Design of Omnidirectional Dual-Polarized Antenna in Slender and Low-Profile Column

Yue Li, Zhijun Zhang, Zhenghe Feng, and Magdy F. Iskander

***Abstract*—In this communication, a dual-polarized diversity antenna with azimuthally omnidirectional patterns is designed inside a slender and low-profile columnar structure. The proposed antenna is composed of a cavity-backed notch for horizontal polarization and a folded slot for vertical polarization. The most important contribution of this communication is to reduce the antenna dimension, maintain high port isolation, broaden impedance bandwidth, and generate azimuthally omnidirectional radiation patterns. The overall volume of the proposed antenna is $42 \times 12 \times 12\ \mathrm{mm}^3$ $(0.336\lambda_0 \times 0.096\lambda_0 \times 0.096\lambda_0)$. A prototype of the proposed antenna is built and measured for 2.4-GHz wireless local area network (WLAN) applications to validate the idea.**

***Index Terms*—Antenna diversity, antenna minimization, antenna radiation patterns, slot antennas.**

I. Introduction

Dual-polarized antennas are studied for the merit of high-spectrum efficiency, and employed as polarized multiple-input-multiple-output (MIMO) antennas, instead of two spatially separated antennas with single polarization [1]–[3]. The isolation between the two polarizations is an important quality, and can be achieved by different radiating and feeding structures [4]–[14]. We also pay our attention to the radiation patterns and dimensions of the dual-polarized antennas. For the small-volume applications, such as access points and mobile repeaters, antennas with omnidirectional radiation pattern and compact dimension are more preferred.

Recently, our research group was focusing on the topic of small-volume multiple antenna system design [15], [16]. In the columnar structure, co-located monopole and slot are used for vertical and horizontal polarizations. For the 2.4-GHz WLAN application, the volume is $50 \times 16 \times 16\ \mathrm{mm}^3$ and the isolation is lower than -36 dB [15]. To achieve omnidirectional patterns in the azimuthal plane, two co-located slots are employed for dual polarizations [16]. For the same operating WLAN band of 2.4–2.48 GHz, the volume is only $83 \times 11 \times 11\ \mathrm{mm}^3$ and the port isolation is higher than 33.5 dB. Additionally, the azimuthally omnidirectional patterns are achieved for both of the polarizations with measured gain variations less than 2.9 dB and 2.1 dB. However, in order to match the impedance of the cavity-backed vertical slot, the slot length is tuned to 73 mm, which makes the overall height quite large. The antenna in [16] is difficult to be mounted on a mobile device due to its high profile.

In this communication, we have presented a modified antenna structure for dual polarizations and omnidirectional patterns. A cavity-backed notch is employed instead of the cavity-backed slot that is given in [16]. We have also examined the effect of the backing cavity on the notch performance. The volume of this new antenna is $42 \times 12 \times 12\ \mathrm{mm}^3$ $(0.336\lambda_0 \times 0.096\lambda_0 \times 0.096\lambda_0)$, which is only 60% of the antenna volume in [16] for the same operation band. In order to validate the design idea, we have built a prototype of the proposed antenna at 2.4 GHz WLAN band. We also have tested the antenna and discussed the results.

Manuscript received August 03, 2013; revised December 12, 2013; accepted January 25, 2014. Date of publication January 30, 2014; date of current version April 03, 2014. This work was supported in part by the National Basic Research Program of China under Contract 2013CB329002, in part by the National High Technology Research and Development Program of China (863 Program) under Contract 2011AA010202, the National Natural Science Foundation of China under Contract 61301001, the National Science and Technology Major Project of the Ministry of Science and Technology of China 2013ZX03003008-002, and the China Postdoctoral Science Foundation funded project 2013M530046.

Y. Li, Z. Zhang, and Z. Feng are with State Key Laboratory on Microwave and Digital Communications, Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: zjzh@tsinghua.edu.cn).

M. F. Iskander is with Hawaii Center for Advanced Communication (HCAC), University of Hawaii at Manoa, Honolulu, HI 96822 USA (e-mail: iskander@spectra.eng.hawaii.edu).

Color versions of one or more of the figures in this communication are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2014.2303817

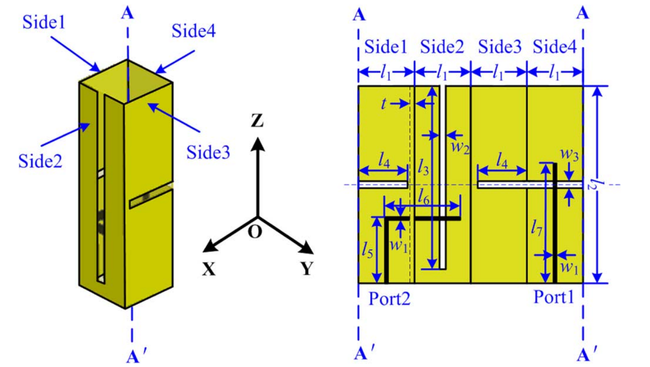

Fig. 1. Geometry and dimensions of the proposed antenna: (a) 3-D view; (b) expanded view.

TABLE I
Detailed Dimensions (Unit: mm)

l_1	l_2	l_3	l_4	l_5	l_6	l_7	w_1	w_2	w_3
12	42	39	10.5	14	15.15	25.5	1.9	1.8	1.5

II. Antenna Design

The geometry of the proposed antenna is shown in Fig. 1. Four walls of the metallic column are named as Side1 to Side4. A vertical notch is etched along Side2, and a horizontal slot is etched on Side1, Side3, and Side4. The four metallic walls are on the outer side of a central-hollow 1-mm-thick FR4 substrate ($\varepsilon_r = 4.4, tan\delta = 0.02$). The slot and the notch are fed by two 50-Ohm microstrip lines, which are on the inner side and shown in the expanded view (Fig. 1(b)). The horizontal slot is fed through Port1 for vertical polarization and the vertical notch is fed through Port2 for horizontal polarization. Ansoft high-frequency structure simulator (HFSS) is used to simulate the antenna structure, with the optimized design parameters listed in Table I. The overall antenna volume is $42 \times 12 \times 12\ \mathrm{mm}^3$ $(0.336\lambda_0 \times 0.096\lambda_0 \times 0.096\lambda_0$, λ_0 is the wavelength in free space at 2.4 GHz, with the value of 125 mm).

A. Notch for Horizontal Polarization

In the previous design [16], a cavity-backed slot is used for horizontal polarization. Two important qualities, the gain variation in the azimuthal plane and the impedance bandwidth, are systematically studied and tuned. As discussed in [16], for this slender column, the omnidirectional pattern is determined by the parameter l_1, and the gain variation in the azimuthal plane deteriorates drastically with increase in l_1. Under a small value of l_1, we have to increase the slot length

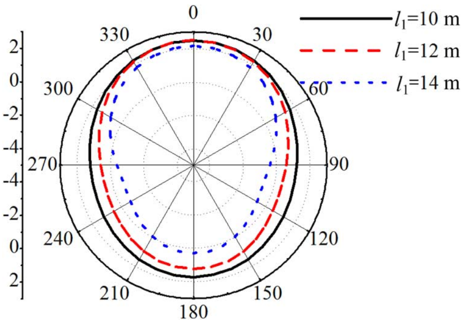

Fig. 2. Simulated gain variation in the azimuthal plane (xy-plane) with different values of l_1.

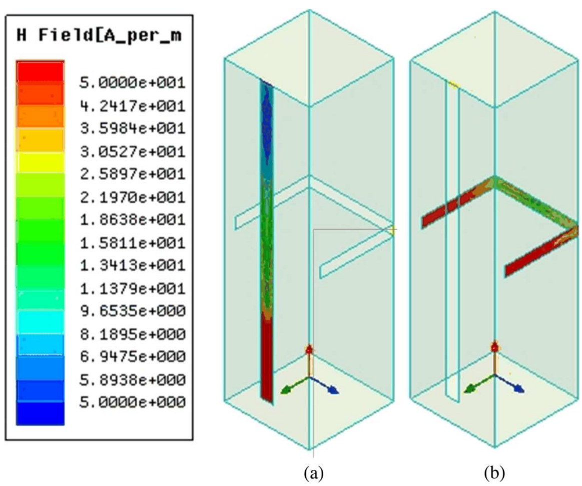

Fig. 3. Complex magnitude of magnetic field distributions of the proposed antenna at 2.44 GHz: (a) fed through Port2; (b) (a) fed through Port1.

for impedance matching. The vertical slot in [16] is operating at half wavelength mode but with a large length of 73 mm.

In order to reduce the overall length, we use a notch instead of the slot. The omnidirectional radiation pattern is less sensitive with different values of l_1, as shown in Fig. 2. The difference between gain variations at $l_1 = 10\ \mathrm{mm}$ and $l_1 = 14\ \mathrm{mm}$ is less than 1.6 dB, which is different from that in [16]. The reason can be explained from the complex magnitude of the magnetic field distribution shown in Fig. 3(a). The notch is operating at a quarter wavelength mode with magnetic field null on the top edge of Side2. Therefore, strong electric current appears on the four top edges, with contribution to the azimuthally omnidirectional pattern.

Similar as [16], the back-cavity also affects the notch length tuning. Different values of l_1 are studied and shown in Fig. 4. The notch is with optimized length of 39 mm and should resonate at the frequency much lower than 2.4 GHz. Larger l_1 makes the notch to be less affected by the neighboring metallic walls and with better impedance matching. Therefore, the value of l_1 is tuned by considering both the gain variation in the azimuthal plane and the impedance bandwidth, and 12 mm is selected with the desired performance. With a reduced length of the notch, the overall dimension of the proposed antenna is much smaller than the antenna in [16].

B. Folded Slot for Vertical Polarization

For vertical polarization, a horizontal slot is arranged in the middle of the column. This horizontal slot is folded on Side1, Side3, and Side4

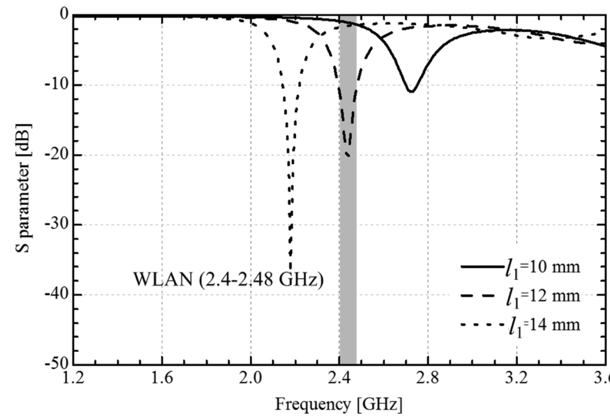

Fig. 4. Reflection coefficient of the proposed antenna fed through Port2 with different values of l_1.

to achieve omnidirectional pattern in the azimuthal plane. Fig. 3(b) shows the complex magnitude of the magnetic field distribution of the proposed antenna fed through Port1 at 2.44 GHz. The horizontal slot operates at the half wavelength magnetic field mode with a null in the middle. Therefore, the operating frequency of the horizontal mode is mainly determined by the slot length $l_1 + l_4 \times 2$. Although the operating frequency of the horizontal folded slot is the same as the slot in [16], the length of the slot is different. The length of the metallic column affects the input impedance of the horizontal slot. However, this effect can be compensated by tuning the values of l_4. When $l_1 = 12\ \mathrm{mm}$ and $l_4 = 10.5\ \mathrm{mm}$, the best impedance matching is tuned into the WLAN band of 2.4–2.48 GHz. For the feeding microstrip line fed through Port1, w_1 is also tuned for 50-Ohm input impedance, and l_7 is tuned for impedance matching.

Compared with the horizontal slot in [16], the gain variation of the vertical polarization in the azimuthal plane is larger. In [16], the horizontal slot is cut on all the four surfaces. In this communication, the horizontal slot is cut on Side1, Side3 and Side4. The gain is lower in the direction of Side2 (+x axis). Due to the small value of l_1, the gain variation is still acceptable, and validated by measurement in the following section.

C. Isolation Discussion

Ports isolation is another key quality for the dual-polarized antennas. For the proposed antenna, the vertical notch and the horizontal folded slot are arranged to be spatially orthogonal. The currents are also found to be spatial symmetric, introducing high isolation between the ports, which can be explained from the electric current distribution. The vector current distributions of the proposed antenna fed through Port1 and Port2 at 2.44 GHz are depicted in Figs. 5 and 6.

As shown in Fig. 3(b), the horizontal folded slot operates at the half wavelength magnetic field mode. There are magnitude field nulls in the middle of the slot. The peak current at the slot ends on Side1 and Side3 are in-phase. The currents coupled to the vertical notch edges on Side2 are also in-phase. No electric field exists in the notch due to the equal potential along the two edges. Therefore, little energy can be coupled to Port2 from Port1. As shown in Fig. 6, the currents along the two edges of the vertical notch are out-of-phase. The coupled currents to the horizontal folded slot are also shown in Fig. 6. Along the upper and lower edges of the folded slot, the currents are also in-phase. Therefore, little energy can be coupled to Port1 from Port2. We also can observe the currents on Side2 (in Fig. 5) are almost orthogonal to those on the same surface (in Fig. 6). Theoretically, high ports isolation can be achieved in such a small volume of $l_2 \times l_1 \times l_1 = 42 \times 12 \times 12\ \mathrm{mm}^3$.

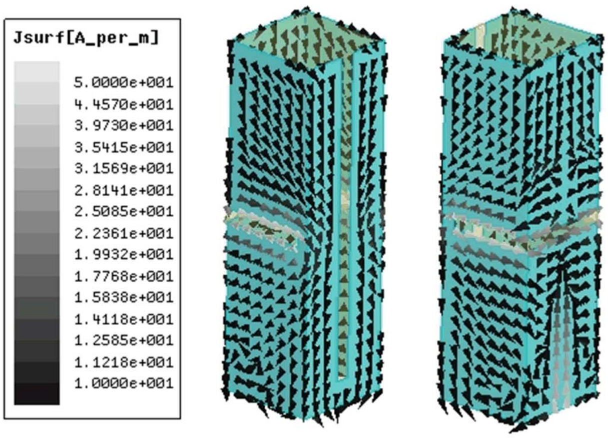

Fig. 5. Vector electric current distribution of the proposed antenna fed through Port1 at 2.44 GHz, (a) Side1 and Side2, (b) Side3 and Side4.

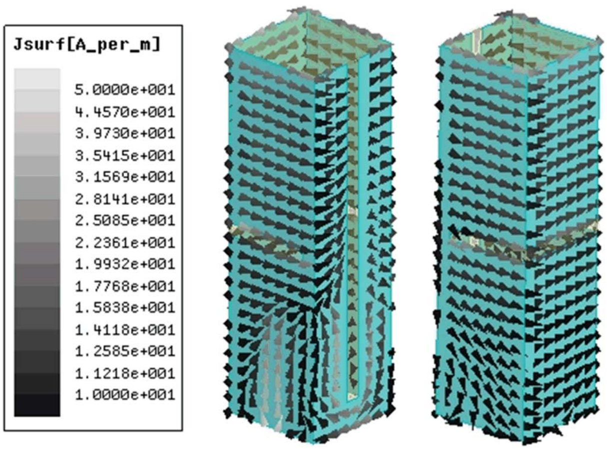

Fig. 6. Vector electric current distribution of the proposed antenna fed through Port2 at 2.44 GHz, (a) Side1 and Side2, (b) Side3 and Side4.

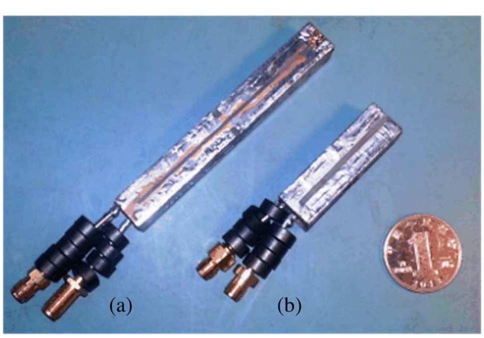

Fig. 7. Photographs of (a) antenna in [16], (b) antenna proposed in this communication.

III. Antenna Measurements

A prototype of the proposed antenna was built for 2.4-GHz WLAN application and shown in Fig. 7. The antenna in [16] is also shown in Fig. 7 for comparison. Although operating in the same frequency, the antenna proposed in this communication is almost half the volume of the antenna in [16]. Ferrite rings are used to eliminate the surface current on the feeding cables.

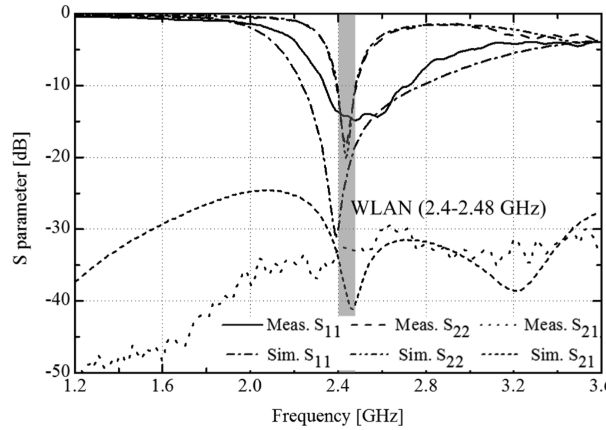

Fig. 8. Measured and simulated S parameters of the proposed antenna.

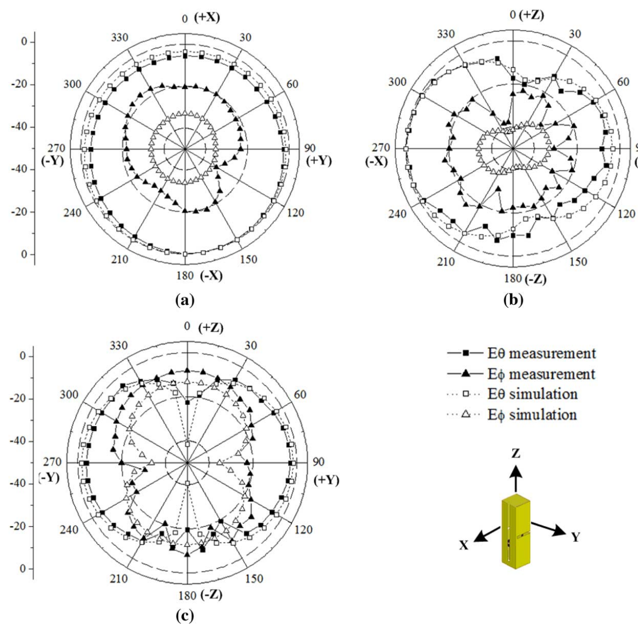

Fig. 9. Simulated and measured radiation patterns of the proposed antenna fed though Port1 at 2.44 GHz, (a) xy-plane, (b) xz-plane, (c) yz-plane.

The measured and simulated S parameters are shown in Fig. 8. The -10 dB bandwidths of the reflection coefficient are 2.34–2.72 GHz for vertical polarization when the antenna is fed through Port1, and 2.39–2.49 GHz (shown in Fig. 4, where $l_2 = 12$ mm) for horizontal polarization when the antenna is fed through Port2. The discrepancy between the measured and simulated S_{11} can be attributed to fabrication error and the modeling error. The horizontal slot is cut on three sides. The right-angle corner formed by any two of the adjoining side walls can affect the results. The port isolation is also illustrated in Fig. 8. S_{21} is higher than 32.5 dB in the band of 2.4–2.48 GHz, agreeing well with the simulated result.

Figs. 9 and 10 illustrate the measured normalized radiation patterns for both of the polarizations at 2.44 GHz. In the xy-plane, the radiation patterns for both of the polarizations are omnidirectional. In simulation, the gain variation (maximum gain minus minimum gain) in the xy-plane is 3.5 dB for vertical polarization and 2.1 dB (shown in Fig. 2, where $l_2 = 12$ mm) for horizontal polarization. The measured gain variations in the xy-plane are 4.5 dB for vertical polarization and 2.4 dB for horizontal polarization. Directivity deteriorates due to manual fabrication error and the unwanted radiation of the feeding cables.

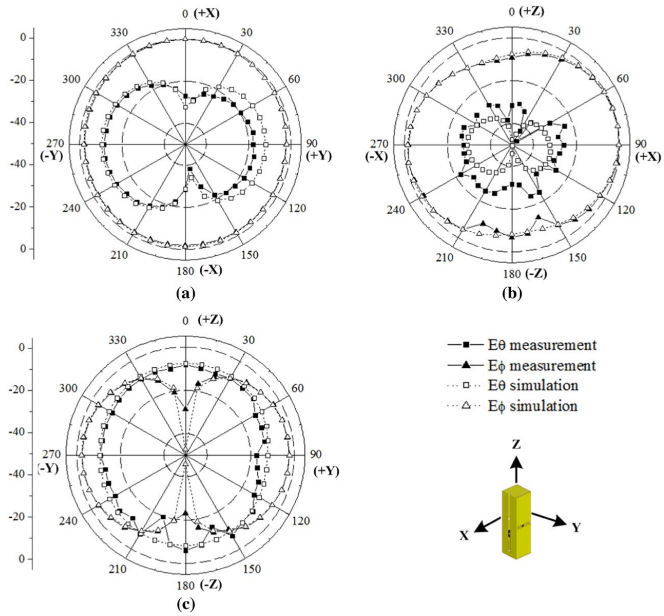

Fig. 10. Simulated and measured radiation patterns of the proposed antenna fed though Port2 at 2.44 GHz, (a) xy-plane, (b) xz-plane, (c) yz-plane.

TABLE II
RADIATION EFFICIENCY

Frequency [GHz]	2.40	2.42	2.44	2.46	2.48
Sim. Ver_pol.	90%	91%	91%	91%	90%
Meas. Ver_pol.	78%	91%	95%	91%	83%
Sim. Hori_pol.	65%	71%	73%	72%	68%
Meas. Hori_pol.	63%	71%	74%	71%	66%

TABLE III
QUALITY COMPARISONS

Quality	Antenna in [16]	Proposed antenna
Volume	83×11×11 mm^3	42×12×12 mm^3
Ports isolation	33.5 dB	32.5 dB
Gain at 2.44 GHz Ver_pol./Hori_pol.	3.39 dB / 1.75 dB	2.78 dB / 1.16 dB
Gain variation at 2.44 GHz Ver_pol./Hori_pol.	2.9 dB / 2.1 dB	4.5 dB / 2.4 dB
2:1 VSWR bandwidth Ver_pol./Hori_pol.	2.31-2.54 GHz / 2.39-2.49 GHz	2.34-2.72 GHz / 2.39-2.49 GHz

Radiating efficiency is measured and compared with its simulation data. As listed in Table II, in the WLAN band, the simulated radiation efficiency is higher than 90% for the vertical polarization but only 65% for the horizontal one. The measured radiation efficiency is higher than 78% for the vertical polarization but only 63% for the horizontal one. As discussed in [16], for a regular slot, the electric field mainly exists in the aperture. However, for a cavity-backed slot, electric field exists not only in the aperture, but it also exists in the backing cavity, suffering more substrate loss. Second, the backing cavity operates as a shunt capacitance, and also affects the impedance matching of the notch. Therefore, the efficiency of the notch is lower than that for a regular slot.

In the WLAN band, the maximum gain of the vertical polarization is 2.78 dBi, fluctuating within 0.65 dB. The maximum gain of the horizontal polarization is 1.35 dBi, with a fluctuation of less than 0.65 dB. An average gain difference of 1.6 dB exists between the two polarizations because they are different in pattern directivity and radiation efficiency.

IV. CONCLUSION

In this communication, a compact dual-polarized antenna with omnidirectional radiation pattern in the azimuthal plane is proposed. By using a notch instead of the slot in [16], 40% volume reduction is achieved without obvious performance deterioration. The comparisons between the antenna in [16] and the proposed antenna are summarized and listed in Table II. The dimension of the proposed antenna is $42 \times 12 \times 12\ \mathrm{mm}^3$, only 60% of the volume in [16] for the same frequency. The omnidirectional performance is worse than the antenna in [16], but still acceptable for practical usage.

REFERENCES

[1] T. Brown, "Indoor MIMO measurements using polarization at the mobile," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 400–403, 2008.
[2] D. Landon and C. Furse, "Recovering handset diversity and MIMO capacity with polarization-agile antennas," *IEEE Trans. Antennas Propag.*, vol. 55, no. 11, pp. 3333–3340, Nov. 2007.
[3] A. Konanur, K. Gosalia, S. Krishnamurthy, B. Hughes, and G. Lazzi, "Increasing wireless channel capacity through MIMO systems employing co-located antennas," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 6, pp. 1837–1844, Jun. 2005.
[4] Y. Guo, K. Khoo, and L. Ong, "Wideband dual-polarized patch antenna with broadband baluns," *IEEE Trans. Antennas Propag.*, vol. 55, no. 1, pp. 78–83, Jan. 2007.
[5] Y. Guo, K. Luk, and K. Lee, "Broadband dual polarization patch element for cellular-phone base stations," *IEEE Trans. Antennas Propag.*, vol. 50, no. 2, pp. 251–253, Feb. 2002.
[6] H. Wong, K. Lau, and K. Luk, "Design of dual-polarized L-probe patch antenna arrays with high isolation," *IEEE Trans. Antennas Propag.*, vol. 52, no. 1, pp. 45–52, Jan. 2004.
[7] S. Gao, L. Li, M. Leong, and T. Yeo, "Dual-polarized slot-coupled planar antenna with wide bandwidth," *IEEE Trans. Antennas Propag.*, vol. 51, no. 3, pp. 441–448, Jan. 2003.
[8] T. Chiou and K. Wong, "Broad-band dual-polarized single microstrip patch antenna with high isolation and low cross polarization," *IEEE Trans. Antennas Propag.*, vol. 50, no. 3, pp. 399–402, Mar. 2004.
[9] M. Barba, "A high-isolation, wideband and dual-linear polarization patch antenna," *IEEE Trans. Antennas Propag.*, vol. 56, no. 5, pp. 1472–1476, May 2004.
[10] H. Li, J. Xiong, Z. Ying, and S. He, "Compact and low profile co-located MIMO antenna structure with polarisation diversity and high port isolation," *Electron. Lett.*, vol. 46, no. 2, pp. 108–110, Jan. 2010.
[11] E. Soliman, M. Ibrahim, and A. Abdelmageed, "Dual-polarized omnidirectional planar slot antenna for WLAN applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 9, pp. 3093–3097, Sep. 2005.
[12] C. Lee, S. Chen, and P. Hsu, "Isosceles triangular slot antenna for broadband dual polarization applications," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3347–3351, May 2009.
[13] Y. Li, Z. Zhang, W. Chen, Z. Feng, and M. Iskander, "A dual-polarization slot antenna using a compact CPW feeding structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 191–194, 2010.
[14] Y. Li, Z. Zhang, W. Chen, Z. Feng, and M. Iskander, "Dual-mode loop antenna with compact feed for polarization diversity," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 95–98, 2011.
[15] Y. Li, Z. Zhang, J. Zheng, and Z. Feng, "Design of dual-polarized monopole-slot antenna with small volume and high isolation," *IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2511–2514, May 2012.
[16] Y. Li, Z. Zhang, J. Zheng, and Z. Feng, "Compact azimuthal omnidirectional dual-polarized antenna using highly isolated co-located slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4037–4045, Sep. 2012.