The Synthesis of Metamaterial Ferrites for RF Applications Using Electromagnetic Bandgap Structures

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I. Introduction

It has been well known for many years that the desirable properties of conventional ferrite materials are seriously degraded for frequencies above 1 GHz. This paper demonstrates that Electromagnetic Bandgap (EBG) structures may be interpreted as an equivalent PEC backed slab of magnetic material with a frequency dependent permeability. This property is exploited in order to develop a design methodology for realizing a metamaterial ferrite, which we call a metaferrite, by means of a Genetic Algorithm (GA) optimization procedure. A High-impedance Frequency Selective Surface (HZ-FSS) is designed by optimizing for a desired surface resistance and reactance at the specified operating frequency or frequencies. These values of surface impedance are shown to be directly related to the real and imaginary parts of the effective permeability of an equivalent magnetic material slab. It will be demonstrated that a properly optimized HZ-FSS can be used to realize a metaferrite structure that retains its desirable magnetic properties at frequencies above 1 GHz. Furthermore, the ability of the design procedure to optimize separately for the real and imaginary parts of the permeability allows for the synthesis of metaferrites with low-loss and either positive or negative values of μ at the desired frequency range of operation. This suggests that properly designed metaferrites may have application to the design of low loss left-handed or double-negative media by providing, in some applications, an alternative to split-ring resonators [1,2].

II. Theoretical Design

Suppose that we consider a conventional HZ-FSS structure, as illustrated in Figure 1, which consists of a frequency selective surface printed on top of a thin PEC backed dielectric substrate with thickness *h* and dielectric constant ε. The surface impedance corresponding to this HZ-FSS will be denoted by

$$Z_{S1} = R_{S1} + jX_{S1} \tag{1}$$

Now suppose we consider a thin slab of PEC backed magnetic material with thickness *d* and permeability μ, as shown in Figure 1. The surface impedance for this structure may be expressed in the form [3]

$$Z_{S2} = Z\tanh(\gamma d) \tag{2}$$

where

$$Z = \eta_0\sqrt{\mu_r} \tag{3}$$

$$\gamma = j\beta_0\sqrt{\mu_r} \tag{4}$$

The next step in the development is to equate the two expressions for surface impedance given in (1) and (2), which leads to the following characteristic equation:

$$R_{S1} + jX_{S1} = \eta_0\sqrt{\mu_r' - j\mu_r''}\tanh\left(j\beta_0 d\sqrt{\mu_r' - j\mu_r''}\right) \tag{5}$$

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Using the small argument approximation for the hyperbolic tangent function $(i.e., \tanh(x) \approx x)$ results in the following useful set of design equations:

$$\mu_r' = \frac{X_{S1}}{\eta_0 \beta_0 d} \tag{6}$$

$$\mu_r'' = \frac{R_{S1}}{\eta_0 \beta_0 d} \tag{7}$$

These equations represent the effective permeability (real and imaginary parts) that would be required by the equivalent metaferrite slab shown in Figure 1. Thus, we have developed a set of equations that relate the surface resistance and surface reactance of a HZ-FSS structure to the imaginary and real parts, respectively, of the metaferrite permeability. Furthermore, as will be demonstrated in the next section, a GA can be used to synthesize a design for a HZ-FSS structure that exhibits a specified value of permeability at the desired frequency of operation.

III. Genetic Algorithm Optimization of Metaferrites

In this section an optimization strategy is discussed for synthesizing metaferrite structures via HZ-FSS design parameters. A GA is a global stochastic search method that is ideally suited for finding the optimal solution to complex multi-variable design problems [4]. The GA is able to determine a global minimum or maximum by evolving successive populations of potential solutions. A GA has previously been successfully used to optimize a HZ-FSS structure for desired reflection coefficient properties [5], which is similar to the optimization strategy required here for metaferrites. Due to the rather long convergence time required for a conventional GA, a micro-GA can be used to reduce the overall simulation time [6]. The input parameters for the GA are the desired values of complex permeability, the specified value of operating frequency, and the desired effective thickness of the metaferrite material. The GA optimizes the FSS unit cell size, screen geometry, dielectric parameters (thickness and complex permittivity), and the resistance of the FSS screen.

IV. Results

By optimizing a HZ-FSS design for the appropriate values of R_{S1} and X_{S1}, a high frequency artificial ferrite metamaterial can be synthesized with almost any desired value of real and imaginary permeability. Materials with these properties have not previously been physically realizable at frequencies above 1 GHz. To illustrate this design procedure, a GA was used to optimize a HZ-FSS structure for an AMC (Artificial Magnetic Conductor) condition near 1.575 GHz. The unit cell and screen geometries for this HZ-FSS are shown in Figure 2. The unit cell for this structure measures 1.849 cm by 1.849 cm, with a dielectric constant of $\varepsilon_r = 13 - j0.025$, and dielectric thickness of 3.175 mm. The corresponding surface resistance and surface reactance near the resonant frequency of the HZ-FSS are plotted in Figure 3.

The surface resistance and reactance plots shown in Figure 3 may be used in conjunction with equations (7) and (8) to derive the characteristic curves for μ_r' and μ_r''. Plots of the real and imaginary parts of the metaferrite permeability are shown in Figure 4 for values of effective thickness between 5 and 20 mm. It is interesting to note that above 1.59 GHz the real part of the permeability is negative, while the imaginary part is relatively small. Hence, in this frequency range, the metaferrite is behaving as a low-loss negative μ material. This suggests the possibility that such metaferrites may have application in the design of low-loss left-handed or double-negative media. Moreover, the GA procedure introduced here is easily modified in order to synthesize a HZ-FSS that would exhibit the desired negative μ properties called for in a specific application.

V. Conclusions

A design methodology has been presented for realizing a metaferrite material using a GA optimization procedure. A standard HZ-FSS structure has been shown to be equivalent to a thin PEC backed slab of magnetic material with a frequency dependent permeability. By optimizing the surface impedance of the HZ-FSS, it is possible to synthesize a metaferrite with nearly any desired real and imaginary values of permeability. Finally, this design procedure allows for a low-loss negative permeability metaferrite to be realized, with potential application to the design of left-handed or double negative media.

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VI. References

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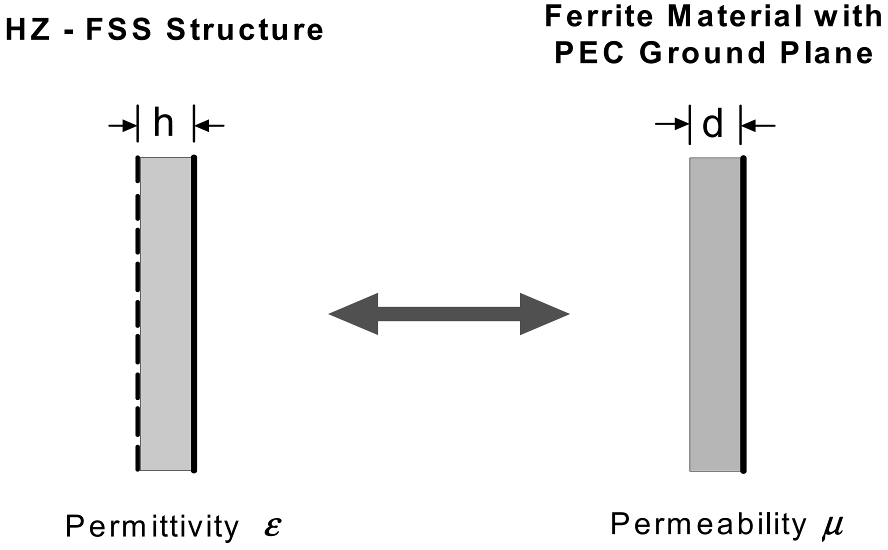
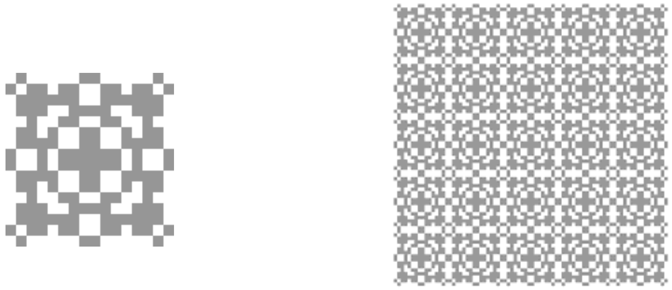
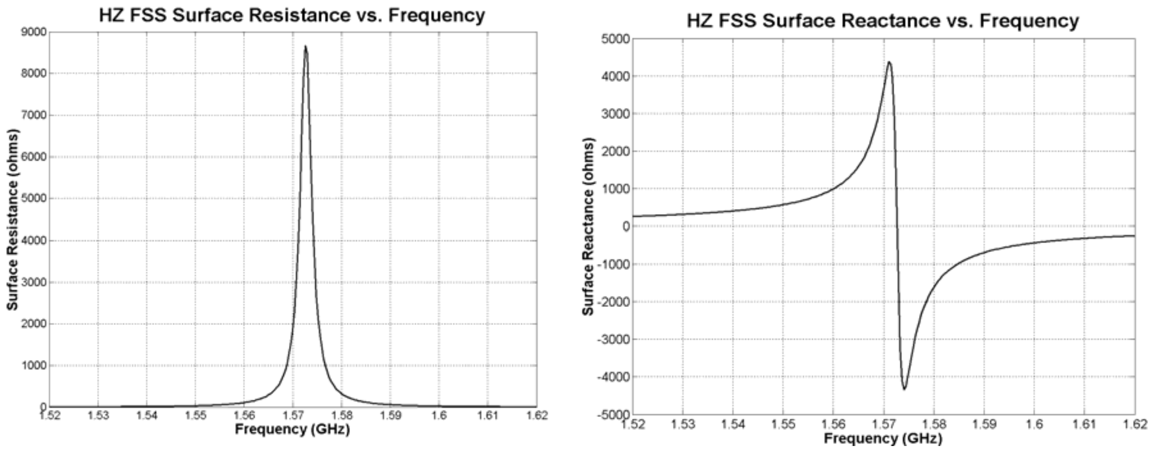


Figure 1: Equivalence between HZ-FSS structure with characteristic permittivity and magnetic (ferrite) material with PEC back plane and characteristic permeability.



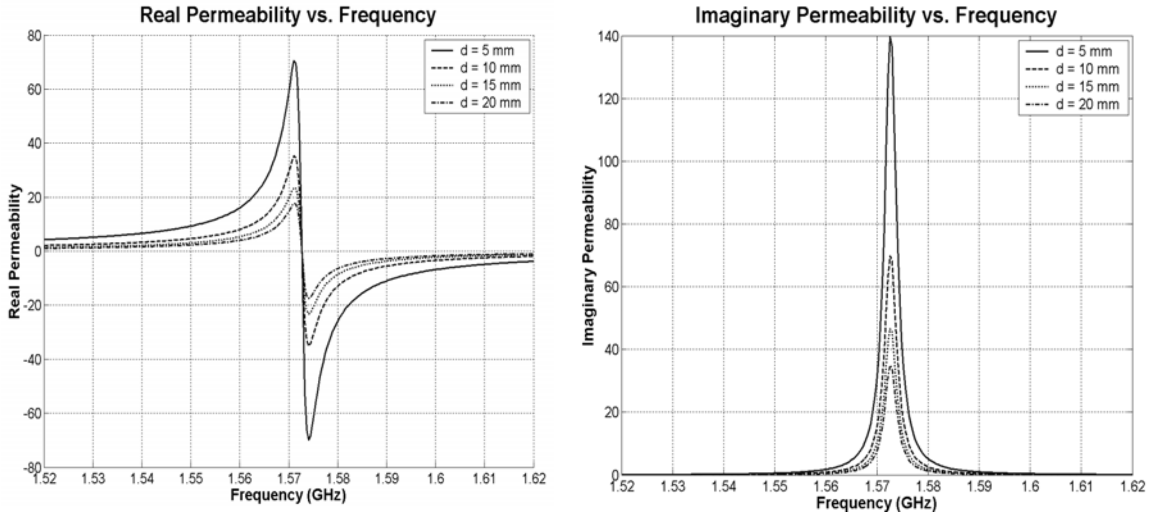
(a) **(b)**

Figure 2: HZ-FSS geometry optimized for operation at 1.575 GHz. Unit cell geometry (a), and FSS screen geometry (b).



(a) **(b)**

Figure 3: Surface impedance response of HZ-FSS. Surface resistance versus frequency (a), and surface reactance versus frequency (b).



(a) **(b)**

Figure 4: Metaferrite permeability versus frequency for different effective thicknesses. Real part of permeability versus frequency (a), and imaginary part of permeability versus frequency (b).