Progress In Electromagnetics Research, Vol. 119, 423–433, 2011

A LOW-PROFILE UNIDIRECTIONAL CAVITY-BACKED LOG-PERIODIC SLOT ANTENNA

J. Ouyang*, S. Bo, J. Zhang, and Y. Feng

University of Electronic Science and Technology of China (UESTC), China

Abstract—A low-profile unidirectional cavity-backed coplanar waveguide-fed uniplanar log-periodic slot antenna suitable for the ultra-wideband applications (3–18 GHz) is presented. Due to the inherent balanced structure compared with the unbalanced antennas, such as dipole or loop antenna, the impedance matching and radiation performances of the proposed antenna are quite stable and satisfactory. There is a potential advantage for low profile ultra-wideband unidirectional antennas, and this paper demonstrates a technique for transforming the bidirectional beam into a unidirectional beam by using a special cavity in this ultra-wideband antenna. Meanwhile, the multi-resolution time domain (MRTD) method is applied to analyze this antenna. Experimental results reveal that the cavity has a small affect on the S-parameter of the origin antenna, and remains the perfect reflection property within the desired operation band.

1. INTRODUCTION

Since the approval of ultra-wideband (UWB) by the Federal Communications Commission (FCC) in 2002 [1], the UWB technology has gained more and more popularity and become an important candidate for short-range high-speed indoor data communication applications [2, 3]. Nevertheless, the antenna design for these systems still encounters several distinct challenges, including relative wide operation band and nearly invariable inband performances. However, with the non-resonating structures, most UWB antennas have bidirectional beams [4–11]. For unidirectional communications, the bidirectional beams must be transformed into unidirectional ones or choose a new antenna form as vivaldi antenna [12]. The transformation

Received 5 July 2011, Accepted 11 August 2011, Scheduled 16 August 2011
* Corresponding author: Jun Ouyang (antenna_ou@163.com).

can be easily achieved with a cavity [13–16], which reflects the negative direction wave from the antenna at the bottom and re-radiates out to combine with the wave radiated directly from the antenna toward free space.

Two techniques, one based on the method of moments (MoM) and the other one based on the finite-difference time-domain method (FDTD), are primarily used for antenna analysis. The MoM is suitable for analyzing an arbitrarily shaped finite-length wire antenna, where a free-space Green's function is used to obtain the current distribution, while the FDTD is powerful for analyzing a finite-size plate antenna with or without a conducting cavity. Detailed information on these methods can be found in the literature [17–21]. As new time-domain numerical methods, multi-resolution time domain (MRTD) method [22, 23] presents many advantages, such as lower consumption of computer memories, high efficiency, and it is regularly utilized to design antennas and circuits and has a good performance [24–28].

In this paper, we propose a coplanar waveguide (CPW)-fed log-periodic slot antenna with a special cavity for transforming the bidirectional beam into a unidirectional beam at the desired frequency band. Different cavities have been discussed to choose the best one. A special cavity and a loss dielectric material are adopted for low-profile design in this paper. Meantime, the multi-resolution time domain (MRTD) method is used to analyze this antenna, and measured results is illustrated and compared with the simulated results. Experimental results reveal that the cavity affects little on the S-parameter of the origin antenna, and remains the perfect reflection property within the desired operation band.

2. ANTENNA DESIGN

Considering a structure whose size is magnified (or lessens) by a factor K, if the resulting structure is the same as the original one, the antenna structure is called a self-similar structure. An antenna that has a self-similar structure is called a self-similar antenna. Therefore, this log-periodic slot antenna is a self-similar antenna which has the broadband characteristic in essence.

The geometry of the proposed CPW-fed log-periodic slot antenna is depicted in Fig. 1. The dimension of this antenna is annotated in the front view Fig. 2. This antenna possesses a simple structure with only one metal covered dielectric substrate layer. The successive slot lengths and distances are in the common ratio M.

$$\frac{L_{n+1}}{L_n} = \frac{l_{n+1}}{l_n} = \frac{D_{n+1}}{D_n} = \frac{d_{n+1}}{d_n} = M \tag{1}$$

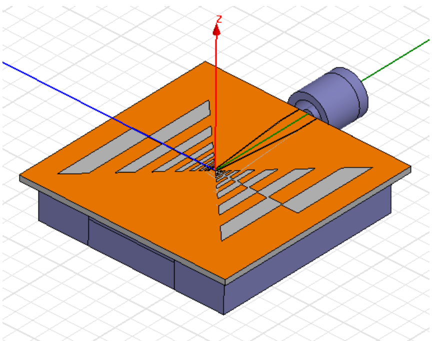


Figure 1. Geometry of unidirectional cavity-backed log-periodic slot antenna fed by a CPW.

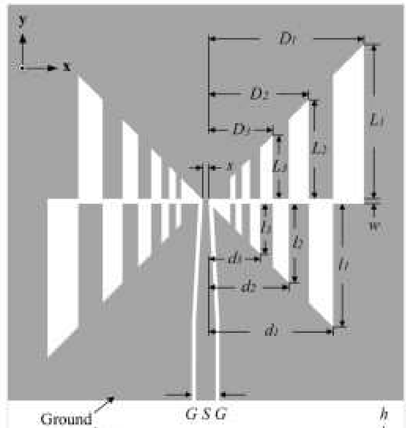


Figure 2. The dimension of the proposed antenna.

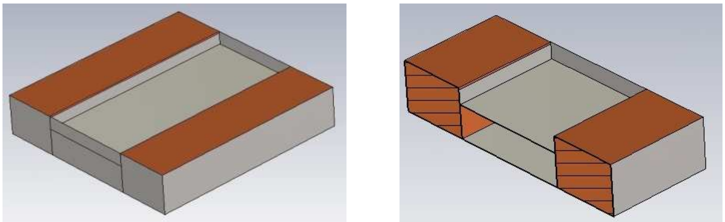
and

$$\frac{l_n}{L_n} = \frac{d_n}{D_n} = \sqrt{M} \tag{2}$$

Which makes the spacing between any two adjacent vertical slots on the same quadrant of the antenna equals to the geometric mean of their widths. Each of the slot paths from the feeding terminals to the oblique edges of vertical slots equals uniquely a half guided-wavelength of the slot line resonating at the corresponding in band frequency, and the lower frequency limit of the operating band can be determined by the total path length from the terminal to the tip of the outermost vertical slot.

The wave radiated in the negative direction from the slot antenna is reflected at the bottom of the cavity and is reradiated out of the cavity (free space), superimposing with the wave radiated directly from the slot antenna toward free space, and thus the radiation from the antenna becomes unidirectional, as desired. However, the depth of traditional cavity needs to be a quarter maximum wavelength or it's multiple for superimposing inphase.

To keep impedance input and radiation characteristics constant as much as possible, an absorbing strip (ABS) is attached to the vertical wall of the cavity, and two layers cavity backed structure is shown in Fig. 3. The ABS is specified by thickness t, relative permittivity ε_r, and conductivity σ.



(a) Two layers cavity-backed (b) cavity-backed section with ABS

Figure 3. The proposed cavities.

(a) top view (b) cavity top view

Figure 4. Antenna photos.

3. ANTENNA SIMULATION AND EXPERIMENTAL RESULTS

Both the original and the cavity back log-periodic slot antennas fed by the CPW are implemented. They are fabricated on the same substrate with dielectric constant 2.2, loss tangent 0.0015, and thickness 1.5 mm. The widths of the strip and gap of the 50 Ω CPW feed line S and G are chosen to be 5.0 and 0.2 mm, respectively. To simplify the design process, D_n is assumed to equal L_n; and consequently, d_n equals l_n. The detailed parameters are listed as follows:

$$L1 = 24\,\text{mm};\;\; w = 0.4\,\text{mm};\;\; M = 0.63;\;\; s = 0.4\,\text{mm};$$

The slot number on one quadrant of the proposed antenna is eight.

The exterior size of this proposed cavity is designed as $54 \times 54 \times 12\,\text{mm}^3$. The depth of the larger cavity is 12 mm, which is eight times to the maximum wavelength. The second layer cavity size is $54 \times 25 \times 3.5\,\text{mm}^3$, which is located at the center of the larger cavity and the longer side is parallel to the slots.

As shown in Fig. 3, a ABS is attached to the vertical wall of the cavity and it is specified by thickness $t = 12\,\text{mm}$, relative permittivity $\varepsilon_r = 1.1$, conductivity $\sigma = 0.125$, width 14.5 mm, and length 54 mm.

Fig. 4 is the photo of the proposed antenna. Fig. 4(a) is the top view of this antenna, Fig. 4(b) shows the cavity structure.

These antennas are simulated by MRTD method, based on analyzing the EM transmission in CPW. The feeding model of the CPW structure is illustrated in Fig. 5, in which "C" denotes the integral path of the current; "L" denotes the integral path of the voltage at the CPW port. The port impedance can be achieved by Equations (3)–(5).

$$I(z,t) = \oint_c \vec{H}(x,y,z,t)\cdot d\vec{l} \tag{3}$$

$$U(z,t) = \int_L \vec{E}(x,y,z,t)\cdot d\vec{l} \tag{4}$$

$$Z_0(f) = \frac{F(U(t))}{F(I(t))} = \frac{U(f)}{I(f)} \tag{5}$$

where, "F( )" denotes the Fourier transform.

The antennas are tested through SATIMO anechoic chamber as shown in Fig. 6.

Simulated and measured return losses of the slot antenna without cavity are shown in Fig. 7. It is clear that the corresponding curve of the original design stays below -8 dB across the entire band from 3.0

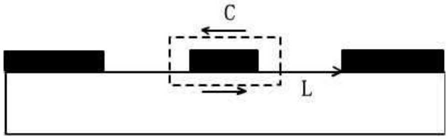


Figure 5. The feeding model of the CPW structure with MRTD.

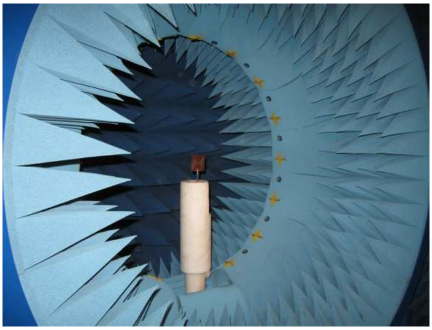


Figure 6. Antennas were tested through SATIMO anechoic chamber.

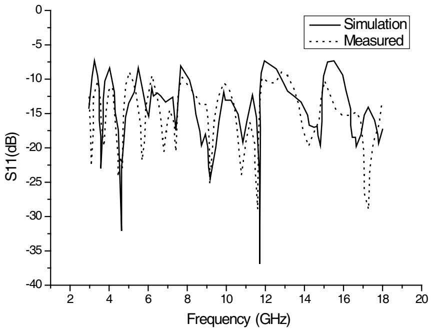
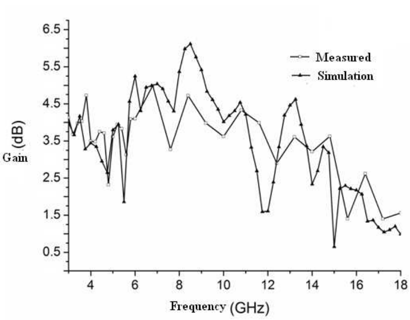
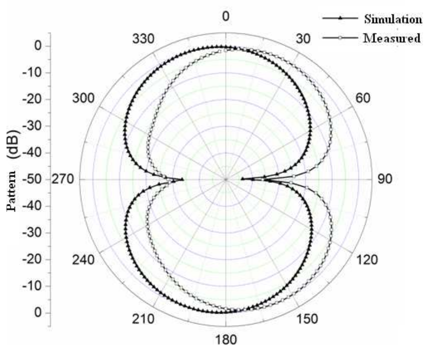


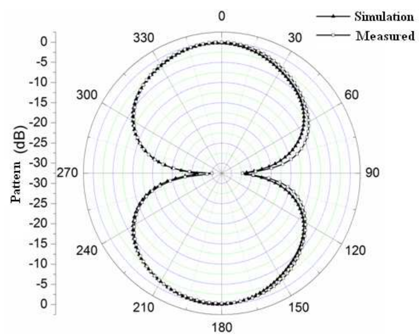
Figure 7. The return losses of the slot antenna without cavity.



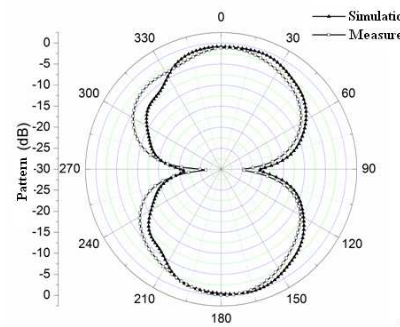
(a) Gain



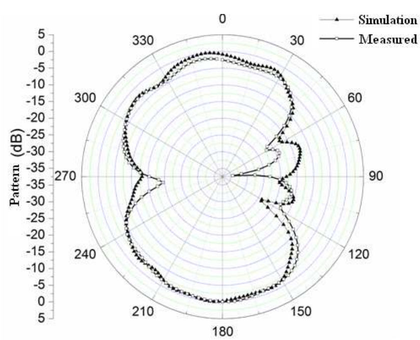
(b) 3 GHz Pattern



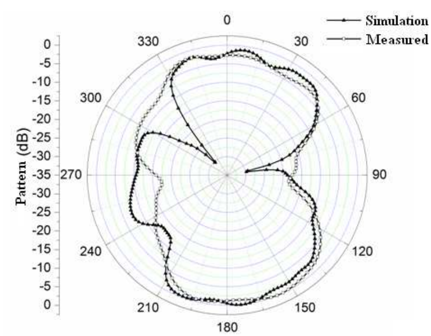
(c) 6 GHz Pattern



(d) 10 GHz Pattern



(e) 14 GHz Pattern



(f) 18 GHz Pattern

Figure 8. The radiation characteristics of the slot antenna without cavity.

to 18.0 GHz. Fig. 8 shows the comparisons of the patterns obtained from simulation and measurement for the slot antenna without cavity. As this figure indicates, the broadside and bidirectional radiation patterns are quite stable. Furthermore, the measured gains for different frequencies agree with the simulation ones quite well.

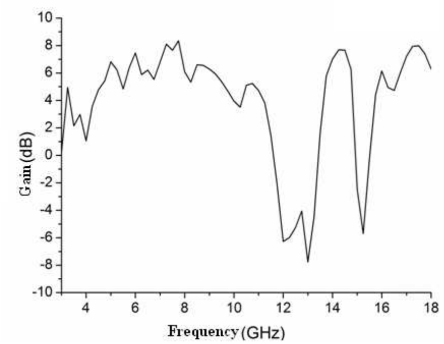
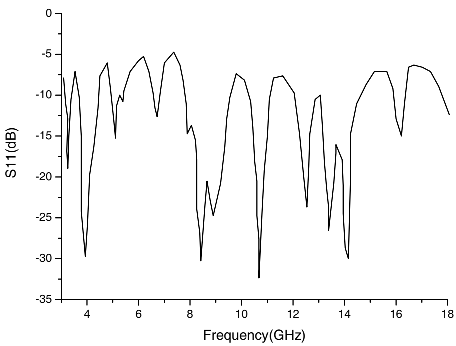
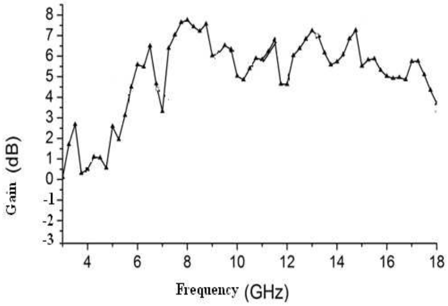


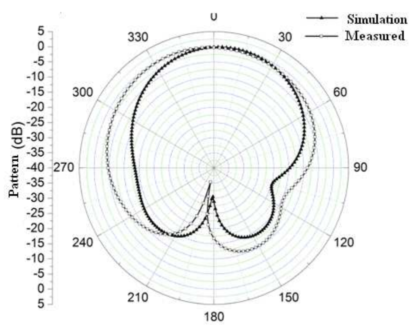
Figure 9. The measured gains of this slot antenna with one layer cavity.



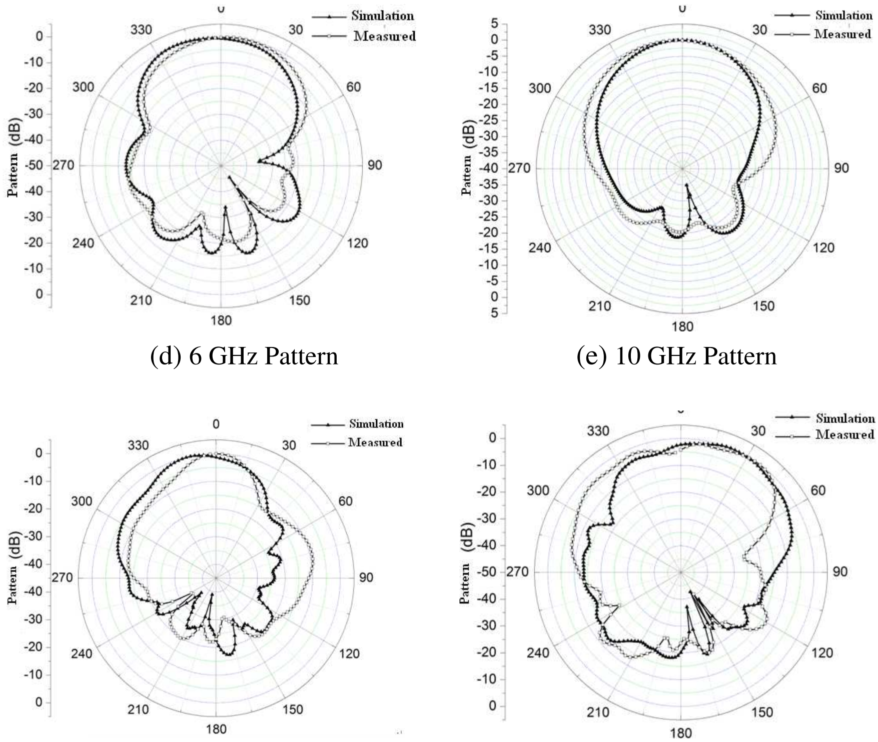
(a) Measured S_{11}



(b) Gain



(c) 3 GHz Pattern



(d) 6 GHz Pattern (e) 10 GHz Pattern

(f) 14 GHz Pattern (g) 18 GHz Pattern

Figure 10. The proposed antenna with two layer cavity and ABS.

The measured gains in the operation band of this slot antenna with one layer cavity are shown in Fig. 9. It is clear that the curve neighboring to 12 GHz exhibits an obvious dropping, because the height of this cavity is close to $\lambda/2$ at this frequency. This is unacceptable in the practical applications.

To solve this problem, a new cavity with two reflectors and an ABS attached to the vertical wall of the cavity is proposed in this paper. The two layer reflectors are used to reflect the EM-wave at low frequencies with the thick cavity and high frequencies with the thin cavity respectively.

With the advanced operation principle of this Log-Periodic Slot antenna, this two layer cavity takes a good performance, which has been shown in Fig. 10. Due to the similarity among the radiation patterns of the three antenna prototypes, only those of the design measured at some in-band frequencies are plotted in Fig. 10. It is clear that the responsive curve of the original design stays below −6 dB across the entire band from 3.0 to 18.0 GHz. As this figure indicates, the gain is larger than 0 dBi and the broadside and unidirectional radiation patterns are quite stable throughout the operating band too.

4. CONCLUSION

The CPW-fed log-periodic slot antennas with unidirectional back cavity has been proposed and investigated in this paper. Due to the inherent balanced structure compared with the unbalanced antennas, such as dipole or loop antenna, the slot antenna has a potential advantage for low profile ultra-wideband unidirectional antennas. Therefore, a new cavity with two layer reflectors and an ABS attached to the vertical wall of the cavity is presented in this paper. The measured results illustrate that the proposed antenna possesses quite stable unidirectional radiation patterns and acceptable gains throughout the operating band. These characteristics and the simple, compact, and uniplanar configuration make the proposed log-periodic slot antennas highly suitable for applications in the UWB and system detections in military.

ACKNOWLEDGMENT

This work was supported by the postdoctoral Science Foundation of China (No. 20090461325, No. 201003690), the Natural Science Foundation of China (No. 61001029, No. 10876007), and the Fundamental Research Funds for the Central Universities (No. 103.1.2 E022050205).

REFERENCES

1. FCC, "FCC first report and order on ultra-wideband technology," 2002.
2. Siwiak, K., "Ultra-wide band radio: Introducing a new technology," *Proc. IEEE Vehicular Technology Conf.*, Vol. 2, 1088–1093, May 2001.
3. Porcino, D. and W. Hirt, "Ultra-wideband radio technology: Potential and challenges ahead," *IEEE Commun. Mag.*, Vol. 41, No. 7, 66–74, Jul. 2003.
4. Chen, D. and C.-H. Cheng, "A novel compact ultra-wideband (UWB) wide slot antenna with via holes," *Progress In Electromagnetics Research*, Vol. 94, 343–349, 2009.

5. Fallahi, R., A. A. Kalteh, and M. G. Roozbahani, "A novel UWB elliptical slot antenna with band-notched characteristics," *Progress In Electromagnetics Research*, Vol. 82, 127–136, 2008.
6. Kiminami, K., A. Hirata, and T. Shiozawa, "Double-sided printed bow-tie antenna for UWB communications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 3, 152–153, 2004.
7. Low, Z. N., J. H. Cheong, and C. L. Law, "Low-cost PCB antenna for UWB applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 4, 237–239, 2005.
8. Xia, Y.-Q., J. Luo, and D. J. Edwards, "Novel miniature printed monopole antenna with dual tunable band-notched characteristics for uwb applications" *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 13, 1783–1793, 2010.
9. Zheng, Z.-A., Q.-X. Chu, and T.-G. Huang, "Compact ultra-wideband slot antenna with stepped slots," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 8–9, 1069–1078, 2010.
10. Hu, Y.-S., M. Li, G.-P. Gao, J.-S. Zhang, and M.-K. Yang, "A double-printed trapezoidal patch dipole antenna for uwb applications with band-notched characteristic," *Progress In Electromagnetics Research*, Vol. 103, 259–269, 2010.
11. Ren, W., J. Y. Deng, and K. S. Chen, "Compact PCB monopole antenna for UWB applications," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 10, 1411–1420, 2007.
12. Lin, S., S. Yang, A. E. Fathy, and A. Elsherbini, "Development of a novel UWB Vivaldi antenna array using SIW technology," *Progress In Electromagnetics Research*, Vol. 90, 369–384, 2009.
13. Okabe, Y., J. Yamauchi, and H. Nakano, "A strip spiral antenna with absorbing layers inside a cavity," *Proc. 2001 Communications Society Conference of IEICE, B-1-107*, Chofu, Tokyo, Japan, Sep. 2001.
14. Qu, S.-W., C. H. Chan, and Q. Xue, "Ultrawideband composite cavity-backed rounded triangular bowtie antenna with stable patterns," *Journal of Electromagnetic Wave and Applications*, Vol. 23, No. 5–6, 685–695, 2009.
15. Zhang, M., Z. Shen, and Y. Guan, "Dual-feed cavity-backed slot antennas," *Journal of Electromagnetic Wave and Applications*, Vol. 24, No. 1, 13–23, 2009.
16. Yang, D., J. Pan, Z. Zhao, and Z.-P. Nie, "Design of trapezoidal cavity-backed resistance loaded bow tie antenna with ultra-wideband and high directivity," *Journal of Electromagnetic Wave*

and Applications, Vol. 24, No. 11–12, 1685–1695, 2010.
17. Harrington, R. F., *Field Computation by Moment Methods*, Macmillan, New York, 1968.
18. Moore, J. and R. Pizer, *Moment Methods in Electromagnetics*, Research Studies Press, Series No. 4, John Wiley & Sons, NewYork, 1984.
19. Yamashita, E., *Analysis Methods for Electromagnetic Wave Problems*, Vol. 2, Chapter 3, Artech House, Norwood, MA, 1996.
20. Yee, K. S., "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas and Propagation*, Vol. 14, No. 3, 302–307, May 1966.
21. Taflove, A., *Computational Electrodynamics*, Artech House, Norwood, MA, 1995.
22. Dogaru, T. and L. Carin, "Multiresolution time-domain algorithm using CDF biorthogonal wavelets," *IEEE Trans. Microwave Theory and Techniques*, Vol. 49, No. 5, 902–912, 2001.
23. Dai, S.-Y., C. Zhang, and Z.-S. Wu, "Electromagnetic scattering of objects above ground using MRTD/FDTD hybrid method," *Journal of Electromagnetic Wave and Applications*, Vol. 23, No. 16, 2187–2196, 2009.
24. Tentzeris, M. E., L. Robertson, et al., "Application of the multiresolution time domain technique (MRTD) to microwave circuit and antennas geometries," *Microwave Conference, 28th European*, Vol. 2, 718–723, 1998.
25. DeJean, G., N. Bushyager, E. Dalton, M. M. Tentzeris, and J. Papapolymerou, "Design and optimization of silicon-based patch antennas using time-domain techniques," *Topical Meeting Silicon Monolithic Integrated Circuits in RF Systems,* 329–332, 2004.
26. Goverdhanam, K. and L. P. B. Katehi, "Applications of Haar wavelet based MRTD scheme in the characterization of 3D microwave circuits," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 4, 1475–1478, 1999.
27. Ju, S., Y. Vin, and H. Kim, "Modal MRTD approaches for the efficient analysis of waveguide discontinuities," *IEEE Microwave and Wireless Components Letters*, Vol. 11, 352–354, 2001.
28. Bushyager, N. and M. M. Tentzers, "Practical considerations in the MRTD modeling of microwave structures," *IEEE/ACES International Conference Wireless Communications and Applied Computational Electromagnetics*, 281–284, 2005.