Miniature Low-Loss CPW Periodic Structures for Filter Applications

James Sor, *Student Member, IEEE*, Yongxi Qian, *Senior Member, IEEE*, and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*—Several novel periodic structures for coplanar waveguides are presented. The proposed structures exhibit low insertion loss in the passband, simple fabrication, and slow-wave characteristics. These structures are applied to realize miniature low-pass filters one-tenth the size of conventional filters, with spurious-free response and deep attenuation levels using only three cells.**

***Index Terms*—Coplanar waveguide, filters, periodic structures.**

I. Introduction

PERIODIC structures of various types have always been a favorite topic of researchers and are currently enjoying renewed interest in the microwave field for their applications in the microwave and millimeter-wave regime [1]. For example, planar periodic structures have been used to achieve high-performance filters, to perform harmonic tuning in power amplifiers, and to suppress leakage in CB-coplanar waveguide (CPW) and stripline circuits [2]–[5]. These applications are possible because periodic structures exhibit distinctive bandstop characteristics when patterned on the microstrip ground plane. Additionally, the slow-wave characteristics exhibited by periodic structures can be exploited to reduce microstrip circuit component size. With chips sizes currently being limited by the size of passive components rather than of the active devices, it becomes increasingly attractive to develop a complementary CPW slow-wave structure for the miniaturization of microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs). Many exotic schemes have been proposed to this end. Metal–insulator–semiconductor (MIS) CPW lines can achieve very high slow-wave factors, but suffer from low impedance values and high insertion loss, making MIS CPW lines impractical at higher frequencies. MIS loss may be improved by introducing cross-tie periodic structures or by inhomogeneously doping the semiconductor, but these methods necessitate additional fabrication processes [6], [7]. An ideal slow-wave structure with low loss properties, moderate impedance, and easy fabrication still remains the objective of many researchers. This paper entails our efforts to develop such a structure for CPW transmission lines.

Manuscript received April 2, 2001; revised August 15,2001. This work was supported by the Multidisciplinary University Research Initiative Army Research Office under Contract DAAH04-96-1-0005 and Contract DAAH04-96-1-0389.

J. Sor and T. Itoh are with the Microwave Electronics Laboratory, University of California at Los Angeles, Los Angeles, CA 90095 USA (e-mail: jsor@ee.ucla.edu).

Y. Qian was with the Microwave Electronics Laboratory, University of California at Los Angeles, Los Angeles, CA 90095 USA. He is now with the MicroWaveSys Division, Microsemi Corporation, Irvine, CA 92614 USA.

Publisher Item Identifier S 0018-9480(01)10460-6.

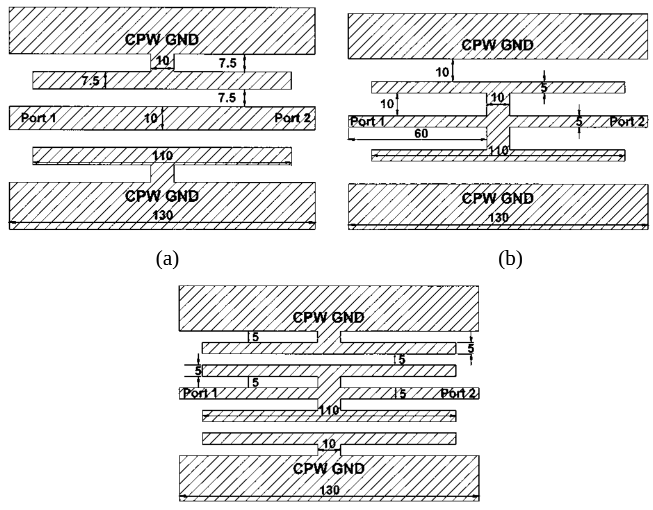


Fig. 1. Unit cells of proposed periodic structures (units in millimeters). Structures are symmetric about both axes and drawn to scale. (a) Structure A. (b) Structure B. (c) Structure C.

II. Design Considerations

From transmission-line theory, the propagation constant and phase velocity of a lossless transmission line are given, respectively, as $\beta = \omega\sqrt{LC}$ and $v_p = 1/\sqrt{LC}$, where L and C are the inductance and capacitance per unit length along the transmission line. Thus, slow-wave propagation can be accomplished by effectively increasing the L and C values. One way to do this is by introducing periodic variations along the direction of propagation, such as by drilling holes in the substrate or by etching patterns in the microstrip ground plane [8]. Because the fields in a microstrip line are concentrated in the dielectric substrate region, these periodic variations strongly perturb the nature of the microstrip field distributions. In contrast, the fields in CPW are localized in the two slots, so that perforation of the two ground planes will have little effect on CPW guided-wave propagation. Therefore, in order to increase the effective capacitance and inductance along the CPW line, we propose several periodic structures of the form depicted in Fig. 1. In each of these schemes, the width of the CPW center conductor is narrowed, enhancing the inductance per unit length. To increase the capacitance to ground, the two ground planes of the CPW line are brought closer in proximity to the center conductor. This can be accomplished by branching out the two ground planes, as in Fig. 1(a), by branching out the center conductor, as in Fig. 1(b), or by combining the two effects, as in Fig. 1(c). The proposed unit cells offer several advantages over existing structures. First, the overall footprints of the periodic

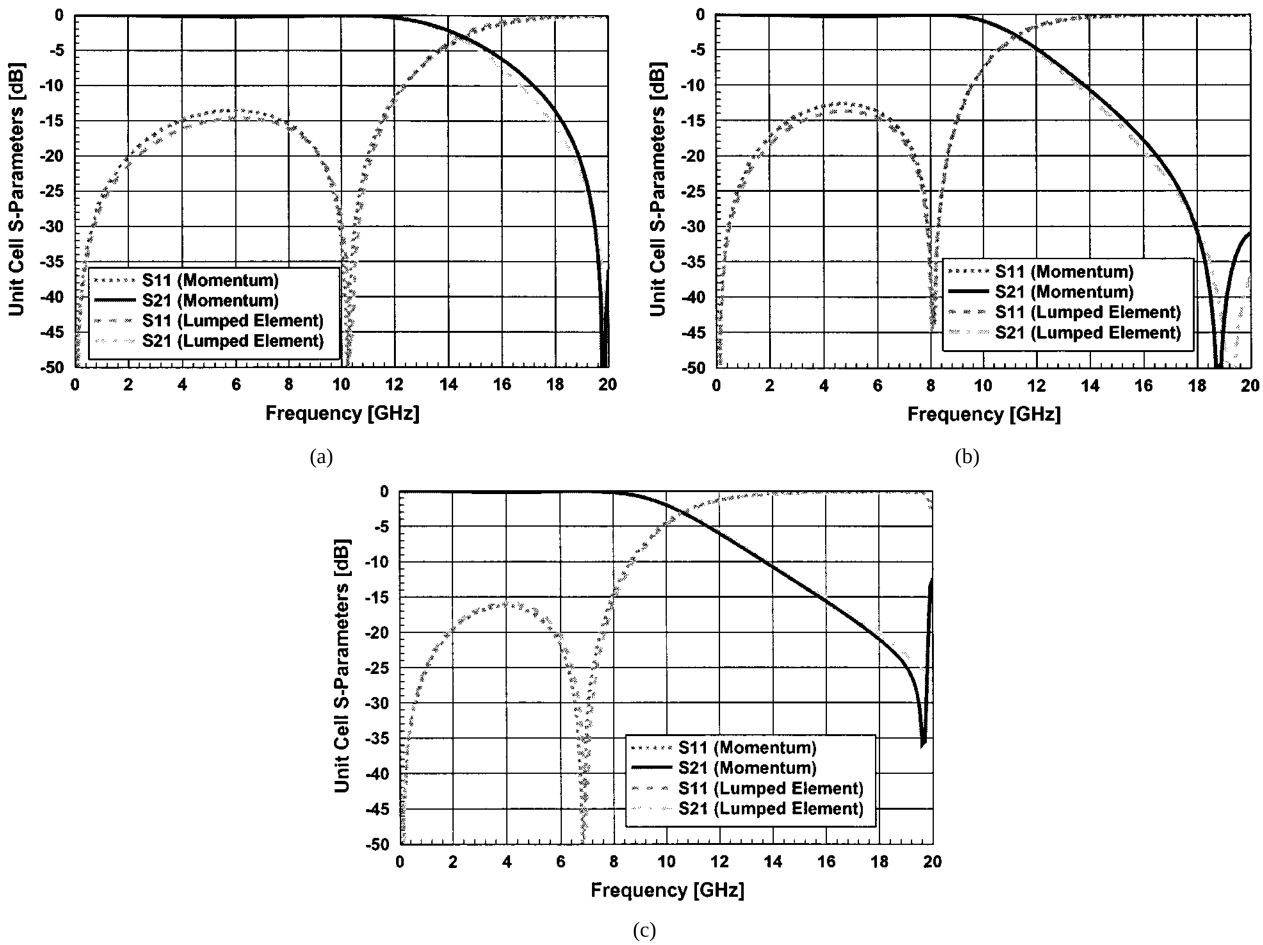
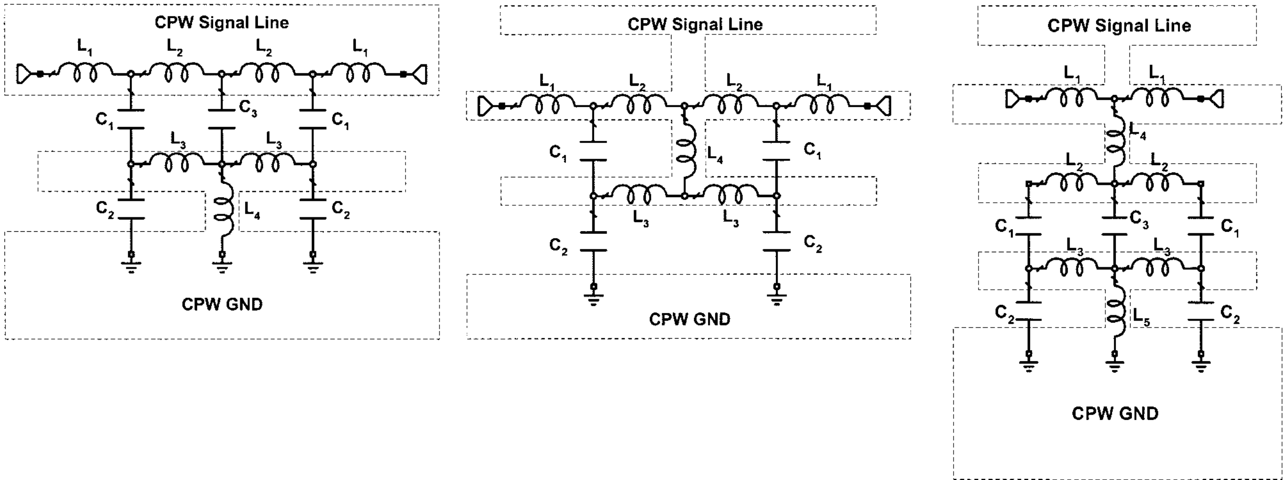


Fig. 2. Simulated method-of-moments response of unit cells and extrapolated lumped element response.

structures remain the same when compared to a standard 50-Ω CPW transmission line. Although perforating the edges of the two ground planes can potentially enhance the capacitive and inductive effects, doing so reduces the transmission line's compatibility with active devices and increases the overall footprint of the periodic structure [9]–[11]. Second, the completely uniplanar geometries of the structures eliminate any uncertainty in positioning the signal line in reference to the ground plane. This differs from some microstrip periodic structures, where the insertion loss and return loss vary depending upon where the top conductor is placed in reference to the periodically etched ground plane [12]. Finally, the proposed periodic structure offers very simple fabrication that can be implemented on one side of a dielectric substrate using standard etching techniques. No additional procedures in the form of ion-implanting or cross-tie overlays are required, and the smallest dimensions of the unit cells are still large enough such that no photoreduction or photolithographic processes are required.

A complete full-wave analysis is required for accurate analysis of each unit cell, since the inductive and capacitive values of any periodic structure are not entirely independent owing to coupling effects [13]. The scattering parameters for each of the unit cells are simulated using Agilent's Momentum software and shown in Fig. 2. These are shown together with the scattering parameters of the corresponding lumped-element models, which have been extrapolated by experimentally curve fitting the results from the full-wave analysis. These equivalent lumped-element circuits are shown in Fig. 3, and the corresponding lumped-element component values can be found in Table I. In the equivalent circuits, each narrow conducting line in the unit cells can be modeled as an inductance while any pair of parallel conducting edges is represented by some capacitance value. For modeling purposes, it is assumed that the branched arms of the CPW ground plane in Structures A and C are not at ground potential. In Structure C, the capacitances connecting the input/output ports to the C1 capacitors were found to be negligible and, thus, have been left out. Also, it should be noted that while these lumped-element models give accurate results for a single unit cell, cascading the cells in series may not give entirely accurate results due to the coupling interaction between cells. Each individual cell will couple with not only the immediately adjacent cell, but to all other cells in the periodic chain as well. This distributed nature of the periodic structures prevents the extraction of a cascadable model, even after a coupling capacitor is inserted between single-cell models and extensive optimizations are performed. However, the equivalent-circuit models provided here can give insight as to how the individual components of the proposed structures interact with each other and can be used to facilitate optimization and design of these periodic structures. For reference, each unit cell is connected to a 50-Ω CPW line with center conductor width of 25 mm and gap spacing of 15 mm built on a 25-mil $\varepsilon_r = 10.2$



(a) (b) (c)

Fig. 3. Lumped-element equivalent-circuit models for unit cells of proposed periodic structures (not to scale).

TABLE I
LUMPED-ELEMENT CIRCUIT PARAMETERS

Parameter	Structure A	Structure B	Structure C
C_1 [pF]	0.11	0.02	0.09
C_2 [pF]	0.11	0.17	0.57
C_3 [pF]	0.05	NA	0.26
L_1 [nH]	0.55	0.67	1.03
L_2 [nH]	0.15	0.27	0.08
L_3 [nH]	0.02	0.03	0.06
L_4 [nH]	0.14	0.14	0.02
L_5 [nH]	NA	NA	0.01

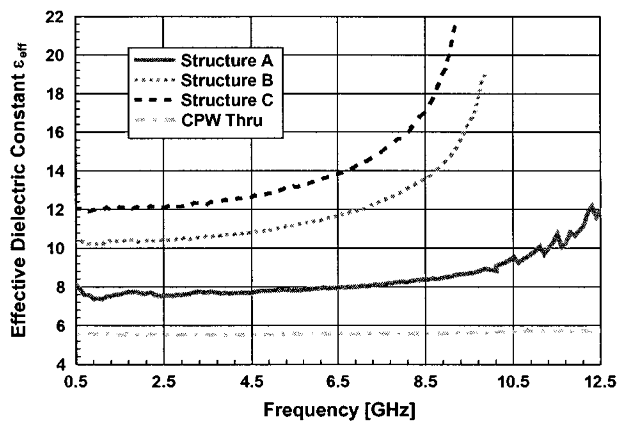


Fig. 4. Measured effective dielectric constant of proposed periodic structures (11 cells) compared to a reference 50-Ω CPW line on the same substrate.

Duroid substrate. The unit cells exhibit minimal insertion loss (better than -1.0 dB) from dc to 10 GHz (± 1 GHz). Potentially wide stopbands exist above this region, which can be enhanced by cascading several periods in series.

III. MEASURED RESULTS

To analyze the slow-wave characteristics of the periodic structures, an 11-cell series cascade of unit cells is built for each topology. Phase information is extracted from a network analyzer and unwrapped to obtain the slow-wave factor. To ensure accurate measurements, the phase is measured using two different methods. A thru-reflect-line (TRL) calibration is used to verify the results of a standard two-port calibration where the phase of all 50-Ω feed lines and connectors have been subtracted out. Good agreement is obtained between the two methodologies. From the phase information, the effective dielectric constant ε_{eff} is calculated and presented in Fig. 4. The slow-wave enhancement can be defined as the ratio of $\sqrt{\varepsilon_{\text{eff}}}$ of the proposed structure divided by $\sqrt{\varepsilon_{\text{eff}}}$ for a standard 50-Ω CPW line. A minimum (dc) slow-wave enhancement of 20% is obtained by branching out the two ground planes of the CPW, as done in Structure A. A stronger slow-wave effect of at least 42% is achieved when the branching is done through the center conductor of the CPW line (Structure B). When the two effects are combined as in Structure C, the minimum slow-wave enhancement is measured to be better than 54%. In the passband of these structures, the increased inductance and

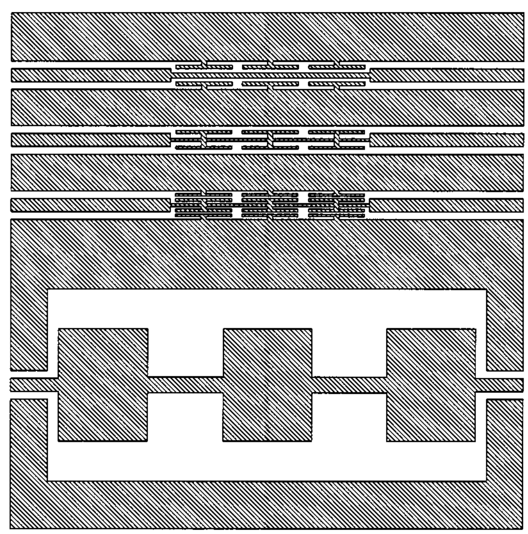


Fig. 5. Mask illustrating the reduced size of proposed periodic filters versus three-stage conventional stepped-impedance filter. Actual mask size is 1 in $\times$ 1 in.

capacitance per unit cell result in a slow-wave enhancement factor that is up to 1.8 times higher than that of a reference 50-Ω

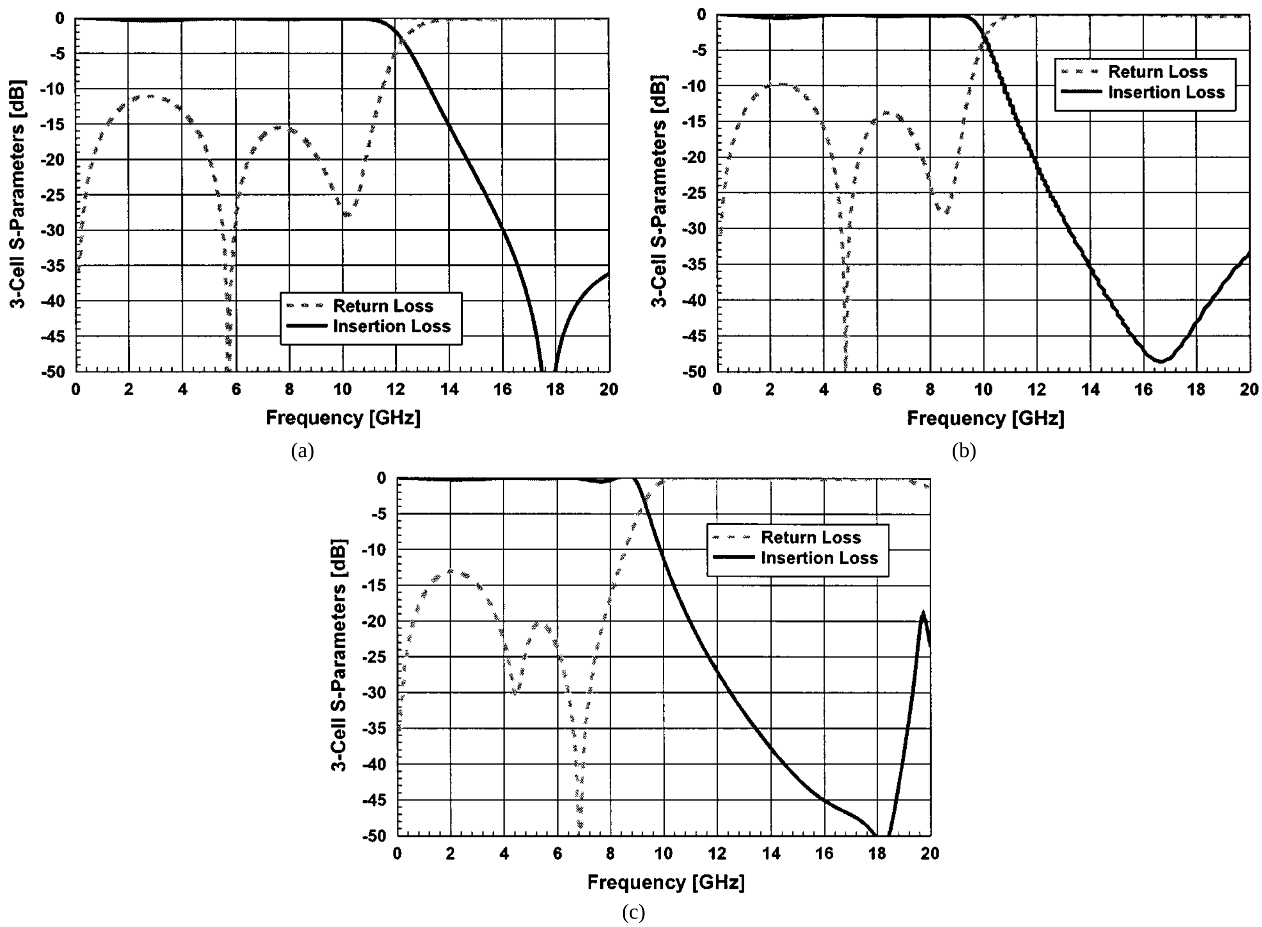


Fig. 6. Simulated method-of-moments response of three-cell periodic filters.

CPW line on the same substrate. Above these frequencies, the phase velocity increases exponentially, establishing a broad stopband effect that begins when the unit cell length equals one-half the guided wavelength in the periodic transmission line. The required unit cell length for this cutoff frequency f_c can be estimated as

$$l = \frac{c_0}{2 f_c \sqrt{\varepsilon_{\text{eff}}}} \tag{1}$$

where the effective dielectric constant ε_{eff} was previously given in Fig. 4 for our proposed structures. In reality, ε_{eff} will depend on the number of unit cells in the periodic structures. That is, an ideal periodic structure infinite in extent will experience a higher effective dielectric constant than for periodic structures with a finite number of cells owing to the coupling interaction between cells. We believe that the slow-wave factor of the periodic structure can be further enlarged by narrowing the width of the inductive branch or by bringing the two branched arms closer to the ground planes, but this comes at the cost of tighter fabrication precision.

An immediate and straightforward application of these slow-wave periodic structures is a miniature low-pass filter. Traditionally, slow-wave structures have not been used extensively as passive filters because of the large number of periods needed to establish deep attenuation levels and the associated increase in insertion loss of these structures. Moreover, reducing the size of filters generally tends to reduce the filter performance [14]. To demonstrate the filtering capabilities of the proposed structures, a series cascade of three unit cells is fabricated and measured for each topology. Since the proposed periodic structures are each entirely integrated into the CPW transmission line itself, filter size is dramatically reduced. For illustrative purposes, a mask of the three-cell proposed periodic filters is shown in Fig. 5 alongside a conventional three-stage CPW stepped-impedance low-pass filter with about the same cutoff frequency as Structure B. A twofold reduction in filter length and a tenfold reduction in filter area is achieved when comparing Structure B to the stepped-impedance filter. A filter with the same cutoff frequency, but based on the unit cell construction of Structure C, would be even smaller in size since the guided wavelength for Structure C is the shortest among all the proposed periodic structures. Figs. 6 and 7 depict the simulated and measured responses of the newly proposed periodic filters, respectively. Despite the extremely small size of the periodic filters, spurious-free response and deep attenuation levels can be observed in the stopband of Structures B and C. In fact, the attenuation levels achieved from just three cells of the proposed CPW structures are comparable to those of equivalent microstrip configurations that utilize the combined effects of a low-pass filter and a periodically etched ground plane [15]. An important consideration in any periodic structure is its associated loss. CPW MIS transmission lines are not used in practice due to their high loss, particularly at frequencies above 5 GHz. The insertion loss of the proposed periodic filters in the passband region, where the periodic structures serve as slow-wave transmission lines, compare very

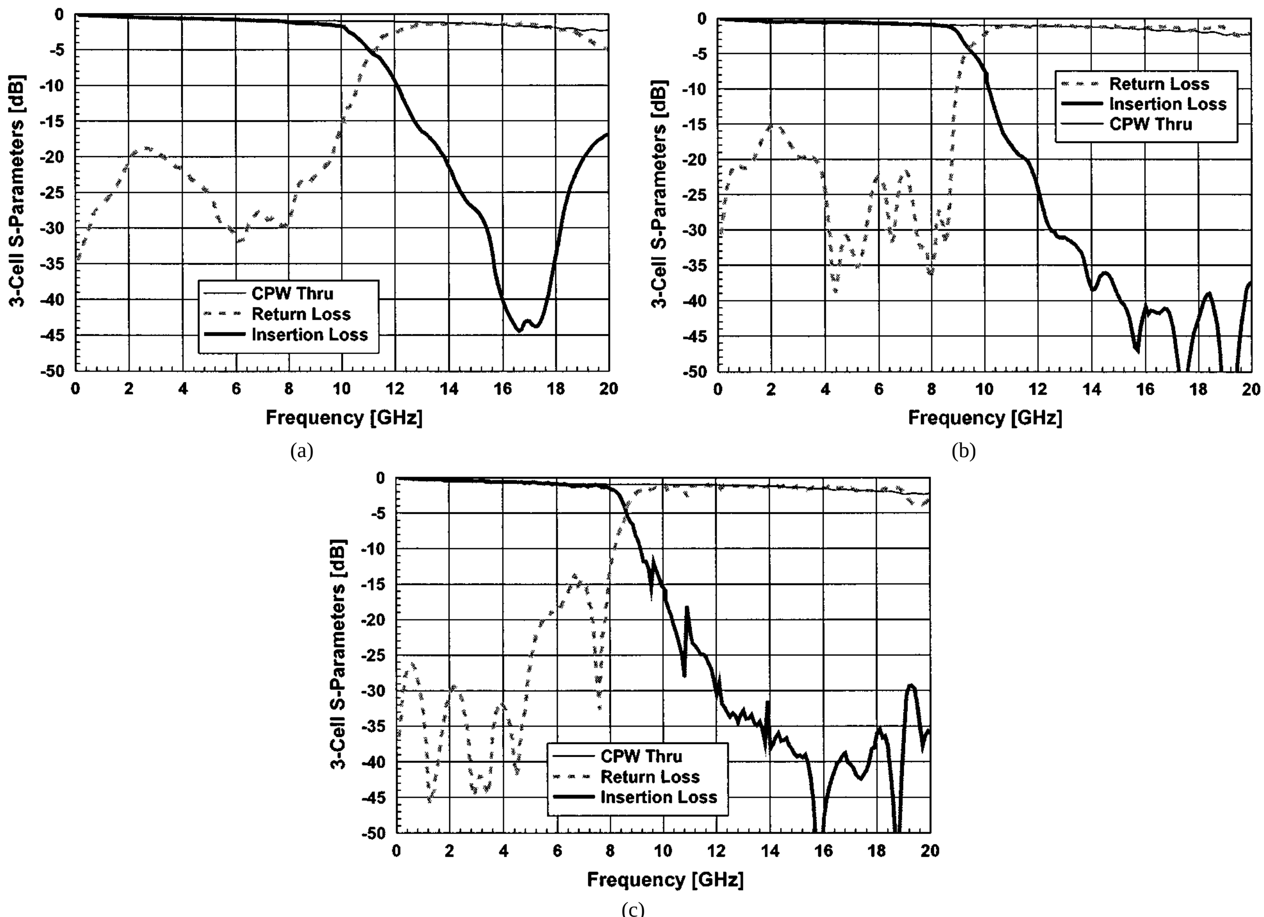


Fig. 7. Measured response of three-cell periodic filters.

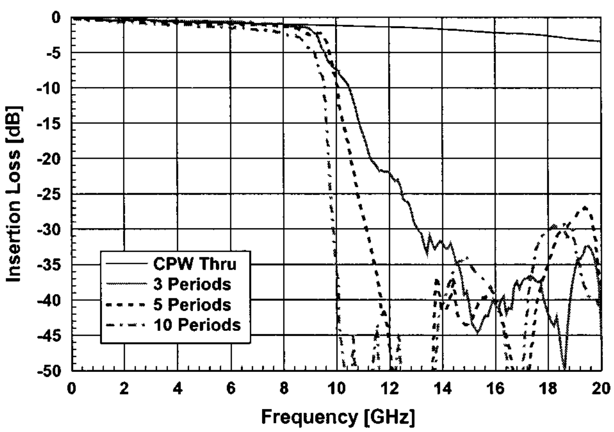


Fig. 8. Effect of additional cells on filter rolloff of Filter B.

well to that exhibited by a standard 50-Ω CPW line up to the respective cutoff frequencies, where we begin to see the effects of the filter rolloff take effect. Finally, since the filters are based upon the construction of periodic structures, filter synthesis is greatly simplified. A sharper rolloff can be accomplished simply by inserting more cells, as demonstrated in Fig. 8, while the length of the unit cell determines the cutoff frequency.

IV. Conclusion

In this paper, we have presented several novel periodic structures for a CPW waveguide. In the passband, a minimum slow-wave enhancement factor of up to 54% is recorded when compared to a reference 50-Ω CPW line on the same substrate. Taking up no more space than a standard CPW transmission line, the periodic structures offer very easy fabrication, very low insertion loss, and simple filter synthesis. A three-cell series cascade results in miniature low-pass filters that offer high attenuation levels in the stopband while reducing filter area size by over 90%. These novel periodic structures should find a wide variety of applications in microwave integrated circuits and help to significantly reduce MMIC chip sizes.

Acknowledgment

The authors wish to acknowledge and thank C. C. Chang, Microwave Electronics Laboratory, University of California at Los Angeles (UCLA), J. Fredrick, Microwave Electronics Laboratory, UCLA, and J. Y. Park, Microwave Electronics Laboratory, UCLA, for their helpful discussions.

References

[1] E. Yablonovitch, "Photonic band-gap structures," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 10, pp. 283–295, Feb. 1993.
[2] F. R. Yang, R. Coccioli, Y. Qian, and T. Itoh, "Analysis and application of coupled microstrips on periodically patterned ground plane," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, June 2000, pp. 1529–1532.
[3] C. Hang, V. Radisic, Y. Qian, and T. Itoh, "High efficiency power amplifier with novel PBG ground plane for harmonic tuning," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, June 1999, pp. 807–810.
[4] F. R. Yang, K. P. Ma, Y. Qian, and T. Itoh, "A novel TEM waveguide using compact photonic-bandgap (UC-PBG) structure," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2092–2098, Nov. 1999.

[5] K. P. Ma, J. Kim, F. R. Yang, Y. Qian, and T. Itoh, "Leakage suppression in stripline circuits using a 2-D photonic bandgap lattice," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, June 1999, pp. 73–76.

[6] S. Seki and H. Hasegawa, "Cross-tie slow-wave coplanar waveguide on semi-insulating GaAs substrate," *Electron. Lett.*, vol. 17, no. 25, pp. 940–941, Dec. 1981.

[7] K. Wu and R. Vahldieck, "Hybrid-mode analysis of homogeneously and inhomogeneously doped low-loss slow-wave coplanar transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1348–1360, Aug. 1991.

[8] V. Radisic, Y. Qian, R. Coccioli, and T. Itoh, "Novel 2-D photonic bandgap structure for microstrip lines," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 69–71, Feb. 1998.

[9] A. Görür, "A novel coplanar slow-wave structure," *IEEE Microwave Guided Wave Lett.*, vol. 4, pp. 86–88, Mar. 1994.

[10] A. Görür, C. Karpuz, and M. Alkan, "Characteristics of periodically loaded CPW structures," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 278–280, Aug. 1998.

[11] L. Zhu and K. Wu, "Model-based characterization of finite-periodic finite-ground coplanar waveguides," in *Asia–Pacific Microwave Conf. Dig.*, vol. 1, Nov. 1999, pp. 112–115.

[12] F. R. Yang, Y. Qian, R. Coccioli, and T. Itoh, "A novel low-loss slow-wave microstrip structure," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 372–374, Nov. 1998.

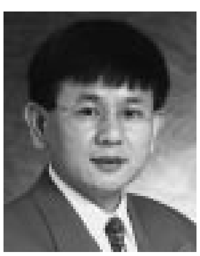
[13] K. Wu, D. Maurin, and R. Bosisio, "An explicit design technique for wide-band couplers and high quality filters using periodic topology," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, June 1993, pp. 1085–1088.

[14] M. Lancaster, F. Huang, A. Porch, B. Avenhaus, J. S. Hong, and D. Huang, "Miniature superconducting filters," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1339–1346, July 1996.

[15] F. R. Yang, Y. Qian, and T. Itoh, "A novel uniplanar compact PBG structure for filter and mixer applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, June 1999, pp. 919–922.

James Sor (S'00) was born in Battambang, Cambodia, in 1976. He received the B.S. and M.S. degrees in electrical engineering from the University of California at Los Angeles (UCLA), in 1999 and 2000, respectively, and is currently working toward the Ph.D. degree in electrical engineering at UCLA.

His research interests include leaky waves, novel antenna structures, and periodic structures.



Yongxi Qian (S'91–M'93–SM'00) was born in Shanghai, China, in 1965. He received the B.E. degree from Tsinghua University, Beijing, China, in 1987, and the M.E. and Ph.D. degrees from the University of Electro-Communications, Tokyo, Japan, in 1990 and 1993, respectively, all in electrical engineering.

From 1993 to 1996, he was an Assistant Professor at the University of Electro-Communications, Tokyo, Japan. From April 1996 to January 2001, he was a Post-Doctoral Fellow, Assistant Research Engineer, and Lecturer in the Electrical Engineering Department, University of California at Los Angeles (UCLA). In February 2001, he joined the Microsemi Corporation, Irvine, CA, where he is the Director of Technology and Applications at the MicroWaveSys Division and focuses on advanced heterojunction bipolar transistor (HBT) integrated circuits (ICs) for third-generation wireless local area networks (LAN) and high-speed fiber-optic applications. His research interests included numerical techniques for microwave and millimeter-wave circuits and antennas, generation and transmission of picosecond electrical pulses, crosstalk problems in high-density MMICs, miniature circuits for mobile communications, 60-GHz millimeter-wave focal plane imaging arrays, broad-band planar antennas, smart antennas and arrays for wireless communications, high-efficiency microwave power amplifiers, RF interconnect for mixed signal silicon MMICs, quasi-optical power combining, photonic bandgap (PBG) structures, active integrated antennas for indoor LANs, and high-power broad-band RF photonic devices for millimeter and submillimeter-wave photomixing. He has authored or co-authored over 200 refereed journal and conference papers, two books, and several book chapters.

Dr. Qian was the recipient of the 1998 Japan Microwave Prize presented at the Asia-Pacific Microwave Conference, the 1999 Best Student Paper presented at the 29th European Microwave Conference, and the 2000 ISAP Paper Award presented at the International Symposium on Antennas and Propagations.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois at Urbana-Champaign. From April 1976 to August 1977, he was a Senior Research Engineer in the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor at the University of Kentucky, Lexington. In July 1978, he joined the faculty at The University of Texas at Austin, where he became a Professor of electrical engineering in 1981 and Director of the Electrical Engineering Research Laboratory in 1984. During the summer of 1979, he was a Guest Researcher at AEG-Telefunken, Ulm, Germany. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at The University of Texas at Austin. In September 1984, he became an Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department, The University of Texas at Austin. In January 1991, he joined the University of California at Los Angeles (UCLA), as a Professor of electrical engineering and Holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He was an Honorary Visiting Professor at the Nanjing Institute of Technology, Nanjing, China, and at the Japan Defense Academy. In April 1994, he became an Adjunct Research Officer for the Communications Research Laboratory, Ministry of Post and Telecommunication, Japan. He currently holds a Visiting Professorship at The University of Leeds, Leeds, U.K., and is an External Examiner of the Graduate Program of the City University of Hong Kong. He has authored 280 journal publications, 585 refereed conference presentations, and 30 books/book chapters in the area of microwaves, millimeter waves, antennas, and numerical electromagnetics. He has generated 49 Ph.D. students.

Dr. Itoh is a member of the Institute of Electronics and Communication Engineers of Japan, and Commissions B and D of the USNC/URSI. He serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He was vice president of the IEEE MTT-S in 1989 and president in 1990. He was the editor-in-chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1983–1985) and the IEEE MICROWAVE AND GUIDED WAVE LETTERS (1991–1994). He was the chairman of the USNC/URSI Commission D (1988–1990), and chairman of Commission D of the International URSI (1993–1996). He is chair of the Long Range Planning Committee of the URSI. He serves on advisory boards and committees for a number of organizations. He was elected as an Honorary Life Member of the IEEE MTT-S in 1994. He has been the recipient of numerous awards, including the 1998 Shida Award presented by the Japanese Ministry of Post and Telecommunications, the 1998 Japan Microwave Prize, the 2000 IEEE Third Millennium Medal, and the 2000 IEEE MTT-S Distinguished Educator Award.