Progress In Electromagnetics Research, PIER 104, 113–123, 2010

SUBWAVELENGTH MICROWAVE GUIDING BY PERIODICALLY CORRUGATED STRIP LINE

J. J. Wu

Department of Electrical Engineering
Chung Hua University
Hsinchu 30012, Taiwan, R.O.C.

Abstract—A new type of microwave transmission line structure is proposed in order to reduce the crosstalk between transmission line circuits. In this structure, the edge of the metal strip line is periodically corrugated with subwavelength grooves of appropriate geometric parameters, and thus the transmission lines can support highly localized spoof surface plasmon polaritons (SPPs) at microwave frequencies. The theoretical simulation shows that the crosstalk between such a transmission line and a conventional strip line is very low at microwave frequencies, and this is further verified experimentally. This type of transmission line structures has great potential applications in high speed circuit systems.

1. INTRODUCTION

Recently, the signal transmission in high-speed circuits requiring conduction wires high density has attracted increased attention. Thus, crosstalk between conductor wires within the circuit has become a serious problem. One of the widely adopted methods to reduce the crosstalk is to decrease the coupling length and hence increase the rising time and move the strips farther apart, however such method leads to the growing of the circuit area and the decreasing of the transmission rate.

As a promising approach, SPPs provide the possibility of guiding electromagnetic (EM) waves beyond the diffraction limit. SPPs are electromagnetic excitations propagating as evanescent waves along the planar interface between a metal and a dielectric medium [1]. They have been at the centre of an unprecedented interest in the photonics community [2–6]. It would be greatly advantageous to take

Corresponding author: J. J. Wu (jjwu@chu.edu.tw).

concept of highly localized SPPs to the microwave regime, which could open up a previously inaccessible length scale for microwave research, with promising applications in the miniaturization of microwave circuits as well as microwave imaging and sensing. At microwave frequencies, however, metals resemble a perfect conductor as their plasma frequencies are often in the ultraviolet part of the spectrum, leading to SPPs highly delocalized on both flat and cylindrical surfaces. As a consequence, SPPs suffer serious radiation loss (due to bends or nearby objects) and undesired coupling between adjacent waveguides. To enable high confinement of EM fields at lower frequencies, an idea of engineering surface plasmon at any frequency was proposed [7–10]. By cutting holes or grooves in flat metal surfaces, the penetration of EM fields into the metal increases and the frequency of existing surface plasmons can be tailored at will. The existence of such geometry-controlled SPPs, named spoof SPPs, has recently been verified experimentally in the microwave regime [11]. More recently, it has been reported that spoof SPPs at terahertz (THz) frequencies can be sustained on periodically corrugated metal wires [12–14]. The absorption loss of spoof SPPs in corrugated wires has also been studied at THz and microwave frequencies [15, 16]. In this paper, a new type of transmission line corrugated with periodical subwavelength grooves is proposed to introduce SPPs into microwave regime for reducing the crosstalk between transmission line circuits. The crosstalk between non-uniform strip line and uniform strip line also had been systematic investigated in [17, 18]. A directional coupler, whose two strip lines are separated by a distance of the line width, is designed and simulated numerically and measured experimentally over the frequency range 200 MHz $\sim$ 12 GHz. The results from measurement and simulation are in good agreement. This type of structure has potential application in high density microwave circuit and EMC systems.

Consider a periodically corrugated metal strip line for the microwave regime, as illustrated in Fig. 1(a). This structures is formed by an array of periodical grooves in the metal strip with depth d, width a, and lattice constant Λ, which is on a substrate with a thickness h and dielectric constant ε_r. In what follows, the dielectric constant and thickness of the substrate are taken to be $\varepsilon_r = 3.37$ and $h = 0.508\,\mathrm{mm}$, respectively. The metal strip is assumed to be copper, with thickness $t = 0.0175\,\mathrm{mm}$, width $w = 1.2\,\mathrm{mm}$, and relative permittivity $\varepsilon_m = i\sigma/2\pi\varepsilon_0 f$, where $\sigma = 5.8 \times 10^7\,\mathrm{S/m}$ [19], ε_o is the free-space permittivity, and f is the microwave frequency. To reflect the pattern of structured surface more clearly, we use the normalized groove width $\bar{a} = a/\Lambda$ instead of a when describing the geometry of the strip line structure. The characteristic impedance of the uniform strip-

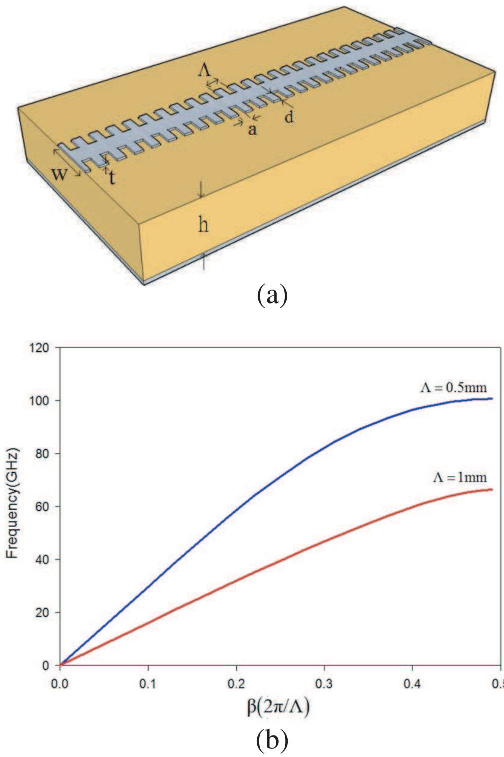


Figure 1. (a) Periodically corrugated metal strip line structure. (b) Dispersion curves for corrugated metal strip lines with two different periods of 0.5 mm and 1 mm.

line is 50 Ω. We are interested in quasi TEM-polarized surface waves propagating along the strip line. A full-vector finite-element method and uniaxial perfectly matched layers are used to analyze the properties of the periodically corrugated metal strip line. Finite element method can provide the precise values of modal propagation constant for the waveguide and of the S-parameters, so we can fully analyze the transmission characteristics of the waveguides. The properties of spoof SPPs in a corrugated strip line are closely controlled by the geometric parameters of the strip line structure. Fig. 1(b) shows the dispersion curves for spoof SPPs (also called SPP bands) on strip lines with different lattice constants Λ. For all cases in Fig. 1(b), the groove depth is $d = 0.3w$, and the normalized groove width is constant, $\bar{a} = a/\Lambda = 0.5$. It should be noted that the propagation constant (β) of spoof SPPs is limited to the first Brillouin zone, i.e., $|\beta| \leq \pi/\Lambda$,

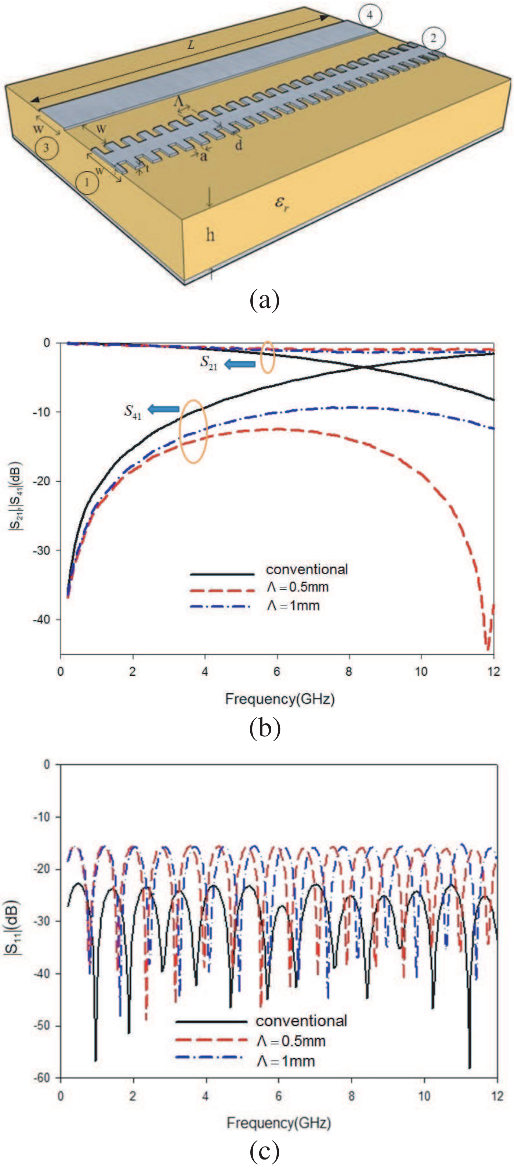


Figure 2. (a) Coupled a periodically corrugated metal strip line and a conventional strip line. (b) Values S_{21} of S_{41} and obtained from the numerical simulation. (c) Values ofobtained from the numerical simulation.

so its actual range changes when Λ varies. As seen from Fig. 1(b), the asymptotic frequency (f_s) of spoof SPPs, which is evaluated at the border of the first Brillouin zone ($\beta = \pi/\Lambda$), is $f_s \approx 95.9\,\text{GHz}$ for $\Lambda = 0.5\,\text{mm}$, and $f_s \approx 65.1\,\text{GHz}$ for $\Lambda = 1.0\,\text{mm}$. For both cases, the asymptotic frequency lies in the microwave regime, which provides the possibility to tightly confine the fields guided by the periodically corrugated strip line at microwave frequencies. It is naturally desired that periodically corrugated strip lines can be used in the dense circuit system to greatly reduce the crosstalk between neighbouring strip lines. To demonstrate this, we consider the crosstalk between a periodically corrugated and a conventional metal strip lines as shown in Fig. 2(a).

We use finite element method to theoretically analyze the properties of wave transmission and coupling for coupled periodically corrugated and conventional metal strip lines, as illustrated in Fig. 2(a). An initial power is assumed to be injected into port 1. The S parameters of the coupled metal strip lines as functions of frequency are shown in Fig. 2(b). As the parameter S_{41} corresponds to the coupling efficiency, it can also be used to analyze the EM field confinement on the periodically corrugated metal strip line. In this numerical simulation, we still use the substrate of Ro4003 with the thickness $h = 0.508\,\text{mm}$. The length of strip line is 10 cm, line width $w = 1.2\,\text{mm}$, groove depth $d = 0.3w$, $\bar{a} = a/\Lambda = 0.5$, $\varepsilon_r = 3.37$, and $t = 0.0175\,\text{mm}$. The maximal frequency range available for our next experimental investigation is chosen in the calculation of the S parameters. For comparison, the values of S_{41} and S_{21} for the coupled traditional strip-lines are also plotted as black lines in Fig. 2(b). The parameters of the coupled traditional strip-lines are comparable with those of the coupled periodically corrugated and conventional metal strip lines, and we find that at $f = 8\,\text{GHz}$, S_{21} is $-3.217\,\text{dB}$ and S_{41} is $-3.896\,\text{dB}$. Blue dash-dot curves represent S-parameters for the periodically corrugated and conventional metal strip lines, where the period of the former strip line is $\Lambda = 1.0\,\text{mm}$. The value of S_{21} of the periodically structured metal strip-line decreases slowly when the frequency increases to 12 GHz. But for the coupler with conventional strip line S_{21} shows monotonically decreasing as frequency increases up to 12 GHz. When the frequency increases to 12 GHz, the S_{41} of the conventional metal strip-line increases monotonically. But for the periodically corrugated metal strip-line coupler, S_{41} increases first and then decreases with the frequency. At 8 GHz, the magnitudes of S_{21} and S_{41} are $-1.318\,\text{dB}$ and $-9.358\,\text{dB}$, respectively. It is valuable to mention that the coupler with periodically corrugated metal strip-line coupler for $\Lambda = 0.5\,\text{mm}$ couple less energy than that for $\Lambda = 1.0\,\text{mm}$. Let us point out, $S_{21} = -3.217\,\text{dB}$ and $S_{41} = -3.896\,\text{dB}$

for conventional coupler at 8 GHz, the S_{21} and S_{41} at this frequency for periodically corrugated metal strip-line coupler with $\Lambda = 0.5$ mm are -0.943 dB and -13.919 dB, respectively. In particular, the frequency near to 12 GHz, the S_{41} can be less than -40 dB. In Fig. 2(b), we also find that S_{41} of coupler with conventional microstrip increases monotonously from 200 MHz and intersects the S_{21} curve at 8.4 GHz. At 12 GHz, S_{41} even rises to -1.584 dB. Therefore large amount of energy couples into another microstrip line, resulting in serious crosstalk between conventional microstrip lines at high frequencies. In the engineering point of view, the tolerable crosstalk between two spaced microstrip lines is below -10 dB. For our considered strip line system with $\Lambda \leq 0.5$ mm, the crosstalk S_{41} is below -12.7 dB in the frequency range of our interest. Clearly, the use of periodically corrugated metal strip line can facilitate the design of high-speed circuits for a broad regime. Fig. 2(c) shows the values of S_{11} for the same structures as in Fig. 2(b). The impedance of the periodically corrugated strip line is not strictly equal to 50 Ω, and thus the value S_{11} for the present structure is larger than that for the conventional structure. However, this value of S_{11} is still within the acceptable range.

The reduction of the crosstalk between a periodically corrugated and a conventional strip lines is achieved by improving field confinement of the first strip line. To characterize the field confinement of the periodically corrugated strip line and compare it with that of the conventional strip line, we introduce the field decay length defined as the distance away from the edge of the strip line (in free space), at which the field amplitude has decayed by a factor of e^{-1}. Fig. 3(a) shows the field decay length as a function of frequency for both the periodically corrugated (solid line) and conventional (dashed line) strip lines. In the frequency range of our interest, the field decay length is nearly $\delta = 0.18w$ (w is the width of the strip line) for the periodically corrugated strip line, and it is considerably smaller than that for the conventional one, which is about $\delta = 0.45w$. However, the strong field confinement on the periodically corrugated strip line may lead to a large absorption loss in the metal. As the field confinement on the periodically corrugated strip line is closely related to the departure of the wave frequency from the asymptotic frequency (f_s) of spoof SPPs, for a given frequency the behavior of the coupled periodically corrugated and conventional strip lines are closely dependent on the period Λ. To determine an appropriate value of Λ, the dependences of S_{41} and S_{21} on Λ at 8 GHz are displayed in Figs. 3(b) and 3(c), where the length of the coupled strip lines are $L = 5$ cm. Interestingly, there exists a local minimum of S_{41} at $\Lambda = 0.1$ mm and meanwhile,

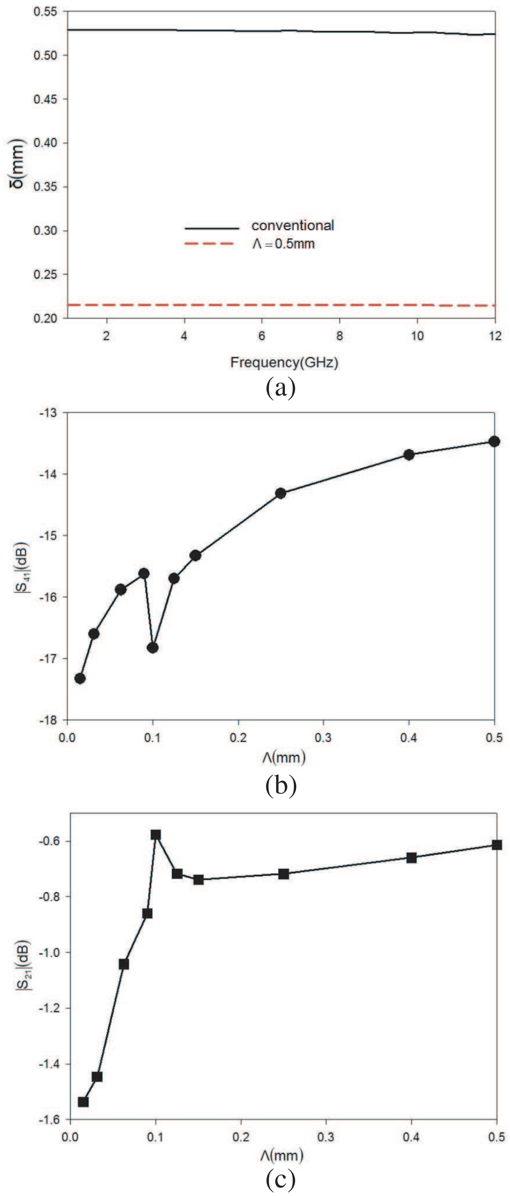
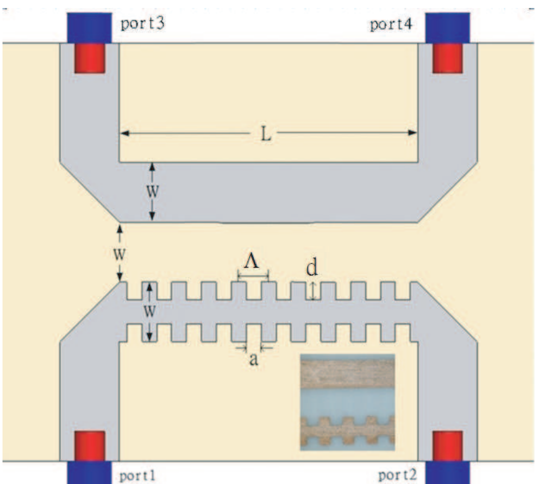
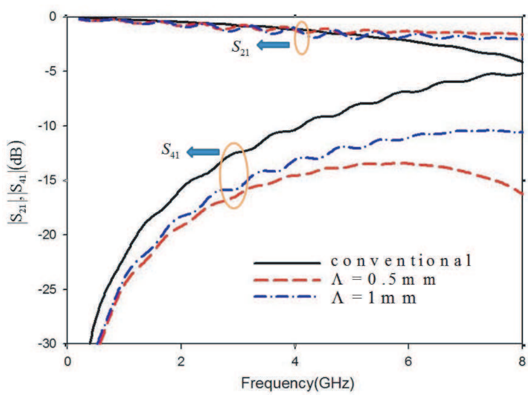


Figure 3. (a) Field decay length as a function of frequency. (b) Dependence of S_{41} on period Λ. (c) Dependence of S_{21} on Λ. The length of the coupled strip lines are $L = 5\,\mathrm{cm}$.

S_{21} reaches its maximum at this point, so the value of $\Lambda = 0.1$ mm is a good choice for the considered strip line system. Evidently, there exists a trade off between the crosstalk and energy loss for the application of periodically corrugated strip line in circuit system. Our numerical simulations show that by properly choosing the parameters of the periodically corrugated strip line, low crosstalk is still feasible with energy loss at an acceptable level, if the periodically corrugated and conventional strip lines are alternately arranged in the dense high speed circuit system (containing tens or hundreds of strip lines).



(a)



(b)

Figure 4. (a) Experimentally measured structure: Periodically corrugated couple metal strip line, (b) experimentally measured data of S parameters with the groove depth $d = 0.3w$ and $\bar{a} = a/\Lambda = 0.5$.

In order to verify that the new strip line structure can reduce the crosstalk, we make an experimental investigation for our coupled strip line circuit with four ports as shown in Fig. 4(a). The confinement strength of EM waves on this new transmission line can be analyzed through the S-parameter measurements with the ZVB8 VNA manufactured by R&S. Signal is injected into the circuit through port 1, then the S parameters were measured at four ports. Coupling between the conventional microstrip line and the periodically corrugated metal stripline is measured for $\varepsilon_r = 3.37$ (Ro4003), $w = 1.2\,\mathrm{mm}$, and a stripline length of $L = 10\,\mathrm{cm}$. Two different periods of $\Lambda = 1.0\,\mathrm{mm}$ and $0.5\,\mathrm{mm}$ are analyzed. The experimental results of S parameters for the groove depth $d = 0.3w$, $\bar{a} = a/\Lambda = 0.5$ are shown in Fig. 4(b). In Fig. 4(b), there are two black curves represent S_{41} and S_{21} for the conventional coupler with symmetrical microstrip line, respectively. When the frequency grows, the magnitude of S_{41} increases and the magnitude of S_{21} gradually decreases, and the highest operation frequency available in our experiment is 8 GHz. Two blue dash-dot curves represent S-parameters between periodically corrugated metal stripline with and conventional microstrip line, the magnitudes of S_{21} and S_{41} at $f = 8\,\mathrm{GHz}$ equal to $-2.004\,\mathrm{dB}$ and $-10.565\,\mathrm{dB}$, respectively, showing the suppression of crosstalk. For the additional case of periodically corrugated metal stripline with $\Lambda = 0.5\,\mathrm{mm}$, the magnitudes of S_{21} and S_{41} at this frequency are equal to $-1.621\,\mathrm{dB}$ and $-16.211\,\mathrm{dB}$, respectively, showing a better suppression of crosstalk, and apparently mitigation of energy decreases in the through-port. Highly confinement of EM waves is observed at microwave range since such subwavelength periodically corrugated metal stripline have low crosstalk characteristic, indicating great potential applications in high-speed circuit and EMC systems.

2. CONCLUSION

In conclusion, we have numerically and experimentally analyzed the guiding properties of periodically corrugated metal strip lines at microwave frequencies. We have presented the dispersion characteristics of these periodically corrugated metal strip lines. The asymptotic frequency of a corrugated metal strip structure can be tailored by varying the period of the structure. Strong field confinement of spoof SPPs at microwave frequency can be achieved in these waveguide structures. We have demonstrated experimentally that there is low coupling or crosstalk between a transmission line of this type and a conventional strip line. Therefore, this type of waveguide structure may be extensively used in electromagnetic compatibility area.

ACKNOWLEDGMENT

We would like to acknowledge the National Science Council of ROC for the financial support through the grant number NSC 98-2221-E-216-001.

REFERENCES

1. Raether, H., *Surface Plasmons*, Springer-Verlag, Berlin, 1988.
2. Ebbesen, T. W., H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through subwavelength hole arrays," *Nature*, Vol. 391, 667–669, 1998.
3. Pendry, J. B., "Negative refraction makes a perfect lens," *Phys. Rev. Lett.*, Vol. 85, 3966–3969, 2000.
4. Barnes, W. L., A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, Vol. 424, 824–830, 2003.
5. Girard, C., "Near fields in nanostructures," *Rep. Prog. Phys.*, Vol. 68, 1883–1933, 2005.
6. Sihvola, H., "Character of surface plasmons in layered spherical structures," *Progress In Electromagnetics Research*, PIER 62, 317–331, 2006.
7. Pendry, J. B., L. Martin-Moreno, and F. J. Garcia-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, Vol. 305, 847–848, 2004.
8. Garcia-Vidal, F. J., L. Martin-Moreno, and J. B. Pendry, "Surfaces with holes in them: New plasmonic metamaterials," *J. Opt. A: Pure Appl. Opt.*, Vol. 7, S97–S101, 2005.
9. Jiang, T., L. Shen, X. Zhang, and L. Ran, "High-order modes of spoof surface Plasmon polaritons on periodically corrugated metal surface," *Progress In Electromagnetics Research M*, Vol. 8, 91–102, 2009.
10. García de Abajo, F. J. and J. J. Sáenz, "Electromagnetic surface modes in structured perfect-conductor surfaces," *Phys. Rev. Lett.*, Vol. 95, 233901, 2005.
11. Hibbins, P., B. R. Evans, and J. R. Sambles, "Experimental verification of designer surface plasmons," *Science*, Vol. 308, 670–672, 2005.
12. Maier, S. A., S. R. Andrews, L. Martin-Moreno, and F. J. Garcia-Vidal, "Terahertz surface plasmon-polariton propagation and focusing on periodically corrugated metal wires," *Phys. Rev. Lett.*, Vol. 97, 176805-1-4, 2006.

13. Chen, Y., Z. Song, Y. Li, M. Hu, Q. Xing, Z. Zhang, L. Chai, and C. Y. Wang, "Effective surface plasmon polaritons on the metal wire with arrays of subwavelength grooves," *Opt. Express*, Vol. 14, 13021–13029, 2006.
14. Wang, K. and D. M. Mittleman, "Dispersion of surface plasmon polaritons on metal wires in the terahertz frequency range," *Phys. Rev. Lett.*, Vol. 96, 157401-1-4, 2006.
15. Shen, L. F., X. D. Chen, Y. Zhong, and K. Agarwal, "The effect of absorption on terahertz surface plasmon polaritons propagating along periodically corrugated metal wires," *Phys. Rev. B*, Vol. 77, 075408-1-7, 2008.
16. Wu, J. J., T. J. Yang, and L. F. Shen, "Subwavelength microwave guiding by a periodically corrugated metal wire," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 1, 11–19, 2009.
17. Khalaj-Amirhosseini, M., "'Wideband differential phase shifter using microstrip nonuniform transmission lines," *Progress In Electromagnetics Research Letters*, Vol. 3, 151–160, 2008.
18. Khodabakhshi, H. and A. Cheldavi, "EM field coupling to non-uniform microstrip lines using coupled multi-conductor strips model," *Progress In Electromagnetics Research B*, Vol. 17, 309–326, 2009.
19. Collin, R. E., *Foundations for Microwave Engineering*, McGraw-Hill, New York, 1992.