A Uniplanar Compact Photonic-Bandgap (UC-PBG) Structure and Its Applications for Microwave Circuits

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***Abstract*—This paper presents a novel photonic bandgap (PBG) structure for microwave integrated circuits. This new PBG structure is a two-dimensional square lattice with each element consisting of a metal pad and four connecting branches. Experimental results of a microstrip on a substrate with the PBG ground plane displays a broad stopband, as predicted by finite-difference time-domain simulations. Due to the slow-wave effect generated by this unique structure, the period of the PBG lattice is only $0.1\lambda_0$ at the cutoff frequency, resulting in the most compact PBG lattice ever achieved. In the passband, the measured slow-wave factor (β/k_0) is 1.2–2.4 times higher and insertion loss is at the same level compared to a conventional 50-Ω line. This uniplanar compact PBG (UC-PBG) structure can be built using standard planar fabrication techniques without any modification. Several application examples have also been demonstrated, including a nonleaky conductor-backed coplanar waveguide and a compact spurious-free bandpass filter. This UC-PBG structure should find wide applications for high-performance and compact circuit components in microwave and millimeter-wave integrated circuits.**

***Index Terms*— Bandpass filter, conductor-backed coplanar waveguide, photonic bandgap, slow-wave factor.**

I. INTRODUCTION

RECENTLY, there has been much interest in the field of photonic bandgap (PBG) engineering [1], [2]. Extensive studies have been conducted in applying the PBG phenomena for practical uses both in the optical regime and microwave and millimeter-wave domains [3]–[5]. Applications of PBG materials at microwave frequencies have been proposed, such as microstrip antennas [6]–[8], resonant cavities, and filters [9]. Microstrip lines with periodic elements etched in the ground plane have been found to behave like a PBG structure with forbidden bands for electromagnetic transmission [10]. This type of PBG structure has been employed for harmonic tuning in a broad-band power amplifier [11].

Practical application of a PBG structure usually has difficulty in accommodating its physical size since the period of a PBG lattice has to be a half-wavelength at the stopband frequency. Recently, a compact PBG structure consisting of small metal pads with grounding vias has been demonstrated to improve the performance of a patch antenna [12]. In this paper, we present another new concept of the PBG structure for planar microwave circuits. This uniplanar compact PBG (UC-PBG) structure is realized with metal pads etched in the ground plane connected by narrow lines to form a distributed *LC* network. Vias holes or multilayer substrates are not required in this novel PBG structure. A distinctive stopband over a wide range of frequency is observed and the measurement results agree with finite-difference time-domain (FDTD) simulations.

Another unique feature of this new PBG structure is the realization of a slow-wave microstrip line with low insertion loss. Slow-wave-mode propagation is of great interest for its use in reducing the dimension of distributed components in integrated circuits. Slow-wave transmission lines such as a metal–insulator–semiconductor (MIS) structure have been extensively investigated [13], [14]. However, MIS structures have disadvantages including large ohmic loss and low impedance, which cause difficulties in high-frequency applications [15]–[17]. In this paper, the slow-wave effect is verified when investigating the propagation characteristics of a UC-PBG structure in the passband. The advantages of low loss, moderate impedance, and uniplanar features make the UC-PBG structure a very promising candidate as a slow-wave transmission line.

This paper presents both basic characteristics and applications of this new uniplanar compact PBG structure. Design of the UC-PBG structure is introduced in Section II, where the geometry of the PBG lattice is illustrated. A numerical method (FDTD) is applied to characterize the proposed structure, and simulation results are shown in Section III. Experimental data including stopband and slow-wave properties are discussed in Section IV. Two application examples are demonstrated in Section V, followed by conclusions in Section VI.

II. DESIGN

Fig. 1(a) shows the schematic of the proposed PBG structure patterned in the ground plane of a microstrip line. Each element of this PBG lattice consists of a square metal pad with four connecting branches, as shown in Fig. 1(b). These narrow branches, together with insets at connections, introduce additional inductance seen by the microstrip, and the gaps between neighboring pads enlarge capacitance. The series reactive elements combined with the shunt capacitances determine the propagation constant, which is much larger than that of a conventional microstrip line. When the stopband

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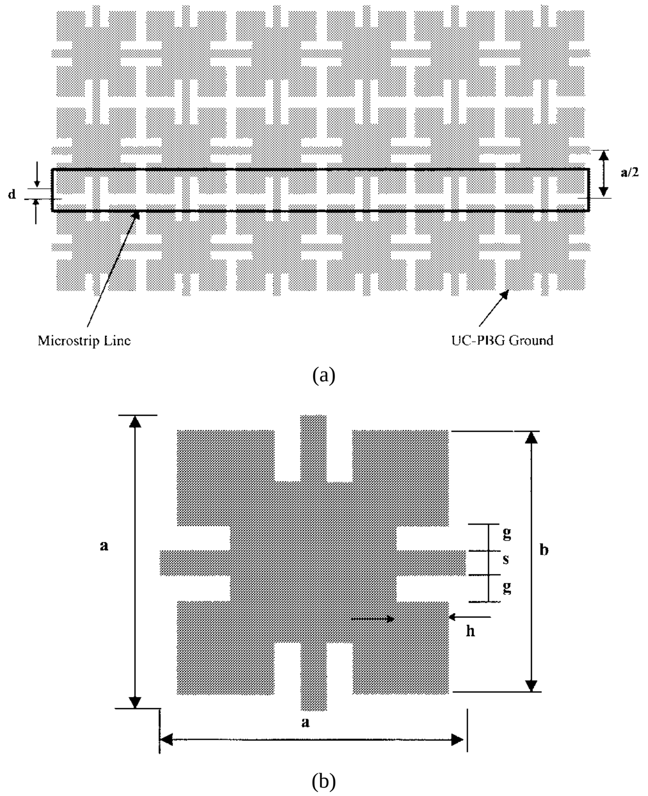


(a)

(b)

Fig. 1. (a) Schematics of microstrip line on the UC-PBG ground plane. (b) Details of one unit of the two-dimensional PBG lattice.

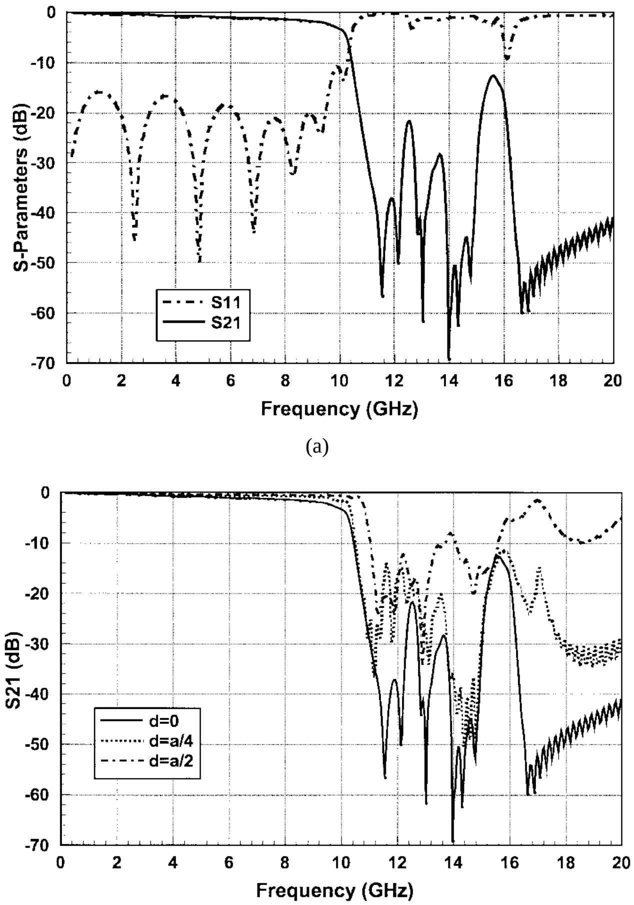
condition ($\beta_a = \pi$, β is the propagation constant and a is the lattice period) is satisfied, the propagation of the quasi-TEM mode along the microstrip line will be prohibited, resulting in a deep stopband in its transmission coefficient (S_{21}). Since the propagation constant (β) is increased significantly in this structure, as will be shown later, we expect that it will be an ideal candidate for designing very compact PBG structures. It can also be predicted that the conductor loss will not be increased by the PBG structure because the lattice is constructed in the ground plane where the current density is not highly concentrated.

III. Numerical Simulation

The FDTD method is applied to simulate the proposed structure shown in Fig. 1. The simulation model consists of a microstrip line with a 3 × 6 lattice of the UC-PBG as its ground plane. The substrate used is RT/Duroid 6010 with a dielectric constant of 10.2 and thickness of 25 mil. The microstrip width is 24 mil, corresponding to a 50-Ω line on a conventional, unperturbed ground plane. The metal pad and inductive branch have the following dimensions:

1) $a = 120$ mil;
2) $b = 108$ mil;
3) $s = g = 12$ mil;
4) $h = 30$ mil.

Another parameter is the alignment offset between the microstrip and PBG lattice d, which ranges from 0 to $a/2$, and periodically repeats anywhere else.



(a)

(b)

Fig. 2. (a) FDTD simulation results of S-parameters of the microstrip on the PBG ground plane. (b) Dependence of S_{21} on the alignment offset.

Fig. 2(a) shows the simulation results of the S-parameters. A distinctive stopband has been observed at frequencies above 10 GHz, where the transmission coefficient (S_{21}) is lower than 20 dB, except for a small passband at 15–16 GHz. No ripples of S_{21} have been found in the passband, which is favorable to filter applications. The return loss (S_{11}) is close to 0 dB in the stopband, indicating little radiation loss, thus verifying the PBG property. It is also important to see sensitivity of the stopband behavior to the alignment offset (d). Fig. 2(b) shows simulation results of the dependence of S_{21} for three cases where $d = 0$, $a/4$, and $a/2$, respectively. Although the depth and width of the stopband varies with d, a distinctive stopband always exists. The band edge is around 10 GHz for all three cases, showing that the PBG effect is relatively insensitive to the alignment offset between the microstrip and PBG lattice in the ground plane.

IV. Experimental Results

A 24-mil-wide 1-in-long microstrip on the UC-PBG ground plane has been fabricated and tested. The PBG section is 720-mil long, which corresponds to six periods. A short length (140 mil) of solid ground plane has been included at each end of the microstrip line to facilitate the connection with subminiature A (SMA) connectors. The effect of these two short pieces of normal 50-Ω microstrip lines has been

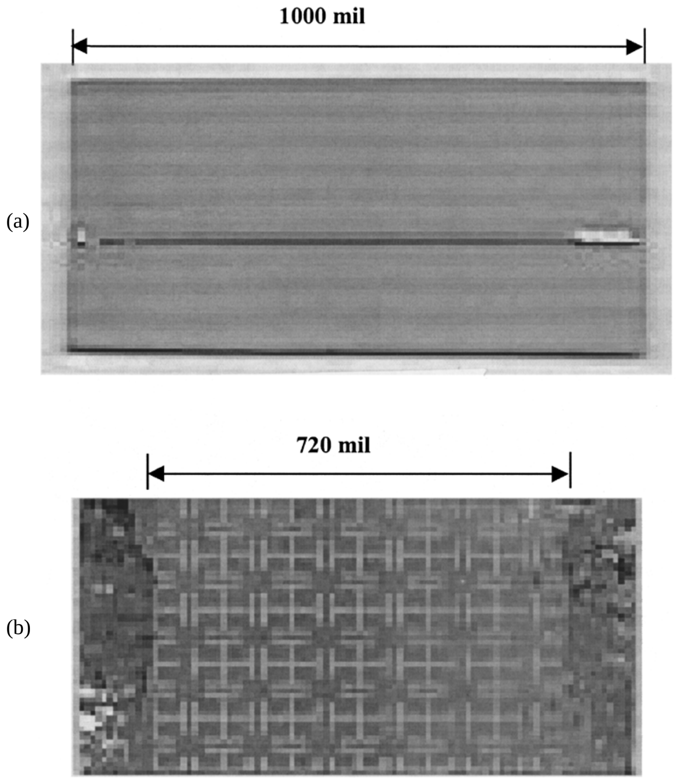
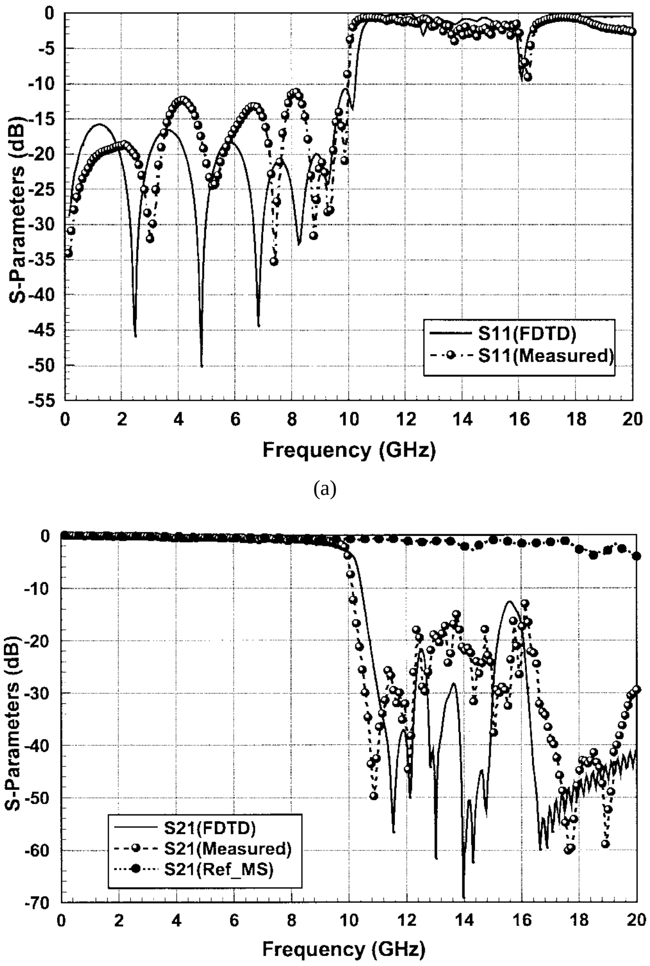


Fig. 3. Photographs of the fabricated microstrip line on the UC-PBG ground plane. (a) Top view. (b) Bottom view.

included in the FDTD simulation. Figs. 3 and 4 show the photographs and measurement results of the proposed PBG structure, respectively. Fig. 4(a) displays the return loss of the microstrip line on the UC-PBG ground plane. The measured insertion loss of a conventional microstrip line with the same length (1 in) has been plotted for comparison in Fig. 4(b). As can be seen, excellent agreement between the measurement and FDTD prediction has been obtained. The slight difference might be due to overetching and the effect of SMA connectors. As shown in Fig. 4(b), the insertion loss of the proposed PBG line is low and comparable to that of a conventional microstrip line, indicating that the line impedance is close to 50 Ω.

Fig. 5 displays the slow-wave factor (β/k_0) of this UC-PBG structure in conjunction with that of a conventional microstrip line. It can be observed that the slow-wave effect is significant even at very low frequencies and the slow-wave factor (β/k_0) has been found to be 1.2–2.4 times higher than that of an ordinary 50-Ω line. It is believed that the slow-wave factor can be further enlarged by controlling each element in the PBG structure. It was also found that the variation of the slow-wave factor is less than ±5% for different alignment offsets between the microstrip and PBG lattice, which is advantageous for practical applications.

Additionally, the fact that the UC-PBG structure is well matched over a wide range of frequency can be explained by the relatively constant characteristic impedance. At frequencies lower than the stopband, inductance and capacitance seen by the microstrip increase simultaneously and keep the impedance at a constant level. Unlike the case of other slow-wave structure, such as MIS transmission lines, the problem of low characteristic impedance does not exist here. The UC-PBG structure exhibits the same slow-wave effect as for a conventional microstrip line with a higher dielectric constant, but without major consequential increase in conductor loss. For example, the conductor loss of a 50-Ω line on the UC-PBG



(a)

(b)

Fig. 4. Comparison of simulation and measurement results of: (a) S_{11} and (b) S_{21} of the microstrip line on the UC-PBG ground plane.

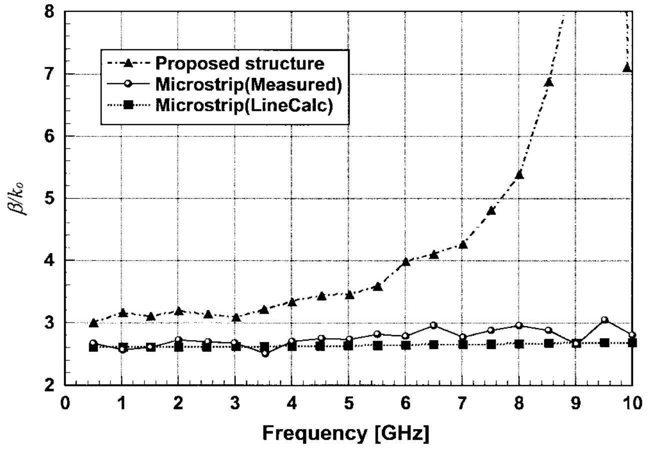


Fig. 5. Slow-wave factor of a microstrip line on the UC-PBG ground plane in comparison with a conventional microstrip line.

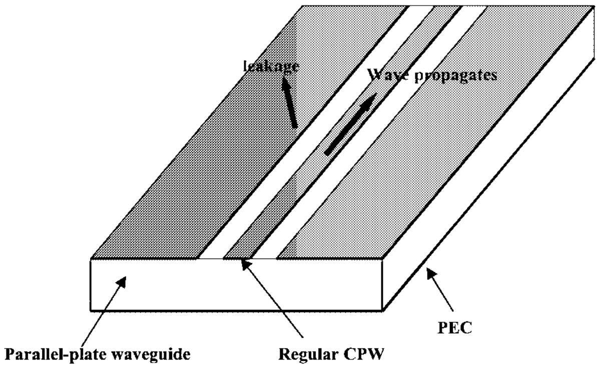


Fig. 6. The structure view of a conventional CB-CPW.

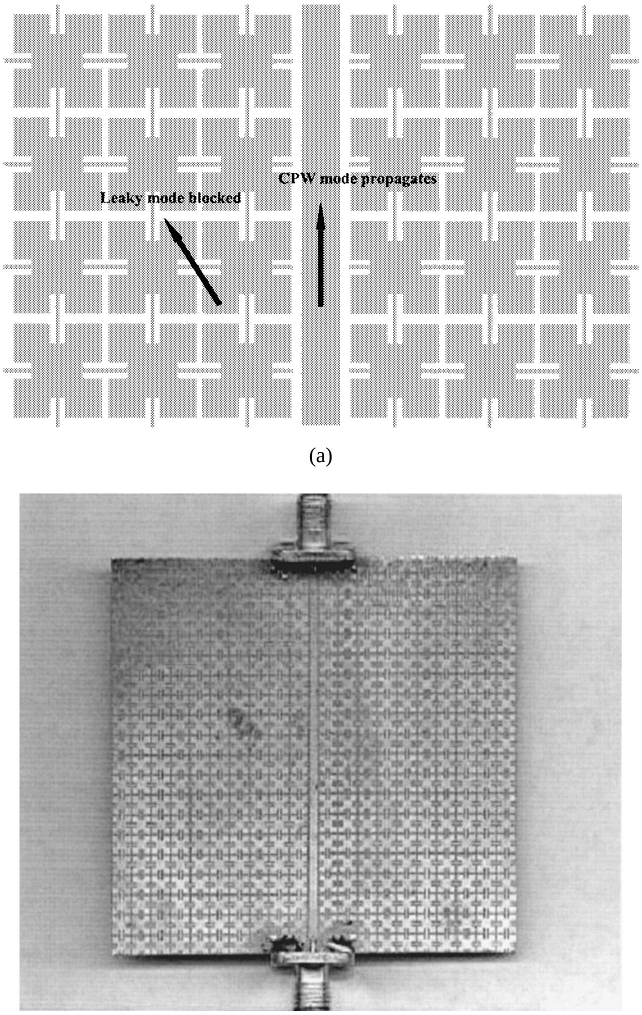
ground is 0.17 dB/in at 6 GHz. On the other hand, the conductor loss of a conventional microstrip line with the same impedance and propagation constant would be 0.46 dB/in, since the microstrip width has to be reduced substantially to keep the line impedance at 50 Ω due to an increase of the dielectric constant of the substrate. The MIS structures with low characteristic impedances also face the necessity of using accurate photolithography for very fine features [17]. The microstrip integrated with the UC-PBG ground plane demonstrates the advantages of low loss, moderate impedance level and simple fabrication process, which can be exploited to build a new type of slow-wave structure.

V. APPLICATIONS

A. Nonleaky CB-CPW

Coplanar waveguide (CPW) has been investigated comprehensively for applications both in microwave integrated circuits (MIC's) and monolithic-microwave integrated circuits (MMIC's) since its first introduction [18], [19]. The conventional CPW is often backed with another ground plane to increase mechanical strength, realize mixed CPW microstrip circuits, or provide a heat sink [20]. The conductor-backed CPW (CB-CPW), however, will excite the parallel-plate mode and deteriorate CPW performance. Several approaches have been presented to overcome the leakage problem, such as using posts to short the unwanted mode or using multilayered substrates to shift the dispersion curve of the parallel-plate mode [21]. However, a planar circuit is preferable for the fabrication process of integrated circuits. The proposed UC-PBG structure with a wide stopband can be easily etched in the top ground planes of a CB-CPW circuit without using any extra masks or via holes and, therefore, is very promising for stopping the power leakage due to the parallel-plate mode.

Fig. 6 shows the schematic of a conventional CB-CPW, where an additional ground plane is added to the back of a conventional CPW. A parallel-plate waveguide will be formed between top and bottom ground planes. The energy will leak along a particular angle once the wave is launched. This leakage is significant even at low frequencies, which will cause a severe effect, such as crosstalk, with neighboring circuits. The wide stopband of a UC-PBG structure can be used to suppress the propagation of this parallel-plate mode. Fig. 7(a) and (b) shows the schematic and photograph of the nonleaky CB-CPW, where the UC-PBG lattice is constructed into the top ground planes. The measured transmission coefficient (S_{21}) of the proposed nonleaky CB-CPW is displayed in Fig. 8, together with the measured S_{21} of a conventional CPW as well



(a)

(b)

Fig. 7. (a) Schematic of the proposed nonleaky CB-CPW with the UC-PBG structure in the ground planes. (b) Photograph of the fabricated nonleaky CB-CPW.

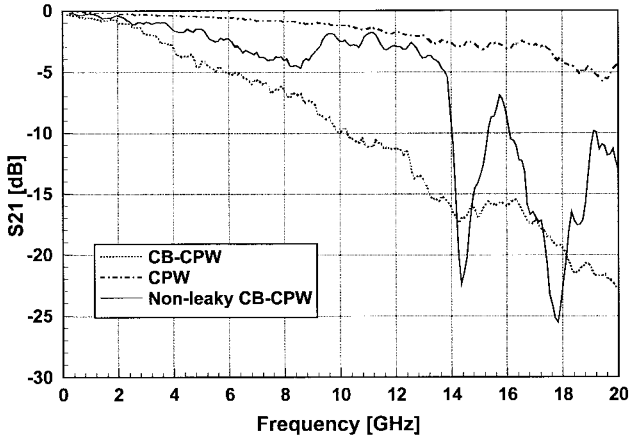
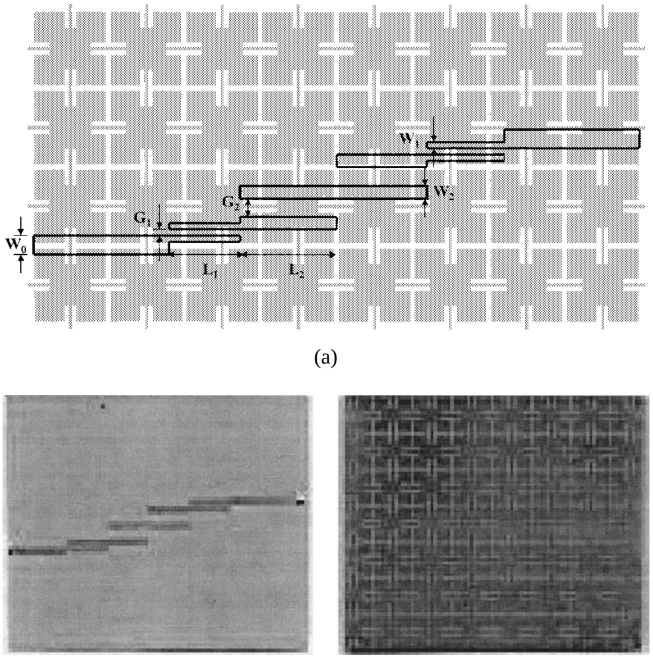


Fig. 8. Measured S_{21} of the fabricated nonleaky CB-CPW. The insertion losses of the conventional CPW and CB-CPW are also shown for comparison.

as a CB-CPW. It is found that for a conventional CB-CPW, the leakage is significant at all frequency ranges. Meanwhile, the insertion loss of a conventional CPW is relatively low as expected at frequencies below 13 GHz, and starts rippling at higher frequencies due to the reflections caused by SMA connectors.

As shown by the solid curve in Fig. 8, for the proposed CB-CPW with a UC-PBG lattice, power leakage is still present in the range between dc and 9 GHz, which is the passband of the PBG structure. However, the insertion loss has been improved significantly and is comparable to that of a conventional CPW between 9–14 GHz, indicating that the leakage loss has been suppressed almost completely at that frequency range that corresponds to the stopband of the UC-PBG structure. This novel CB-CPW structure shows great potential for applications in various types of CPW-based circuits, such as CPW-fed slot antennas.



(a)

(b) (c)

Fig. 9. Microstrip BPF on the UC-PBG ground (a) Schematic. (b) Top view. (c) Bottom view.

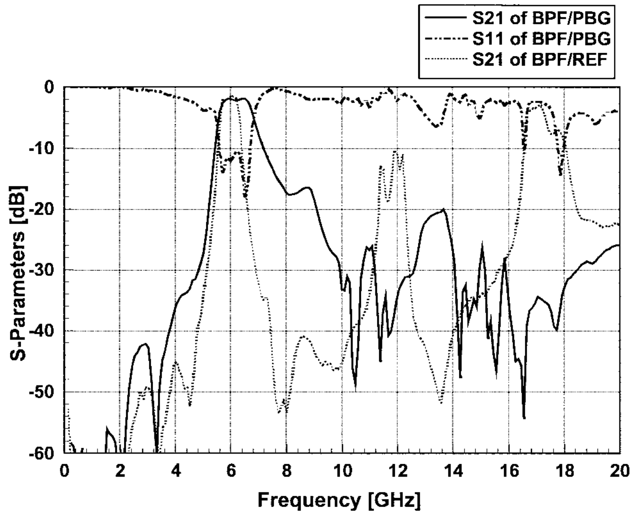


Fig. 10. Measured S-parameters of the fabricated PBG BPF. The S_{21} of a conventional BPF is also plotted for comparison (indicated by BPF/REF).

B. Compact Microstrip Bandpass Filters (BPF's) with Intrinsic Spurious Suppression

Microstrip BPF's are widely used in microwave integrated circuits [22]. Conventional parallel-coupled BPF's, however, present spurious passbands at harmonic frequencies, which tend to degrade the performance of the overall RF system. Extra filters are usually required to suppress spurious transmissions and, as a consequence, the insertion loss will be increased. The advantages of the UC-PBG can be applied to construct a compact microstrip BPF with intrinsic spurious rejection. First of all, the well-matched microstrip on the UC-PBG ground plane is appropriate for the use as a low-loss transmission line. Second, the wide and deep stopband of the UC-PBG structure can be employed to suppress the spurious passbands at higher harmonics. Since the stopband is intrinsic, extra filters are not required. Furthermore, the slow-wave effect reduces the physical length of the filter circuit integrated with the UC-PBG structure.

Fig. 9 shows the schematic and pictures of a parallel-coupled BPF using the UC-PBG structure in the ground plane. The design of the parallel-coupled BPF follows the standard procedures in the literature [23]. The BPF is designed with four coupling sections, a 0.5-dB equal-ripple response, and a center frequency of 6 GHz. The dimensions of the coupled-lines are $W_1 = 17$ mil, $W_2 = 21$ mil, $G_1 = 8$ mil, and $G_2 = 28$ mil. The width of microstrip feed lines is 24 mil, corresponding to a 50-Ω microstrip line on a conventional ground plane. The normalized propagation constant (β/k_0) is measured to be 3.97 at 6 GHz, and the physical length of the coupled-lines section (L_1 and L_2) is 145 mil, which is 20% shorter than that of a conventional quarter-wavelength line.

Fig. 10 shows the results of the proposed PBG BPF. For comparison, the insertion loss of a conventional edge-coupled BPF is also plotted. As can be seen, the measured transmission coefficients of a conventional BPF are -10 dB and -5 dB at 12 and 17 GHz, respectively. On the other hand, the experimental result of the BPF on a UC-PBG ground shows a 30–40-dB suppression of the spurious response. It should be mentioned here that in designing the PBG BPF at center frequency of 6 GHz, the lengths of the microstrip resonators have been scaled appropriately according to the slow-wave factor. On the other hand, the coupling gaps were kept unchanged. This explains the increased fractional bandwidth (21.6%) of the PBG filter and a slower rolloff. The bandpass characteristics can be improved by optimizing the coupling coefficients between the resonators in a similar manner to conventional BPF design. The minimum insertion loss of the PBG filter is 1.9 dB at 6.39 GHz, which includes the effect of two SMA connectors. The passband loss is comparable to that of a conventional BPF, as can be observed in Fig. 10.

VI. CONCLUSION

A new type of two-dimensional PBG structure is presented for applications in microwave circuits. This novel structure has a wide stopband and compact size, as well as a uniplanar configuration, which can be easily incorporated into the ground planes of microstrips or any other planar structures. The broad stopband and the slow-wave effect of the UC-PBG structure have been employed to design a nonleaky CB-CPW and a compact BPF with spurious-free response. This UC-PBG structure will find many other applications in various areas, such as compact antennas, surface wave suppression, and harmonic tuning for microwave power amplifiers.

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His current interest is in wireless technology.

Yongxi Qian (S'91–M'93), for photograph and biography, see this issue, p. 1424.

Tatsuo Itoh (S'69–M'69–SM'74–F'82–LF'94), for photograph and biography, see this issue, p. 1425.