Degenerate Band Edge Crystals and Periodic Assemblies for High Gain Antennas

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Abstract- Periodic arrangements of metallo-dielectric structures have been shown to exhibit novel phenomena that can be exploited for microwaves. Among them, regular band edge (RBE) structures are known for their high Q properties, and left handed materials lead to much smaller phase shifters and couplers. More recently, a new class of periodic arrangements, referred to as magnetic photonic crystals (MPCs) and degenerate band edge crystals (DBEs) have been shown to significantly improve matching of the incoming fields and support slow wave phenomena (frozen modes) leading to very large wave fields within the crystal over a relatively wide bandwidth. Thus, they can be used for much greater sensitivity antennas. In this paper, we experimentally demonstrate for the first time the support of such phenomena using a newly designed crystal from very low cost materials. We demonstrate that the purported slow wave and high amplitude phenomena can be observed using on periodic cells with a finite aperture. These experiments are corroborated with numerical data, making the utilization of these new class crystals for high gain and narrow beam scanning antennas a practical possibility.

Introduction

Photonic crystals have been the subject of extensive research for almost twenty years [1]. Initial research was focused mostly on photonic crystals composed of isotropic dielectric block arrangements. However, recent studies have shown that more sophisticated arrangements of the materials can result in qualitatively new features and novel phenomena. Among them is a class of crystals exhibiting electromagnetic unidirectionality and frozen mode regime. The resulting structures are referred to as Magnetic Photonic Crystals (MPCs) [2-3], and are associated with significant wave slowdown that leads to high amplitude fields within the periodic medium. In the context of the $k - \omega$ diagram, the frozen mode is associated with a Stationary Inflection Point (SIP), viz. $\omega'(k) = 0$, $\omega''(k) = 0$, $\omega''(k) \neq 0$, whereas other periodic media exhibit a simple stationary point, $\omega'(k) = 0$ (Fig. 1).

For microwave applications, the key property of MPCs is the efficient conversion of the incoming waves into a slow-wave mode. Once inside the MPC crystal, the wave can exhibit huge amplitude growth that can be harnessed for proportional increase in antenna reception sensitivity and radiation gain under reciprocal conditions. Some recent studies

![Fig. 1 Sample Band Structures Illustrating (a) Regular Band Edge (b) Degenerate Band Edge (c) Double Band Edge (d) Stationary Inflection Point](image-url)
allowed for the characterization and rigorously analysis of the MPC and other photonic structures, including Degenerate Band Edge crystals (DBE) [2-3]. DBEs exhibit a flatter band structure as compared to the Regular Band Edge (RBE) crystals. (see Fig.1b). As a result, the wave group velocity within the DBE crystal decreases faster, implying larger field coupling into the periodic structure. For this reason, DBE crystals can be potentially harnessed for antenna miniaturization applications without a need to employ magnetic materials [3]. Specifically, it was shown that a newly designed and realizable DBE crystal leads to a field increase by a factor of 4 using 20 unit cells. This increase concurrently implies that a small dipole embedded within the DBE layers can achieve up to 12 dB greater gain than an identical antenna embedded in a homogeneous dielectric layer of the same thickness. Further, the thickness can more effectively be utilized by populating it with an array of dipoles to yield a gain increase of more than 20 dB. This paper provides computational analyses and demonstrates the benefit and potential of MPC and DBE crystals. For the first time, experimental data are given for a finite aperture crystal demonstrating the remarkable performance of the DBE crystals. The reported 3D realization removes potential doubts relating to the support of the frozen mode in a practical setting and demonstrates that typical material losses do not significantly affect the benefit of these crystals.

**Realization of Degenerate Band Edge Phenomenon**

As can be expected, there is a limitation on the DBE crystal construction and furthermore there are performance concerns due to loss, anisotropy and the measurement technique. Previous analyses [2-3] were based on available rutile layers. However, low loss pure rutile samples are expensive, implying a strong interest in constructing similar materials using artificially engineered structures. It has already been shown that periodic arrangement of short metallic wires emulates an anisotropic dielectric material in the long wavelength limit [4]. Hence, small metallic inclusions can be used to realize the degenerate band edge (DBE) behavior. More specifically, two misaligned stacks of printed dipole frequency selective surfaces (FSS) followed by a free space layer were used to form the unit cell of the DBE crystal. Using 3-D periodic Finite Element Method (FEM) analysis, this periodic cell was optimized as shown in Fig. 2a to obtain the band structure. As seen in Fig. 2c, the proposed geometry exhibits the DBE behavior (by reference to Fig. 1b, implying a flatter $k-\omega$ diagram) at 10 GHz. The unit cell of the

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Fig. 2-(a) Unit Cell of the DBE Crystal (b) Stacks Forming the DBE (c) Band Structure
The designed crystal is composed of two Rogers RO4350 laminates ($\varepsilon_r=3.48$, $\tan\delta=0.0037$) having printed metallic strips on both sides, two laminates having their strips rotated at a 45° angle, followed by the free space layer as shown. The total crystal is formed by stacking printed laminates of several strips, separated accordingly (Fig. 2b).

**Experimental Demonstration of Interior Field Growth**

To measure the performance of the designed DBE crystal, it was illuminated by a horn antenna within the X-band as shown in Fig. 3b. As a first step, we proceeded to measure the field growth within the constructed 8-unit-cell DBE crystal of total thickness 5.84 cm and aperture size 10.92x10.92 cm². In order to measure the interior crystal fields, a monopole probe was constructed by removing the outer shield layer of a microwave coaxial cable and inserted at the free space layers (a total of 7 positions along the depth of the crystal). The probe length was 0.5 cm (less than $\lambda/5$) and the transmitting X-band horn was placed 2-2.5 cm away from the crystal to minimize the edge-diffractions. A network analyzer (Agilent E8362B, 10MHz-20GHz PNA Series Network Analyzer) was employed for the measurement setup. It is important to note that the test was done at a non-resonant frequency (10.06 GHz) to allow for field pick up without substantially distorting the interior field distribution. One of the several measurements carried out is shown in Fig. 3a and as seen it shows excellent agreement with the calculations from the finite element boundary integral (FE-BI) code [5]. This agreement is impressive given that the FE-BI code was based on an infinitely periodic crystal (ignored its finiteness). The oscillatory interior field behavior is typical and its amplitude increases as the crystal is brought to resonance. We observed the maximum field amplitude of 4.36 dB at 10 GHz corresponding to the flat portion of the $\omega-k$ diagram. It is important to note that this large field amplitude is specifically attributed to the DBE crystal behavior, and does not occur for the case of Regular Band Edge (RBE) or the Double Band Edge crystals shown in Fig. 1. Further, it should be pointed out that the field amplitude along the crystal is reduced gracefully as it reaches the crystal faces implying that a distribution of printed across its volume would lead to substantial received power and antenna gain increase as compared to similar arrays in free space. Next, we proceed to provide validation/demonstration for a single dipole embedded within the DBE crystal.

**Fig. 3-(a) Field Amplitude Profile Coupled at DBE Frequency (b) Experiment Setup**

**Antenna Directivity and Gain**

Once the field amplitude growth was verified, we proceeded to perform antenna gain measurements and calculations. For this purpose, a dipole (2 cm in total length) was
constructed and embedded in the 3rd free space layer of the 8-cell crystal. The measured receiving pattern is shown in Fig. 4a and again shows good agreement with the FE-BI calculations (the latter based on the field amplitudes corresponding to different illumination angles). It should first be remarked that the dipole within the crystal displayed a higher received power of nearly 5 dB as compared to a dipole in free space. Of most importance from the measurement/analysis in Fig. 4 is the remarkable gain of the dipole. Specifically, the crystal managed to cause half power beam width (HPBW) values of 26° and 25° in the azimuth and elevation planes. These HPBW values correspond to a directivity of 18.05 dBi.

Fig. 4-(a) Receiving Pattern of a Dipole Embedded within the DBE Layers (b) θ- φ planes

The above results are specific to crystal orientation and were repeated several times over several day intervals to assure their accuracy. Also, it is noted that the performance of the crystal was limited by the anisotropy ratio that is directly proportional to the ratio of strip length to the separation distance between successive strips (the latter was 0.09/0.007 for the measured structure based on the limitations of the chosen manufacturing company). That is, substantially higher gains can be realized by increasing the anisotropy ratio. Even with the extremely simple and low cost structure manufactured, the obtained field growth and gain are truly remarkable and leave much promise for substantial improvements from new crystal designs. These options will be discussed at the conference.

References: