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Planar PBG Structures: Basic Properties and Applications

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SUMMARY This paper reviews recent progresses in the research and development of planar photonic band-gap (PBG) structures, also called electromagnetic crystals, for microwave and millimeter-wave applications. Planar electromagnetic crystals are particularly attractive and intensively investigated because of their easy fabrication, low cost, and compatibility with standard planar circuit technology. Two configurations and their applications are described in this paper: a square lattice of holes etched in a ground plane and the recently developed Uniplanar Compact PBG (UC-PBG) structure. Basic properties as well as applications to microwave circuits are reported. These include harmonic tuning in power amplifier, leakage suppression in conductor-backed coplanar waveguide (CB-CPW), realization of planar slow-wave structure, and performance improvement in microstrip filters and patch antennas.

key words: *photonic band-gap (PBG), electromagnetic crystal, conductor-backed coplanar waveguide (CBCPW), microstrip filter, patch antenna*

1. Introduction

Photonic band-gap structures are artificially made structures with periodicity either in one, two, or three dimensions. Because of their similarity with the periodic structure of natural crystals, they are also called electromagnetic crystals. Although one- and two-dimensional periodic structures have long been investigated in the microwave community, new concepts and ideas recently developed in the optics regime [1], [2] have renewed the interest also in the microwave area. Among the new ideas, the most attractive to microwave engineers is probably the capability to forbid electromagnetic propagation in either all or selected directions to realize spatial filters. Extensive investigations have been conducted to translate and apply these new concepts in the microwave and millimeter-wave domain [3]–[5], and several applications at microwave frequency have been developed, including antenna substrates [6]–[8], resonant cavities, and filters [9].

Electromagnetic crystals at microwave frequency have been initially realized by scaling the structures used at optical frequency. That implied micromachining holes into dielectric slabs to create a two-dimensional [10] periodic variation of the material refractive dielectric. Machined slabs can also be stacked to create a three-dimensional periodic variation of the refractive index [11]. However, those configurations have two main drawbacks: They are not easy to fabricate, and are big in terms of wavelength.

Reducing electromagnetic crystals dimension is one of the most important issues that have to be solved for a convenient integration of their functionality in microwave circuits. Successful steps in this direction have been made using metallo-dielectric structures [12]–[14]. The basic idea behind this development is the introduction of a periodic network of LC-elements to shorten the wavelength of the propagating wave. An effective example of metallo-dielectric crystals is given by the high-impedance ground plane described in [15], and employed to improve patch antenna performances in [16]. It is comprised of a grounded dielectric slab periodically loaded with a square lattice of square metallic pads. The edges of the pads are a few mils apart, realizing a 2D periodic network of capacitors. Each pads is connected to the ground through one via at its center, which provides the inductive part of the LC-network.

The above approach, although very effective, requires a non-planar fabrication process. Recent research efforts at the authors group focused on the development of planar electromagnetic crystal that do not need via and that can be easily integrated in microwave and millimeter-wave circuits. In the following sections, two of the developed structures will be described along with some of the applications conceived. The first structure is comprised of a square lattice of holes etched in the ground plane of grounded dielectric slab, while the second is a more compact crystal, henceforth referred to as Uniplanar Compact PBG (UC-PBG), which realizes a 2D periodic network of LC circuits without introducing vias.

2. Square Lattice of Circles Etched in Ground Plane

2.1 Basic Properties

Figure 1 shows one of the first planar crystal structure realized at the authors lab [17]. It is comprised of a two-dimensional square lattice of circles etched in the ground plane of a 50-Ω microstrip line. The function of

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the holes is to create a spatially periodic variation of the effective dielectric constant of the line, which produces the desired stopbands and passbands. The substrate is built using RT/Duroid 6010 with dielectric constant of 10.2 and thickness 25 mil. The stopband center frequency f_0 is determined by the lattice period a and can be estimated using the relation $\beta a = \pi$ where β is the propagation constant at the center frequency. Because the propagation constant of the PBG structure cannot be analytically determined, full-wave analysis is required to accurately compute f_0. Lattices with period of 200 mil and different radii of circles r have been measured and they have been found to have a stopband that becomes more distinctive as the circle radius increases. Ripples in the passband also become larger as the radius increase and this is due to a higher degree of mismatching between the microstrip line impedance and the impedance of the microstrip running on top of the etched ground plane. Figure 2 shows the simulated and measured S-parameter for an optimized structure with a radius to period ratio $r/a = 0.25$, which provides a wide stopband and small passband ripples.

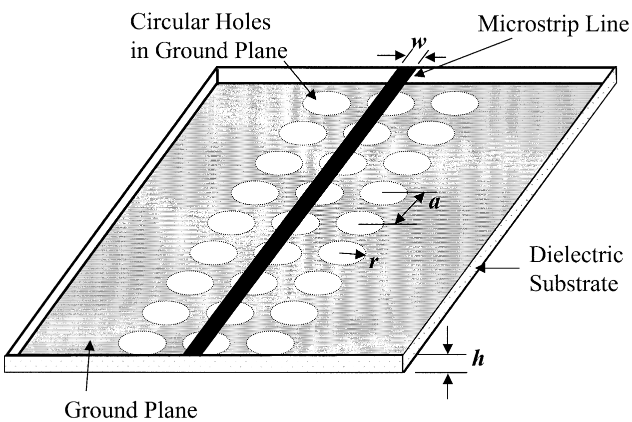

Fig. 1 Schematic of a microstrip on PBG ground plane. The PBG structure is a square lattice of etched circles.

2.2 Applications

Broad-band operation of power amplifiers requires harmonic filtering and tuning that is typically difficult to realize. The wide stopband characteristic of microstrip on PBG ground plane can be used as broad-band harmonic tuner for power amplifiers to increase power added efficiency. A class AB power amplifier integrated with a slot antenna and PBG structure has been presented in [18], [19]. Figure 3 shows the prototype of the proposed power amplifier circuit built on a 31-mil-thick RT/Duroid 5870 ($\varepsilon_r = 2.33$) substrate. The PBG square lattice has a period of 480 mil and circle radius of 110 mil. Figure 4 shows that PAE greater than 50% was achieved in the 3.7–4.0 GHz frequency range.

Other applications of this type of PBG structure have also been demonstrated. For example, Rumsey et al. [20] proposed a lowpass filter with a wide high-frequency rejection bandwidth using cascaded sections

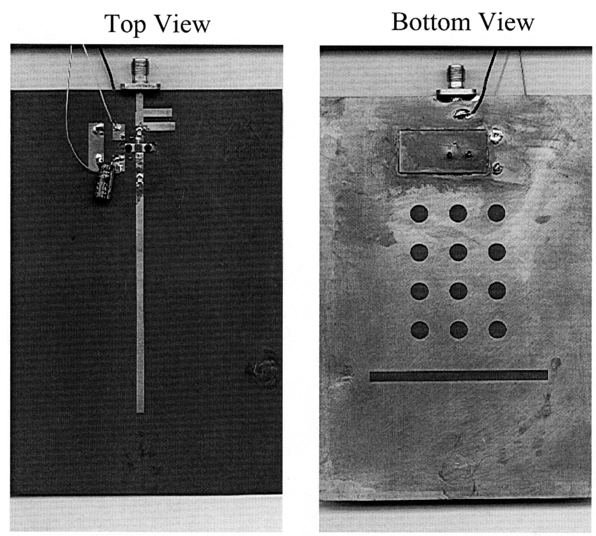

Fig. 3 Top and bottom view of the broadband active slot antenna amplifier integrated with PBG ground.

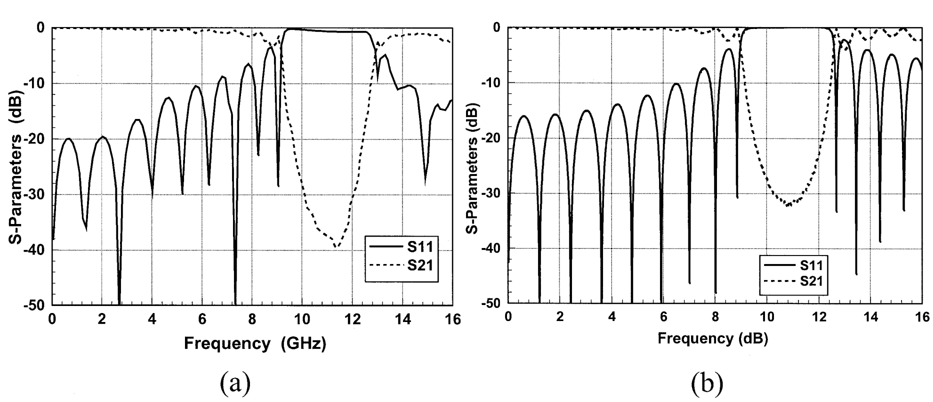

Fig. 2 (a) Measured and (b) simulated S-parameters of the microstrip on PBG ground plane.

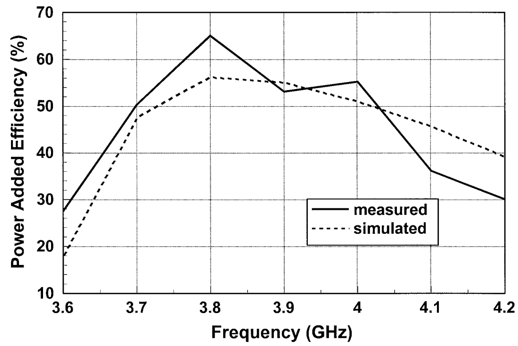

Fig. 4 Measured and simulated PAE for the broad-band power amplifier integrated with slot and PBG ground.

of PBG structures with different lattice periods. Horii et al. presented a microstrip patch antenna with PBG ground plane to suppress radiation at harmonic frequencies [21] while Deal et al. used the same structure to reduce power lost to surface waves [22]. Chang et al. demonstrated PBG resonators for microstrip line and CPWs [23].

3. Uniplanar Compact PBG (UC-PBG) Structure

3.1 Basic Properties: Microstrip-Guided Wave in UC-PBG Substrate

The crystal structure previously described has planar geometry and is effective, however, it has the drawback of being large in terms of wavelength. This problem has been overcome by the recent development of the Uniplanar Compact PBG (UC-PBG) structure sketched in Fig. 5(a). The UC-PBG structure is comprised of a square lattice of square metallic pads, each one connected to the four adjacent ones through a narrow strip. Figure 5(b) shows a single unit cell of the crystal. The narrow strips together with insets at connections introduce lumped inductive elements, while the gaps between neighboring pads introduce lumped capacitors. The effect of the two-dimensional periodic LC-network is that of reducing the wavelength of an electromagnetic wave propagating along the structure.

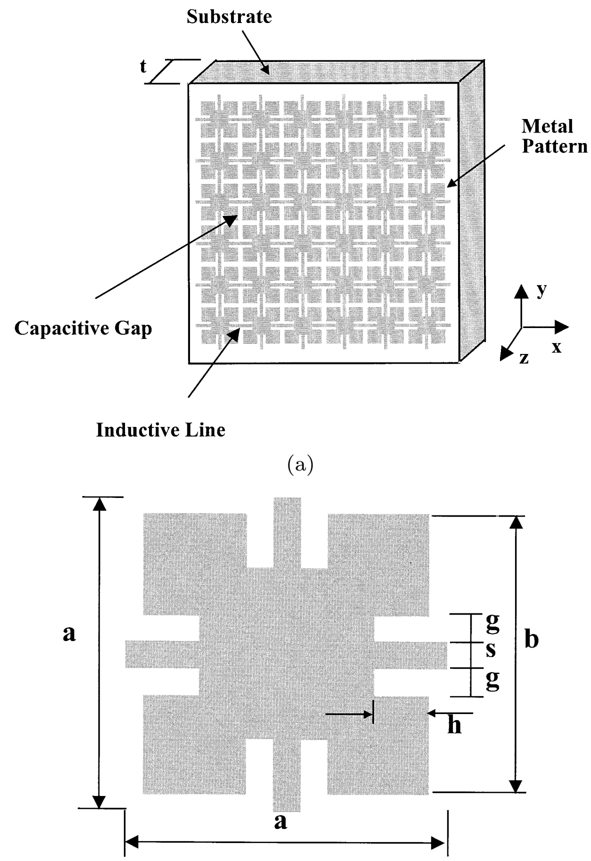

Fig. 5 (a) Schematic of UC-PBG metallic pattern on a dielectric slab with relative dielectric constant 10.2 and thickness 25 mil. (b) Unit cell of the UC-PBG structure. Parameters: $a = 120$ mil; $b = 110$ mil; $h = 27.5$ mil; $s = g = 10$ mil.

Figure 6 shows a 24-mil wide microstrip line etched on RT/Duroid 6010 substrate with a dielectric constant of 10.2 and thickness of 25 mil. The UC-PBG metallic pattern is etched on the opposite side of the dielectric slab. Figure 7 shows the FDTD simulated and measured scattering parameters of the microstrip line. 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. S_{21} is quite flat in the low-frequency passband, which is favorable to filter applications, and remains flat also when an alignment offset between microstrip and UC-PBG lattice is present [24]. The slow-wave factor introduced by the UC-PBG metallic pattern has been measured to be 1.2 to 2.4 times larger than that of a conventional microstrip [25]. The slow-wave effect is due to the increased inductance and capacitance per

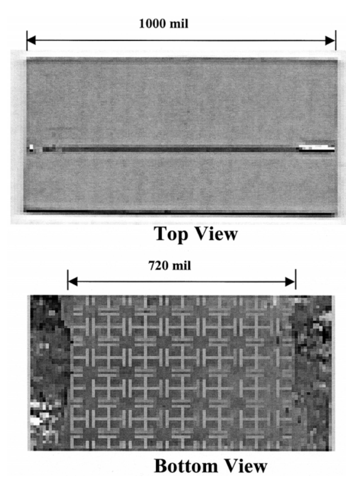

Fig. 6 Photographs of top and bottom sides of the microstrip on UC-PBG ground plane.

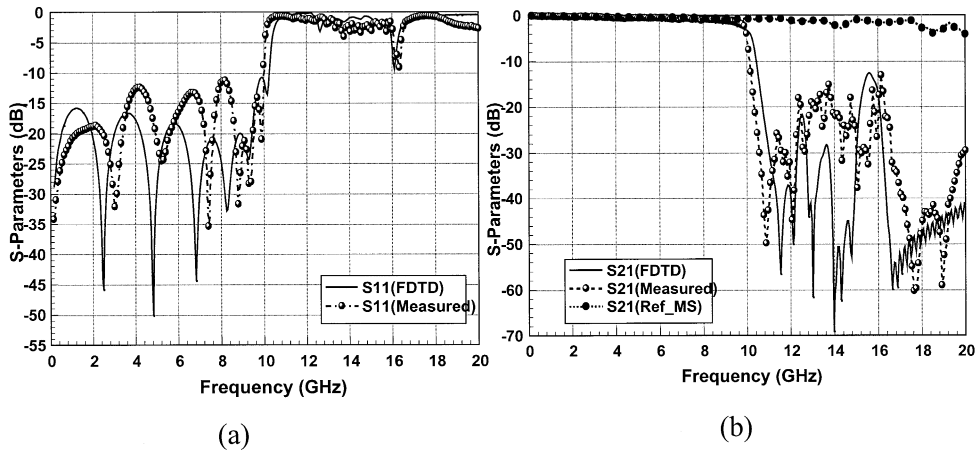

Fig. 7 Simulated and measured scattering parameters of microstrip on UC-PBG ground. (a) Return loss, (b) insertion loss.

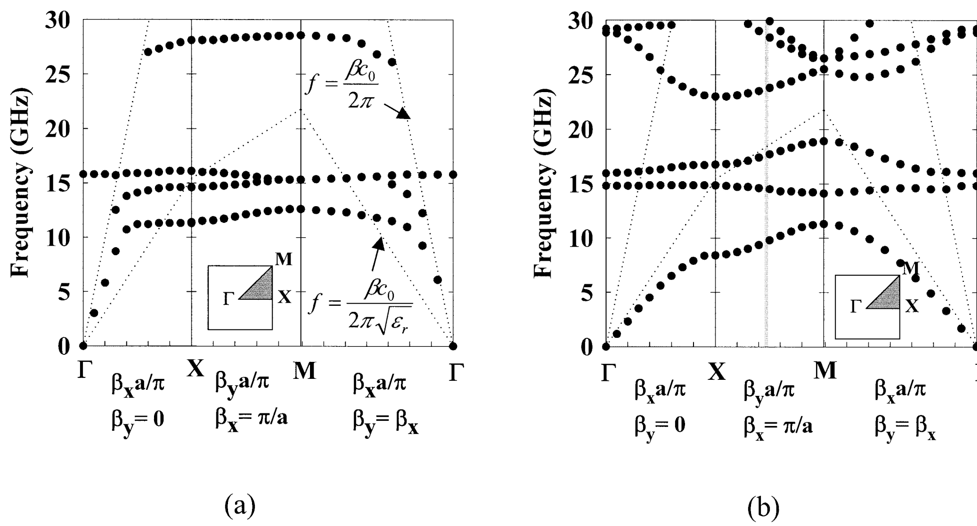

Fig. 8 Dispersion diagrams of UC-PBG structures patterned on (a) bare slab and (b) grounded slab.

unit length. Since both inductance and capacitance per unit length increase, impedance of the microstrip on UC-PBG ground plane remains close to 50-Ω below the cutoff, and this explain the flatness of the low frequency passband.

3.2 Basic Properties: Surface Waves in UC-PBG Substrate

Two structures have been analyzed to investigate surface wave propagation along the UC-PBG substrates: metallic pattern etched on a bare dielectric slab and a grounded dielectric slab. In both cases a stopband for surface waves propagating along the structure still appears when the condition $\beta a = \pi$, is satisfied. However, the presence of the LC-networks reduces the wavelength of the surface wave, so that the period of the UC-PBG is significantly smaller than a half wavelength in free-space.

Figure 8 shows the dispersion diagram for the structure shown in Fig. 5 for the two different cases of UC-PBG used on a bare dielectric slab (Fig. 8(a)) and on a grounded dielectric slab (Fig. 8(b)). Several differences can be noted between the two diagrams. First, while the UC-PBG on a bare dielectric slab presents a wide stopband between the third and fourth mode in the frequency range 16.1 to 26.1 GHz, the UC-PBG on a grounded dielectric slab has two stopbands. The first stopband is between the first and second mode, spanning the frequency range 11.3 to 14.1 GHz; the second is between the third and fourth mode in the frequency range 18.9 to 23 GHz. Moreover, the second and fourth modes of the grounded slab UC-PBG do not show any cut-off frequency as seen instead for the second and fourth modes of the bare slab UC-PBG.

The fundamental mode of both structures is a TM-

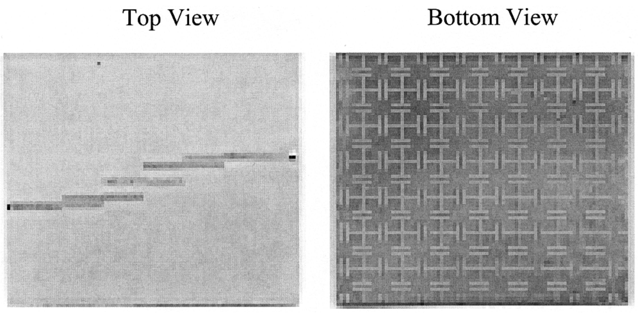

Fig. 9 Photographs of top and bottom sides of the microstrip bandpass filter above UC-PBG ground plane.

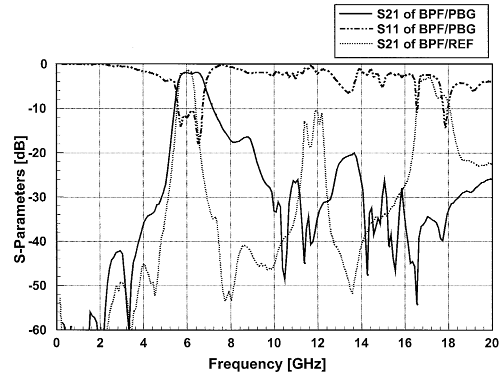

Fig. 10 Measured S-parameters of the BPF on UC-PBG ground. The insertion loss of a conventional BPF is also shown for comparison.

like mode with strong longitudinal component of electric field. Computations show that, as expected, the effective dielectric constant of such mode is higher in the case of grounded slab UC-PBG. This is due to the fact that the ground plane confines the electric field inside the high permittivity region. Second and third modes for both cases are predominantly TE modes with strong transverse component of the electric field.

Results of microstrip-based UC-PBG structure presented in the previous subsection can be further elucidated by considering the dispersion behavior of the first TM-like mode in the section (Γ-X) of the two dispersion diagrams of Fig. 8. The Γ-X section describes mode propagation along the UC-PBG structure in a direction parallel to the primitive vectors ($a\hat{\boldsymbol{x}}$, $a\hat{\boldsymbol{y}}$ in Fig. 5(a)) of the square lattice. The first TM-like mode has a cut-off frequency at the X point of 11.4 GHz for the case of UC-PBG on a bare dielectric slab, and 8.4 GHz for the case of UC-PBG on a grounded dielectric slab. The measured cut-off frequency for the microstrip- guided mode is 10 GHz. As expected, this value is between the two extreme cases of UC-PBG on a bare and grounded dielectric slab.

3.3 Applications

3.3.1 Spurious-Free Microstrip Filters

The broad stopband shown by the previous structure can be exploited to suppress spurious passband always present in conventional microstrip filters [26], [27]. The sharp cutoff (Fig. 7) can be exploited to improve the roll-off of a lowpass filter [27], meanwhile, the slow-wave effect reduces the resonator length of the filter integrated with UC-PBG ground plane [26]. Figure 9 shows the prototype of an edge-coupled bandpass filter with center frequency of 6 GHz on UC-PBG ground and Fig. 10 shows the measured results. For comparison the insertion loss (S_{21}) of a conventional bandpass filter is also plotted. As can be seen, the measured S_{21} of a conventional bandpass filter are -10 dB and -5 dB at 12 GHz and 17 GHz, respectively. In contrast, the experimental result of the bandpass filter on the UC-PBG ground shows a 30 to 40 dB suppression of the spurious response. It should be mentioned here that in designing the PBG bandpass filter the lengths of the microstrip resonators have been scaled appropriately according to the slow-wave factor. The coupling gaps, on the other hand, have been kept unchanged. This explains the increased bandwidth of the PBG filter and a slower roll-off. The bandpass characteristics can be improved by optimizing the coupling coefficients between the resonators, similarly to conventional BPF design. The minimum insertion loss from connector to connector of the PBG filter is 1.9 dB at 6.39 GHz, and it is comparable to that of a conventional filter.

The UC-PBG structure can also be integrated with a conventional stepped-impedance lowpass filter to enhance its performance [27]. The prototype realized (Fig. 11) has shown stopband attenuation 38 dB higher than that of a conventional LPF (Fig. 12). Integration of this PBG lowpass filter with a drain mixer has been presented in [27], where conversion gain enhancement and LO leakage reduction have been demonstrated.

3.3.2 Harmonic Tuning in Power Amplifier

Harmonic tuning in power amplifier using the UC-PBG has been demonstrated [28]. Figure 13 shows the realized prototype of an S-band class AB power amplifier integrated with UC-PBG microstrip. The UC-PBG dimensions were designed to have a cut-off frequency at 6 GHz and measured S_{21} showed a wide stopband from 6 to 15 GHz [28]. Output level of second and third harmonics has been reduced from -11 dB and -30 dB to -48 dB and -60 dB, respectively, in comparison with the case of a reference amplifier terminated with standard 50-Ω load. A 10% increase in PAE and 1.3 dB in output power have also been measured.

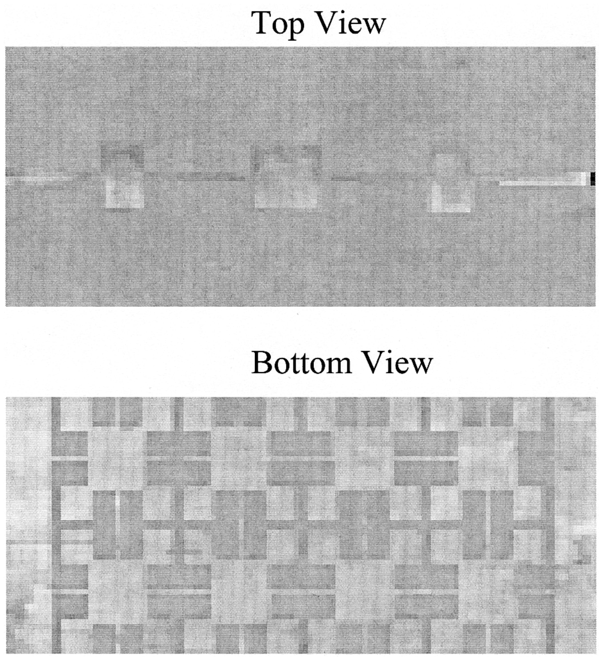

Fig. 11 Photographs of top and bottom sides of the microstrip lowpass filter on the UC-PBG ground plane.

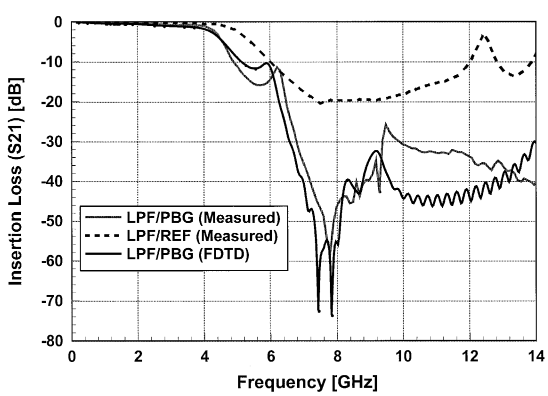

Fig. 12 Measured and simulated insertion loss of the LPF on UC-PBG ground. S_{11} of a conventional LPF is also plotted for comparison.

3.3.3 Leakage Suppression in CB-CPW

Coplanar waveguide (CPW) has been studied extensively and applied both to MIC and MMIC [29] for its low dispersion characteristic. A ground plane on the back-side of a CPW is often required for practical reasons such as to enhance mechanical strength or provide heat sink [30]. The main drawback of the conductor-backed CPW (CB-CPW) is the power leakage due to unwanted parallel-plate mode, which can be suppressed using shorting posts [31]. Although effective, this solution is costly and a planar structure would be useful to reduce complexity of the fabrication process. The 2-D stopband of the UC-PBG structure on a grounded dielectric slab has been exploited to stop parallel-plate mode of the CB-CPW [32].

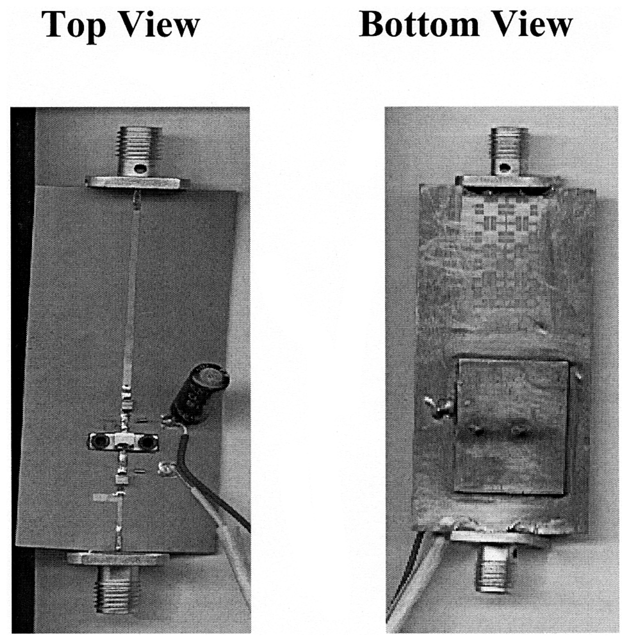

Fig. 13 Photographs of the S-band class AB power amplifier integrated with UC-PBG microstrip for harmonic tuning.

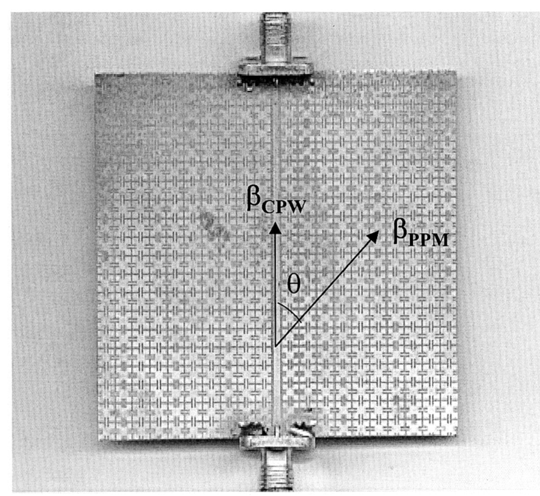

Fig. 14 Photograph of the CB-CPW with UC-PBG lateral ground planes. Propagation directions of CPW and Parallel-plate modes are indicated. Substrate used is Duroid 6010 with 25 mil thickness.

Figure 14 shows the novel CB-CPW where the UC-PBG lattice is etched on the top ground planes. Measured transmission coefficient (S_{21}) of the proposed CB-CPW and the conventional CPW and CB-CPW as references are displayed in Fig. 15. For a conventional CB-CPW, the leakage is significant at all frequencies, as expected. Insertion losses of a conventional CPW are relatively low at frequencies below 13 GHz, and start rippling at higher frequencies due to reflections caused by connectors. As can be seen from Fig. 14, power leakage

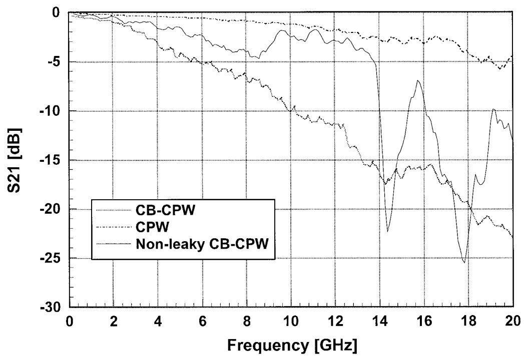

Fig. 15 Measured insertion loss of the CB-CPW with lateral UC-PBG ground. S_{21} of conventional, non-leaky CPW and CB-CPW are also plotted for comparison.

of the CB-CPW with UC-PBG is significantly reduced between 9 GHz and 14 GHz. This frequency range is wider than that of the complete stopband of the UC-PBG structure on a grounded dielectric slab with same value of relative permittivity and thickness (Fig. 8(b)). This can be explained by considering the propagation angle θ of the TEM parallel plate mode responsible for power leakage. When measured from the CPW axis, θ can be estimated as

$$\theta = \cos^{-1}\left(\frac{\beta_{CPW}}{\beta_{PPM}}\right) \tag{1}$$

where β_{CPW} and β_{PPM} are the propagation constant of the CPW and the parallel plate mode, respectively. In the case of the standard CB-CPW with dimensions given in Fig. 14, θ is about 36.5° degrees in the frequency range 9 to 14 GHz. In the case of CB-CPW with UC-PBG, β_{PPM} can be estimated using the computed dispersion diagram (Fig. 8(b)). The average effective dielectric constant of the first mode in the (X-M) section of the dispersion diagram, which describes propagation for angles from 0° to 45° with respect to the lattice primitive vectors, is 34.3. Using this value is possible to estimate the propagation constant and propagation angle θ of the parallel plate mode. It is found that for the CB-CPW line with UC-PBG the angle θ varies in the range 64° to 65.7° for frequency in the range 9 to 14 GHz. These values of θ correspond to directions of propagation for the parallel plate mode in the shadowed region of the dispersion diagram (Fig. 8(b)). The computed stopband for those directions of propagation is seen to be in the range 9.5 to 14.35 GHz, which agree well with measured data (Fig. 15).

3.3.4 Aperture Coupled Patch Antenna on UC-PBG Substrate

Microstrip patch antennas are extensively used in communication systems for their low profile, low cost and easy fabrication [33]. Patch antennas are usually built on low permittivity substrates for optimum performance, since surface waves are excited on high dielectric constant substrate. On the contrary, MIC and MMIC are usually built on high dielectric constant substrates to reduce dimensions. To achieve a high degree of integration for both circuits and antenna is desirable to realize planar antennas with good performance on high dielectric substrates. The complete stopband provided by the UC-PBG structure can be employed to reduce surface wave losses of patch antennas on high dielectric constant substrate [34], [35]. Figure 16 shows the top view of an aperture coupled patch antenna surrounded by three periods of UC-PBG lattice. The antenna has been designed to resonate at a frequency inside the UC-PBG stopband so that excitation of surface waves is reduced as much as possible. Details on the antenna and feeding structure geometry can be found in [35]. Figure 17 shows the measured Co-polar E- and H-plane patterns of the UC-PBG antenna mounted on wide substrate and a reference antenna with same dimensions but without UC-PBG. It is seen that excitation of surface waves is strongly reduced on the E-plane and that directive gain at broadside of the UC-PBG antenna is 3 dB higher than that of the reference patch. Measurements have been done at slightly different frequency for the two antennas in order to have the same return loss ($S_{11} = -20$ dB) for both of them. Cross-polarization level on both planes is below -10 dB.

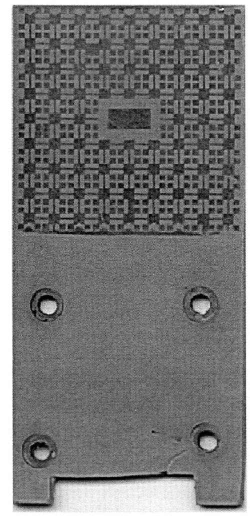

Fig. 16 Top view of aperture coupled patch antenna surrounded by three periods of UC-PBG lattice.

4. Conclusion

Basic properties of planar PBG structures and applications to microwave circuits and antennas have been presented. The planar characteristic of the electromagnetic crystals presented makes them very attractive for applications to MICs and MMICs because of their easy and low cost realization as well as compatibility with standard fabrication techniques.

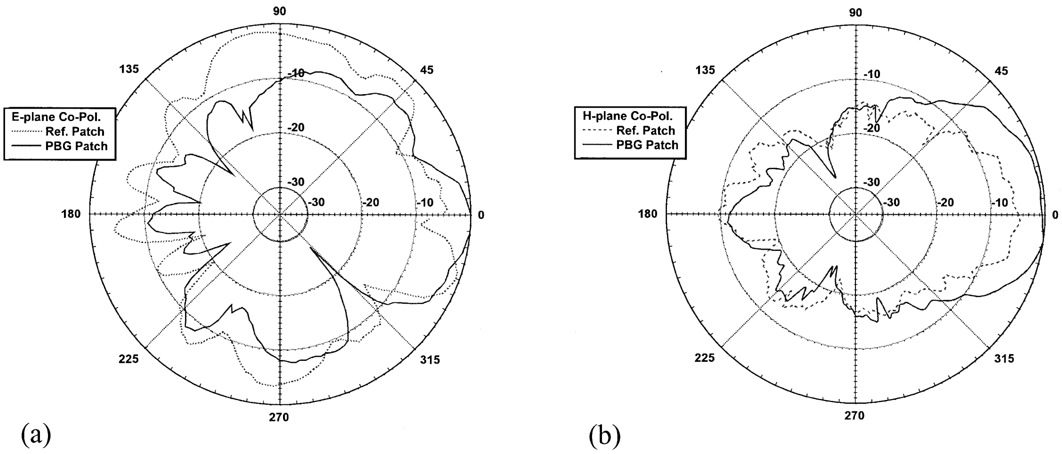

Fig. 17 Top view of aperture coupled patch antenna surrounded by three periods of UC-PBG lattice.

The 2-D square lattice of etched circles in ground plane of a microstrip exhibits a wide stopband for transmission and has been exploited as harmonic tuner in a power amplifier. The novel UC-PBG structure realizes a 2-D periodic LC network that increases the propagation constant of waves traveling along the structure itself. The dispersion diagrams of UC-PBG metallic pattern on both bare and grounded dielectric slab have been calculated using FDTD, and show complete stopbands, in different frequency ranges.

The unique features of the UC-PBG structure have been applied to different types of microwave circuits. Its broad stopband has been exploited to suppress the harmonics of power amplifier output and spurious passbands of conventional microstrip filters. The slow-wave effect generated by the UC-PBG structure has allowed reducing of 20% the resonator length of the realized edge-coupled bandpass filter. Other applications that have been demonstrated include reduction of parallel-plate mode leakage in CB-CPW and surface wave loss of patch antennas on high dielectric constant substrates.

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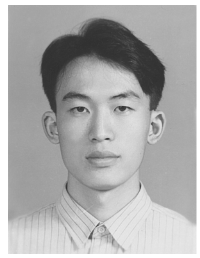

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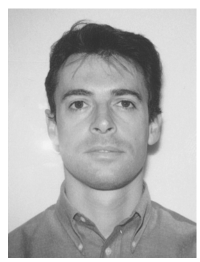

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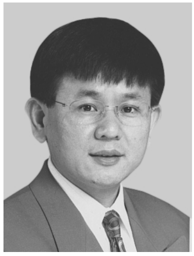

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