Photonic Crystals: A New Quasi-Optical Component for High-Power Microwaves

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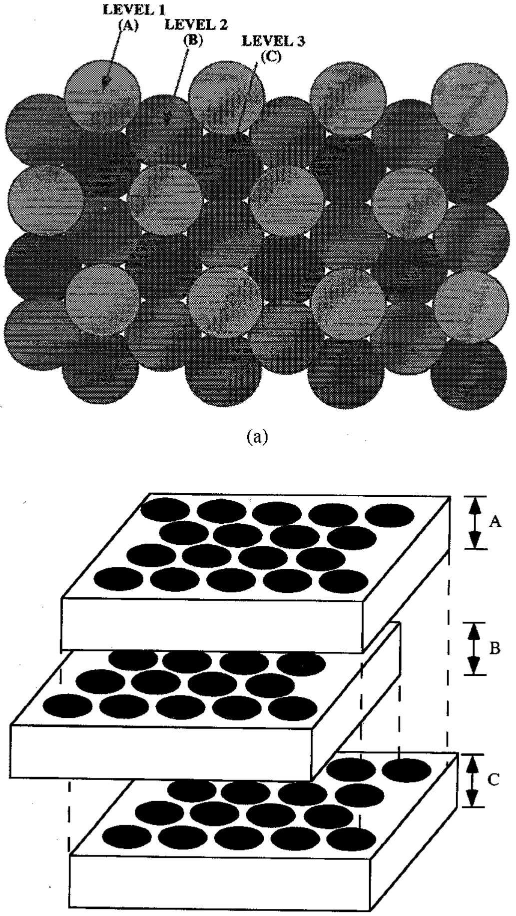
Abstract— **The interaction of a high-power microwave beam with a face-centered-cubic photonic crystal is studied. A Sinus-6 high-power relativistic repetitively pulsed electron beam accelerator was used to drive a slow wave structure in vacuum to generate 450 MW at 9.65 GHz. It is shown that the photonic crystal, comprised of a periodic arrangement of air holes in a dielectric host, is capable of performing as a quasi-optical reflector similar to a metal. The crystals can be designed to operate as efficient frequency-selective reflectors over narrow frequency ranges. We propose that photonic crystals can have many applications in high-power microwave research.**

I. Introduction

PHOTONIC crystals (PC's) are three- or lower-dimensional periodic dielectric structures that exhibit ranges of frequencies (stopbands) where electromagnetic radiation is forbidden. If the stopbands are omnidirectional, the PC dispersion relation exhibits a forbidden region or bandgap. These structures are therefore known as photonic bandgap structures [1], [2]. The width, depth, and location of the stopband are determined by the shape, size, and location of the macroscopic "atoms" (scattering centers), as well as the longitudinal (along the direction of propagation) periodicity of the structure. Fig. 1 presents a schematic of the photonic crystal used in this work.

There are many low-power applications for PC's that are under investigation. For example, antennas printed on dielectric substrates suffer severe losses due to energy leakage into the substrate [3]. Printing the antenna on a PC substrate with the driving frequency in the stopband of the crystal enhances the radiation into free-space owing to the reflective properties of the crystal [4]. However, the operational frequency of the PC antenna is limited to the width of the stopband. For ultrawideband (UWB) excitation, PC's of different periodicities can be stacked in tandem to obtain a photonic crystal capable of providing UWB reflectivity [5]. All these applications utilize the frequency selective reflective characteristics of the PC.



(a)

(b)

Fig. 1. (a) Top view of the photonic crystal. (b) Extended view of the photonic crystal. Vertical holes are drilled in a dielectric host and then configured in an A-B-C configuration. Three plates constitute one period of a face-centered-cubic (fcc) lattice.

In this paper, we present results from experiments where a PC is used, for the first time, as a quasi-optical component for high-power microwaves (HPM's). Traditionally, reflectors used in HPM research have been made from conductors. For these applications, one can model these structures as reradiating surface current sources, as is prescribed by the Equivalence Principle [6]. These current sources, coupled with

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TABLE I
SUMMARY OF BEAM PARAMETERS

Cathode Voltage (kV)	Beam Current (kA)	Power Density (kW-cm^{-2})	RF Frequency (GHz)
595	5.1	325	9.7
490	4.0	270	9.6

the finite conductivity of metals, provide for ohmic losses which can exceed dielectric losses in the frequency range of interest. The PC's used in these experiments have been fabricated exclusively from a low-loss high-dielectric-constant material which can potentially address the ohmic loss issue. Furthermore, since the PC is a distributed reflector, the amount of energy reflected by each layer is significantly lower than a metal, which can alleviate surface breakdown problems as well. Although frequency-dependent reflective characteristics can be achieved using frequency selective surfaces such as gratings or inductive meshes, these structures are typically metallic or metal composites [7]. Suggested HPM applications emerging from this work utilize the PC as a quasi-optical reflector, filter, and beam forming component for both space- and ground-based systems. To the authors' knowledge, this is the first report of HPM measurements performed on photonic crystals. It is anticipated that PC's can be further exploited as an important new component for HPM source research and applications.

The remainder of this paper is organized as follows. Section II describes the experimental setup, including the source and the fabrication of the PC. Section III discusses the results of the experiments, and Section IV provides conclusions and other potential applications of PC's in HPM systems.

II. EXPERIMENTAL SETUP

The source of the HPM's used in this work is the Sinus-6 electron-beam accelerator-driven backward wave oscillator (BWO) [8]. Two different beam parameters were used and are summarized in Table I. A mode converter was placed between the BWO and the conical horn antenna to convert the output TM_{01} mode from the BWO into a TE_{11} mode. This mode converter was constructed based on the design of Denisov and colleagues at the Institute of Applied Physics (Nizhny Novgorod, Russia) [9]. The measured RF frequency and the peak power densities 1.16 m downstream from the horn antenna are also shown in Table I. All the results reported here are obtained by averaging over many shots from the Sinus-6.

The PC used in the experiments is a three-dimensional (3-D) face-centered-cubic (fcc) structure with cylindrical air atoms as the basis. The fabrication of these structures entails drilling vertical holes in a host dielectric (in contrast with the original PC [1] where three holes were drilled at 35° at each lattice site), as shown in Fig. 1. The host material used is Stycast, a TiO_2-based compound with a dielectric constant of 10. The 3-D periodicity is obtained by offsetting three plates in an A-B-C configuration leading to the fcc structure [10]. Each A-B-C (three plates) configuration constitutes one period of an fcc structure in the longitudinal direction. Low-power network analyzer measurements indicate that with one period (three plates), the attenuation in the stopband for these PC's is approximately 7 dB down from the reference [5].

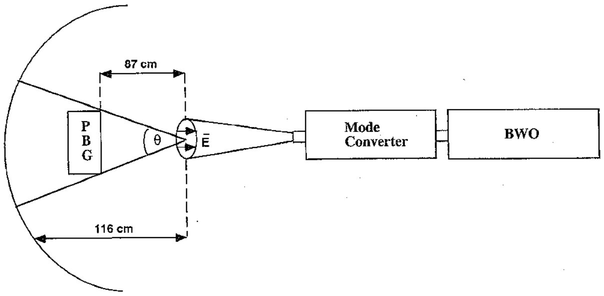


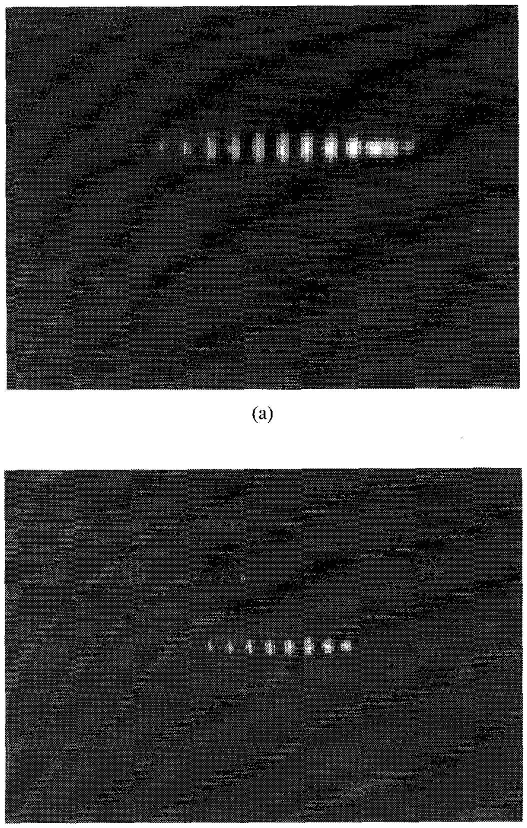
Fig. 2. Schematic of the experimental setup. The receiver is scanned behind the photonic crystal in the angular dependence measurements. The polarization of the electric field is indicated.

Since the Sinus-6 BWO is a narrow-band source, two PC's having different periodicities were used in this study. The first crystal (termed the in-gap crystal) was designed to have a stopband centered about 9.5 GHz and a stopband width of approximately 1.5 GHz (measured from the start of rejection to the beginning of transmission). The thickness of each plate was 1.27 cm (0.5 in), corresponding to 3.81 cm (1.5 in) per period. The other crystal (out-of-gap crystal) had a stopband centered about 19.5 GHz and a stopband width of approximately 4 GHz. The thickness of these plates were 0.508 cm (0.2 in) such that each period was 1.52 cm (0.6 in).

The experimental setup is shown in Fig. 2. The initial experiments were to assess the performance of the photonic crystal when compared to a planar metallic reflector. The HPM source was operated at full power (see Table I) to obtain an air breakdown standing-wave pattern. The second set of experiments measured the angular dependence of the transmitted radiation through the photonic crystal. Here, the Sinus-6 BWO was operated at reduced power levels (Table I) to eliminate any air breakdown that may corrupt the measured radiation pattern. The physical dimensions of the PC and the metal plate were chosen to be 15.24 cm × 15.24 cm (6 × 6 in), which corresponds to a half angle of 5° in the angular dependence measurements.

III. EXPERIMENTAL RESULTS

Fig. 3(a) shows a metal plate placed 87 cm away from the edge of the horn antenna. The photograph shows ionization near the antenna indicating the existence of a standing wave between the antenna and the metal plate. Fig. 3(b) is the same setup with the metal plate replaced by the two-period in-gap crystal. Although both the metal plate and the in-gap crystal effectively generate an air breakdown standing wave pattern, it is evident by the visible number of peaks in the standing-wave that the metal reflects slightly more energy than the crystal. (Note that as expected, the separation of peaks in the two standing-wave patterns remains unchanged, indicating that the PC response was still linear under high field excitation.) This can be compensated for by increasing the number of periods in the crystal to enhance the amount of energy reflected [10].



(a)

(b)

Fig. 3. (a) Breakdown pattern for the HPM beam being reflected from a planar metal plate. (b) Breakdown pattern for the HPM beam reflected from a two-period in-gap photonic crystal.

However, to concurrently address practical issues such as size and weight, only two periods were used.

Fig. 4 shows the transmission characteristics of the metal plate and the two-period in-gap crystal along with the patterns in direct transmissions (i.e., no crystal or metal plate). For the PC, from $-5°$ to $+5°$ (corresponding to the physical dimensions of the crystal), the radiation is attenuated. On the other hand, the response of the metal from $-5°$ to $+5°$ varies from 20 kW cm^{-2} at approximately 1° to 100 kW cm^{-2} at $+5°$. This fluctuation in power density is caused by the reradiation of the surface currents at the edge of the metal (edge diffraction). Beyond $+5°$, both the PC and the metal plate response approach the direct transmission response.

Fig. 5 shows a comparison between the one-period in-gap crystal and the one-period out-of-gap crystal angular responses. As in Fig. 4, the direct transmission, which can be considered as a reference, is also shown (note once again that the physical dimensions of the PC ranged from $-5°$ to $+5°$). For the out-of-gap crystal, there is a 3 dB enhancement in the power density at 0°. For the in-gap crystal there is a redistribution of the energy, but since there is significant reflection due to the stopband of the crystal, no enhancement is observed. The out-of-gap crystal enhancement suggests a simple method of obtaining higher power densities.

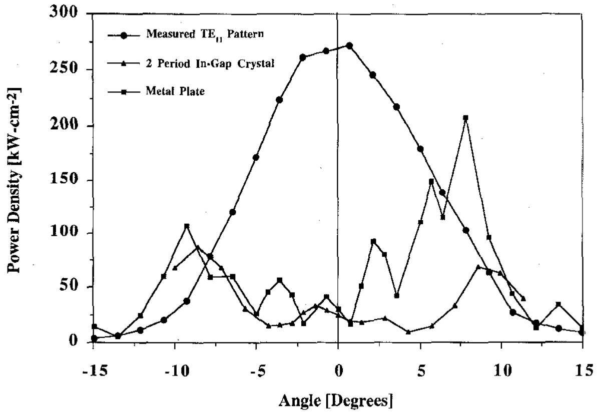


Fig. 4. Measured radiation pattern of the reference direct transmission (circles), the two-period in-gap photonic crystal (triangles), and the metal plate (squares).

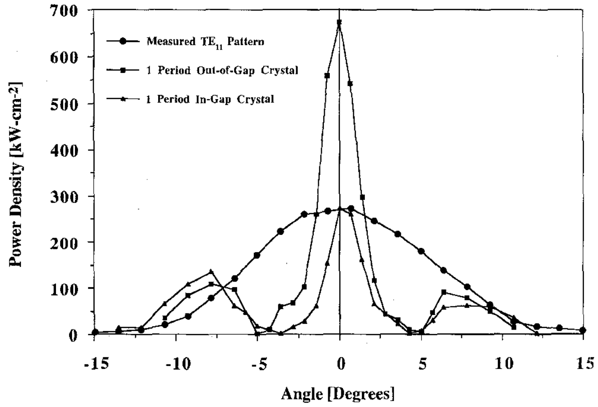


Fig. 5. Comparison between the reference (circles), the one-period out-of-gap photonic crystal (squares), and the one-period in-gap photonic crystal (triangles). Note the enhancement in the out-of-gap response.

The receiving antenna used in these experiments consisted of an open-ended section of WR-90 waveguide with a geometrical cross-sectional area of 2.32 cm^2, which can be approximated as a point detector. The discrete mapping revealed the enhancement in the out-of-band crystal. Previous low-power transmission measurements used standard gain horn antennas which integrated the incident radiation over the relatively large surface of the horn, thereby masking the enhancement [11]. As in the previous case, both crystal responses approached the direct transmission response beyond 5°.

Integration of the responses in Figs. 4 and 5 yields total transmitted power. Upon integrating the direct transmission from $-15°$ to $+15°$, a power level of approximately 400 MW is obtained. For the higher power levels, accurate measurement of the power was unattainable because of air breakdown; however, it was estimated to be at least 450 MW. In order to obtain the PC power levels, the integration was performed from $-5°$ to $+5°$ (see Table II for a summary of the results). The power scattered from the metal plate is 6 dB below the reference while the power transmitted through the in-gap crys-

TABLE II
SUMMARY OF DIFFRACTED AND TRANSMITTED POWER FROM −5° TO 5°

Direct Transmission	Metal Plate	In-Gap (2 periods) PC	Out-of-Gap (1 period) PC
173 MW	42 MW	28 MW	60 MW

tal is approximately 8 dB below the reference. This indicates that the in-gap crystal diffracts less than the comparable size metallic plate. The power transmitted through the out-of-gap crystal is 4.6 dB below the reference. This is not surprising since this crystal was designed with a stopband at 19.5 GHz, well above the operating frequency of the Sinus-6 BWO. In the long-wavelength limit for behavior of periodic structures, attenuation is dominated by effective bulk material properties.

IV. DISCUSSIONS AND CONCLUSIONS

The interaction of an HPM beam with a PC was studied. The reflection measurements indicated that similar standing-wave patterns exist for the metal plate and the two-period in-gap PC. It is evident that the PC performance as a microwave reflector is comparable to that of a metal plate.

In the angular transmission studies, the PC response was more uniform than the metal plate because of edge diffraction for conductors. This implies that, for applications where finite reflector size is a consideration, the PC will provide less diffraction away from the crystal and more diffraction toward the center as indicated in Fig. 5. Fig. 5 also showed a 3 dB enhancement in power density by using the out-of-gap photonic crystal. This enhancement can be used to easily achieve higher power densities for HPM applications at the expense of some total power loss, but is not yet fully understood.

Integration of the radiation patterns indicated that more power is diffracted behind the metal plate as compared to the PC. This implies that by adding more periods to the PC, there will be an enhanced reflectivity without any losses due to edge diffraction. Hence a finite size PC may be a more efficient reflector than a comparable size conductor.

The PC was demonstrated to be an effective frequency-selective quasi-optical reflector of HPM radiation. The PC can be utilized as a simple frequency diagnostic, analogous to cutoff filters. Furthermore, the out-of-band PC was demonstrated to enhance radiated power density by 3 dB. For the out-of-gap crystal we are approaching the long-wavelength limit for a periodic structure so that it should behave as an effective dielectric medium. Although nulls appear in the enhanced radiation pattern, it is uncertain whether the observations can be attributed solely to bulk properties or the periodicity. This observed enhancement is currently being studied. Additional applications of this material to HPM's will certainly be emerging.

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