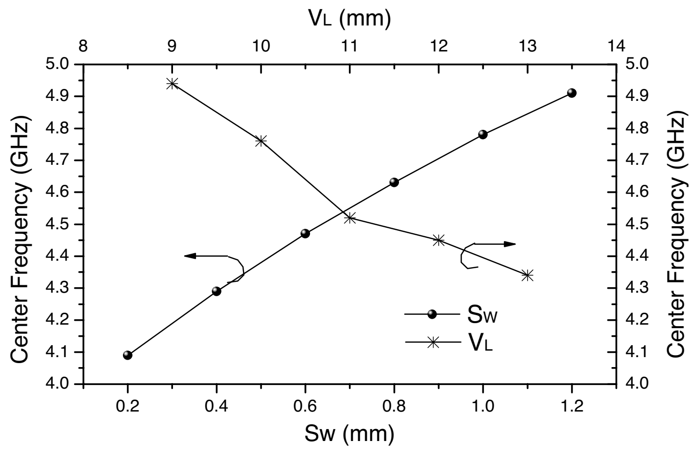

Figure 5. Simulated center frequency of the proposed antenna versus S_W and V_L. For V_L studies: $S_L = 14$, $S_W = 0.4$, $V_W = 0.25$, $P_L = 25$, $P_W = 19$, $C_{HL} = 3$, $C_{HW} = 5$, $C_{VW} = 2$, $W_H = 8$, $G_W = G_L = 50$, $W_W = 14$, $W_L = 15$ (in millimeter). For S_W studies, the other parameters are same to those in Fig. 4 ($V_L = 13.5$).

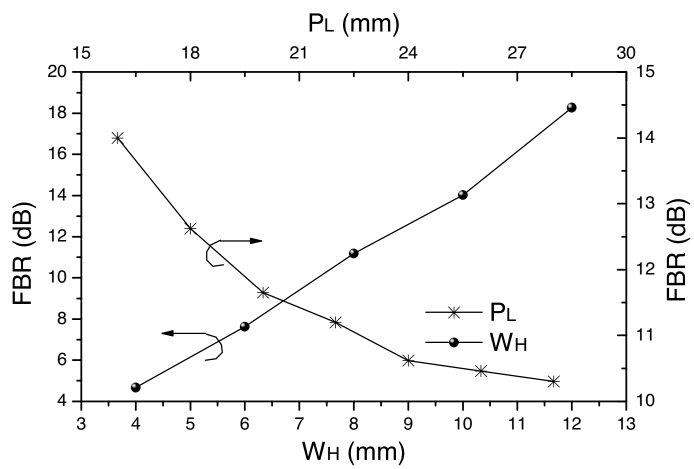

Figure 6. Simulated FBR of the proposed antenna versus W_H and P_L. For W_H studies: $S_L = 14$, $S_W = 1$, $V_W = 0.25$, $V_L = 13.5$, $P_L = 25$, $P_W = 19$, $C_{HL} = 3\,\mathrm{mm}$, $C_{HW} = 5$, $C_{VW} = 2$, $G_W = G_L = 50$, $W_W = 14$, $W_L = 15$ (in millimeter). For P_L studies: $P_W = 16$, $W_H = 8$, and the others are same to those of the former.

3.2. Design Procedure

After the key structure parameters that affect the antenna performance are presented, a simple design procedure of the proposed unidirectional slot antenna is given as follows:

1) *H-shaped slot design*: One can follow the design procedure in [19] for the H-shaped slot, but because of the effect of the vertical wall the designed center frequency should be about 10% lower than the desired one.
2) *Vertical wall*: To achieve a strong coupling between the H-shaped slot and the vertical wall, we suggest that the vertical wall should be close to the edge of H-shaped slot. Large values of W_W and W_L are not suitable and unnecessary, and the wall height can be set to $0.12\lambda_0$.
3) *C-shaped slots and the ground plane*: By changing the parameters of the C-shaped slots and the distance between them, the FBR and the impedance bandwidth can be adjusted. The size of the ground plane is more critical for the impedance BW than for the FBR, and its initial value can be set to $0.7\lambda_0 \times 0.7\lambda_0$.

In this paper two prototypes were designed by following the procedure mentioned above for 2.4 GHz wireless communication applications. To achieve an accurate center frequency, the parameters of the antenna should be adjusted carefully after a rough model is designed.

3.3. Tradeoff for Bandwidth

Two prototypes of the proposed antenna were designed. They demonstrate the tradeoff between impedance BW and FBR. The first prototype is emphasized on bandwidth consideration with the center frequency at 2.4 GHz. The microstrip feed line and the slots are etched on the substrate mentioned above. The vertical wall is made by folding a rectangular strip with a thickness of 0.1 mm and soldered on the ground plane. The structure parameters, in millimeters, are as follows: $S_L = 28.5$ $(0.228\lambda_0)$, $S_W = 1.8$, $V_L = 29$ $(0.232\lambda_0)$, $V_W = 0.3$, $P_L = 41$ $(0.328\lambda_0)$, $P_W = 33.5$ $(0.268\lambda_0)$, $C_{HL} = 6$, $C_{HW} = 11$, $C_{VW} = 2$, $W_L = 30$ $(0.24\lambda_0)$, $W_W = 29.5$ $(0.236\lambda_0)$, $W_H = 16$ $(0.128\lambda_0)$, $G_W = 80$ $(0.64\lambda_0)$, $G_L = 105$ $(0.84\lambda_0)$.

An HP8510C network analyzer and a compact range antenna measurement chamber with an HP85103C antenna measurement system were used to measure the return loss and the radiation patterns of the proposed antenna. Fig. 7 shows the simulated and the measured return losses, which agree well with each other. The measured

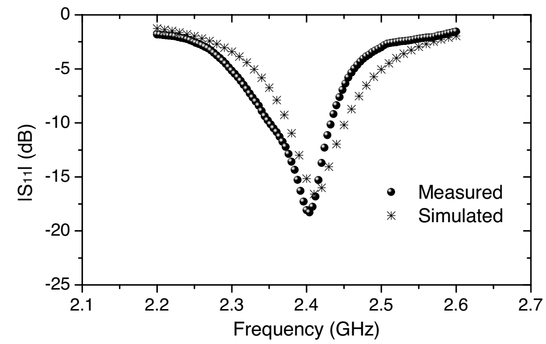

Figure 7. Measured and simulated return losses of the first prototype.

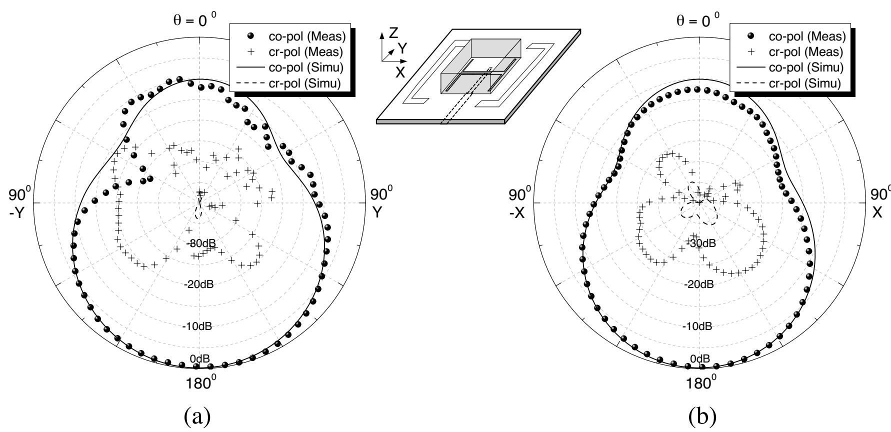

Figure 8. Measured and simulated radiation patterns at 2.4 GHz of the first prototype, (a) E plane, (b) H plane.

operating frequency band for SWR ≤ 2 covers from 2.345 to 2.435 GHz and the corresponding fractional BW is 3.8%. This BW can meet many requirements, for examples, the IEEE 802.11b wireless local area network (WLAN) and ISM (Industrial, Scientific, and Medical) frequency band at 2.4 GHz. The measured and simulated patterns in the E and H planes at 2.4 GHz are shown in Figs. 8(a) and (b), respectively. The patterns of the proposed antenna are stable across the whole band. The measured cross-polarization (cr-pol) is about -20 dB in both E and H planes, in contrast to -36 dB in the E plane and -33 dB in the H plane of the computed results. The measured half-power beamwidths are 90° in the E-plane and 71° in the H-plane, which are close to the simulated results of 86° and 72°. The FBR is another important specification, and the measured result is 10 dB, in good agreement with the simulated one. The gain is measured by comparing with a standard-gain horn antenna, and the measured value is 4.6 dBi. The measurements show that this antenna has a more symmetrical radiation pattern in H plane than that in E plane, due to the non-symmetrical structure caused by the feed network perpendicular to the x-z plane. Additionally, the SMA connector and the coaxial feed line, which are necessary in the experiments and located along $-Y$ direction, will cause random diffractions and also affect the symmetry of the measured results.

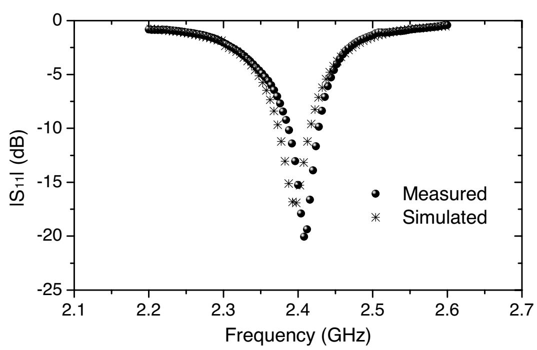

Figure 9. Measured and simulated return losses of the second prototype.

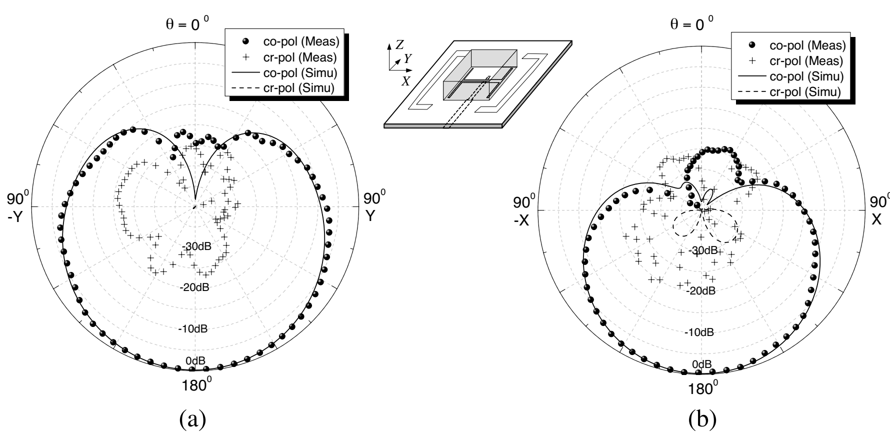

Figure 10. Measured and simulated radiation patterns at 2.4 GHz of the large FBR design, (a) E plane, (b) H plane.

3.4. Tradeoff for FBR

From the parametric studies, in order to obtain a design for 20-dB FBR, one effective method is to increase the height of the vertical wall (see Fig. 6). However, it increases the electrical thickness of the antenna as well. Here, we adjust other parameters to achieve our goal of large FBR. The parameters of the second prototype with a large FBR, in millimeters, are listed below, $S_L = 26$ $(0.208\lambda_0)$, $S_W = 0.7$, $V_L = 25$ $(0.2\lambda_0)$, $V_W = 0.3$, $P_L = 28$ $(0.224\lambda_0)$, $P_W = 35$ $(0.28\lambda_0)$, $C_{HL} = 11.5$, $C_{HW} = 8$, $C_{VW} = 3$, $W_L = 27$ $(0.216\lambda_0)$, $W_W = 26$ $(0.208\lambda_0)$, $W_H = 16$ $(0.128\lambda_0)$, $G_W = G_L = 80$ $(0.64\lambda_0)$. The measured and simulated return losses are shown in Fig. 9, where they agree well with each other. The measured frequency band for SWR ≤ 2 covers from 2.385 to 2.429 GHz, corresponding to a fractional BW of 1.83%. The measured and simulated patterns in the E and H planes at 2.4 GHz are given in Fig. 10 with reasonably good agreements, especially in the co-polarized main beam direction. The antenna has a measured FBR of 21 dB and 24 dB in E and H planes respectively. Meanwhile it has a very large beam width, 99° in the E-plane and 78° in the H-plane, and it shows a measured gain of 4.1 dBi. The measured cross-polarization radiations are about −20 dB in both E and H planes.

4. CONCLUSION

A novel slot antenna with unidirectional radiation patterns is proposed in this paper. The H-shaped slot, which is enclosed by a short rectangular conducting wall, radiates as a magnetic dipole. The electric currents induced on the conducting wall radiates as electric dipoles. A pair of C-shaped slot was employed to confine the induced currents within the region enclosed by the wall. Constructive and destructive interferences of the magnetic and electric dipoles make unidirectional radiation patterns possible for slot antennas. Parametric studies were performed to determine structure parameters that are sensitive to antenna performances. Two prototypes of the proposed antenna were fabricated. One is for wide-band design, and the measurement shows that it has an impedance BW of 3.8% for SWR ≤ 2 and a 10-dB FBR. The size of the ground plane is $0.84\lambda_0 \times 0.64\lambda_0$. For the large FBR design, the antenna has a measured impedance BW of 1.83% and over 20-dB FBR. The size of the ground plane is $0.64\lambda_0 \times 0.64\lambda_0$. The height of the rectangular conducting wall is only $0.128\lambda_0$ for both prototypes. Both antennas have a wide main beam and a medium gain.

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REFERENCES

1. Balanis, C. A., *Antenna Theory: Analysis and Design*, John Wiley & Sons, Inc., New Jersey, 2005.
2. Janaswamy, R. and D. H. Schaubert, "Analysis of the tapered slot antenna," *IEEE Trans. Antennas Propagat.*, Vol. 53, 1058–1065, Sept. 1987.
3. Yang, Y., Y. Wang, and A. E. Fathy, "Design of compact Vivaldi antenna arrays for UWB see through wall applications," *Progress In Electromagnetics Research*, PIER 82, 401–418, 2008.
4. Zhang, X. C., J. G. Liang, and J. W. Xie, "The quasi-Yagi antenna subarray fed by an orthogonal T junction," *Progress In Electromagnetics Research Letters*, Vol. 4, 109–112, 2008.
5. Pozar, D. M. and D. H. Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*, IEEE Press, New York, 1995.
6. Lai, H.-W. and K.-M. Luk, "Design and study of wide-band patch antenna fed by meandering probe," *IEEE Trans. Antennas Propagat.*, Vol. 54, 564–571, Feb. 2006.
7. Lai, H.-W. and K.-M. Luk, "Wideband stacked patch antenna fed by meandering probe," *Electron. Lett.*, Vol. 41, 297–298, Mar. 2005.
8. Mak, C.-L., H. Wong, and K.-M. Luk, "High-gain and wide-band single-layer patch antenna for wireless communications," *IEEE Trans. Vehicular Technology*, Vol. 54, 33–40, Jan. 2005.
9. Ghorbani, K. and R. B. Waterhouse, "Dual polarized wide-band aperture stacked patch antennas," *IEEE Trans. Antennas Propagat.*, Vol. 52, 2171–2174, Aug. 2004.
10. Rowe, W. S. T. and R. B. Waterhouse, "Reduction of backward radiation for CPW fed aperture stacked patch antennas on small ground planes," *IEEE Trans. Antennas Propagat.*, Vol. 51, 1411–1413, June 2003.
11. Khodaei, G. F., J. Nourinia, and C. Ghobadi, "A practical miniaturized U-slot patch antenna with enhanced bandwidth," *Progress In Electromagnetics Research B*, Vol. 3, 47–62, 2008.

12. Ansari, J. A. and R. B. Ram, "Broadband stacked U-slot microstrip patch antenna," *Progress In Electromagnetics Research Letters*, Vol. 4, 17–24, 2008.
13. Ansari, J. A., P. Singh, and S. K. Dubey, "H-shaped stacked patch antenna for dual band operation," *Progress In Electromagnetics Research B*, Vol. 5, 291–302, 2008.
14. Ataeiseresht, R., Ch. Ghobadi, and J. Nourinia, "A novel analysis of minkowski fractal microstrip patch antenna," *J. of Electromagn. Waves and Appl.*, Vol. 20, No. 8, 1115–1127, 2006.
15. Bao, X. L. and M. J. Ammann, "Comparison of several novel annular-ring microstrip patch antennas for circular polarization," *J. of Electromagn. Waves and Appl.*, Vol. 20, No. 11, 1427–1438, 2006.
16. Bilotti, F., M. Manzini, A. Alù, and L. Vegni, "Polygonal patch antennas with reactive impedance surfaces," *J. of Electromagn. Waves and Appl.*, Vol. 20, No. 2, 169–182, 2006.
17. Abbaspour, M. and H. R. Hassani, "Wideband star-shaped microstrip patch antenna," *Progress In Electromagnetics Research Letters*, Vol. 1, 61–68, 2008.
18. Cui, B., J. Zhang, and X.-W. Sun, "Single layer microstrip antenna arrays applied in millimeter-wave radar front-end," *J. of Electromagn. Waves and Appl.*, Vol. 22, No. 1, 3–15, 2008.
19. Azadegan, R. and K. Sarabandi, "A novel approach for miniaturization of slot antennas," *IEEE Trans. Antennas Propagat.*, Vol. 51, 421–429, Mar. 2003.
20. Sarabandi, K. and R. Azadegan, "Design of an efficient miniaturized UHF planar antenna," *IEEE Trans. Antennas Propagat.*, Vol. 51, 1270–1276, June 2003.
21. Zheng, B. and Z. Shen, "Effect of a finite ground plane on microstrip-fed cavity-backed slot antennas," *IEEE Trans. Antennas Propagat.*, Vol. 53, 862–865, Feb. 2005.
22. Luk, K.-M and H. Wong, "A new wideband unidirectional antenna element," *International Journal of Microwave and Optical Technology*, Vol. 1, 35–44, June 2006.
23. Kong, J. A., *Electromagnetic Wave Theory*, Wiley, New York, 1990.
24. Zhu, L., R. Fu, and K.-L. Wu, "A novel broadband microstrip-fed wide slot antenna with double rejection zeros," *IEEE Antennas and Wireless Propagation Letters*, Vol. 2, 194–196, 2003.