ANISOTROPIC PERIODIC ASSEMBLIES AND METAMATERIALS FOR APPLICATIONS TO ANTENNAS AND MICROWAVE DEVICES[1]

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ABSTRACT:

This presentation will cover the basic microwave properties of magnetic photonic (MPC) and degenerate bandedge (DBE) crystals both mathematically and experimentally. Two dimensional and three dimensional models will be presented demonstrating the very high sensitivity and field growth associated with the crystals. A major part of the presentation will be on the development of realistic anisotropic periodic structures using a combination of layers constructed from thin film Frequency Selective Surfaces (FSS), Alumina, Titanate and CVG materials. Measurements for antenna applications will be also presented demonstrating and validating the theoretical performance of the MPC and DBE crystrals. The latter part of the paper will present an exciting and promising development relating to microwave circuit applications. Specifically, a novel dual-line printed circuit will be presented to emulate propagation in anisotropic media. As such, the MPC and DBE phenomena can thus be created using very simple printed circuits (couple lines).

1. INTRODUCTION

Engineered materials, such as new composites, electromagnetic bandgap [1], [2], and periodic structures have attracted considerable interest in recent years due to their remarkable and unique electromagnetic behavior. As a result, an extensive literature on the theory and application of artificially modified materials has risen. Already photonic crystals have been utilized in RF applications such as waveguides, filters, and cavities due to their extraordinary propagation characteristics [3]-[8]. One of the most interesting properties associated with photonic crystals relates to their high Q resonances, achieved when a defect is introduced within the periodic structure. When an antenna element is placed within the high Q cavity, it is then possible to harness the high fields and generate exceptional gain. Experiments have already demonstrated this enhanced gain by placing small radiating elements into a cavity built around a photonic crystal. Specifically, Temelkuran, et.al. [7] and Biswas, et.al. [8] reported a received power enhancement by a factor of 180 at the resonant frequency of the cavity.

More recently, computations using double-negative materials [9] illustrate that extraordinary gain can also be achieved when small dipoles are placed inside other exotic materials that exhibit resonance at specific frequencies [10]. However, an issue with the double negative and left-handed materials is their practical realization. In this paper, we present a new class photonic crystals [9]-[18] fabricated from available material structures such as rutile, alumina, titanates and CVGs. Of importance is that these crystals exhibit much larger gain without requiring excessive volume. As such, they may be applicable for hand held devices. Of importance is also their greater bandwidth and improved matching (due to their resonance away from the band edge). Specifically (see Figure 1), they combine the two unique properties of (a) minimal reflection at the interface of the periodic assembly forming the crystal, implying impedance matching, and (2) wave slow down leading to miniaturization, and concurrently causing large amplitude growths within the material. The latter is of importance in realizing high gain antennas using smaller volumes. Recent computational examples have demonstrated a gain increase of as much as 15dB for a small dipole placed within the crystal [14]-[16]. Experiments using periodic assemblies of FSS that realize the desirable band-diagram have also validated this gain increase.

[1] This paper also given as a plenary talk at the 2006 EuCap Conference, Nice, France.

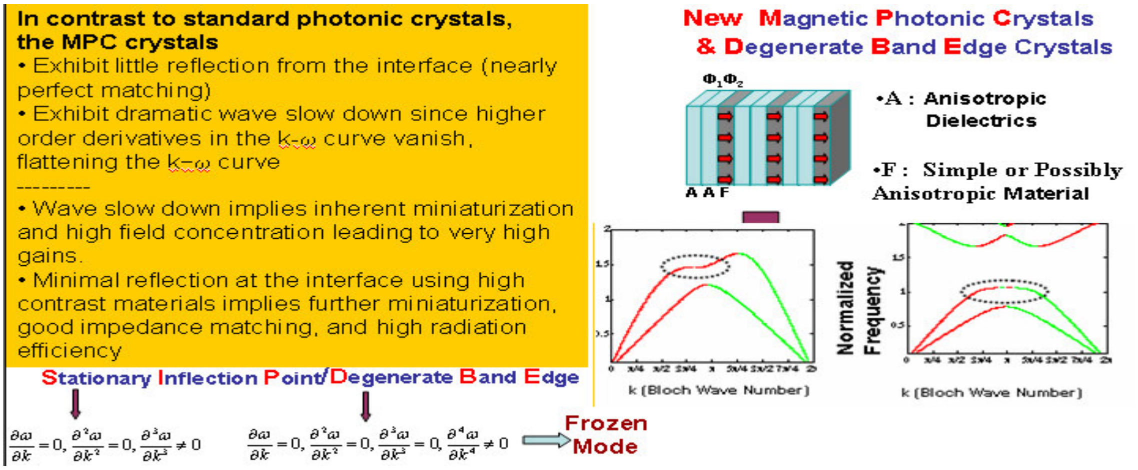


Figure 1. Properties of the magnetic photonic crystals (MPC) and their related Degenerate BangEdge (DBE) crystals formed by an periodic array of 3-layer unit cells. MPCs require at least one layer of magnetic materials whereas the DBEs are non-magnetic and therefore easily realizable. Both, MPCs and DBEs require the presence of anisotropy to realize their unique band diagrams.

The presentation will discuss some of these successes, and then proceed with a discussion on the challenges of fabricating high contrast materials, their loss properties, and their integration with printed antennas. The potential of fabricating printed microstrip lines that exhibit the same band diagram is a recent discovery that could lead to a variety of miniature microwave components as well as high sensitivity sensors.

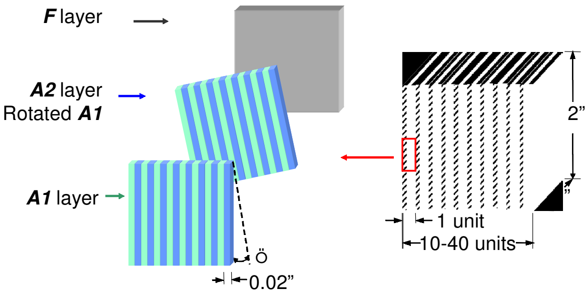


Figure 2. MPAs design : A1, A2 are two of the same anisotropic dielectric layers with ö being the misalignment angle between A1 and A2. F is the Faraday rotation ferrimagnetic layer.

2. MPC AND DBE DEMOS FOR HIGHER GAIN ANTENNAS

In [14], we demonstrated that the so-called *frozen mode* can indeed be realized in finite thickness magnetic photonic assemblies (MPAs) using a practical combination of materials. The arrangement of two misaligned anisotropic dielectric layers and an isotropic layer into a unit cell is shown in Figure 2. It was shown in [18] that it is possible to achieve a four-fold amplitude increase in the coupled electric field amplitude using 20 such unit cells to form a degenerate band edge (DBE) crystal which does not even require magnetic materials. As a direct consequence of this spatial focusing, the directivity and gain of a simple dipole antenna placed within the MPC crystal (see Figure 3) was shown [14] to increase by 12.7 dB (~20 fold). Also shown in Figure 3 is the effect of material loss on the overall gain of the dipole embedded within. A very slight loss of tanä= 10^{-5} reduces antenna gain by only 2 dB, and this gives much promise for the practical realization of those materials.

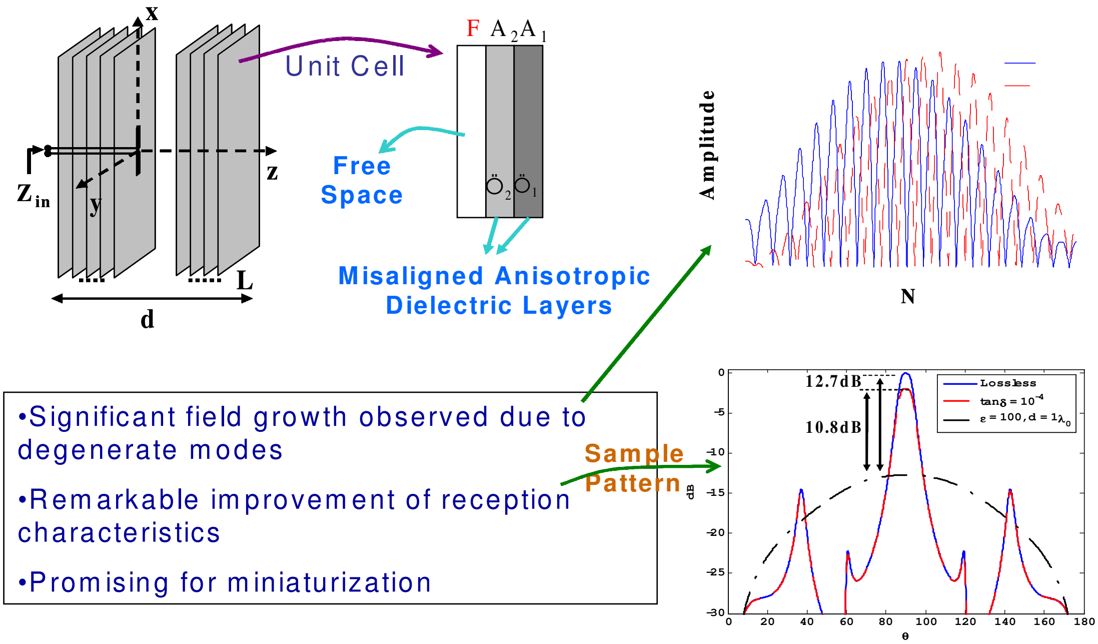


Figure 3. Demonstration of the field amplitude growth and antenna gain realization using the non-magnetic DBE crystals (periodic assemblies).

Of even greater importance is the realization of significant gain using periodic assemblies forming the so called DBE crystal. The fabrication of the DBE crystal can be done without magnetic materials and even more importantly using an arrangement or stacks of Frequency Selective Surfaces (FSS) surfaces as displayed in Fig. 4. In doing so, we mimicked the anisotropy in the dielectric layers by printing very thin conducting strips on low-loss Rodgers RO4350 substrate and designed the DBE band structure with proper F-layer thicknesses and misalignment angles as shown in Fig. 4. The Bloch band structure is shown in Fig. 5(a). Using a Tx-Rx antenna pair and a network analyzer, our first experiment demonstrated the existence of the regular and degenerate band edges as plotted in Figure 5 (c).

Further, we proceeded to demonstrate the focusing effect of the DBE crystal via probing of the field amplitudes within each free-space layer as shown in Figure 6. These tests provided further verification of the field amplitude growth realization and possible miniaturization afforded by the proposed MPC and DBE materials. We are currently exploring the possibility of designing the anisotropic material layers via a careful combination of isotropic building blocks as outlined below.

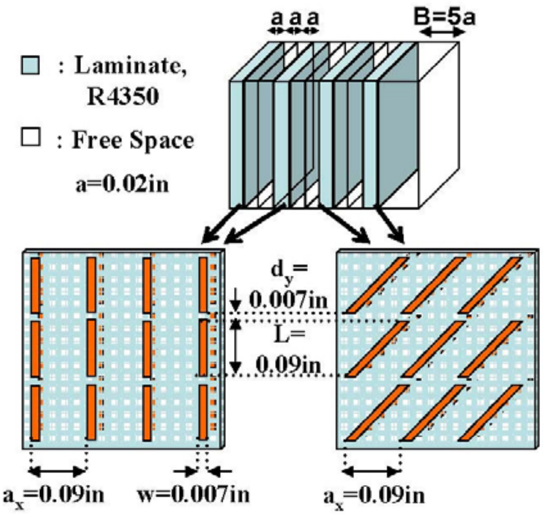
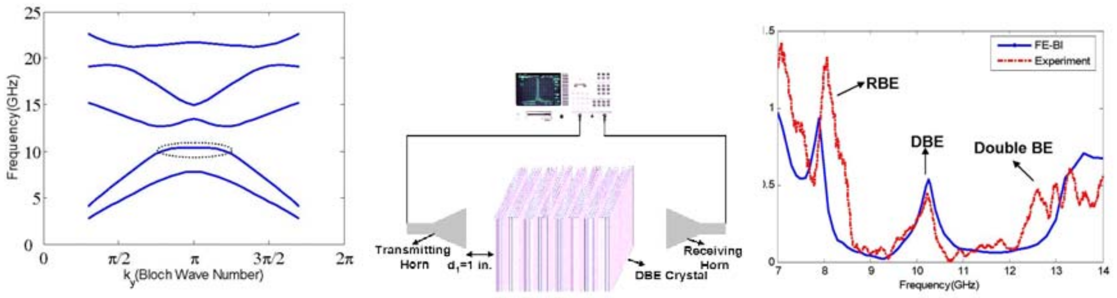


Figure 4 DBE design using PCB technology.

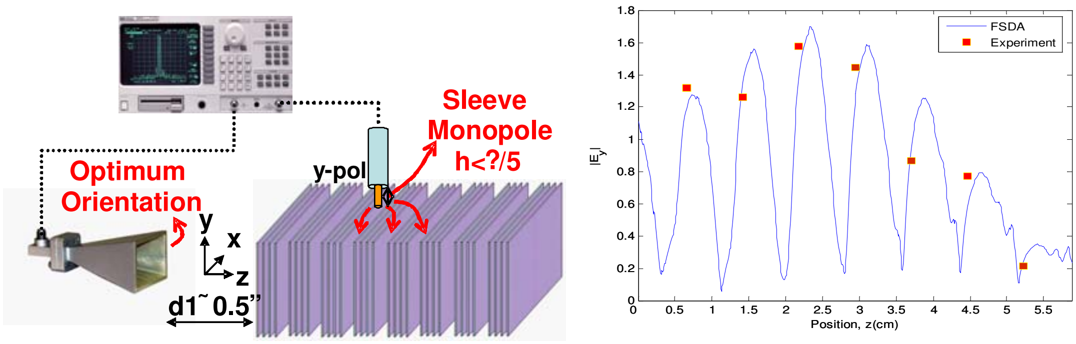


(a) **(b)** **(c)**

Figure 5: Experimental verification of the field behavior within a DBE; (a) Designed band structure showing the DBE behavior, (b) Setup for polarimetric thru-transmission measurements using the Agilent E8362B, 10MHz-20GHz PNA Series Network Analyzer, (c) Transmission through the crystal (different band edges are indicated).

3. FABRICATING PERIODIC ASSEMBLIES OF DBES AND MPCS

Practical MPCs consist of 10-40 unit cells, with each cell composed of two "A" layers rotated with respect to each other and one "F" layer, as shown in Fig. 2. To realize the predicted gains, each layer needs to be made as a thin sheet, typically of dimensions 2"×2"×0.02", and a low dielectric loss tanδ, preferably $<10^{-5}$. Examples of possible sheet materials are rutile single crystals for the A layers, and Ca, V-doped Yttrium Iron Garnet ceramics (CVGs) for the F layer. However the rutile crystals are not available with the desired 2"×2" dimensions and their cost may prohibit practical realization. In addition, the measured losses of commercially available rutile crystals are $>10^{-4}$ while there is little opportunity to improved this number by modifying the composition. The properties of commercially available CVG materials are promising but are yet to be explored for this application and further developed. Little is also know about the compatibility and manufacturability of these materials into an operational device. These factors have inhibited the realization of a prototype. To overcome these issues we have been working with Prof. Verweij (Material Science Dept. at The Ohio State University)[2] on approaches as discussed below.



(a) **(b)**

Figure 6. Experimental verification of the DBE Field amplitude focusing: (a) Setup for field probing measurement using the Agilent E8362B, 10MHz-20GHz PNA Series Network Analyzer, (b) Calculated vs. Measured electric field strength within the DBE crystal.

[2] Information on material properties and choices listed here are credited to Prof. Verweij's group at the Ohio State Univ.

4. EXPLORATION OF STACKS FROM COMMERCIAL CERAMIC SHEETS

Recent investigations, carried out in close co-operation with Prof. Verweij have demonstrated that fully functional MPCs and DBEs may well be realized through advanced ceramic processing. It was found that use of anisotropic single crystals can be avoided by realizing artificial anisotropic dielectrics, exactly as in Figure 7. The shown platelets consist of parallel arrangements of alternating ceramic beams. The ceramic route towards the manufacturing of A layers starts with stacking alternating layers of two different ceramics with low $\tan\delta$ and largely different dielectric constants, ε. After an adhesion treatment, the stacks are sliced in perpendicular direction to form the "striped" composite A layer.

The two ceramic compositions chosen for the laminate were α-Al_2O_3 with reported best values of $\varepsilon_r = 10$ and $\tan\delta = 2\times10^{-5}$ [19] and TiO_2 with reported best values of $\varepsilon_r = 100$ and $\tan\delta = 6\times10^{-5}$ [20]. Dense-ceramic Al_2O_3 sheets are commercially available. But since this is not the case for TiO_2, commercially available Ba-titanate (TD82) substrates were obtained that have a similar ε_r~82 but a higher loss of $\tan\delta = 3.7\times10^{-4}$ at 2.13 GHz. The stacks are shown in Figure 8. Without adhesive, they were found to have an anisotropic dielectric constant as predicted from mean field theory, and a loss $\tan\delta$~9.3×10^{-4} at 8.36 GHz. This higher loss is likely related to the presence of absorbed water on the individual layers and effects of the interfacial gaps due to less than perfect flatness of the platelets.

The possibility to prepare striped layers was explored by Prof. Verweij's group using an organic polymer adhesive, followed by lamination. However, the organic adhesives were found to further increase the losses of the stacks to a $\tan\delta$~1.9×10^{-3} for liquid adhesive (3M 4475) and 2.5×10^{-3} for double sided tape (3M 9492MP). The laminates were cut into 1 mm thick slices with a thin diamond blade using oil cooling. A first result is shown in Figure 8a, but more focus is still necessary on avoiding deformation and in constructing materials that can exhibit loss tangents better than 10^{-5}

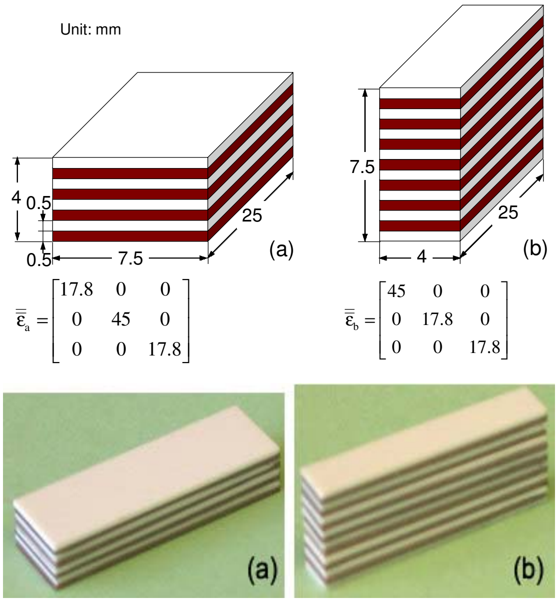


Figure 7. *Upper*: geometry and theoretical dielectric tensor of two stacks, used for in-cavity dielectric measurements at the electro-science lab (ESL). The white and brown layers are Al_2O_3 and TD82 respectively. *Lower*: anisotropic dielectric laminates from commercial Al_2O_3|TD82 substrates, stacked without adhesive, and the same dimensions.

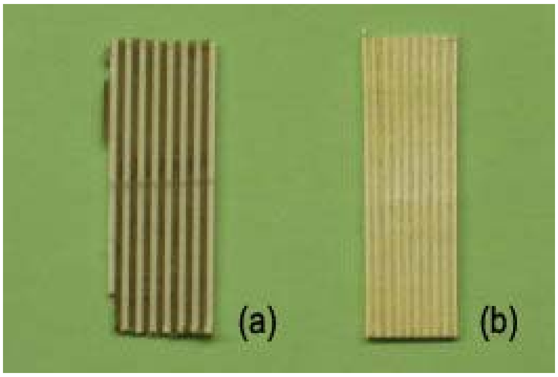


Figure 8. 1 mm thick slices cut from (a) a commercial Al_2O_3|TD82 stack with organic adhesion and (b) a homemade Al_2O_3|TiO_2 stack with self-aligned, reactive adhesion.

5. Remarks on Material Losses

Results obtained up to now make it abundantly clear that efforts to realize viable periodic stacks should focus on further reduction of electro-magnetic losses. Full control of the composition and micro-structure of the layers, cells, and stack is a necessary step to reducing losses. For example, better control of the employed chemicals and powders with optimized purity and morphology is required. In this Sheets of partly densified Al_2O_3 and TiO_2 ceramics were made by tape casting of water-based dispersions with a binder, followed by temperature-programmed debindering and sintering. To obtain the dimensions of Figure 1 , Al_2O_3 as well as TiO_2 tapes were cut into small pieces, but 10% larger than the target in plane dimensions, to account for ceramic shrinkage during sintering. The cut tape pieces were alternatively laminated and debindered and sintered in air. The sintered stacks remained intact and flat with distinct white Al_2O_3 layers and TiO_2 layers. The samples were then embedded in polymer, followed by trimming-off uneven edges and slicing with a diamond blade. The first result is shown in Figure 8b. As we are searching for low loss dielectrics, the following issues must be addressed:

◊ Stiffness of the crystal structure, such that energy dissipation through lattice modes is minimized.
◊ Absence of ferro-elastic or ferro-electric domains, so that energy dissipation through domain wall motion is avoided.
◊ A filled conduction band and a large bandgap, such that energy dissipation through electronic conductivity can be minimized.
◊ Absence of ionic mobility through interstitial or vacancy mechanisms. This likely excludes all alkali ion and protonic compounds.
◊ Absence of unpaired magnetic spins, such that energy dissipation through exitation of magnetic states is avoided.
◊ Fairly simple and stable composition (line compound) to avoid mobile charged species, *and* for easy control of stoichiometry to avoid formation of second phase compound.
◊ Thermo-chemical stability under operational conditions; no phase transformations during foreseen thermal processing.

These conditions imply that low-å selection can be made out of Al_2O_3, Sc_2O_3, Ga_2O_3, Y_2O_3, RE_2O_3, and possibly AlN and $MgSiN_2$. For high-å materials (oxides) a compromise is needed since high å at GHz frequencies implies polarizability and hence mobility in the lattice. Pure TiO_2 is the most obvious candidate that has a high å due to polarizability of the Ti lattice with respect to the oxygen lattice. However other candidates will be considered that have a potential for minimizing dielectric loss. The comprises on non-magnetic and magnetic materials will be further discussed at the presentation.

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