EBG Design using FSS Elements in Rectangular Waveguide

R. S. Kshetrimayum[1] and L. Zhu[2]

[1]Microwave Lab, Electronic Communication Engineering, Indian Institute of Science, Bangalore, India 560012
Email: krakhesh@ece.iisc.ernet.in
[2]Communication Research Laboratory, School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore 639798

Abstract — A novel waveguide based EBG structure is originated by periodically loading FSS strip elements in rectangular waveguide. Efficient and accurate Hybrid MoM-Immiittance Approach is used for the full-wave characterization, which is validated by experimental results. A parametric study of effect of various factors on the EBG width has been done. Various existing and novel FSS strips have been investigated to improve the roll-off characteristics in the passband. Double square loop FSS strip loaded waveguide gives improvement in the roll-off factors. Such novel waveguide based EBG structures may be used in the design of harmonic suppressed waveguide filters, band reject filters and suppression of harmonics for waveguide resonators or antennas.

I. INTRODUCTION

Photonic bandgap (PBG) structures are artificially made structures with periodically loaded obstacles in 1-D, 2-D, or 3-D. They are capable of forbidding electromagnetic propagation in either all or selected directions [1]-[3]. Although periodic structures have been investigated in microwave community for many decades, new ideas and concepts developed in optical domain [4]-[5] have renewed interest in microwave area. EM waves behave in such crystals similar to that of electronic behavior in semiconductors hence it is also named as Electromagnetic bandgap (EBG) structure. In microwave community, preferable nomenclature is EBG structure [6]. As in Photonic crystals (PC), photon propagation is impeded by periodic discontinuity, EM waves in EBG materials are hindered by periodic discontinuity making it a slow wave structure. The slow wave behavior in passband characteristics of EBG structures can be used as a slow wave medium for size miniaturized microwave devices and circuits [7]. Surface waves propagating in high dielectric constant slabs carry substantial energy in unwanted directions and create unnecessary coupling between the devices. EBG structures can used to alleviate these problems by suppressing higher order modes and surface waves [8]. In filters, EBG structures are employed for harmonic suppression and improving filter performance without increasing dimension of the device [9]. In antenna design, EBG structures can be used to enhance antenna broadside gain, to suppress surface waves and to reduce cross-polarization levels [10]. On the basis of dimensions in which periodic perturbations like dielectric rods, holes and patterns in waveguides and microstrip substrates are introduced, EBG structures can be categorized as 1-D, 2-D or 3-D. Conventional EBG structures are 1-D/2-D/3-D periodic structures that satisfy Bragg's conditions, i.e, inter-cell separation (period) is close to half guided wavelength. Frequency Selective Surface (FSS) is widely used in microwave and optical engineering as spatial and frequency filters [11]-[12]. In this paper, we have originated an alternative 1-D waveguide based EBG structure by periodically loading rectangular waveguide with FSS strip elements printed on dielectric substrate. Efficient and accurate Hybrid MoM-Immittance Approach [13] has been used for all the simulation works.

II. ORGANIZATION OF THE PAPER

First, a wide resonant strip in X-band waveguide is validated with experimental results. There is good agreement between the Hybrid MoM-Immittance and experimental results. Next, we study the effect of various parameters on the EBG width for simple square FSS strip loaded waveguide. From the parametric study of effect of various factors on the EBG width, we have designed an optimized wideband EBG structure using the FSS square strip. It has been observed that although square FSS strip loaded periodic waveguide structure gives a very broad EBG width, the roll-off characteristics in the passband of the periodic waveguide structure is not good. Hence we try to improve this performance by considering various existing FSS and novel FSS strip elements loaded waveguide structure. Seven FSS strip structures viz., square (FSS1), square loop (FSS2), ring (FSS3), cross (FSS4) and other novel FSS structures: double square loop (FSS5), FSS6 (FSS2+FSS4) and FSS7 (FSS1+FSS4) loaded waveguide has been investigated. Double square loop loaded periodic waveguide structure shows a promising candidate for improving the roll-off factors in the waveguide based EBG structures. The scattering performance for a periodic waveguide based EBG structure loaded with different number of double square loop unit/cells have been investigated. It is observed that with the increase of number of unit/cells, insertion loss goes into deep rejection band and roll-off factor in the passband improves. Such waveguide based EBG structures can be used for various applications like design of harmonic suppressed waveguide filters, band rejection filters and harmonic suppression of waveguide resonators.

III. EXPERIMENTAL VALIDATION OF HYBRID MOM-IMMITTANCE APPROACH

Hybrid MoM-Immittance approach is the hybrid of MoM and Immittance approach [13]. In this method, Galerkin's MoM method and Fourier transform techniques are employed to transform the electric-field integral equation (EFIE) into a matrix system of linear equations. Dyadic Greens' functions are calculated from the TE and TM circuit models for 1-D inhomogeneous multilayered structures. It has been employed for study of guided-wave characteristics of printed periodic waveguide structures [14]. This method has been validated for various waveguide based structures in comparison with analytical results [14] and HFSS simulation results [13]-[14]. Here we will do an experimental validation of this efficient and accurate approach. Fig. 1(a) shows a X-band waveguide with a centered strip of width=0.280 inch and depth=0.360 inch. The equivalent circuit of the waveguide structure under investigation can be represented by a shunt susceptance as shown in Fig. 1(b). Fig. 1(c) illustrates the normalized susceptance versus frequency. Note the choice of basis functions: half-basis functions are employed at the edge where the strip touches the waveguide walls. It can be observed that there is close agreement between the Hybrid MoM-Immittance Approach and experimental results from [15].

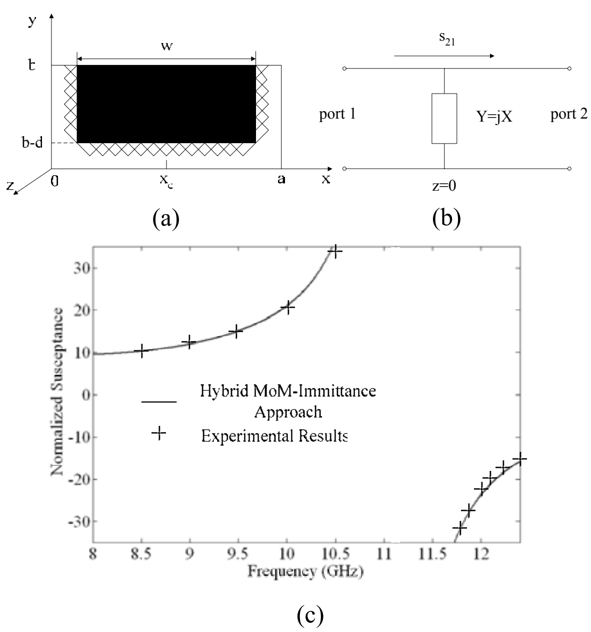


Fig. 1. A rectangular waveguide with a wide resonant strip (a) Cross section, (b) Equivalent circuit, and (c) Normalized susceptance of a centered strip of w=0.280 inch and d=0.360 inch.

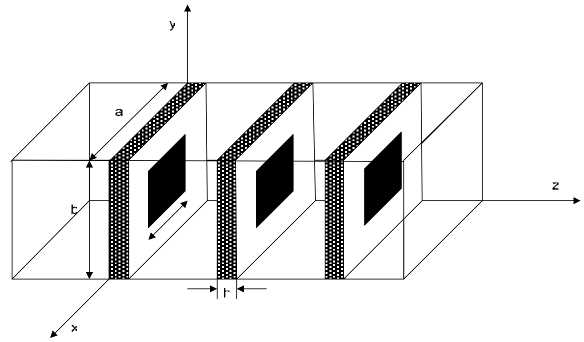


Fig. 2. 3-D geometry of a rectangular waveguide (a × b) loaded with a square strip (l) printed on a dielectric layer of thickness h (3 unit cell).

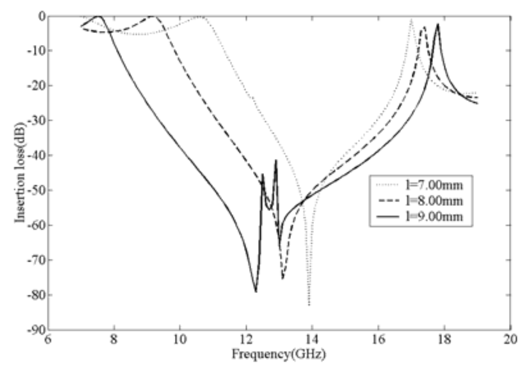


Fig. 3. Insertion loss versus frequency for different dimension of square strip (l).

IV. EFFECT OF VARIOUS PARAMETERS ON EBG WIDTH

Figure 2 shows a rectangular waveguide loaded with three transverse layers of FSS square strips printed on dielectric layer of thickness h. In order to understand the EBG performances properly, let us investigate the effect of various parameters on the EBG width. The actual waveguide based EBG structure composed of periodic waveguide structures with many transversal layers of FSS strips. Here, we have considered a three unit/cell finite periodic waveguide structure for investigation on the -10 dB insertion loss EBG width. The various parameters which may control the EBG performances are:

1) Dimension of FSS square strip (l),
2) Dielectric constant of dielectric layer on which the FSS elements are printed (ε_r),
3) Thickness of the dielectric layer (h),
4) Period of the periodic waveguide structure (p),
5) Number of unit/cells (h).

The square FSS strip elements are printed on a dielectric layer of ε_r = 3 and thickness h = 1mm. The waveguide dimensions are a = 22.86 mm and b = 10.16 mm and the dimension of the FSS square strip elements is chosen as l = 7 mm.

A. Dimension of FSS Square Strip (l)

It has been observed that with increase of dimension for the FSS square strip from l = 7 mm, 8 mm, and 9 mm (other parameters kept the same), there is downward shift in the resonant frequency of the FSS square strip element as illustrated in Fig. 3. There is also significant increase in the -10dB insertion loss EBG width with increase in the dimension of FSS square strip (refer to Table I).

B. Dielectric Constant of Dielectric on which the FSS Elements are Printed (ε_r)

As the relative permittivity (ε_r) of the dielectric layer on which FSS square strip are printed increases from 3, 4, and 5.7 (other parameters kept constant for all the three cases), the resonant frequency of FSS square printed waveguide structure decreases as depicted in Fig. 4 and the fractional EBG width increases as tabulated in Table I.

C. Thickness of the Dielectric Layer (h)

An interesting observation is that when we increase the thickness of the dielectric layer, the fractional EBG width decreases. For a dielectric layer of ε_r = 3 and thickness of the dielectric layer h = 1 mm, the fractional EBG width is 24% (refer to Fig. 5 and Table I). It reduces to 13.51% as we increase the dielectric layer thickness h to 3 mm, keeping same the other parameters of the waveguide structure of Fig. 2.

D. Periodicity (p)

It is a good idea to investigate the role of periodicity p in increasing the EBG width. Fig. 6 illustrates the bandstop of square FSS printed waveguide structure of Fig. 2 for various periodicity p. It can be observed that there is a downward frequency shift in bandstop as periodicity p is increased from p = 4.8 mm, 5.8 mm, and 6.8 mm. Besides, there is visible enhanced bandwidth for periodicity of p = 4.8 mm in comparison to other values of p. It is because the connecting waveguide section approaches half guided-wavelength, the frequency at which each square loop resonates, thereby further widening the EBG width. The scattering parameter results shown are for two unit/cells i.e., n = 2 for periodic waveguide structure.

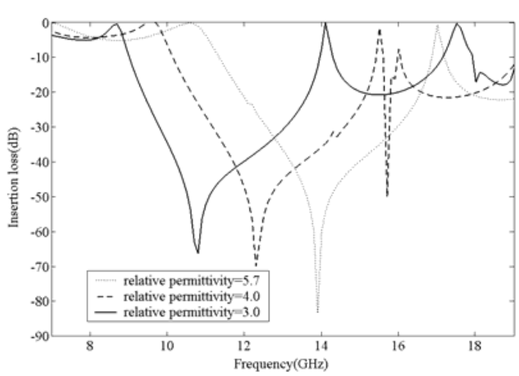


Fig. 4. Insertion loss versus frequency for different values of relative electrical permittivity (ε_r).

E. Number of Unit/cells (n)

Fig. 7 shows insertion loss (S_{21}) for the finitely extended periodic structure with number of unit cells varying from n = 2, 3, and 5 for a fixed periodicity p = 4.8 mm. It can be observed that as number of unit cells (n) increases, insertion loss goes into deep rejection band as mentioned in many literatures [3]. There is also slight decrease in the EBG width as the number of unit/cells increases as shown in Fig. 7.

Table I. -10 dB insertion loss EBG width versus various parameters.

a	9mm	8mm	7mm
EBG width	(18.4-8.0)/13.2	(18.2-12.2)/15.2	(18.2-14.3)/16.2
	78.78%	39.47%	24%
Relative permittivity	3	4	7
EBG width	(18.2-14.3)/16.25	(16.7-12.7)/14.7	(14.8-10.8)/12.8
	24%	27.2%	31.25%
h	1mm	2mm	3mm
EBG width	(18.2-14.3)/16.25	(16.4-13.8)/15.1	(15.8-13.8)/14.8
	24%	17.21%	13.51%
p	4.8mm	5.8mm	6.8mm
EBG width	(15.5-9.6)/12.55	(15.3-10.1)/12.7	(15.2-10.8)/13.0
	47.01%	40.94%	33.84%

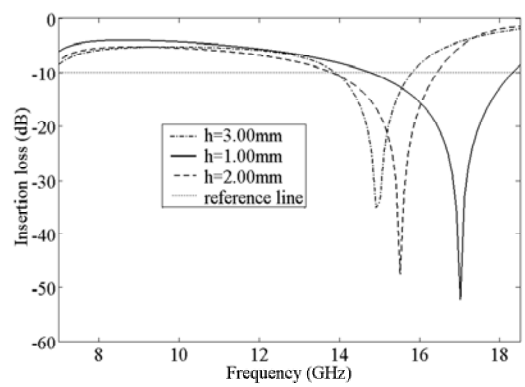


Fig. 5. Insertion loss versus frequency for different thickness of the dielectric layer (h).

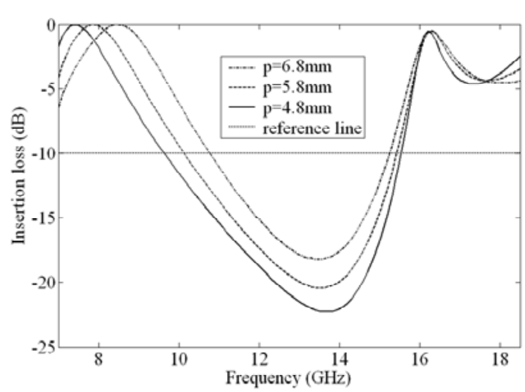


Fig. 6. Insertion loss versus frequency for different period (p).

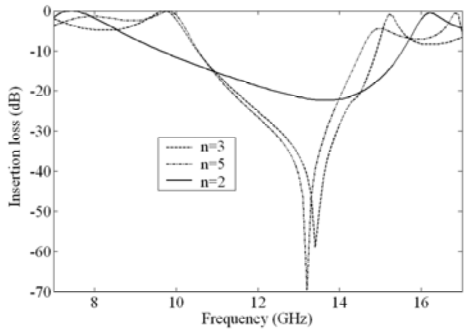
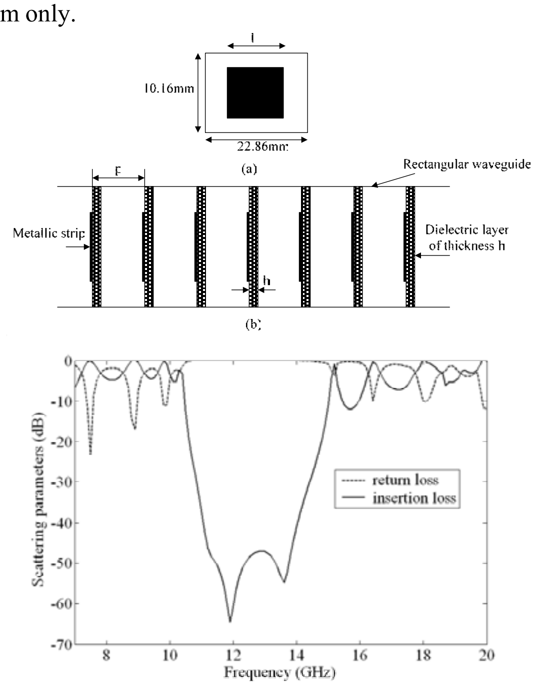


Fig. 7. Insertion loss versus frequency for different number of units/cells (n).

V. COMPACT WAVEGUIDE BASED EBG STRUCTURE

A waveguide based EBG structure is constructed by periodically loading FSS square strips in rectangular waveguide whose geometry (side view) is shown in Fig. 7 (b) and its front view is depicted in Fig. 7 (a). The thickness of the dielectric layer h is chosen as 1m and the relative permittivity of the dielectric layer is 3. The period p is chosen approximately $\lambda_g / 2$ (at the Bragg's frequency) which is equal to 4.8 mm. The scattering performance of the designed EBG structure is plotted in Fig. 7 (c). It can be observed that there exists a deep bandgap or forbidden band with $|s_{11}|$ of about 0dB in the frequency region from 10.5 GHz to 15.5 GHz. The EBG structure is compact because of the increased slow-wave factor due to the dielectric layer. For n=5, the overall length of the 1-D EBG structure is 5 mm × 4.8 mm = 24 mm only.



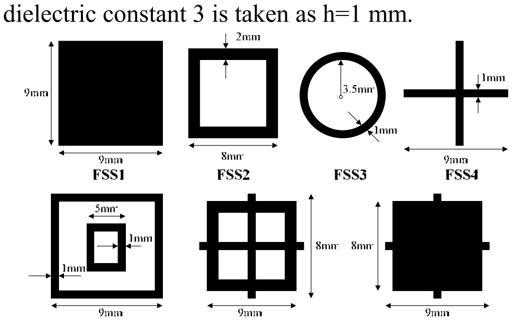
(c)

Fig. 8. Geometry of the waveguide based EBG structure; (a) Front view, (b) Side view, and (c) Scattering performance of the waveguide based EBG structure.

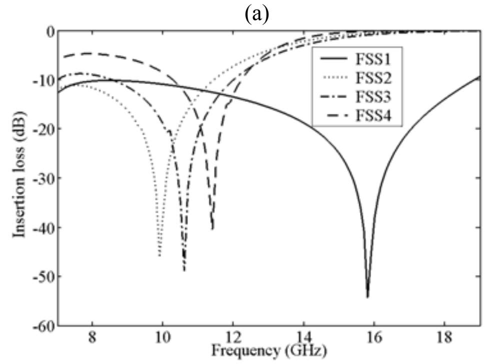
VI. IMPROVING THE ROLL-OFF CHARACTERISTICS

In this section, we will consider various FSS strip loaded waveguide structure to improve the EBG roll-off characteristics in the passband. Several FSS strip structures viz., square (FSS1), square loop (FSS2), ring (FSS3), cross (FSS4) and other novel FSS structures: double square loop (FSS5), FSS6 (FSS2+FSS4) and FSS7 (FSS1+FSS4) loaded waveguide have been investigated and their front view is depicted in Fig. 9 (a). The insertion loss in dB for first 4 FSS structures loaded waveguide structure is shown in Fig. 9(b). The insertion loss in dB for remaining 3 novel FSS structures loaded waveguide structure is depicted in Fig. 9(c). It can be observed that the insertion loss characteristics after resonance go upward towards zero as the frequency increases whereas the insertion loss before resonance usually touches around -10 dB and goes downward further as the frequency decreases. To improve the roll-off characteristics, it should go to 0 dB instead of -10 dB and then should go down as the frequency decreases. The best insertion loss characteristics for improving the EBG roll-off characteristics is for FSS 5 i.e., double square loop FSS structure.

Since the double square loop FSS strip loaded waveguide unit/cell gives the best roll-off characteristics. Let us study the effect of number of unit/cells on the EBG performance specially the roll-off characteristics. From Fig. 10 (b), we can see that as the number of unit/cells of the finite periodic waveguide structure whose geometry depicted in Fig. 10 (a), the roll-off factor increases. The dimensions of the double square loops are chosen as l_1=9 mm and l_2= 5mm. Both the square loops have strip thickness 1mm. They are transversely put in a X-band waveguide. The period p is chosen as 5.58 mm and thickness of the dielectric layer of dielectric constant 3 is taken as h=1 mm.



(a)



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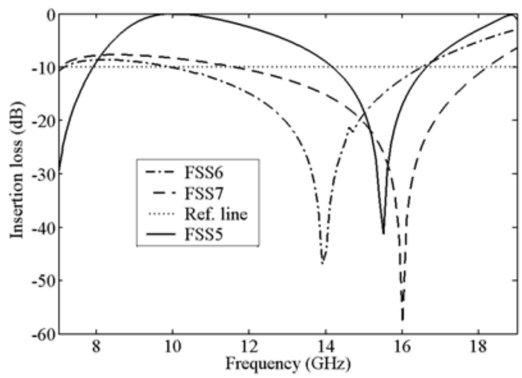
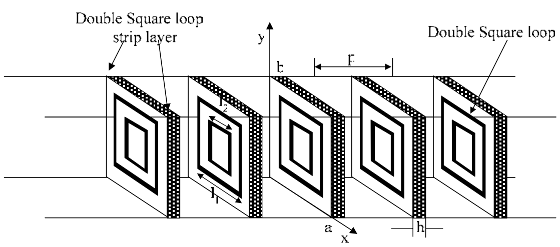
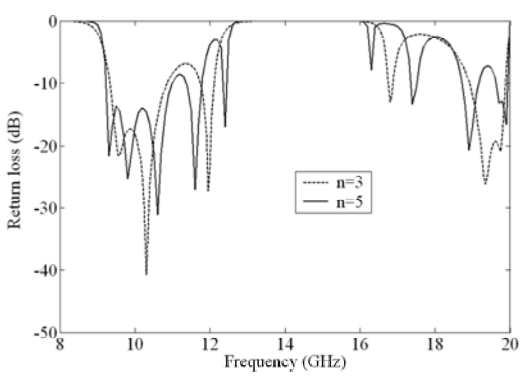


(c)

Fig. 9. (a) Front view of the waveguide loaded with various FSS strips, Insertion loss for (b) first 4 FSS strip elements, and (c) remaining 3 novel FSS strip elements.



(a)



(b)

Fig. 10. (a) Geometry of double square loop FSS printed finite periodic waveguide structure acting as EBG structures and (b) Magnitude of scattering parameters.

VII. CONCLUSION

In this paper, we have originated and investigated a novel EBG structure by periodically loading transversally FSS strip elements in rectangular waveguide. First, we have done a parametric study on effect of various factors on the EBG width. Based on the parametric study, an optimized wideband waveguide based EBG structure using the square FSS strip element has been designed. Although, the EBG structure using simple square FSS strip elements exhibits broad EBG width, the roll-off factor in the passband is not good. We have investigated various existing and novel FSS strip elements to improve its roll-off factors. Double square loop FSS printed waveguide structure shows a promising candidate for this. It has also been observed that with the increase of number of unit/cells, the insertion loss goes into deep rejection band and the roll-off factor in the passband improves. Such EBG structures can be used in the design of harmonic suppressed waveguide filters, band rejection filters and harmonic suppression of waveguide resonators.

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Rakhesh Singh Kshetrimayum (S'01-M'05) received the B. Tech. (first class honors) degree in Electrical Engineering from the Indian Institute of Technology, Bombay, India, in 2000 and the Ph.D. degree in Electrical and Electronic Engineering from the Nanyang Technological University, Singapore, in 2005. From 2001 to 2002, he was a Software Engineer at the Mphasis Architecting Value, Pune, India. From 2004 to 2005, he was a Research Associate at the Electrical Communication Engineering Department, Indian Institute of Science, Bangalore, India. From May-July 2005, he was a Post-Doctoral Visiting Scholar at the Electrical Engineering Department, Pennsylvania State University, Pennsylvania, USA. Presently, he is a faculty at the Electronics and Communication Engineering department of the Indian Institute of Technology, Guwahati. His research interests include printed periodic structures, filters, EBG, metamaterials, computational electromagnetics, scattering problems and microstrip antennas. Dr Kshetrimayum is also a member of the IEICE, Japan and IEE, UK. He was awarded the KTH-Royal Institute of Technology-Stockholm Electrum Foundation Scholarship (2003-2004), the Nanyang Technological University - Singapore PhD Research Scholarship (2001-2004), the Travel Grant to attend the International Symposium on Microwave and Optical Technologies ISMOT 2005 at Fukouka, Japan. He is listed in Who's Who in the World 2006 23rd Edition.

Lei Zhu (S'91-M'93-SM'00) received the B.Eng. and M.Eng. degrees in radio engineering from the Nanjing Institute of Technology (now Southeast University), Nanjing, China in 1985 and 1988, respectively and the Ph.D. degree in Electronic Engineering from the University of Electro-Communications, Tokyo, Japan in 1993. From 1993 to 1996, he was a Research Engineer with Matsushita-Kotobuki Electronics Industries Ltd., Tokyo, Japan. From 1996 to 2000, he was a Research Fellow with Ecole Polytechnique de Montréal, Montréal, QC, Canada. Since July 2000, he has been an Associate Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His current research interests include the study of planar integrated dual-mode filters, ultra-broad bandpass filters, broad-band interconnects, planar antenna elements/arrays, uniplanar coplanar waveguide (CPW)/coplanar stripline (CPS) circuits as well as full-wave three-dimensional (3-D) method of moments (MoM) modeling of planar integrated circuits and antennas, numerical deembedding or parameter-extraction techniques and field-theory-based computer-aided design (CAD) synthesis/optimization design procedures. Dr. Zhu had held as an Associate Editor of the *IEICE Transactions on Electronics* (2003 -2005) and a member of the Editorial Board of the *IEEE Transactions on Microwave Theory and Techniques* (2000-2005). He was the recipient of the Japanese Government (Monbusho) Graduate Fellowship (1989–1993). He was also awarded the 1996 Silver Award of Excellent Invention presented by the Matsushita-Kotobuki Electronics Industries Ltd., Japan, the 1997 Asia–Pacific Microwave Prize Award presented at the Asia–Pacific Microwave Conference, Hong Kong. In 2002, he was a Japan Society for Promotion of Science (JSPS) Research Fellow and a Guest Professor at the University of Ulm, Germany in 2005.