A Novel TEM Waveguide Using Uniplanar Compact Photonic-Bandgap (UC-PBG) Structure

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***Abstract*—A novel waveguide using a photonic bandgap (PBG) structure is presented. The PBG structure is a two-dimensional square lattice with each cell consisting of metal pads and four connecting lines, which are etched on a conductor-backed Duroid substrate. This uniplanar compact PBG structure realizes a magnetic surface in the stopband and is used in the waveguide walls to provide magnetic boundary conditions. A relatively uniform field distribution along the cross section has been measured at frequencies from 9.4 to 10.4 GHz. Phase velocities close to the speed of light have also been observed in the stopband, indicating that TEM mode has been established. A recently developed quasi-Yagi antenna has been employed as a broad-band and efficient waveguide transition. Meanwhile, full-wave simulations using the finite-difference time-domain method provide accurate predictions for the characteristics of both the perfect magnetic conductor impedance surface and the waveguide structure. This novel waveguide structure should find a wide range of applications in different areas, including quasi-optical power combining and the electromagnetic compatibility testing.**

***Index Terms*—Perfect magnetic conductor, phase velocity, photonic bandgap, quasi-Yagi antenna, TEM waveguide.**

I. Introduction

PHOTONIC bandgap (PBG) materials have been exclusively investigated for their versatility in controlling the propagation of electromagnetic waves [1], [2]. The fact that PBG structures are scalable makes them useful not only in the optical regime, but also in the microwave or millimeter-wave domain. Practical applications in microwave frequency such as microstrip antenna [3]–[6] and power amplifiers [7] have been presented. Two-dimensional PBG materials have also been applied as planar reflectors, which can be used in antennas and waveguide structures [8]–[10]. Recently, several PBG structures have been proposed and demonstrated to be useful in enhancing performances of microwave circuits or antennas. For example, a high-impedance ground plane has been realized using metal plates with vertical vias [11]. A uniplanar compact photonic bandgap (UC-PBG) structure has also been presented for various applications [12], [13]. This novel PBG structure has several advantages, including compact size, planar feature, low loss, and broad stopband. While many existing PBG materials focus on the applications of bandgaps, the UC-PBG structure can be exploited for multiple purposes. For instance, the passband of a UC-PBG structure has been use as a slow-wave medium, which reduces dimensions of the circuits integrated on it [14]. The wide stopband has been applied to suppress spurious transmission of filters [15] and leakage of guided-wave structures, including conductor-backed coplanar waveguides (CB CPW's) [16], and striplines [17]. Furthermore, a UC-PBG structure can realize a magnetic surface at the stopband frequency when using it as a planar reflector [18].

The quasi-optical amplifiers is of great interest for its potential to efficiently combine the output power generated from a large number of active device [19]. Power combining using waveguides becomes a popular approach because the diffraction loss can be avoided [20] and the broad-band responses can be achieved [21]. Dielectric-loaded or oversized waveguides are often used in spatially combined amplifier arrays since uniform aperture field distribution are required [10], [21]. However, for a dielectric-loaded waveguide with small size, it shows no advantage over a conventional empty waveguide [22]. The performance can be improved using high dielectric constant material or longitudinal corrugations, but the bandwidth will be smaller as a consequence [22]. The unique characteristic of the UC-PBG structure allows for the possibility of building a TEM waveguide with a uniform field distribution.

The UC-PBG reflector has been demonstrated to behave like a PMC at the stopband frequency where the periodic loading changes the surface impedance to an open-circuit condition [18]. The concept of the PMC surface can be applied to build a TEM waveguide with a uniform field distribution. When the two sidewalls of a rectangular waveguide are replaced by UC-PBG structures, a parallel-plate mode will be established by the magnetic boundary conditions. This novel PBG waveguide is a promising candidate as a feeding structure in the quasi-optical power-combining amplifier array. The UC-PBG structure can be fabricated on a thin substrate using the standard etching technique, which is easier than the manufacturing process of conventional hard horns with high dielectric-constant materials or corrugations.

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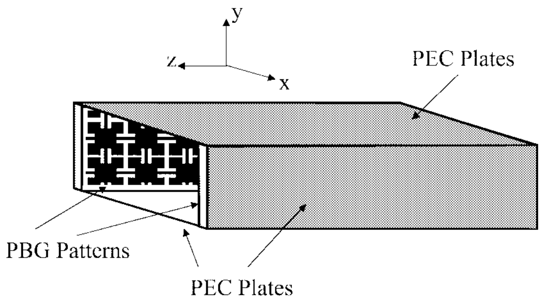


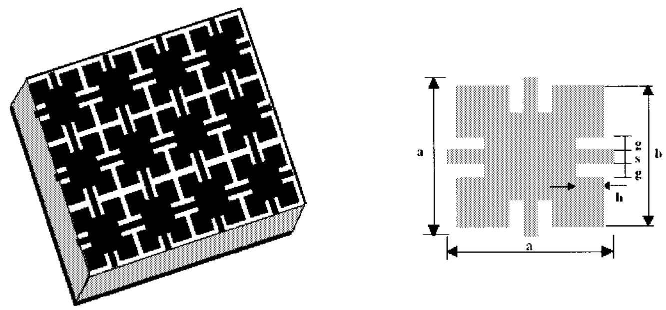
Fig. 1. Schematic of a UC-PBG waveguide.

This paper proposes a novel TEM waveguide using a UC-PBG structure, which accomplishes a PMC surface at the stopband frequency. Characteristics of the UC-PBG structure is introduced in Section II and the realization of a PMC surface is presented. Analysis of the PBG waveguide is performed in Section III, where a simple circuit model and full-wave simulation are applied. Section IV shows the experimental results of the PBG waveguide, including phase velocities and field profiles at different frequencies along the cross section. The performance of the microstrip-to-waveguide transition is also mentioned in Section IV and is followed by conclusions in Section V.

II. Characteristics of the Novel PBG Structure

Fig. 1 shows the proposed TEM-waveguide using the UC-PBG structures in two sidewalls. The UC-PBG structure is a two-dimensional periodic lattice patterned on a conductor-backed dielectric substrate. The unit cell of the PBG lattice consists of square pads and narrow lines with insets, as displayed in Fig. 2(a). The gaps between adjacent cells provide capacitive coupling and the narrow branches have inductive behavior, which is further enhanced by insets. The surface impedance of the proposed structure is frequency-sensitive since the PBG structure actually forms a distributed *LC* network with specific resonant frequencies. At the frequencies where the periodic loading becomes an open circuit, an equivalent magnetic surface is created. This interesting phenomenon can be explained using a simple transmission-line model, shown in Fig. 2(b). The UC-PBG surface is modeled by an *LC* tank with a resonant frequency corresponding to the center frequency of the stopband. As frequency approaches the resonant frequency, the imaginary part of the input impedance becomes infinity, indicating a perfect magnetic surface, as illustrated in Fig. 2(b).

The characteristics of the PMC behavior of a PBG surface can be verified by measuring the reflection coefficient for a uniform incident plane wave. The phase of the reflection coefficient of a PMC plane should exhibit a difference of 180° compared to that of a perfect electric conductor (PEC) plane. Fig. 3(a) shows the experimental setup of a scattering measurement. X-band horn antennas A and B are used for transmitting and receiving, respectively. Plastic foam with a relative dielectric constant of 1.0 is inserted between two horns as a holder for the scatterer. Two types of scatterer used in this experiment are an intact copper sheet (PEC) and a UC-



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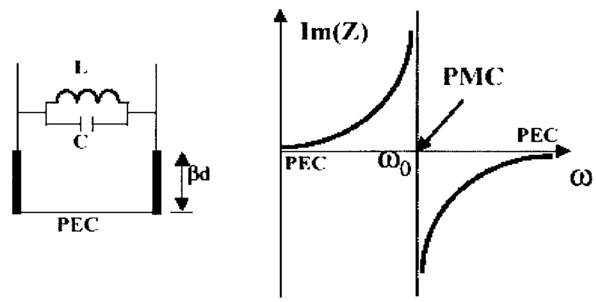
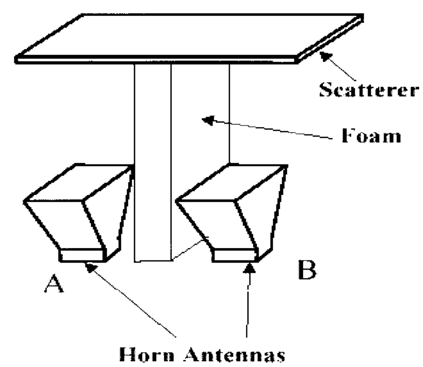


(b)

Fig. 2. (a) Schematic of a two-dimensional UC-PBG lattice on the Duroid substrate with the outline of a unit cell. (b) Equivalent-circuit model of the UC-PBG structure and the input impedance.



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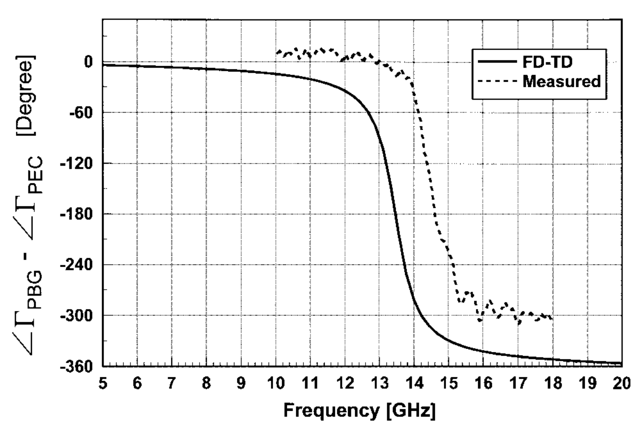


(b)

Fig. 3. (a) Setup for the reflection coefficient measurement. (b) Measured and simulated results of phase differences in reflection coefficients between the PBG and PEC surface.

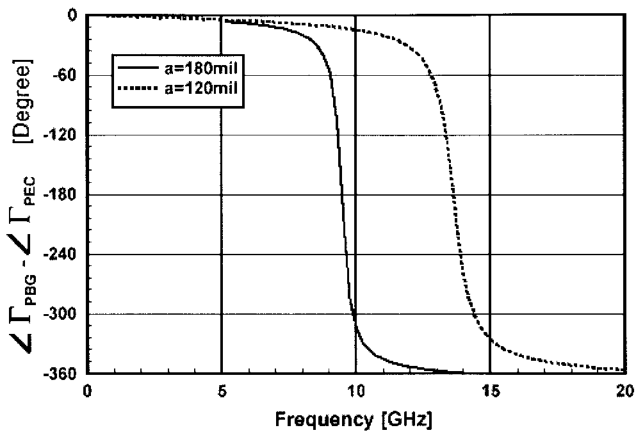


Fig. 4. Frequency scaling of the UC-PBG structure.

PBG surface, both fabricated on a conductor-backed Duroid substrate (Duroid 6010) with dielectric constant of 10.2 and thickness of 25 mil. The UC-PBG structure is a 40 $\times$ 60 array with a period (a) of 120 mil.

Fig. 3(b) shows the phase difference in reflection coefficients between PBG and PEC surfaces. As can be seen, a 180° phase difference occurs around 14.5 GHz, indicating that a magnetic surface has been successfully realized. The PBG surface is inductive below 14.5 GHz and becomes capacitive above the resonant frequency. Finite-difference time-domain (FDTD) simulation shows a close agreement with an error of 6%, which might be caused by the finite substrate and over-etching effects. Several measurements with different spacing between two horns and different distances from the PBG surface to antennas have been performed. The results are insensitive to those variations, implying the robustness of the realized magnetic surface.

The PBG structure is scalable and can be applied in different frequency bands. Fig. 4 shows the simulated result of a UC-PBG structure with a linearly scaled lattice built on the same substrate. The scaled PBG structure with a period of 180 mil has a resonant frequency of 9.5 GHz and will be used in the following waveguide experiments.

III. Analysis of PBG Waveguide

The prototype of the PBG waveguide is an X-band waveguide (WR-90) loaded by the UC-PBG structures, as shown in Fig. 1. The UC-PBG structure used here has the same dimensions as those of the scaled version introduced at the end of Section II. The *LC* circuit model is applied again to provide the first-order approximation. Fig. 5 shows the cross section of the PBG waveguide and an equivalent circuit. The transverse resonance technique is applied to obtain the dispersion relation and the condition of a resonant line is satisfied when [23]

$$Z_{\text{in}}^{r}(x) + Z_{\text{in}}^{l}(x) = 0, \qquad \text{for any } x. \tag{1}$$

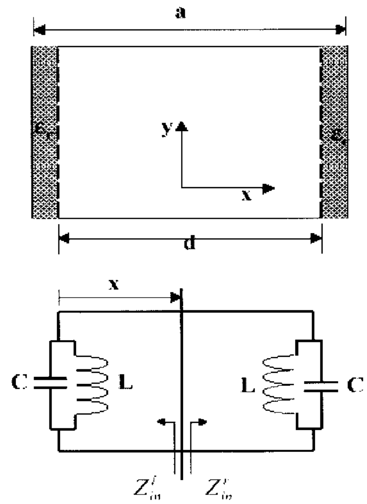


Fig. 5. The cross section (xy-plane) and an equivalent-circuit model of the PBG waveguide where $a = 900$ mil and $d = 850$ mil.

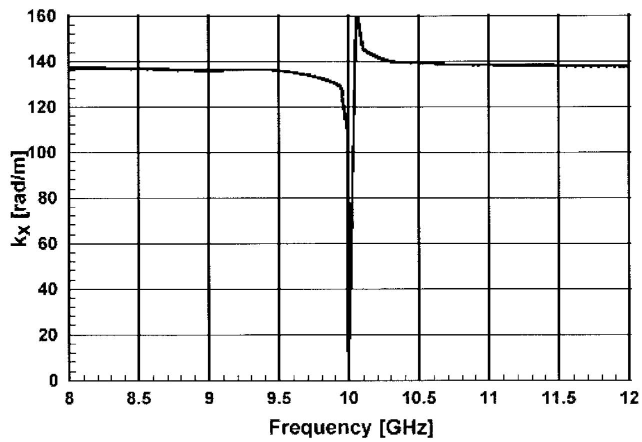


Fig. 6. Calculated wavenumber in the x-direction (k_x) of the PBG waveguide by the transverse resonance technique.

The following transcendental equation is then obtained after plugging the L and C into (1) as the load:

$$\tan(k_x d) = \frac{2Z_0 \cdot \dfrac{\omega L}{1-\omega^2 LC}}{\left(\dfrac{\omega L}{1-\omega^2 LC}\right)^2 - Z_0^2}, \qquad \text{where } Z_0 = \frac{\omega\mu_0}{k_x}. \tag{2}$$

Fig. 6 shows the wavenumber in the x-direction (k_x) calculated from (2), with the values of L and C chosen to resonate at 10 GHz. As can be seen, k_x is decreased as frequency increases and it experiences a singularity when the *LC* load becomes open, indicating that a phase velocity equal to the speed of light (c) has been achieved at that frequency. However, this lumped-element model can only provide the conceptual understanding of the waveguide nature owing to its simplicity. In order to perform a rigorous analysis, full-wave simulations using the FDTD method is applied to characterize the PBG waveguide.

Fig. 7 shows the simulated result for the phase velocity of the PBG waveguide with the velocity of a standard metallic waveguide plotted as a reference. The PBG waveguide has a

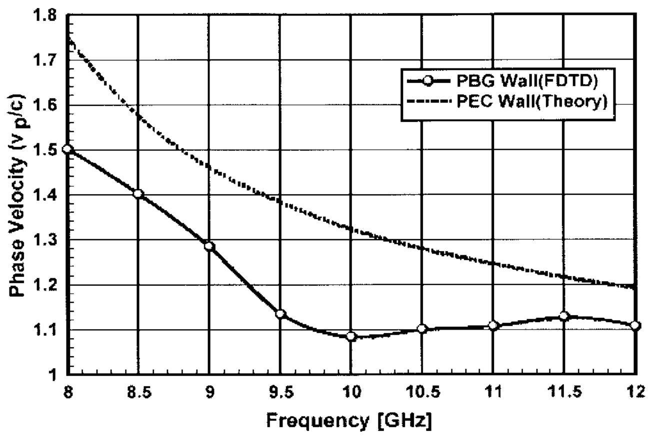


Fig. 7. Simulated phase velocity of the PBG waveguide and a theoretical value of phase velocity for a regular waveguide.

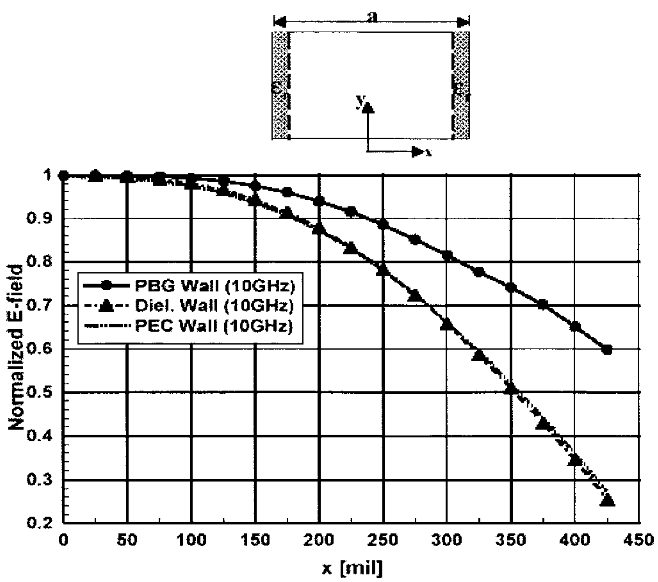


Fig. 8. Simulated field profile in the PBG waveguide.

significantly lower phase velocity over entire X-band and a smooth transition from the inductive to capacitive region. E-field distributions in the waveguides with different sidewalls have been simulated at the frequency of 10 GHz, as displayed in Fig. 8. As can be seen, the PBG waveguide has a relatively uniform field distribution compared to a standard waveguide. A dielectric-loaded (without PBG surface) waveguide are also analyzed for comparison and its field profile has a similar shape as that of a standard waveguide, implying that the more uniform field of the PBG waveguide is indeed generated by the PBG structure, not from the dielectric loading effect.

IV. Experimental Results

A. Excitation Mechanism

Since the PBG waveguide has different characteristic impedance from that of a conventional rectangular waveguide, a special waveguide transition must be designed for an efficient excitation. A quasi-Yagi antenna has been proposed and successfully applied as a TE wave launcher for an X-band

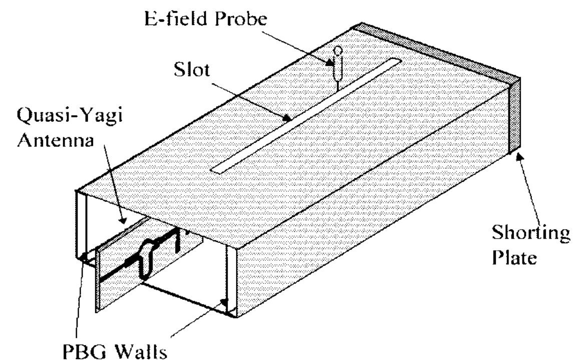


Fig. 9. Drawing of the PBG waveguide used in phase velocity and field profile measurements.

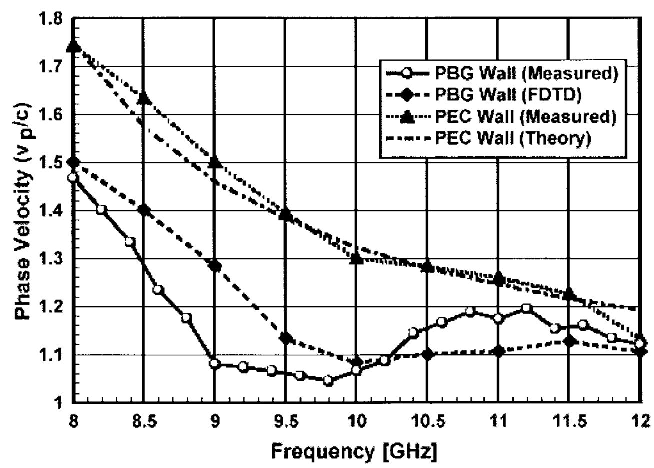


Fig. 10. Measured phase velocity with the FDTD result repeated for comparison.

waveguide [24], [25]. A broad-band response (40%) with a low return loss (<-12 dB) has been reported in [25]. Fig. 9 shows the schematic of the PBG waveguide used for measurements. The quasi-Yagi antenna with a substrate width equal to the waveguide height is inserted in the E-plane of the waveguide to launch a TE wave.

B. Measurement of Phase Velocity

The PBG waveguide with a narrow slot on the top plate is built for the phase velocity measurement. An HP 8350B sweep oscillator is connect to the quasi-Yagi antenna to generate the modulated signal and the E-field probe is connected to an HP 415E SWR meter for determining the guided wavelength, λ_g, from which the phase velocity can be calculated. The measured result is shown in Fig. 10, where the simulated data of the PBG waveguide is repeated here for comparison. The measured phase velocity is 20% slower than that of a regular waveguide and reaches a minimum of $3.14 \cdot 10^8$ m/s at 9.8 GHz. The velocity curve is relatively flat and close to the speed of light from 9 to 10.2 GHz, indicating that a TEM mode is generated. The experimental results agree well with the FDTD simulation, except for a frequency offset. The fact that the antenna structure and over-etching of the PBG

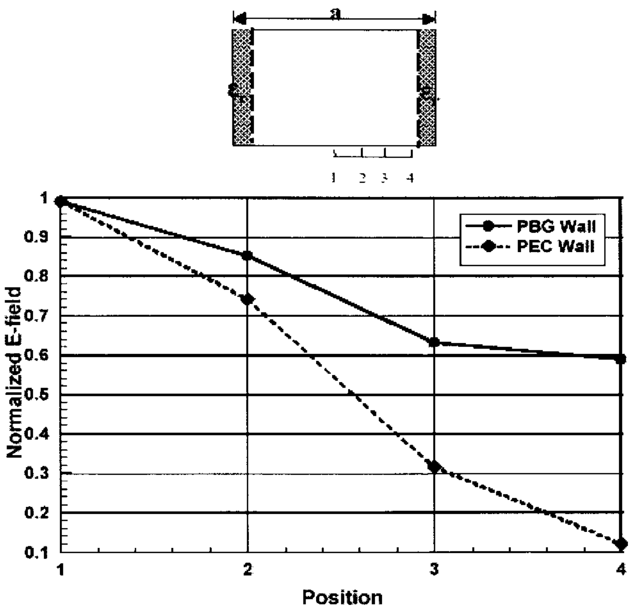
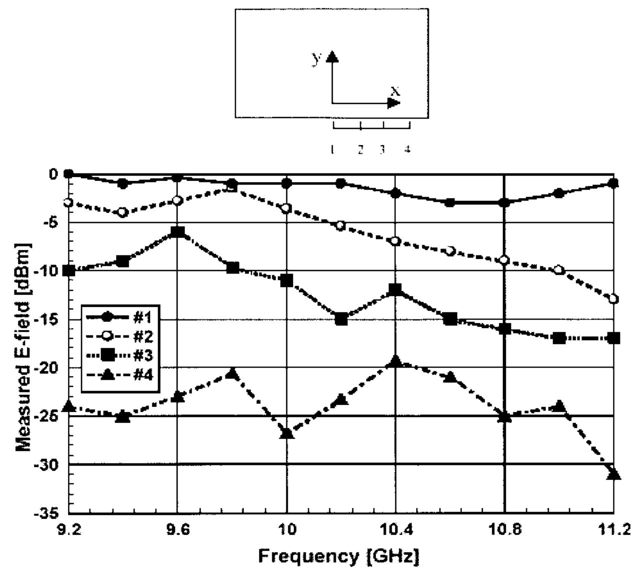


Fig. 11. Measured E-field strength of a PBG waveguide with a standard waveguide as a reference.

lattice are not considered in the simulation may explain the discrepancy.

C. Measurement of Field Profile

The PBG waveguide used in the previous experiment has been slightly modified for the E-field profile measurement. The top plate is replaced by a solid cover and a conductor-backed dielectric slab with a small iris is attached at the end of the waveguide as a shorting plate. The E-field probe is placed above the surface of the dielectric slab so that it does not disturb the field inside the waveguide, and the image problem is avoided. Shorting plates with the iris at different locations along the x-axis have been used to measure the field profile. The same sweep oscillator used in the velocity measurement again serves as a signal generator and the probe is connected to a power meter. Fig. 11 shows the measured E-field strength of a PBG waveguide with the data of a standard waveguide plotted as a reference. For the standard waveguide, E-field strength decreases substantially as the probe moves toward the wall. At the location near the sidewall ($x = 25$ mil), the field strength decreases to 10% of the maximum value measured at the center. On the other hand, the E-field in the PBG waveguide shows a more uniform distribution and the field strength is 60% of the peak value when probing close to the wall. One thing that should be pointed out here is that the peak value of the E-field in the PBG waveguide is lower than that in the PEC waveguide due to the field flattening and metallic loss. Fig. 12(a) and (b) displays the measured field strength with respect to frequency for a standard and PBG waveguide, respectively. The curve number represents the position where the E-field was probed. As can be seen in Fig. 12(b), spacing between curves is much smaller than that in Fig. 12(a), especially from 9.5 to 10.4 GHz, corresponding to the frequency range where the PBG walls behave like PMC surfaces. The optimum operating point is at 9.8 GHz and the



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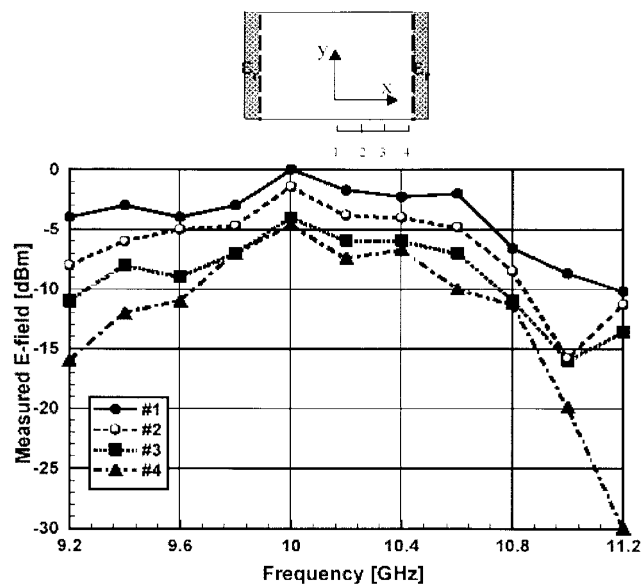

(b)

Fig. 12. Measured E-field profile of (a) a standard metallic waveguide and (b) the PBG waveguide, with respect to frequency.

difference between the maximum and minimum field strength is only 4 dB. The results show that a fairly uniform field distribution along the x-direction has been obtained and the experimental data agree well with out FDTD simulation.

V. Conclusions

A novel TEM-waveguide using the PBG structure has been presented. The proposed waveguide was construct using PBG structure as the sidewalls. The UC-PBG structure has been demonstrated to behave as a PMC surface at the stopband frequency. The PBG waveguide generates a relatively uniform field distribution from 9.4 to 10.4 GHz. Phase velocities close to the speed of light have been measured and the velocity curve is flat at operating frequencies, indicating a TEM mode has been established. Numerical simulation using FDTD show good agreement with experiments both in phase velocity and field profile. A quasi-Yagi antenna has been used as an efficient wave launcher for the entire X-band. This new type of PBG waveguide should find several applications, such as a feeding structure for quasi-optical power combining amplifiers and TEM cells in EMC measurements.

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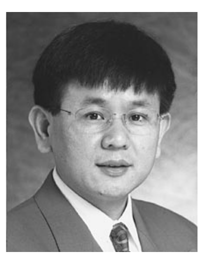

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