Progress In Electromagnetics Research, PIER 65, 261–273, 2006

DESIGN OF A NOVEL 3 DB MICROSTRIP BACKWARD WAVE COUPLER USING DEFECTED GROUND STRUCTURE

R. Sharma, T. Chakravarty, and S. Bhooshan

Department of Electronics and Communication
Jaypee University of Information Technology
Waknaghat, Solan, H.P. 173215, India

A. B. Bhattacharyya

Department of Electronics and Communication
Jaypee Institute of Information Technology
Noida, U.P. 201307, India

Abstract—In this paper an edge coupled microstrip coupler with defected ground structure is presented. A normally 7 dB coupler designed on Alumina substrate is converted into a 3 dB coupler by cutting single rectangular slot in the ground plane encompassing the two transmission lines. Other properties of backward wave coupler remain the same, except for a tighter coupling. With this method of design optimization, it will be possible to fabricate a 3 dB coupler in compact form without strain in fabrication process. The structure is analyzed considering magnetic and electric coupling between the two transmission lines. Simulation based studies show reasonable agreement between analytical results and corresponding simulation results.

1. INTRODUCTION

Defected Ground Structures (DGS) have gained significant interests. It rejects certain frequency bands, and hence it is called electromagnetic bandgap (EBG) structures [1–3]. Figure 1 gives the schematic of such a DGS with its approximate surface area [1].

Liu et al. has presented a novel DGS based meander microstrip line providing a broad stopband [4]. Novel Defected Ground Structures with Islands (DGSI) is proposed by Kim et al. in [5]. The DGS

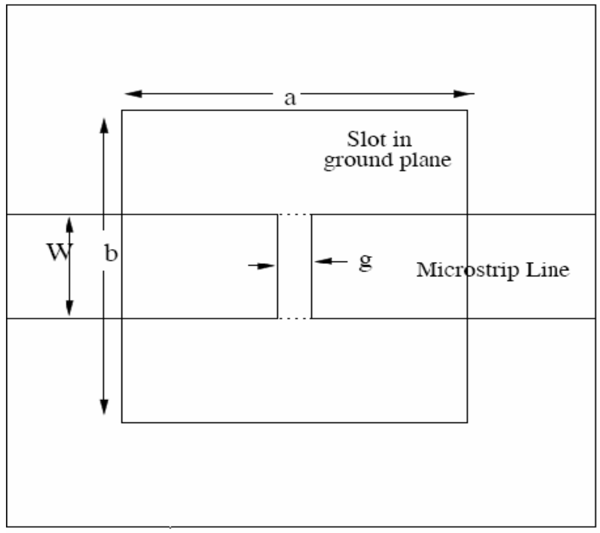

Figure 1. Schematic diagram of a unit DGS cell.

is realized on the bottom plane with two islands placed at both sides of the microstrip line on the upper plane. Careful selection of the line width guarantees 50Ω characteristic impedance (Z_0). The EM simulation results of the DGSI are compared with circuit simulation results using extracted parameters; showing excellent agreement between the two in wide band. Examination of stopband characteristics is studied using concentric circular rings in different configurations [6]. Metallic backing introduced here, significantly reduces interference effects, harmonics and phase noise. Several novel 1-D DGSs are presented in [7, 8] for microwave integrated circuits (MIC), monolithic MIC (MMIC), low temperature co-fired ceramic (LTCC) including RF front-end applications.

DGS have gained quite significance in filter design [9, 10] showing optimal passband and stopband responses plus sharp selectivity and ripple rejection. Application of CPW-based spiral-shaped DGS to mimic for reduced phase noise oscillator is presented in [11], while [12] shows how active devices (BJT and FET) can also be mounted using DGS technique. High amount of isolation is achieved in microstrip diplexer [13]. It may be of interest to the reader to know that significant change in the characteristics including slow-wave factor (SWF) of periodic structures like transmission lines [14–16] is achieved using quite a few unconventional DGS like spiral-shaped and vertically periodic DGS. Vertically periodic DGS (VPDGS) have been used in reducing the size of MIC and amplifiers, thus increasing SWF significantly. Harmonic control can also be achieved ion microstrip antenna structures using 1-D DGS [17].

The objective of this presentation is to demonstrate a 3 dB microstrip coupler using edge coupled techniques. In this work defected ground structure has been utilized. A standard design of a 3 dB coupler requires two quarter-wave microstrip lines to be placed very close to each other and the even mode/odd mode impedances are computed for the given coupling factor. The requirement on fabrication precision in terms of creating the narrow gap is exceptional. The normal techniques of designing 3 dB coupler are branch line couplers and ring hybrids.

In this paper, we have demonstrated an edge-coupled coupler with reasonable spacing between lines. The coupling between the lines is increased by introducing a rectangular slot in the ground plane below the lines. The dimensions of the rectangular slot have been optimized to yield a 3 dB coupling with 90° phase shift between the direct port and the coupled port. This presentation highlights simulation based optimization using FDTD solver CST Microwave Studio. The structure is also analyzed using magnetic and electric coupling concepts between two transmission lines. The size of the ground plane slot has been taken into account for such analysis.

A conventional DGS consists of ground plane slot with a thin slit underneath the microstrip line as shown in Figure 1. Quasi-static modeling of defected ground structure using lumped equivalent circuit has been reported in [18]. However, unlike a conventional DGS, the proposed structure in this paper consists of the ground plane almost fully removed underneath the coupled lines. This can be considered as a series of cascaded DGS. Cascading of DGS structures leads to increase in effective dielectric constant for even mode, thereby increasing coupling value. It is shown in this paper that analysis of such structures can be best done by considering magnetic and electric coupling between two lines embedded in dielectric.

2. SCHEMATIC OF COUPLER

Figure 2 represents a basic quarter-wave backward wave coupler.

Figure 3 displays the schematic diagram of the 3 dB microstrip coupler based on the basic coupler design as given in Figure 2.

Two quarter wave lines of isolated characteristic impedance of 50Ω are placed close to each other with spacing of "s". The frequency of operation is arbitrarily chosen as 5 GHz. In Table 1, the dimensions are represented. The substrate of choice here is alumina ($\varepsilon_r = 9.9$ cm

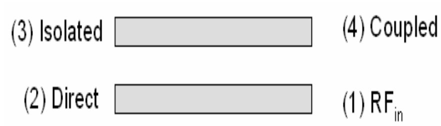

Figure 2. Basic backward wave coupler.

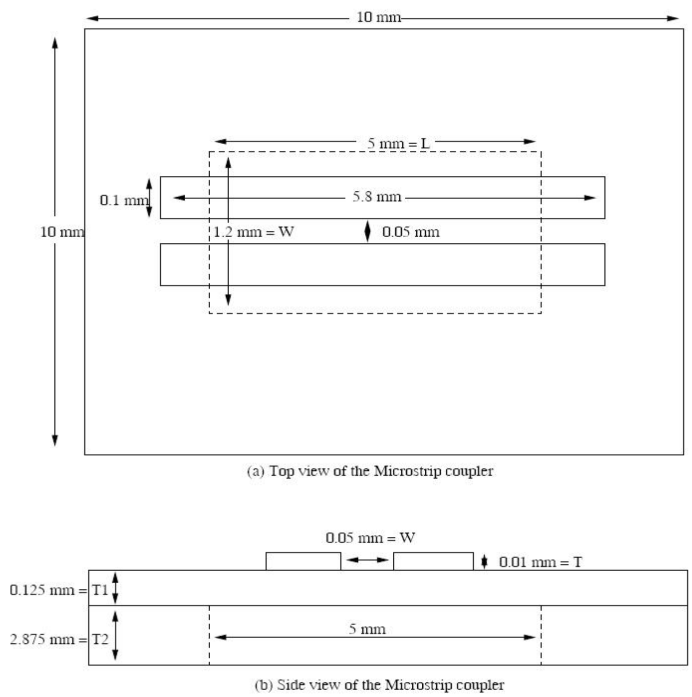

Figure 3. Schematic diagram of a 3 dB microstrip coupler design.

Table 1. Dimensions of the coupler lines.

Line width	Line length	Spacing between lines	Normal coupling
0.104mm	**5.8mm**	**0.05mm**	**-7dB**

and height $h = 0.125$ mm). The length of the lines is $\lambda_g/4$ at 5 GHz.

Below these lines rectangular shaped slot of width 'w' and length 'L' has been cut in the ground plane. The slot is cut in such a way that it encompasses the entire coupling region. The structure with ground plane slots is simulated and optimized for 3 dB coupling. The analytical expressions and results thereof are presented in the following sections.

3. THEORY

In the present proposal, two transmission lines of 50Ω each (in isolation) are placed side by side without ground plane over a significant portion of the line section. This structure can be analytically considered as coupled transmission line embedded in dielectric and the coupling factor between the two transmission lines can be evaluated. Consider Figure 4, in this figure the equivalent two-port network of the coupling between the two lines is presented with coupling impedance Z_{12}.

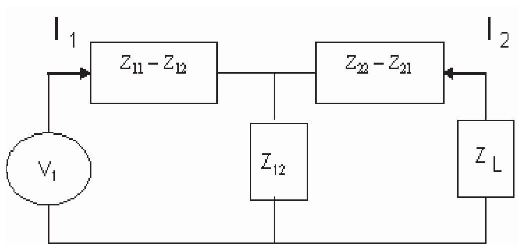

Figure 4. Equivalent two-port network of coupling between transmission lines.

In Figure 4, V_1, I_1 represents voltage and current in line 1, V_2, I_2 represents induced voltage and current in line 2 and Z_{11}, Z_{12}, Z_{21} and Z_{22} are open circuit impedance coefficients. For bilateral medium Z_{21} and Z_{12} are equal and self-impedance of identical lines are equal. We can write the voltage and current produced in line 2 due to current in line 1 as;

$$I_2 = -\frac{Z_{21}}{Z_{22} + Z_L} I_1 \tag{1}$$

$$V_2 = -I_2 Z_L \tag{2}$$

3.1. Magnetic Coupling

The common mode current in line 1 will produce a magnetic field B_1. A part of the magnetic flux caused by B_1 will link to line 2. The mutual flux is then;

$$\varphi_{12} = \int_{S_1} B_1 \cdot ds_2 \tag{3}$$

This can also be written as,

$$\varphi_{12} = M \cdot I_1$$

where, M = mutual inductance. Therefore,

$$\begin{aligned} M &= \frac{1}{I_1} \int_{S_2} B_1 ds_2 \\ &= \frac{1}{I_1} \oint_{C_2} \vec{A}_1 dl_2 \end{aligned} \tag{4}$$

where,

$$A_1 = \frac{\mu_0}{4\pi} \oint_{C_1} \frac{dl_1}{s} \tag{5}$$

's' is the distance between two lines. Therefore,

$$M = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{dl_1 dl_2}{s} \tag{6}$$

where, integration is performed over the line length $\lambda_g/4$ and additional contour on account of size of the ground slot. We can rewrite equation (1) as;

$$I_2 = -\frac{j\omega M}{Z_{22} + Z_L} I_1 \tag{7}$$

For computation of self impedance Z_{22} of a line (without ground plane below) we use the formula for a long, thin cylindrical wire of radius a = linewidth/2 [18].

$$Z_{22} = \frac{j\eta}{2\pi a} \left[\frac{J_0(\beta \cdot a) - jY_0(\beta \cdot a)}{J_1(\beta \cdot a) - jY_1(\beta \cdot a)} \right] \tag{8}$$

where, $J_n(x)$ and $Y_n(x)$ are the Bessel functions of order n. In this case, $\beta = \frac{2\pi}{\lambda_g}$, where $\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$.

The self impedance of a thin rectangular line will be different from a cylinder. This is represented in Figure 5.

We have considered in our simulation work, a copper wire of thickness (t) = 0.01 mm. The self impedance formula given by equation (8) needs to be scaled by a factor $\frac{\pi a^2}{wt}$. Using equation (7), one can compute coupling coefficient,

$$K_1 = 10 \log \left| \frac{I_2}{I_1} \right|^2 \tag{9}$$

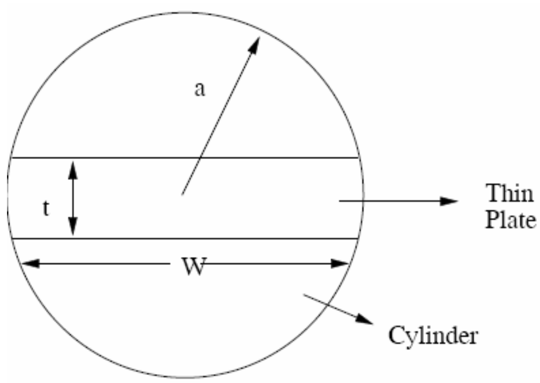

Figure 5. Comparative figure of cylinder and a thin microstrip line.

3.2. Electric Coupling

In this case, we consider the mutual impedance as a capacitor between the two lines. This capacitance is given as,

$$C = \frac{\lambda_g}{4} \frac{\pi \varepsilon_0 \varepsilon_r}{\ln\left(\frac{s}{a}\right)} \tag{10}$$

Using this we can rewrite,

$$I_2 = \frac{-j\omega C}{Z_{22} + Z_L} I_1 \tag{11}$$

and the coupling coefficient

$$K_2 = 10 \log \left| \frac{I_2}{I_1} \right|^2 \tag{12}$$

We evaluate equations (9) and (12) for the given dimensions and compute the coupling coefficients. In case of electrical coupling, the ratio of I_2 to I_1 is due to the mutual capacitance between the two lines; which is different from the case of magnetic coupling where the same is proportional to mutual inductance. The electric coupling is found to be negligible as compared to magnetic coupling in our work.

4. RESULTS

The proposed microstrip coupler is analyzed using equations (9) and (12). The analytical results are compared with simulated results for

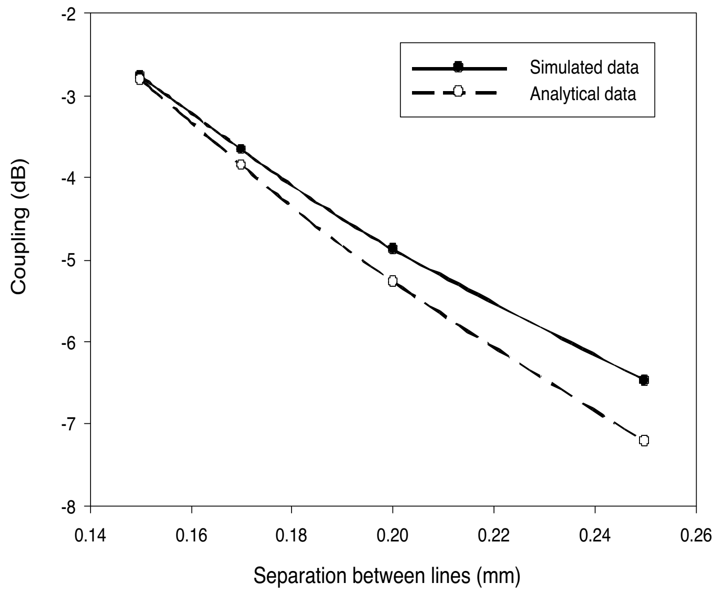

Figure 6. Comparative plots of analytical results versus simulated results.

various lines spacing as shown in Figure 6. The agreement between theory and simulation is reasonable considering the fact that self impedance expression has been derived for a thin cylindrical line, whereas we are using thin microstrip line for coupling.

The design of microstrip coupler is tested by simulation for varying slot lengths and widths to obtain the optimal 3 dB coupling. Simulation is carried out by CST microwave studio, a commercially available FDTD solver [20–23]. Figure 7 shows the coupling and isolation for different lengths as measured at 5 GHz. It can be clearly seen in Figure 7 that 3 dB coupling is obtained for a slot length of 5 mm at 5 GHz. Also at this frequency the S_{11} (return loss) and S_{31} (isolation) happens to be much better than that obtained without ground plane slot, which is quite advantageous in our design.

In Figure 8, it can be noticed that the optimal 3 dB coupling is obtained for a slot width of about 1.2 mm keeping slot length constant at 5 mm. An amplitude imbalance is created between direct port and coupled port on either sides of the optimal slot length and width.

For optimal slot length and width the frequency response is presented in Figure 9. For a design frequency of 5 GHz, 3 dB coupling is obtained for direct and coupled port, and the return loss and isolation

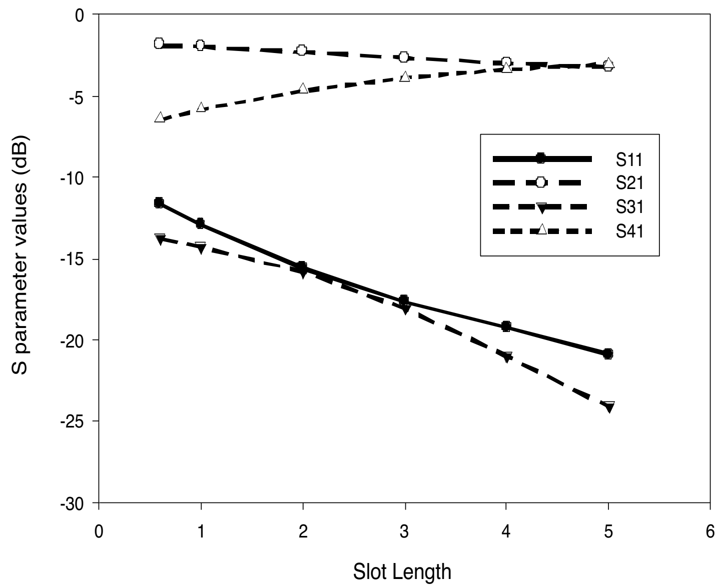

Figure 7. Plot of S-parameters versus ground plane slot length.

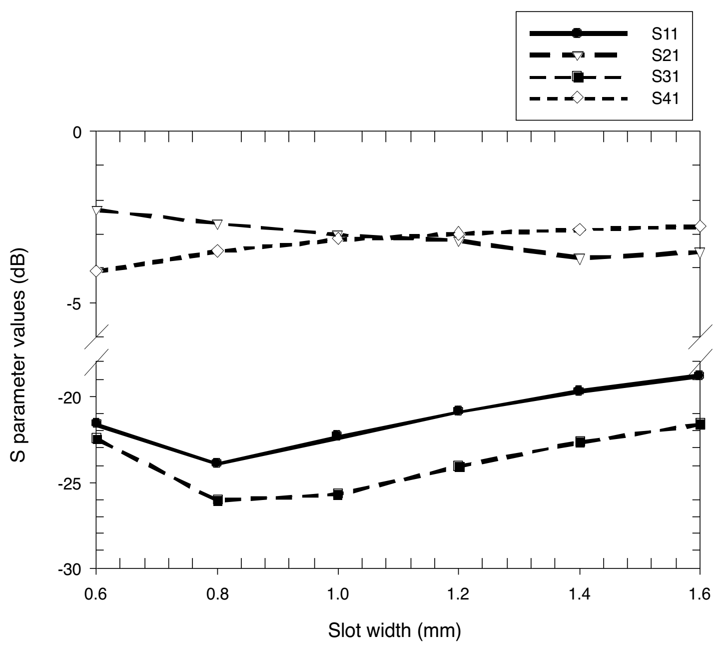

Figure 8. Plot of S-parameters versus ground plane slot width.

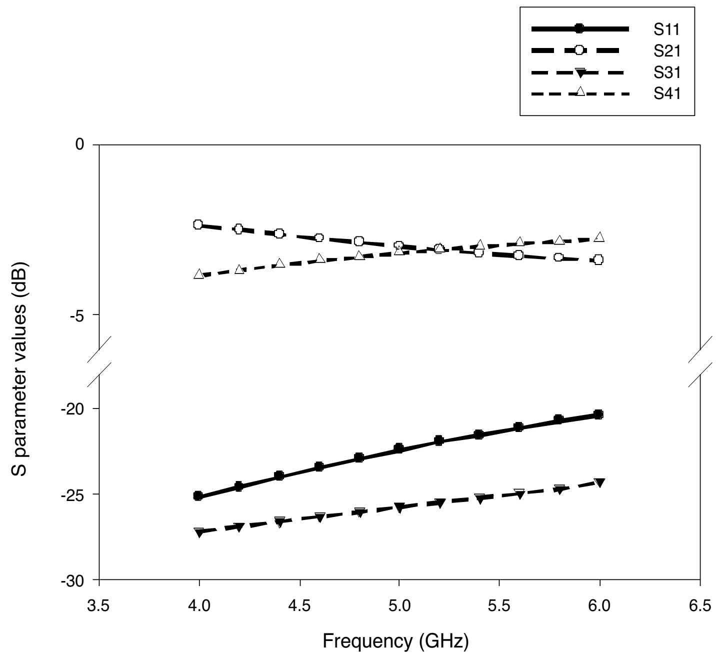

Figure 9. Plot of S-parameters versus frequency.

is below $-20\,\text{dB}$.

From the results it is seen that optimal ground plane slot can be cut for an accurate design of 3 dB coupler at a given frequency. The agreement between theory and simulated results is reasonably good. The above structure is not fabricated since fabrication facilities with such precision are not available at present. However, the references outlined in introduction show good match between simulation results from FDTD solver (CST Microwave Studio) and experimental results. This suggests that for the present case simulation results can considered as accurate.

5. CONCLUSIONS

In this paper, we have presented a novel design of 3 dB coupler for microstrip lines. A normally 7 dB coupler has been converted to 3 dB by cutting slot in the ground plane. The continuous slot can be considered as multiple DGSs. Therefore the effective dielectric constant has increased considerably to show an increase in coupling. An analytical formulation has been derived which considers magnetic coupling and electric coupling between two transmission lines embedded in dielectric. Such simple analytical technique is shown to display reasonably accurate results. Thus equivalent circuit modeling of such structure is not necessary. The ground slot width is also considered in the analysis. It is seen that magnetic coupling plays a crucial role in such structures where electric coupling is negligible. From fabrication point of view, incorporating a single rectangular slot as presented above is much simpler than a traditional DGS with thin slit underneath the lines. The proposed design of a 3 dB microstrip coupler has some advantages over a conventional design. First, the line widths can be chosen straight away for 50Ω characteristic impedance. The two transmission lines can be placed close to each other and coupling be optimized by ground plane slot width and length. This design also displays a possibility of use in compact monopulse comparator if the line length of one of the transmission lines can be adjusted to give 180° coupling

REFERENCES

1. Kim, C.-S., J.-S. Lim, S. Nam, K.-Y. Kang, and D. Ahn, "Equivalent circuit modeling of spiral defected ground structure for microstrip line," *Electronic Letters*, Vol. 38, No. 19, 1109–1110, September 12, 2002.
2. Kim, C.-S., J.-S. Park, D. Ahn, and J.-B. Lim, "A novel 1-D periodic defected ground structure for planar circuits," *IEEE Microwave and Guided Wave Letters*, Vol. 10, No. 4, 131–133, April 2000.
3. Mandal, M. K. and S. Sanyal, "A novel defected ground structure for planar circuits," *IEEE Microwave and Wireless Components Letters*, Vol. 16, No. 2, 93–95, February 2006.
4. Liu, H., Z. Li, and X. Sun, "Compact defected ground structure in microstrip technology," *Electronic Letters*, Vol. 41, No. 3, February 2005.
5. Kim, J.-U., K.-S. Kim, S.-J. Lee, J.-S. Lim, D. Ahn, K.-H. Park, and K.-S. Kim, "A new defected ground structure with islands and equivalent circuit model," *Microwave Conference Proceedings, 2005. APMC 2005. Asia-Pacific Conference Proceedings*, Vol. 1, Dec. 4–7, 2005.
6. Guha, D., S. Biswas, M. Biswas, J. Y. Siddiqui, and Y. M. M. Antar, "Concentric ring-shaped defected ground structures for microstrip applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 5, 402–405, 2006.

7. Liu, H.-W., Z.-F. Li, X.-W. Sun, and J.-F. Mao, "An improved 1-D periodic defected ground structure for microstrip line," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No. 4, 180–182, April 2004.
8. Chung, Y., S.-S. Jeon, S. Kim, D. Ahn, J.-I. Choi, and T. Itoh, "Multifunctional microstrip transmission lines integrated with defected ground structure for RF front-end application," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 5, 1425–1432, May 2004.
9. Mollah, M. N. and N. C. Karmarkar, "A novel hybrid defected ground structure as low pass filter," *IEEE Antennas and Propagation Society International Symposium*, Vol. 4, 3581–3584, June 20–25, 2004.
10. Park, J.-S., J.-H. Kim, J.-H. Lee, S.-H. Kim, and S.-H. Myung, "A novel equivalent circuit and modeling method for defected ground structure and its application to optimization of a DGS lowpass filter," *IEEE MTT-S Digest*, 417–420, 2002.
11. Lee, Y.-T., J.-S. Lim, S. Kim, J. Lee, S. Nam, K.-S. Seo, and D. Ahn, "Application of CPW based spiral-shaped defected ground structure to the reduction of phase noise in V-band MMIC oscillator," *IEEE MTT-S Digest*, 2253–2256, 2003.
12. Jung, M.-S., J.-S. Park, J.-B. Lim, and H.-G. Cho, "A novel defected ground structure and its application to a microwave oscillator," *33rd European Microwave Conference*, 781–784, Munich, 2003.
13. Liu, H. W., T. Yoshimasu, S. Kurachi, J. Chen, Z. F. Li, and X. Sun, "A novel microstrip diplexer design using defected ground structure," *International Conference on Communications, Circuits, and Systems*, 1099–1100, 2005.
14. Kim, C.-S., J.-S. Lim, S. Nam, K.-Y. Kang, J.-I. Park, G.-Y. Kim, and D. Ahn, "The equivalent circuit modeling of defected ground structure with spiral shape," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, 2125–2128, June 2002.
15. Lim, J.-S., Y.-T. Lee, C.-S. Kim, D. Ahn, and S. Nam, "A vertically periodic a novel hybrid defected ground structure and its application in reducing the size of microwave circuits," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 12, 479–481, December 2002.
16. Lim, J.-S., C.-S. Kim, Y.-T. Lee, D. Ahn, and S. Nam, "A spiral-shaped defected ground structure for coplanar waveguide," *IEEE Microwave and Wireless Components Letters*, Vol. 12, Issue 9, 300–332, September 2002.

17. Chang, I. and B. Lee, "Design of defected ground structures for harmonic control of active microstrip antenna," *IEEE Antennas and Propagation Society International Symposium*, Vol. 2, 852–855, 2002.
18. Karmakar, N. C., S. M. Roy, and I. Balbin, "Quasi-static modeling of defected ground structure," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, Issue 5, 2160–2168, May 2006.
19. Jordan, E. C. and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, Prentice-Hall of India, New Delhi, 2004.
20. Ziolkowski, R. W., "FDTD simulations of reconfigurable electromagneticband gap structures for millimeter wave applications," *Progress In Electromagnetics Research*, PIER 41, 159–183, 2003.
21. Kung, F. and H.-T. Chuah, "A finite-difference time-domain (FDTD) software for simulation of printed circuit board (PCB) assembly," *Progress In Electromagnetics Research*, PIER 50, 299–335, 2005.
22. Young, J. L. and R. Adams, "Excitation and detection of waves in the FDTD analysis of N-port networks," *Progress In Electromagnetics Research*, PIER 53, 249–269, 2005.
23. Gao, S., L.-W. Li, and A. Sambell, "FDTD analysis of a dualfrequency microstrip patch antenna," *Progress In Electromagnetics Research*, PIER 54, 155–178, 2005.