Parallel-Plate Transmission Line and L-Plate Feeding Differentially Driven H-Slot Patch Antenna

Shao Wei Liao, Quan Xue, *Fellow, IEEE*, and Jian Hua Xu

***Abstract*—A newly developed patch antenna, designated as the parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna, is presented in this letter. The parallel-plate transmission line will not introduce inductance to the input impedance of a patch antenna, thus the height of the patch can be largely increased. In addition, by employing L-plate feeding and H-slot patch simultaneously, the height of the patch can reach $0.25\lambda_0$. Measurements show that the impedance bandwidth can be extended to 115% (0.79–2.94 GHz) and 3-dB-gain bandwidth can be extended to 83% (0.80–1.93 GHz). The radiation pattern is stable, and the maximum gain is 9.9 dBi within the 3-dB-gain bandwidth.**

***Index Terms*—3-dB-gain bandwidth, differentially driven antenna, impedance bandwidth, parallel-plate transmission line.**

I. Introduction

In RECENT years, differential circuits are becoming more and more popular in microwave circuit design, especially in radio frequency integrated circuits (RFICs) and microwave monolithic integrated circuits (MMICs), due to their good performances such as low noise, harmonic suppression, high linearity, and large dynamic range [1], [2]. However, most antennas are designed for single-ended circuits. When they are integrated with differential circuits, baluns are required to transform differential signals to single-ended signals. Thus, differentially driven antennas are demanded in differential microwave circuit designs to get rid of bulky off-chip and lossy on-chip baluns to improve the receiver noise performance or transmitter power efficiency. Moreover, the cancellation mechanism introduced by the differentially driven scheme largely reduces the cross-polarization radiation and thus enhances the polarization purity of the antenna [3]–[6].

Wide impedance, gain bandwidths, and stable radiation are the most demanded features for patch antennas. The simplest way to enhance the impedance bandwidth is to increase the height of the patch above the ground plane. However, because of the inductance introduced by the feeding structure, the height of the patch has to be restricted within a few percent of a wavelength. For coaxial feeding case, the height of the probe has to be increased with the height of the patch, which introduces extra inductance to the input impedance and deteriorates the input matching of the antenna. This effect limits the impedance bandwidth of patch antennas [7].

To solve this problem, L-probe, meandering probe, U-slot patch, and other bandwidth broadening techniques were invented [8]–[11]. For example, for L-probe feeding, the capacitance formed between the patch and the horizontal portion of the probe can compensate the inductance introduced by the vertical portion of the probe. Thus, it is possible to increase the height of the patch to $0.12\lambda_0$ to achieve a 10-dB impedance bandwidth of 30% for patch antennas with flat ground plane. However, if the height is further increased, the introduced inductance will be too large to be cancelled efficiently by the capacitance over a wide range of frequency. As a result, the impedance bandwidth decreases when the patch height exceeds $0.12\lambda_0$ [10]. Other bandwidth broadening techniques also have similar limitation.

If the height of the patch, without introducing extra inductance, can be further increased, the bandwidth of the patch antenna can be further enhanced [7]. A differentially driven patch antenna makes balanced transmission-line feeding possible, which was originally proposed in [5]. Balanced transmission-line feeding has an inherent advantage that it will not introduce extra inductance. The height of the antenna patch and the impedance bandwidth reach $0.1\lambda_0$ and 34.5%, respectively, in [5]. In [6], by using a folded plate pair to feed the radiation patch, the height of the radiation patch reached $0.12\lambda_0$, and the impedance bandwidth was extended to 74%. The 3-dB-gain bandwidth of the antenna is about 50%, and the average gain across the 3-dB-gain bandwidth is about 8.5 dBi.

A newly developed patch antenna, designated as the parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna, is presented in this letter. The parallel-plate transmission line will not introduce inductance to the input impedance of the patch antenna, thus the height of the patch can be largely increased. In addition, by employing L-plate feeding and H-slot patch simultaneously, the height of the patch can reach $0.25\lambda_0$. Measurements show that the impedance bandwidth can be extended to 115% (0.79–2.94 GHz), and 3-dB-gain bandwidth can be extended to 83% (0.80–1.93 GHz). The radiation pattern is stable, and the maximum gain is 9.9 dBi within the 3-dB-gain bandwidth.

II. Antenna Design

A. Electrical Parameters of Differentially Driven Antenna

The differential input impedance Z_d of a symmetric differentially driven antenna is given by [4]

$$Z_\mathrm{d} = Z_{11} - Z_{21} - Z_{12} - Z_{22} \tag{1}$$

Manuscript received March 07, 2012; revised May 02, 2012; accepted June 01, 2012. Date of publication June 08, 2012; date of current version June 19, 2012.

S. W. Liao and Q. Xue are with the City University of Hong Kong, Kowloon, Hong Kong, China (e-mail: shaoliao@cityu.edu.hk, eeqxue@cityu.edu.hk).

J. H. Xu is with Zhongshan College, University of Electronic Science and Technology of China, Zhongshan 528402, China (e-mail: xujh@zsc.edu.cn).

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

Digital Object Identifier 10.1109/LAWP.2012.2203778

where Z_{11}, Z_{21}, Z_{12}, and Z_{22} are Z-parameters of two input ports when the differentially driven antenna is regarded as a two-port single-ended network. The resonant frequency is defined as where the reactance of the input impedance Z_{d} is equal to zero [4]. From (1), we can derive following relation:

$$S_{\mathrm{dd11}} = \frac{1}{2}(S_{11} - S_{12} - S_{21} - S_{22}) \tag{2}$$

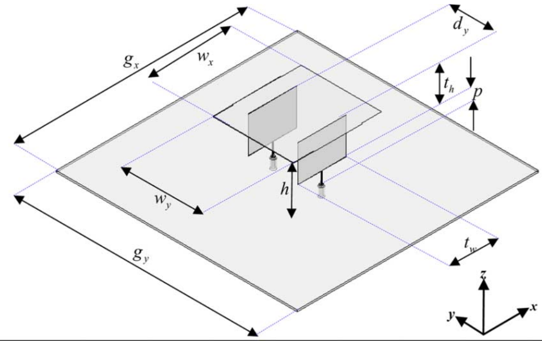
where S_{dd11} is the reflection coefficient of differentially driven antenna. S_{11}, S_{21}, S_{22}, and S_{12} are S-parameters of two input ports when the differentially driven antenna is regarded as a two-port single-ended network. In this letter, the impedance bandwidth of the differentially driven antenna is defined as a range of frequencies over which the differential reflection coefficient is less than -10 dB ($S_{\mathrm{dd11}} < -10$ dB).

B. Antenna Design

The basic structure of the proposed antennas comprises a ground plane, a parallel-plate transmission line formed by two parallel plates, and a radiation patch. For conventional single-ended probe feeding, the series inductance introduced by the probe is from the self-inductance of the probe. The longer the probe is, the larger the inductance will be introduced. This deteriorates the input matching of the antenna. On the other hand, the connection between the parallel plate and other parts of the antenna will also introduce a reactive component to the input impedance. However, according to the transmission line theory, series distributed inductance and shunt distributed capacitance make the parallel plate become a transmission line. From the microwave network theory, we know that the transmission line itself does not introduce a reactive component, but only changes the phase of signals. Thus, no matter how long it is, the parallel plate will not introduce extra inductance to the input impedance. By this way, the height of the patch fed by the parallel plate can be largely increased. Two lower edges of the parallel-plate transmission line are connected to two short feeding probes of two 50-Ω SMA launchers. The characteristic impedance of the differential feeding line, thus, is 100 Ω. The short feeding probes are inevitable, but will only introduce small inductance to the input impedance of the antenna. The two SMA ports below the ground, together, are designated as the "differential input port" of the differentially driven patch antenna. For the antennas proposed in this letter, the ground plane is made of aluminum with the thickness of 2 mm. The radiation patch and parallel-plate transmission line are made of copper with the thickness of 0.3 mm. The radii of the two probes are 0.635 mm.

First, the parallel-plate transmission line is used to feed the radiation patch directly. This means the two higher edges of the parallel plate are connected to the bottom of the patch. Thus, electromagnetic (EM) energy can be transmitted from the parallel plate to the patch directly. The geometry of the first antenna is shown in Fig. 1, where optimized geometrical parameters of the antenna are also given. To optimize the geometrical parameters, a MATLAB script based on pattern search is implemented. The script can automatically analyze the simulation results, generate new geometrical parameters, and drive Ansoft HFSS [12] to simulate the antenna under the new parameters iteratively, until the optimization objective is reached. The optimization objective is maximizing the relative impedance bandwidth under the restriction that the variation of the gain at the broadside of the antenna should be less than 6 dBi within the impedance bandwidth. The radiation patch is placed over a ground at the height of $0.20\lambda_0$ ($f_0 = 1.60$ GHz). The simulated differential reflection coefficient S_{dd11} and gain of the antenna are shown in Fig. 2. The impedance bandwidth of the antenna is 69% (1.05–2.15 GHz) centered at 1.60 GHz, and the 3-dB-gain bandwidth is 66% (0.95–1.88 GHz). It can be observed that the proposed antenna has a maximum gain of 10.3 dBi. Fig. 3 shows the simulated input impedance of the differentially driven antenna. It is noted that the three resonances occur at 1.17, 1.44, and 1.96 GHz, respectively, within the impedance bandwidth (1.05–2.15 GHz). For the patch antenna in the basic form, the resonant frequency of the dominant resonant mode is far away from those of higher resonant modes. For this antenna, the parallel-plate transmission line feeding perturbs the currents on the patch, and two new resonant modes with the resonant frequencies close to that of the dominant mode are created. This gives a wide impedance bandwidth. From the simulation, it can be found that each resonant mode corresponds to a specific current distribution on the patch.

Then, to enhance the bandwidth of the first antenna, the upper edges of the parallel-plate transmission line are bent to be horizontal, which is called L-plate here. L-plate compensates the inductance introduced by the two short coaxial feeding probes,



Parameter	g_x=g_y	t_w	t_h	p	h	d_y	w_y	w_x
Value (mm)	300	74	32.5	5.5	38	30	100	110
Value (λ_0)	1.6	0.39	0.17	0.029	0.20	0.16	0.53	0.59

Fig. 1. Geometry of parallel-plate transmission line, direct-feeding, differentially driven patch antenna.

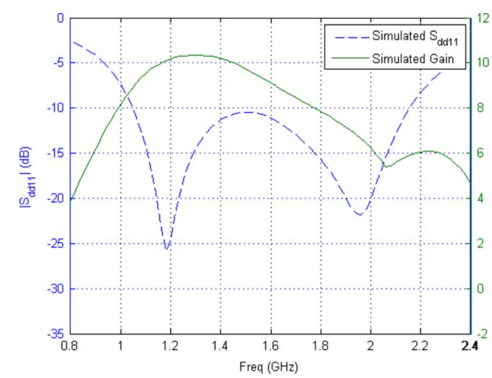


Fig. 2. Simulated S_{dd11} and gain of parallel-plate transmission line, direct-feeding, differentially driven patch antenna.

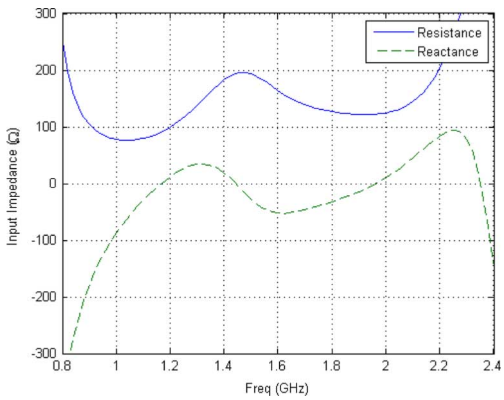
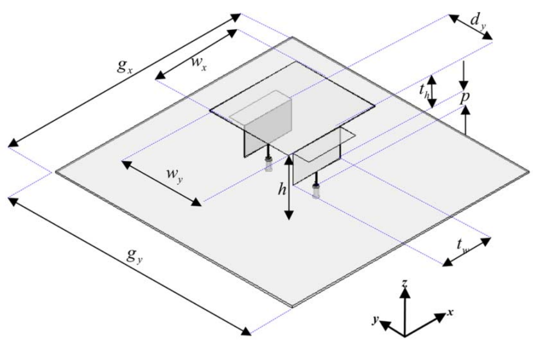


Fig. 3. Simulated differential input impedance Z_{d} of the parallel-plate transmission line, direct-feeding, differentially driven patch antenna.



Parameter	g_x=g_y	t_w	t_h	p	h
Value (mm)	300	60	34	3	43
Value (λ_0)	1.47	0.29	0.17	0.015	0.21
Parameter	d_y	p_g	p_l	w_y	w_x
Value (mm)	43	6	20	100	110
Value (λ_0)	0.21	0.029	0.098	0.49	0.54

Fig. 4. Geometry of parallel-plate transmission line and L-plate feeding differentially driven patch antenna.

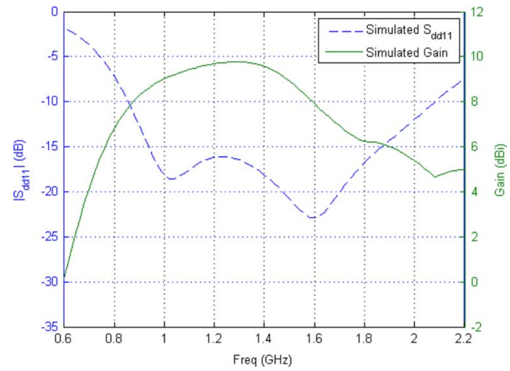


Fig. 5. Simulated S_{dd11} and gain of parallel-plate transmission line and L-plate feeding differentially driven patch antenna.

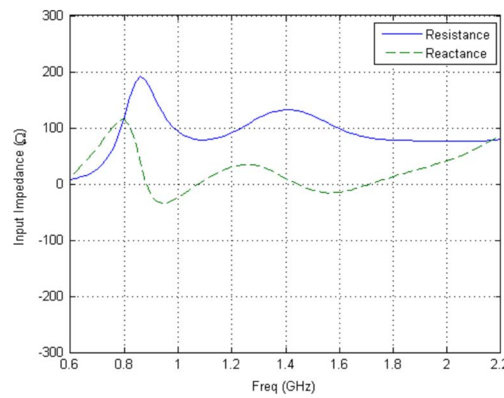
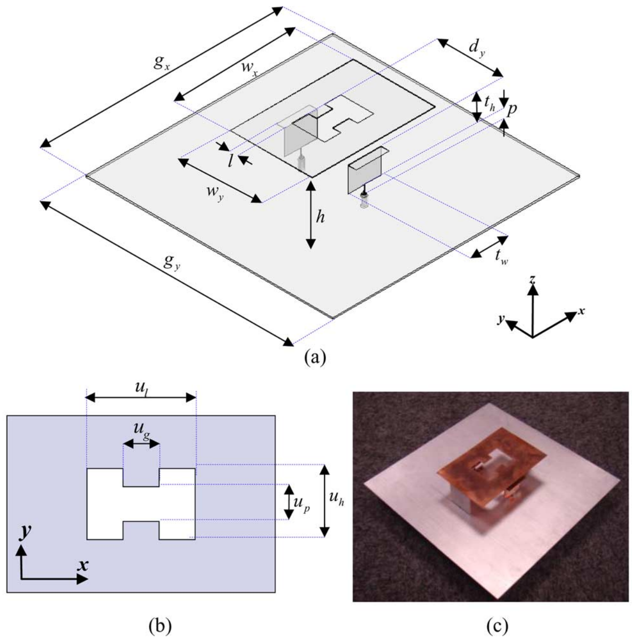


Fig. 6. Simulated differential input impedance Z_{d} of the parallel-plate transmission line feeding differentially driven patch antenna.

just like the L-probe does [10]. The geometry of the second antenna is shown in Fig. 4, where the optimized geometrical parameters of the antenna are also given. The radiation patch is placed over a ground at the height of $0.21\lambda_0$ ($f_0 = 1.47$ GHz), which is $0.01\lambda_0$ higher than that of the first antenna. The simulated differential reflection coefficient S_{dd11} and gain of the antenna is shown in Fig. 5. The impedance bandwidth of the antenna is 83% (0.86–2.08 GHz) centered at 1.47 GHz and the 3-dB-gain bandwidth is 73% (0.80–1.72 GHz). It can be observed that the proposed antenna has a maximum gain of 9.8 dBi within the 3-dB-gain bandwidth. Fig. 6 shows the simulated input impedance of the second antenna. It is noted that the four resonances occur at 0.88, 1.08, 1.44, and 1.71 GHz, respectively, within the impedance bandwidth. For this antenna, the horizontal parts of the L-plate with the patch act capacitively within a certain frequency range. Together with the inductance of the two short probes, the overall structure acts as a series differential resonant element, and a new resonance close to the other three resonances is introduced. Thus, compared tothe first antenna, there is one more resonance.

At last, to further enhance the impedance bandwidth of the second antenna, an H-slot is cut on the radiation patch. The H-slot, originally proposed in [3], is corresponding to the U-slot of single-ended patch antennas [8], which can greatly enhance the impedance bandwidth of differentially driven patch antennas. The geometry of the final antenna is shown in Fig. 7, where the optimized geometrical parameters are also given. This antenna is called *parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna*. The height of the radiation patch reaches $0.26\lambda_0$ ($f_0 = 1.80$ GHz), which is $0.05\lambda_0$ higher than that of the second antenna. Fig. 8 reveals that its simulated impedance bandwidth is 111% (0.80–2.80 GHz) centered at 1.80 GHz, and the 3-dB-gain bandwidth is 80% (0.80–1.93 GHz). The maximum simulated gain is 10.5 dBi occurring at 1.3 GHz. The differential input impedance of the antenna is given in Fig. 9. It is clearly indicated that six resonances—located at 0.87, 1.11, 1.50, 1.80, 2.0, and 2.27—are obtained within the impedance bandwidth. Compared to the first and second antennas, there are three and two more resonances, respectively, which leads to the widest impedance bandwidth. For this antenna, the two new resonances close to the other four are due to the additional paths that the H-slot provides for the currents on the patch. Simulated radiation patterns of the proposed antenna at 0.8, 1.4, and 1.9 GHz are illustrated in Fig. 10, showing that the radiation characteristics are stable across the 3-dB-gain bandwidth. Moreover, due to the symmetry of the structure and excitation, the radiation pattern is symmetric in both E-plane and H-plane at any frequency point. Because of the differentially driven



Parameter	g_x=g_y	t_w	t_h	p	h	d_y	p_g
Value(mm)	300	60	34	3	43	42	6
Value(λ_0)	$1.8\lambda_0$	$0.36\lambda_0$	$0.20\lambda_0$	$0.018\lambda_0$	$0.26\lambda_0$	$0.25\lambda_0$	$0.036\lambda_0$

Parameter	p_l	w_y	w_x	u_l	u_g	u_p	u_h
Value(mm)	20	100	150	60	20	20	40
Value(λ_0)	$0.12\lambda_0$	$0.3\lambda_0$	$0.9\lambda_0$	$0.36\lambda_0$	$0.12\lambda_0$	$0.12\lambda_0$	$0.24\lambda_0$

Fig. 7. Geometry of parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna. (a) Geometry of the proposed antenna (3-D view). (b) Geometry of the radiation patch with H-slot (top view). (c) Photograph of the proposed antenna.

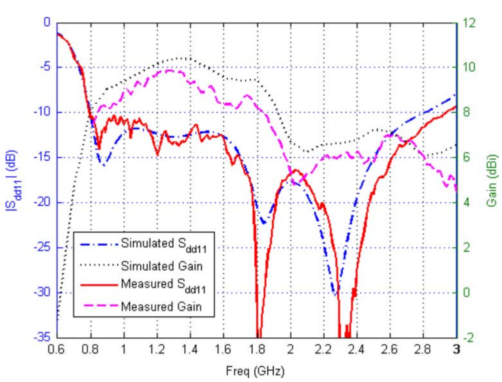


Fig. 8. Simulated and measured differential reflection coefficient S_{dd11} and gain of parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna.

scheme, the cross-polarization level within the impedance bandwidth is lower than -40 dB.

To verify the design, a parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna are fabricated and measured. A photograph of the fabricated proposed antenna is shown in Fig. 7(c). Measured impedance bandwidth and gain given in Fig. 8 reveal that the impedance bandwidth of the antenna is 115% (0.79–2.94 GHz), and the 3-dB-gain bandwidth is 83% (0.80–1.93 GHz). They show good agreement with the simulation results. The measured maximum gain is 9.9 dBi, which occurs at 1.26 GHz. Measured differential input impedance given in Fig. 9 shows that six resonances within the impedance bandwidth are located at 0.87, 1.12, 1.51, 1.83, 1.99, and 2.30, which are very close to the simulated ones. Measured radiation patterns of the proposed antenna in both E-plane and H-plane at 0.8, 1.4, and 1.9 GHz are illustrated in Fig. 10. The agreement between the simulated

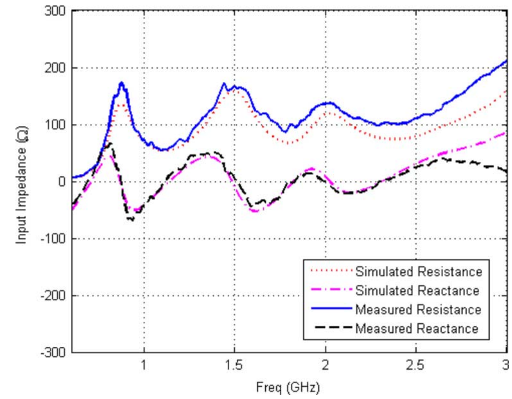


Fig. 9. Simulated and measured differential input impedance Z_{d} of parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna.

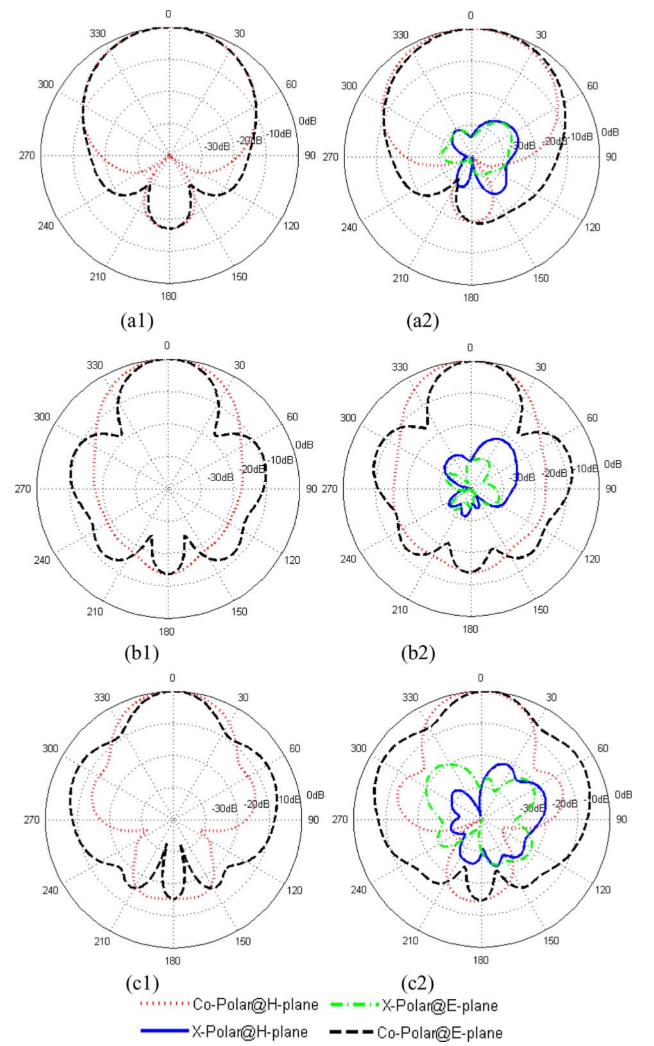


Fig. 10. Simulated and measured radiation pattern of parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna. (a1)–(c1) are simulated radiation patterns, (a2)–(c2) are measured radiation patterns. (a1) 0.8 GHz. (a2) 0.8 GHz. (b1) 1.4 GHz. (b2) 1.4 GHz. (c1) 1.9 GHz. (c2) 1.9 GHz.

and measured radiation patterns is in general acceptable. The measured cross-polarization level is lower than -18 dB within the 3-dB-gain bandwidth.

Compared to the differentially driven patch antenna presented in [6], the impedance and 3-dB-gain bandwidths of the proposed antenna in this letter are 41% and about 33% wider. Simultaneously, the proposed antenna maintains a stable radiation pattern and low cross-polarization level.

III. Conclusion

A newly developed single-patch antenna, called parallel-plate transmission line and L-plate feeding differentially driven H-slot patch antenna, has been designed and implemented successfully. The measured results demonstrated that it has a wide impedance bandwidth of 115% (0.79–2.94 GHz) and also a wide 3-dB-gain bandwidth of 83% (0.80–1.93 GHz). The radiation pattern is stable within the 3-dB-gain bandwidth. Due to the symmetry of the structure and excitation, the radiation pattern is symmetric about both E-plane and H-plane. The maximum gain within the 3-dB-gain bandwidth is 9.9 dBi.

Due to its wide bandwidth, a possible application of the proposed antenna is that it can be used as a base-station antenna, simultaneously providing different wireless access services, e.g., GSM (0.88–0.96 GHz), PCS (1.71–1.88 GHz), WCDMA (1.92–2.17 GHz), and WiMAX (2.50–2.69 GHz).

References

[1] W. R. Eisenstadt, B. Stengel, and B. M. Thompson, *Microwave Differential Circuit Design Using Mixed-Mode S-Parameters*. Boston, MA: Artech House, 2006, pp. 1–25.

[2] A. R. Behzad, M. S. Zhong, S. B. Anand, L. Li, K. A. Carter, M. S. Kappes, T. H. Lin, T. Nguyen, D. Yuan, S. Wu, Y. C. Wong, V. Gong, and A. Rofougaran, "A 5-GHz direct-conversion CMOS transceiver utilizing automatic frequency control for the IEEE 802.11 a wireless LAN standard," *IEEE J. Solid-State Circuits*, vol. 38, no. 12, pp. 2209–2220, Dec. 2003.

[3] Y. P. Zhang, "Design and experiment on differentially-driven microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 55, no. 10, pp. 2701–2708, Oct. 2007.

[4] Y. P. Zhang and J. J. Wang, "Theory and analysis of differentially driven microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 54, no. 4, pp. 1092–1099, Apr. 2006.

[5] Q. Xue, X. Y. Zhang, and C. H. K. Chin, "A novel differential-fed patch antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 5, pp. 471–473, 2006.

[6] C. H. Chin, Q. Xue, and H. Wong, "Broadband patch antenna with a folded plate pairas a differential feeding scheme," *IEEE Trans. Antennas Propag.*, vol. 55, no. 9, pp. 2461–2467, Sep. 2007.

[7] P. Li, K. L. Lau, and K. M. Luk, "A study of the wide-band probe fed planar patch antenna mounted on a cylindrical or conical surface," *IEEE Trans. Antennas Propag.*, vol. 53, no. 10, pp. 3385–3385, Oct. 2005.

[8] K. F. Lee, S. L. S. Yang, A. A. Kishk, and K. M. Luk, "The versatile U-slot patch antenna," *IEEE Antennas Propag. Mag.*, vol. 52, no. 1, pp. 25–39, Feb. 2010.

[9] H. W. Lai and K. M. Luk, "Design and study of wide-band patch antenna fed by meandering probe," *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 564–571, Feb. 2006.

[10] Y. X. Guo, C. L. Mak, K. M. Luk, and K. F. Lee, "Analysis and design of L-probe proximity fed-patch antennas," *IEEE Trans. Antennas Propag.*, vol. 49, no. 2, pp. 145–149, Feb. 2001.

[11] A. C. Lepage and X. Begaud, "A compact ultra wideband triangular patch antenna," *Microw. Opt. Technol. Lett.*, vol. 40, pp. 287–289, 2004.

[12] HFSS. ver. 13.0.0, Ansoft Corporation, Pittsburgh, PA, 2010.