Antennas and RF Components Using Dispersion Engineered Coupled Microstrip Transmission Lines

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Abstract

We present a small printed antenna design based on the emulation of degenerate band edge dispersion using a simple printed partially coupled transmission line pair unit cell geometry. The same topology, when printed on ferromagnetic substrates, is shown to emulate the stationary inflection point in the dispersion that supports frozen modes. Furthermore, we present a thee-way partially coupled topology that supports stationary inflection points for both propagation directions in its dispersion.

1. Introduction

Controllable dispersion characteristics of periodic assemblies, engineered from dielectric and metallic textures, have enabled fundamental improvements on conventional microwave components and antennas. Several research groups published significant developments in negative index/left-handed metamaterials in parallel. For example; negative index transmission line concepts led to the development of very short delay lines, baluns, couplers, and miniature printed antennas (see Chapter 2 in [1]). Likewise, the mushroom structure [2] lead to one and two dimensional left-right handed geometries leading to steerable traveling wave antennas as well as improved couplers and small antennas [3]. Extraordinary refraction, sub-wavelength image resolution and electromagnetic cloaking are among the more talked about aspects of negative index metamaterials [4].

In particular, small antenna demonstrations [1,3,4,5] based on zeroth order resonances (achievable through the negative index) has sparked renewed interest in realizing miniature antennas. Coincidentally, these came at a time when wireless-data-capacity/device-weight-and-cost is becoming one of the bottlenecks in mobile communication systems. Thus, such demonstrations are seen as potentially revolutionary. On the other hand, the Chu-Harrington limits on antenna gain-bandwidth-product fundamentally restrict the desired performance. Hence, any small antenna must be put in the perspective of Chu limits when assessing its performance. Although the small metamaterial antennas may provide much larger operation bandwidths, their efficiencies are typically very poor, thus their performance often cannot reach the optimum Chu-Harrington curve.

Periodic assemblies with ferromagnetic and anisotropic materials have been shown to support a diverse mode structure with extraordinary wave dispersion [6,7]. In addition to band-gap characteristics of ordinary photonic crystals, anisotropic crystals may be tuned to have various and edge characteristics as shown in Fig. 1. If ferromagnetic layers are also included (magnetic photonic crystals-MPCs), a stationary inflection point (SIP) can be realized in the dispersion. These phenomena were recently studied in [6-8] from a theoretical and engineering perspective. A key observation was the directionality and high directivity antennas operating at the DBE and MPC modes. It was also demonstrated that these antennas can achieve optimum gain-bandwidth performance as compared to the Chu-Harrington limits.
2. Realizing DBE and MPC modes via Coupled Transmission Lines

As the realization of DBE and MPC assemblies are rather complex, it is important to realize the same modes on uniform substrates. To do so, we pursued careful understanding of propagation of the MPC/DBE modes within the assembly (see Fig. 2a). It can be stated that the wave slowdown within the crystal is highly correlated to coupling between the $E_x$ and $E_y$ field polarizations. Dispersion of electromagnetic wave propagation in the material assembly, shown in Fig. 2a,b can therefore be replicated for the voltage waves in the transmission line circuit shown in Fig. 2c.

Emulation of wave dispersion in DBE crystal using simple coupled transmission lines allows for a much faster and cheaper investigation of the properties of such structures. Furthermore, various RF components and printed antennas based on the DBE and MPC dispersion can be readily realized using the widely used RF circuit manufacturing techniques.

\[
\begin{bmatrix}
45 & 0 & 0 \\
0 & 17.78 & 0 \\
0 & 0 & 45 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
38.1944 & 11.7876 & 0 \\
11.7876 & 24.5833 & 0 \\
0 & 0 & 45 \\
\end{bmatrix}
\]

Figure 2: Emulation of DBE dispersion in printed microstrip TRLs. (a) 3-unit cell volumetric DBE crystal, (b) DBE dispersion of the volumetric crystal, (c) Printed partially coupled microstrip TRL equivalent of the volumetric DBE unit cell.

This simple partially coupled TRL geometries call for standard transmission line models (see Fig. 3) [9]. Coupling can then be realized using surface mount lumped capacitors and inductors.
Figure 3: (a) DBE-TRL unit cell geometry indication the lumped element equivalences, (b) Simple lumped circuit element model of the DBE-TRL unit cell, (c) Design of the dispersion diagram to minimize the \( K = \pi \) frequency.

Recently, we incorporated measurements of an example showing that these coupled transmission lines due result in optimum gain-bandwidth antennas [9].

Figure 5: DBE-TRL loop antenna, (a) Top view of the metallization, (b) bottom view of the ground plane, (c) side view of the realized antenna, (d) measure return loss, (d) measured radiation pattern.

5. Printed TRLs on Ferromagnetic Substrates

So far, the TRLs have allowed for a DBE mode realization. However, of interest is the emulation of dispersion diagrams with SIP and multiple DBE/MPC modes. A straightforward way to realize the frozen mode is to replace the TRL substrate with a ferrite layer [10]. Doing so gives the results in Fig. 6.

Another approach to realizing the MPC mode and even multiple modes is to print several coupled TRLs on a simple substrate. This is depicted in Fig. 7.
Figure 6: (a) Geometry of the MPC-TRL structure, (b) resulting dispersion diagram displaying a SIP for $s_f=138$ mil

Figure 7: (a) 6th order dispersion in three-way partially coupled microstrip TRL geometry, (b) close-up view of the symmetric SIPs, (c) possible realization of the SIP-TRL unit cell.

7. References