Parallel-Plate Mode Reduction in Conductor-Backed Slots Using Electromagnetic Bandgap Substrates

John D. Shumpert, *Student Member, IEEE,* William J. Chappell, *Student Member, IEEE,* and Linda P. B. Katehi, *Fellow, IEEE*

***Abstract*— By fabricating a resonant slot over a reflecting back plate and filling the resulting parallel-plate with an appropriately designed artificial electromagnetic bandgap (EBG) structure, noticeable enhancements in both radiation pattern and bandwidth are achieved using a significantly lower profile than traditional designs. This design uses a two-dimensional artificial EBG substrate in conjunction with a reflecting plate to completely block radiation from the backside of the slot from propagating to the finite edges of the resulting parallel-plate cavity. Measured and simulated data for conductor-backed slots with homogeneous substrates and with EBG substrates are compared.**

***Index Terms*— Electromagnetic crystals, parallel-plate mode reduction, photonic bandgaps, slot antennas.**

I. Introduction

ELECTROMAGNETIC bandgap (EBG) materials are found to have unique properties that are advantageous in applications involving semiconductor integrated circuits. Such materials offer the possibility of changing the physical properties of substrates used in fabricating planar circuits. A number of applications for such materials can be imagined including dielectric mirrors, resonant cavities, high Q filters, and frequency-selective surfaces (FSS's). Early work by Yablonovitch [1] successfully demonstrated that light propagation could be inhibited in certain frequency gaps in special photonic bandgap (PBG) crystals. Preliminary results suggest that microwave and millimeter-wave frequencies can also be manipulated by carefully designing and fabricating EBG structures composed of regions of differing dielectric constants.

The seminal work that kindled excitement in recent PBG research can be found in [1]. Excellent reviews of PBG research carried out before 1994 can be found in special issues of [2] and [3]. Recently, a book by Joannopoulos *et al.* outlining photonic band theory and covering a wide range of photonic crystal applications was published [4]. A number of researchers have recently begun to design electromagnetic crystal structures for use in planar antenna and circuit applications, particularly for use as reflectors in planar dipole antenna structures [5]–[10]. Recent numerical work in determining theoretical bandgaps for planar microwave antenna applications has been done by Yang *et al.* [11], while Leung *et al.* [12] measured the radiation patterns of a slot antenna placed on a layer-by-layer PBG crystal. For planar antennas operating at a frequency in the bandgap of the three-dimensional PBG crystal, energy which would have been radiated into the substrate is reflected. However, at the interface between the PBG and the air, the periodicity of the PBG is broken and a parasitic mode (surface state) can exist. These surface states decrease the efficiency by stripping power away from the radiating element.

By fabricating the slot over a reflecting back plane and filling the resulting waveguide with an appropriately designed EBG structure, noticeable enhancements in both radiation pattern and bandwidth can be achieved while maintaining the low profile. Traditional designs typically place some type of reflecting surface or cavity behind the slot in order to reduce backside radiation and increase the gain. Unfortunately, increasing the profile of the slot negates one advantage of the planar radiating element. In addition, placing reflecting surfaces behind the slot reduces the efficiency by creating parasitic modes and using a cavity-backed design often necessitates narrowing the bandwidth. If the slot antenna is backed by a metal plate to increase the front-to-back ratio, parallel-plate waveguide (PPW) modes will be excited, both decreasing the efficiency and distorting the pattern. The theory and design of the EBG structure used in our application to minimize these problems is developed in Section II. The folded-slot antenna design and fabrication is outlined in Section III. Observations concerning the performance of the EBG structure (crystal) and its use for backing slot antennas is detailed in Section IV. This paper concludes with general observations about the usefulness and possible applications for these special materials presented in Section V.

II. EBG Theory and Design

In order to determine the frequencies of interest for a complex structure, a full-wave integral equation (IE)/method of moments (MoM) code has been developed [13] to determine the band structure (propagating modes) of a periodic two-dimensional inhomogeneous dielectric region. If the reflecting plate shown in Fig. 1 is located near enough to the slot such that the operating frequency is below the cutoff of the first TE/TM mode, only the dominant TEM mode (TM_0) with zero

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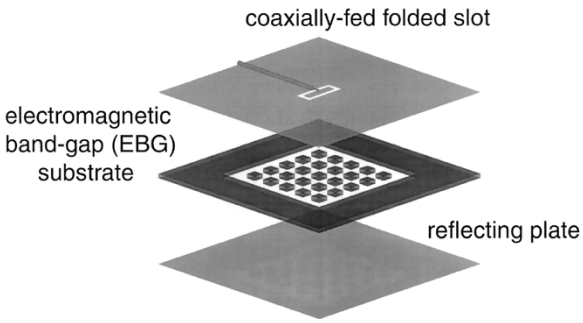

Fig. 1. Conductor-backed folded slot with EBG substrate.

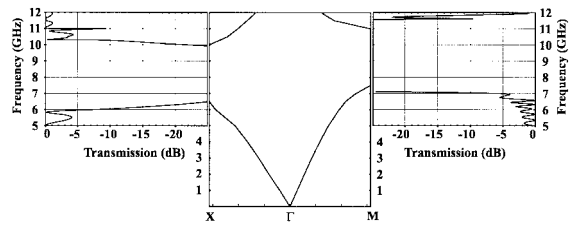

Fig. 2. Simulated (HFSS) transmission spectra for Γ–X (left) and Γ–M (right) directions and calculated (MoM) band diagram (center) of a two-dimensional EBG with $a = 1.2$ cm, $b = 4.8$ mm, and $\varepsilon_r = 10.2$ for TM polarization.

cutoff frequency will propagate. Since the propagation characteristics of the TEM mode of the resulting waveguide are very similar to the propagation characteristics of a uniform plane wave propagating normal to the axis of a two-dimensional structure, the EBG crystal can be modeled as a periodic array of infinite dielectric rods in free space [14]. The dielectric rods are excited by a TEM wave propagating in a direction transverse to the cylinder axis with its electric field parallel to the cylinder axis, thus inducing an electric current with an axial component only. The dielectric rods are replaced by equivalent (polarization) volume currents and the total field is determined as the sum of a time–harmonic $(e^{j\omega t})$ incident field due to radiation from a known source and a scattered field that is due to radiation by the equivalent currents induced in the dielectric by the incident field. One can formulate an electric-field integral equation (EFIE) [13] to determine the equivalent currents, and the MoM is used to numerically solve the resulting matrix equation [15]. The bandgaps determined from the code have been verified with similar gaps in the published literature [16].

For a simple two-dimensional periodic array of dielectric square cylinders, the geometrical parameter combinations (a, b) and electrical parameter combinations (ε_r) of the dielectric posts produce the desired passbands or stopbands [17]. Although some early two-dimensional PBG research focused on using circular rods, square rods of commensurate size are chosen to simplify the formulation and fabrication. A square lattice is chosen over traditional triangular or honeycomb lattices—for parallel (TM) polarization, the square lattice of dielectric columns in air produces a larger gap for relatively lower frequencies [18], [19]. At the frequencies of interest, where the rod spacings are fractions of a wavelength, the only bandgap of interest is the lowest band. The lower the lowest frequency band, the more applicable the EBG structure is for compact circuit applications. In order to achieve a useful stopband, a large (ideally, infinite) number of periods are required. However, significant attenuations can still be achieved using only a small number of periods by designing an appropriate EBG crystal. Our structure is designed to have a omnidirectional stopband between 7.5–10 GHz by using the combination of unit cell size $a = 1.2$ cm, dielectric cell size $b = 4.8$ mm, and relative dielectric constant $\varepsilon_r = 10.2$.

In parallel to the MoM solution for an infinite bandgap, finite-element simulations have been implemented to corroborate the band structure of a realizable EBG structure. To characterize a finite EBG crystal, a finite number of periods must be simulated accurately. The periodically dielectric-loaded parallel-plate is simulated using Hewlett-Packard's commercial FEM simulator HFSS. From image theory, the rods are imaged infinitely in height by using a perfect electric conductor (PEC) boundary and infinitely in width by using a perfect magnetic conductor (PMC) boundary located one-half unit cell away from the center of the rods. A single TEM mode is produced by keeping the separation distance between the plates less than half the guide wavelength. To justify replacing the traditional circular rods by square rods in our application, a variety of simulations were run. The simulations take between four seconds (Γ–X direction of the reduced Brillioun zone for a square lattice) and eight seconds (Γ–M direction) per frequency point for five periods on a 400-MHz Pentium II PC. Since the speed of the simulation is so rapid, EBG crystals for use in this application can be repetitively designed and validated quickly. For our EBG material at the center frequency of the bandgap, 3–4 periods produce omnidirectional attenuations of at least 20 dB and upwards of 45-dB attenuation in specific directions (Fig. 2). For the Γ–X direction configured with square rods $(b/a = 0.4)$, the center frequency of the lowest gap is 8.5 GHz. For the Γ–X direction configured with circular rods $(d/a = 0.4)$ where d is the diameter of the rod and a is defined earlier, the center frequency of the lowest gap is 5% higher at 9.0 GHz. It is also observed that the 10-dB bandwidth of the square rod gap (4.0 GHz) is 5% smaller than the circular rod gap (4.7 GHz).

III. Slot Antenna Design and Fabrication

A conductor-backed folded slot with a homogeneous substrate was designed initially to provide an acceptable match when center fed. Preliminary work using this $\lambda_g/2$ reference slot revealed the difficulty in matching the high input impedance of the slot to the coaxial feed. Consequently, the single $\lambda_g/2$ slot was replaced with a folded λ_g slot. Note that a similar impedance could also have been achieved using a full λ_g slot. Not only is the λ_g slot easier to match to the input impedance of the coaxial feed than the $\lambda_g/2$ slot, but it also has increased bandwidth.

For the EBG-backed folded slot, the EBG material designed in Section II is placed between the slot and back plates. In order to design the slot antenna for optimal performance, the slot is designed to resonate inside the designed bandgap. When the folded slot design is integrated with the EBG crystal,

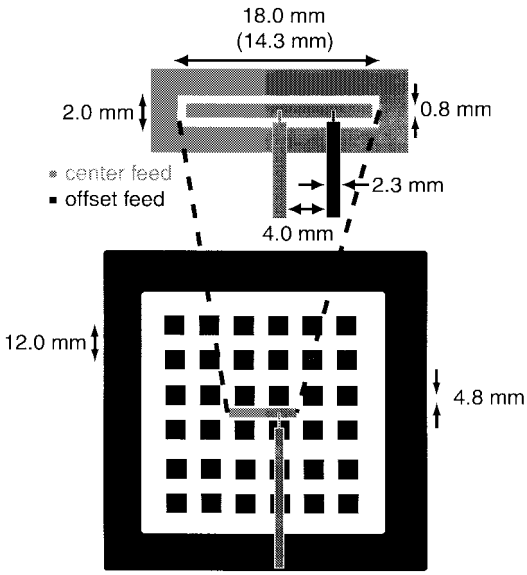

Fig. 3. Top view of conductor-backed folded slot design with EBG substrate ($a = 1.2$ cm, $b = 4.8$ mm, and $\varepsilon_r = 10.2$) where slot dimensions in parentheses refer only to the reference slot design.

as shown in Fig. 1, the energy from the slot is coupled into the parallel-plate mode that is then stored in the EBG crystal lattice, loading the slot inductively. Consequently, an off-center feed is used to provide a better impedance match.

A reference folded slot of length 14.3 mm and width of 2.0 mm (shown in Fig. 3) was fabricated using wet etching on a square copper clad RT/Duroid substrate with dielectric constant of 2.2, a 127-mm (5 in) edge length, and a thickness of 1.65 mm (65 mil). The "half-wave" reference slot was then center fed using a simple coaxial line [20]. Note that the reference slot is simply a truncated conductor-backed slot with a homogeneous dielectric substrate. The slight difference in size of the two slots allows for resonances at equivalent frequencies.

An EBG-backed folded slot of length 18.0 mm and width of 2.0 mm, similar to the reference folded slot was fabricated using wet etching on a square copper clad RT/Duroid substrate with dielectric constant of 2.2, a 127-mm (5 in) edge length, but a thickness of only 127 μm (5 mil). The thin substrate was then bonded to a square copper-clad RT/Duroid substrate with dielectric constant of 10.2, a 127-mm (5 in) edge length, and a thickness of 2.54 mm (100 mil), which had been previously milled as shown in Fig. 3. A small amount of dielectric ($\approx$ 10 mil) was left on the lower plate in order to provide some stability for mounting the slot plate. Simulations have shown that the remaining small amounts of dielectric (10%–20% of the total substrate height) on the back plate change the center frequency and attenuation per period of the bandgap negligibly. To provide more support to mount the slot plate, material at the outer edge of the substrate was not milled, as can be seen in Fig. 3. Simulations have shown that this supporting material does not significantly affect the performance of the slot (see Section IV). The fabricated EBG-backed folded slot design resonates at 9.4 and 9.6 GHz (Fig. 4). Unfortunately, difficulty in bonding the slot plate to the EBG substrate may have introduced additional

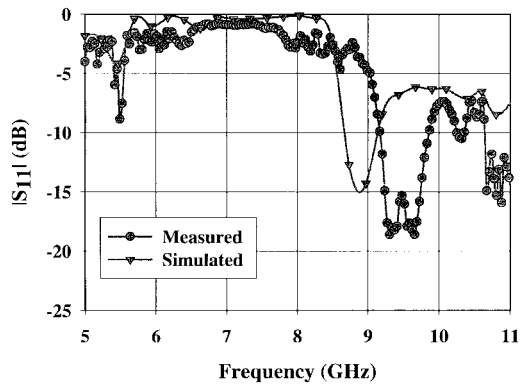

Fig. 4. Measured and simulated frequency response of conductor-backed slot with EBG substrate.

unwanted modes or a shifting of the slot resonance. In the same figure, the simulated EBG-backed folded slot determined by a finite-element simulation finds a resonance slightly below 9.0 GHz. The 4% difference between the simulations and the experiment is due to the simplifications introduced in the structure analyzed by HFSS to reduce computer memory and simulation time.

IV. Results and Discussion

Simulations of coaxially fed slots in a metal plate in free space have relatively large 10-dB bandwidths on the order of 10%–15%. However, since the slot radiates equally into each half-space, the front-to-back ratio is 0 dB. Simulations of a reflector-backed slot with a absorbing boundary condition at the edges of the resulting cavity, effectively modeling an infinite parallel-plate, yields a 10-dB bandwidth of 30%. The large bandwidth is the result of the slot radiating most of its power into the infinite waveguide. If a finite metal plate is used as a reflector, the front-to-back ratio is increased, but the energy trapped in parallel-plate modes radiates at the edges of the finite ground degrading the pattern significantly. Notice the classic interference pattern (7–8 dB "dips" in the pattern), reported earlier [21] to be caused by the radiation from the edges of the finite ground, can be clearly seen in the pattern for the reference in Fig. 5. Some suppression technique must be implemented to eliminate this parasitic radiation.

In order to reduce the effects of the finite ground, a number of suppression techniques are known, including integrating the antenna on a substrate lens [22]. Although useful for providing unidirectional radiation patterns by suppressing substrate surface-wave formation, the lenses are not low profile. Cavity-backed slots are another effective method of increasing the front-to-back ratio. From a simulation of a $\lambda/4$ cavity-backed slot [20], the 10-dB bandwidth was found to be 7.5%. However, this cavity-backed design, much like a lens, is not low profile. Recently, Leung *et al.* fabricated a slot on a synthesized three-dimensional metallic PBG crystal composed of alternating layers of thin metallic rods. Unfortunately, the response of the slot is very sensitive to the placement of the slot over the rods. Gains of 2–3 dB were reported with low cross-polarization levels for specific slot locations and for narrow frequency bands. The bandwidth and frequency

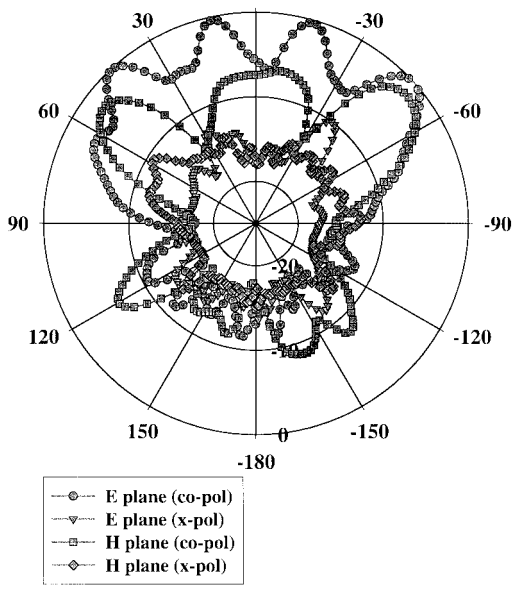

Fig. 5. Measured normalized E- and H-plane antenna patterns (co- and x-pol) of reference slot at 9.7 GHz.

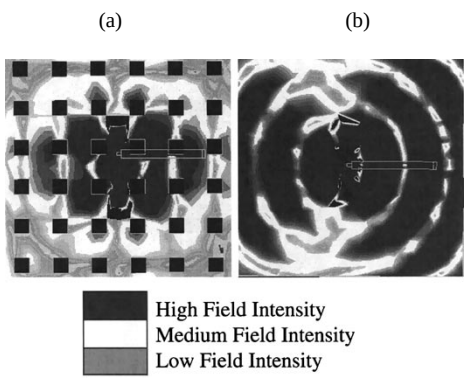

Fig. 6. (a) Evanescent field structure inside EBG-backed substrate and (b) traveling-wave mode in homogeneously filled parallel plate.

response of the antenna was not reported. Although the three-dimensional PBG crystal acts as a good reflector, it does not enhance the transmission signal as much as was expected [12]. As was mentioned earlier, parasitic surface states, which reduce the radiated power, can exist when the periodicity of a three-dimensional EBG is broken. The design presented herein uses a two-dimensional EBG crystal in conjunction with a reflecting plate to completely block radiation from the backside of the slot.

The field distribution inside a slot-fed finite parallel plate is similar to that of a slot-fed metallic cavity with PMC edge boundaries. Reflections from the edges of the PPW effectively create an over-moded cavity. This parasitic radiation from the edges is dependent on the mode that is formed in the cavity. Energy leakage from the substrate through the edges of the cavity manifests itself in unwanted effects such as reduced front-to-back ratio, reduced efficiency, increased cross-polarization level, and pattern distortion, as shown in the reference antenna pattern of Fig. 5. This effect is eliminated when the specially designed periodic EBG crystal is added. If the slot is designed to radiate at a frequency inside the

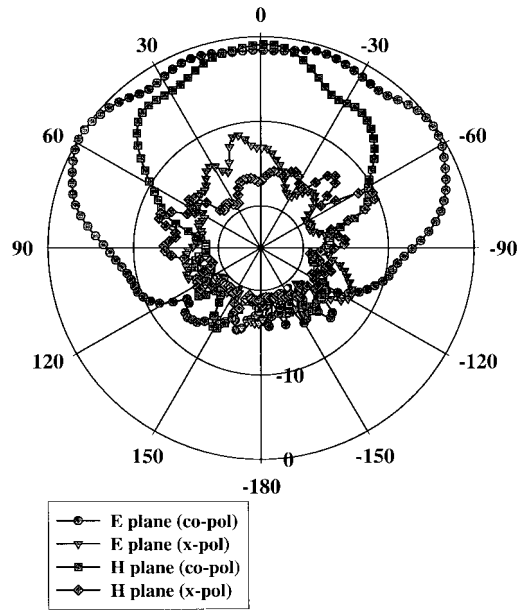

Fig. 7. Measured normalized E- and H-plane antenna patterns (co- and x-pol) of conductor-backed slot with EBG substrate at 9.7 GHz.

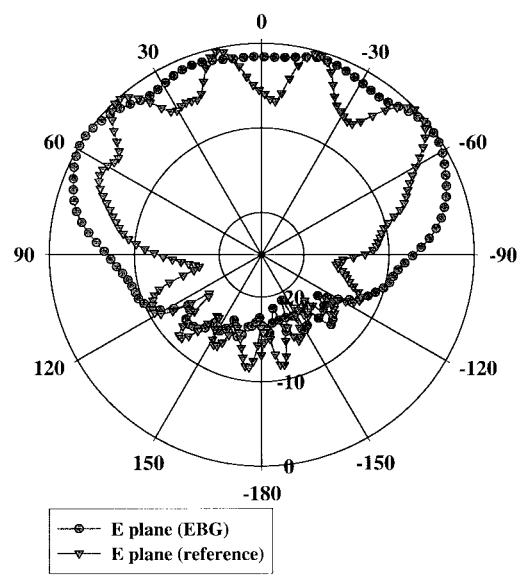

Fig. 8. Measured normalized E-plane antenna patterns (co-pol) of the reference slot and conductor-backed slot with EBG substrate at 9.7 GHz.

bandgap of the two-dimensional EBG, the parallel-plate TEM mode will be trapped in the EBG crystal lattice. An effective cavity is formed since the energy in the parallel-plate mode is reflected back to the radiating slot (Fig. 6). As mentioned previously, the supporting material remaining at the edge of the substrate does not affect the performance of the slot. The removed material was replaced with a metallic boundary condition and the simulations were repeated. No significant change in field strength or structure was observed. The EBG structure has two benefits over traditional metallic cavities. Namely, the reflection from the cavity boundaries can be controlled—adding more layers of EBG material around the slot will increase the reflectivity of the boundaries—and the

boundary conditions of the resulting effective EBG cavity are frequency dependent.

As can be clearly seen in Fig. 7, the EBG-backed slot has a front-to-back ratio of over 15 dB. Low cross-polarization levels were measured in both the E- and H-planes. The 10-dB bandwidth is measured to be 7.5%—lower than that of the single planar slot. Notice the antenna patterns are similar to that of a slot in an infinite ground plane; the significant 7–8 dB "dips" in the reference slot pattern are decreased to 2–3 dB in the EBG-backed slot pattern (Fig. 8). The predicted directivity for a slot in infinite ground is approximately 1.1 (0.60 dB) [20]. For a slot mounted over a back plane, the directivity can be effectively doubled to approximately 2.3 (3.6 dB). The directivity of the EBG-backed folded slot is estimated to be 2.8 (4.5 dB) by numerical integration of a full two-dimensional pattern. The gain of the antenna was found to be approximately 3.7 ± 0.2 dB, yielding an estimated efficiency of between 80%–90%.

V. Conclusions

Although relatively large substrates were used in this paper to demonstrate the usefulness of the conductor-backed folded slot with EBG substrate, similar results can be obtained using significantly thinner substrates. Consequently, very little power is lost to substrate modes. This is very desirable for applications involving packaging, such as layered circuits or vertical integration of components, particularly where ground-plane proximity is a concern. In addition, the cavity resulting from the EBG crystal is frequency dependent and tunable. Above and below the bandgap, the EBG structure allows energy to propagate through virtually unimpeded. In the center of the gap, the EBG structure is virtually impassible. Near the band edges, proper design could further increase the bandwidth of this antenna by decreasing the attenuation per period or by allowing specific modes to propagate unattenuated. Research and design using PBG and electromagnetic crystal materials continues at a rapid pace and promises new microwave and millimeter-wave designs and applications.

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