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Printed Antennas Using Novel Propagation Modes of Periodic Structures[1]

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1. Introduction

Controllable dispersion properties of periodic material assemblies, periodic circuit elements and microwave components have attracted considerable attention over the last decade [1]. Left handed or negative index materials and electromagnetic band gap assemblies are among the most popular in this respect, and applications relating to these have been proposed [2], [3].

Apart from the negative index media, a new class of layered periodic assemblies made up of misaligned anisotropic (dielectric and ferromagnetic) layers were shown to give rise to *frozen* propagation modes [4]. These magnetic photonic crystals (MPCs) have the key properties of (a) coupling the incident electromagnetic energy into the material with minimal reflection, and (b) subsequently slowing down the field (frozen mode) to give rise to a built-up energy inside the crystal. This interesting aspect of propagation within the MPCs was numerically demonstrated in [5] and verified experimentally to lead directive radiation from embedded electrically small sources in [6].

Lack of low-loss ferromagnetic materials for MPC realization led to the degenerate band edge (DBE) assemblies (constructed by removing the ferromagnetic layers from the assembly) and the associated DBE modes [7, 8]. Although DBE assemblies have been manufactured using existing materials (such as single crystal rutile: TiO_2 layers) the design and manufacturing/testing loop turns out to be rather difficult due to multiple disciplines (electrical, materials, and manufacturing). To alleviate this and speed up the study of such exotic modes, we recently demonstrated that the DBE and MPC dispersion relations can be replicated using printed microstrip transmission lines and lumped elements [9]. Specifically (see Fig. 1), a pair of transmission lines (consisting of periodic coupled and uncoupled sections) can be used to emulate the MPC and DBE modes. A typical DBE unit cell and its corresponding dispersion are shown in Fig.2. This simple and easy-to-manufacture model provides means to quickly study, demonstrate, and utilize the MPC/DBE modes in engineering applications, such as antennas and microwave components. This paper focuses on one such application, namely a printed antenna structure, utilizing the DBE dispersion. Measurements on such designs will also be presented at the conference.

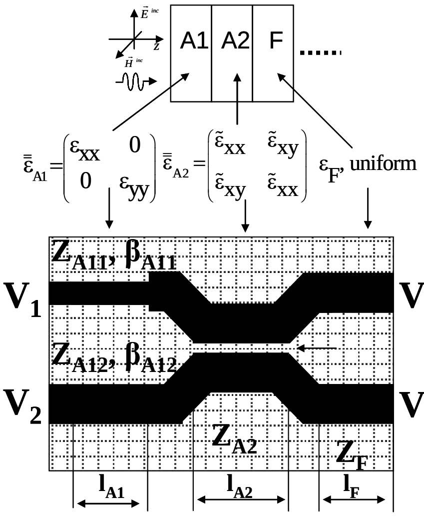

Figure 1: Coupled lines emulating anisotropy in DBE unit cell structure.

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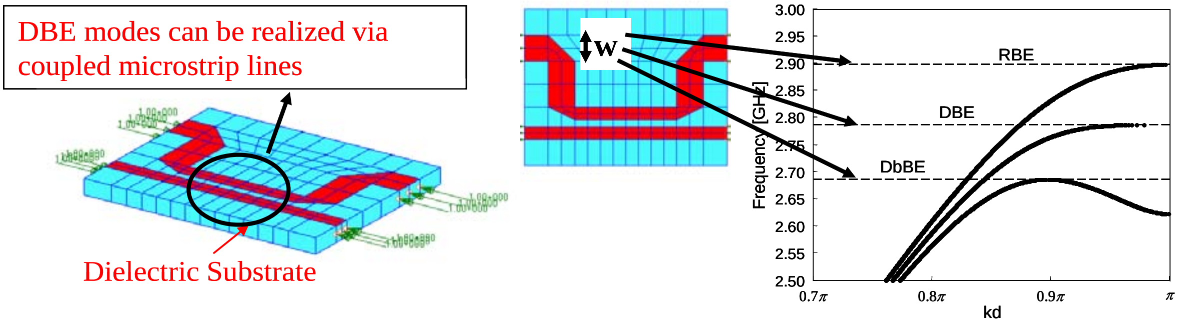
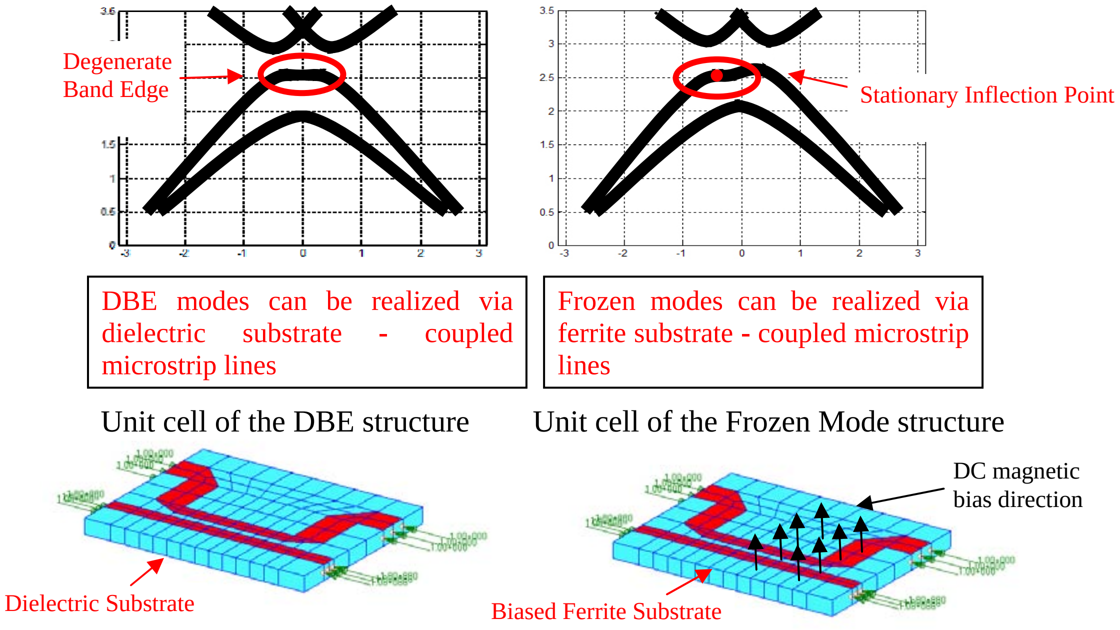
2. Exotic Propagation Modes in Degenerate Band Edge and Magnetic Photonic Crystals

Due to the anisotropic materials forming the MPC/DBE assemblies, the dispersion relation is allowed to have four branches (4 real roots of the characteristic equation) for low frequencies (where the unit cell dimensions are very small as compared to the wavelength). This fourth order system allows for greater design capability when the wavelength is comparable to the unit cell size. Thus, when the operation frequency is close to the band gap, the dispersion relation can be *tuned* to have a maximally flat edge (corresponding to the DBE diagram having ω'=0, ω'' =0, and ω''' =0), a regular band edge (ω'=0), or a double band edge corresponding to a 4th order polynomial behaviour as shown in Fig. 2. Although the crystal does not allow propagation at the band edge frequency, the evanescent waves at the interfaces and the Fabry-Perot resonances of DBE layers allows for the existence of novel modes [7] that can be used to realize novel microwave components and antennas.


DBE modes can be realized via coupled microstrip lines

Dielectric Substrate

Figure 2: DBE unit cell structure (left), and corresponding band edge (k-ω) diagrams realized by varying the thickness (w) of the indicated microstrip section.


Degenerate Band Edge

Stationary Inflection Point

DBE modes can be realized via dielectric substrate - coupled microstrip lines

Frozen modes can be realized via ferrite substrate - coupled microstrip lines

Unit cell of the DBE structure

Unit cell of the Frozen Mode structure

DC magnetic bias direction

Dielectric Substrate

Biased Ferrite Substrate

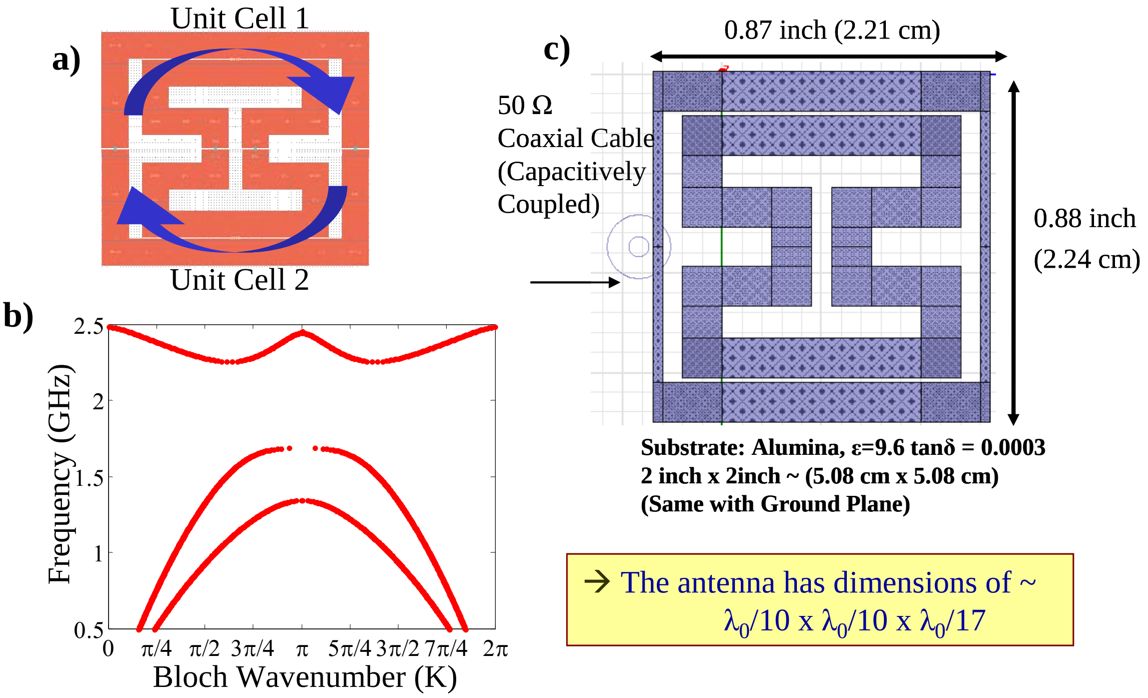
Figure 3: DBE modes of the coupled microstrip lines (left column) become MPC modes with the proper choice of externally biased ferrite substrate (right column)

2.1 Frozen Modes in Magnetic Photonic Crystals

Even more exotic modes can be obtained when a suitable biased ferromagnetic layer is added to the assembly. The presence of the non-reciprocal Faraday rotation layer allows for a more flexible tuning of the 4th order dispersion relation, allowing in turn the occurrence of a stationary inflection point (SIP) with $\omega'=0$ and $\omega''=0$ as shown in Fig. 3. Frozen modes supported by such crystals were discussed in [5]. It is important to note that those frozen modes can be excited with little or no reflection since the SIP is achieved within the propagation spectrum, i.e. not in the band gap or at band edges. Utilization of these frozen modes will be the subject of a future paper. Here we focus on printed antenna concepts using the degenerate band edge modes.

3. Printed Antennas Employing the DBE Dispersion

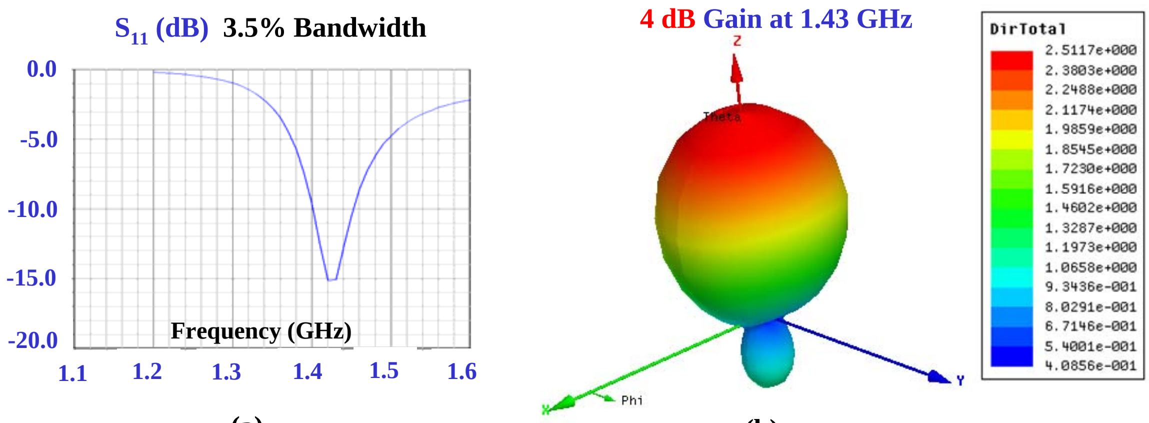
The dispersion relation characterizing the periodic material assembly is an abstraction for an infinite medium. When dealing with finite media, resonances due to the material boundaries are inevitable, giving rise to the well known Fabry-Perot resonances and unwanted diffractions from material edges. Also, radiation loss must be taken into account when computing and designing the k-ω diagrams of printed microstrip DBE (MS-DBE) structures. The infinite nature of the MS-DBE design must therefore be altered in order to realize and manufacture a physical antenna. To best utilize the infinite nature of the array for which a dispersion relation can be formulated, one approach is to cast unit cells into a circular form such that fields within the structure see an infinite medium. The number of unit cells must also be kept at a minimum since physically small antennas are typically desired. A prototype design having an alumina (ε_r=9.6, tan δ~0.0003) substrate is shown in Fig. 4 with the proposed printed topology having two cascaded unit cells. The antenna (i.e. DBE resonance) is designed to resonate at 1.43 GHz and is subsequently coaxial line fed at the uncoupled section. Resulting structure is very small (less that a tenth of the free-space wavelength) in size and has a reasonable bandwidth of 3.5% (-10dB) with a 4dB gain (see Fig. 5).



Substrate: Alumina, ε=9.6 tanδ = 0.0003
2 inch x 2inch ~ (5.08 cm x 5.08 cm)
(Same with Ground Plane)

→ The antenna has dimensions of ~ $\lambda_0/10 \times \lambda_0/10 \times \lambda_0/17$

Figure 4: The DBE antenna concept: (a) 2 DBE unit cells wrapped around to form the antenna resonator, (b) Dispersion diagram of the DBE unit cell, (c) Coaxial fed antenna structure.



(a) **(b)**

Figure 5: DBE antenna performance: (a) Return loss matched to 50Ω at 1.43 GHz (b) Gain pattern at 1.43 GHz.

4. Remarks and Future Direction

This paper demonstrated the practical realization of the novel degenerate band-edge modes using a simple printed circuit. The latter was designed to emulate the usual DBE modes by forming a unit cell consisting of a pair of coupled and uncoupled sections of printed microstrip lines. Further, we used circular periodicity to emulate the periodic assembly using a very small region. Specifically, a remarkable small antenna $\lambda_0/10$ x $\lambda_0/10$ x $\lambda_0/17$ was demonstrated to achieve a gain of 4dB with 3.5% bandwidth.

Perhaps of most importance is that the novel modes (previously demonstrated in actual periodic material assemblies) can now be realized practically overnight using printed circuit (PCB) technologies. Our understanding of the k-ω diagram (the *DNA* of the material) is also opening new directions in how to realize new devices, possibly by also introducing lumped elements into the coupled printed circuit unit cell.

References

[1] *IEEE Trans. on Ant. and Prop.*, Special Issue on Metamaterials, vol. 51, Oct. 2003.

[2] G. V. Eleftheriades and K. G. Balmain, "*Negative-Refraction Metamaterials,*" IEEE Press, John Wiley & Sons, 2005.

[3] R. F. J. Broas, D. F. Sievenpiper, and E. Yablonovitch, "A high impedance ground plane applied to a cell phone handset geometry," IEEE Trans. on Microwave Theory and Tech., vol. 49, no. 7, pp. 1262–1265, July 2001.

[4] A. Figotin and I. Vitebskiy, "Nonreciprocal magnetic photonic crystals", Phys. Rev. E, vol. 63–066609, pp. 1–17, May 2001.

[5] G. Mumcu, K. Sertel, J. L. Volakis, I. Vitebskiy, and A. Figotin, "RF propagation in finite thickness unidirectional magnetic photonic crystals," IEEE Trans. on Ant. and Prop., vol. 53, no. 12, pp. 4026–4034, Dec. 2005.

[6] G. Mumcu, K. Sertel, and J.L. Volakis, "Miniature Antennas and Arrays Embedded Within Magnetic Photonic Crystals" IEEE Antennas and Wireless Prop. Lett., vol.5, no.1, pp. 168-171, Dec. 2006.

[7] A. Figotin and I. Vitebskiy, "Gigantic transmission band-edge resonance in periodic stacks of anisotropic layers," Phys. Rev. E, vol. 72-036619, pp. 1–12, Sep. 2005.

[8] S. Yarga, K. Sertel, and J. L. Volakis, "Degenerate Band Edge Crystals and Periodic Assemblies for High Gain Antennas", 2006 IEEE AP-S/URSI/AMEREM Symposium, Albuquerque, NM, July 2006-101.2.

[9] C. Locker, K. Sertel, and J. L. Volakis, "Emulation of Propagation in Layered Anisotropic Media With Equivalent Coupled Microstrip Lines" IEEE Microwave and Wireless Comp. Lett., vol. 16, no. 12, pp. 642–644, Dec. 2006.