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

Douglas J. Kern
Dr. Douglas H. Werner*
The Pennsylvania State University
Department of Electrical Engineering
Overview

• Motivation for meta-ferrite designs

• Brief summary of High-impedance Frequency Selective Surfaces (HZ-FSS, a.k.a. EBG or AMC)

• Equivalence between HZ-FSS and magnetic substrate backed by a PEC ground plane

• Surface impedance response of HZ-FSS structures

• Meta-ferrite design examples

• Conclusion
Why Meta-ferrites?

- It has been well-known for many years that the desirable properties of conventional ferrite materials are seriously degraded for frequencies above 1 GHz.

- A methodology will be presented here for synthesizing artificial magnetic meta-materials (i.e., meta-ferrites) via HZ FSS or EBG surfaces.

- These meta-ferrites can be engineered to maintain strong magnetic properties for RF applications above 1 GHz, and can be synthesized with almost any desired value of permeability (both real and imaginary parts).

- This technique can also be used to synthesize a negative $\mu$ meta-material that has very low loss with application to left-handed or double-negative media (e.g., provides a low-loss alternative to using split-ring resonators).
EBG High Impedance Surface

**Circuit Model:**

Simple parallel LC circuit can be used to represent the surface impedance

Original High-Z FSS Geometry

Original Dimensions:

$\varepsilon_r = 10.2 \quad h = 25 \text{ mil}$

$a = 120 \text{ mil} \quad w = 10 \text{ mil}$

$d = 27.5 \text{ mil} \quad l = 40 \text{ mil}$

GA-FSS: Dual Band GPS and 4.0 GHz AMC Surface

Artificial Ferrite HZ-FSS Design

HZ - FSS Structure

Ferrite Material with PEC Ground Plane

Surface Impedance:

\[ Z_{s1} = R_s + jX_s \]

Dielectric Permittivity:

\[ \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \]

Surface Impedance:

\[ Z_{s2} = Z \tanh(\gamma d) \]

Dielectric Permeability:

\[ \mu_r = \mu_r' - j\mu_r'' \]

A properly designed high impedance frequency selective surface will be shown to have an equivalent surface impedance to that of a thin magnetic substrate backed by a PEC ground plane.
Consider the conventional HZ-FSS structure, which consists of a frequency selective surface printed above a thin PEC backed dielectric layer with thickness $h$ and permittivity $\varepsilon$. The surface impedance for this structure will be denoted by

$$Z_{s1} = R_s + jX_s$$

Next consider a thin slab of PEC backed magnetic material with thickness $d$ and permeability $\mu$. The surface impedance for this structure may be expressed in the form*

$$Z_{s2} = Z \tanh(\gamma d)$$

where

$$Z = \eta_0 \sqrt{\mu_r}.$$ 

Artificial Ferrite Design Equations

To create an artificial ferrite meta-material from an HZ-FSS design, the two surface impedances must be equal. Thus we have:

$$Z_{s1} = Z_{s2}$$

Substituting the appropriate expressions for both surface impedances into this equation and assuming $$\varepsilon_r = 1$$, (i.e., $$\varepsilon'_r = 1$$ and $$\varepsilon''_r = 0$$) yields a characteristic equation given by

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

where use has been made of the fact that

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

Using the small argument approximation $$[\tanh(x) \approx x]$$ leads to the following useful set of design equations:

$$\mu'_r = \frac{X_{S1}}{\eta_0 \beta_0 d} \quad \text{and} \quad \mu''_r = \frac{R_{S1}}{\eta_0 \beta_0 d}$$
Meta-ferrite Synthesis Procedure

A design methodology utilizing a genetic algorithm optimization is used to evolve a high impedance FSS which acts as an Artificial Magnetic Conductor (AMC) at a desired operating frequency or frequencies.

The AMC condition can be characterized by a relatively high value of surface impedance amplitude with a phase of zero degrees.

The magnitude of the AMC surface impedance is dependent upon how much loss is contained in the structure.

By optimizing an HZ-FSS design for the appropriate values of $R_s$ and $X_s$, it is possible to synthesize a high frequency meta-material that behaves like an artificial ferrite.
A genetic algorithm is used to optimize the HZ-FSS design for AMC condition at the desired operating frequency. This corresponds to optimizing for a reflection coefficient phase of zero degrees. Transmission line theory provides a correlation between the reflection coefficient and the surface impedance.

High-Impedance Frequency Selective Surface Design

FSS Cell Geometry:
dx = dy = 1.849 cm
\(\varepsilon_r = 13\)
h = 0.3175 cm

In this particular HZ-FSS design, the AMC center frequency is 1.575 GHz, where the reflection coefficient phase is zero degrees.

The surface impedance is shown in dB, normalized to free space, 377 Ω. The AMC bandwidth is given by the frequencies for which the normalized impedance is greater than 0 dB (impedance greater than 377 Ω).
Artificial Ferrite HZ-FSS Design

FSS Cell Geometry:
\[ dx = dy = 1.849 \text{ cm} \]
\[ \varepsilon_r = 13 - j0.025 \]
\[ h = 0.3175 \text{ cm} \]
Meta-ferrite Design Parameters

\[ \mu'_r = \frac{X_{S1}}{\eta_0 \beta_0 d} \]

\[ \mu''_r = \frac{R_{S1}}{\eta_0 \beta_0 d} \]

**Real Permeability vs. Frequency**

**Imaginary Permeability vs. Frequency**
Meta-Ferrite Synthesis Technique

Specify Desired Value of $\mu$ ($\mu'$ and $\mu''$)

Specify Desired Values of $f_0$ and d

Calculate Required Value of Surface Impedance $Z_s$ for HZ FSS (Rs and Xs)

Optimization

Parameters of HZ FSS
- FSS cell size
- FSS cell geometry
- Substrate thickness $h$
- Dielectric constant $\varepsilon_r$ ($\varepsilon_r'$ and $\varepsilon_r''$)
- Resistance of FSS screen
Applications

• Improved microwave components and devices

• Substrate meta-materials for microstrip filters and antennas

• Electromagnetic absorbers

• Electronic packaging

• EMI / EMC
Conclusion

• The equivalence between an HZ-FSS and a thin magnetic substrate backed by a PEC ground plane has been demonstrated, and useful design equations were presented.

• This new class of meta-materials behave like artificial ferrites and are appropriately called meta-ferrites.

• A GA design synthesis technique has been introduced for the optimization of meta-ferrite structures for nearly any desired permeability.

• This technique can also be used to synthesize a negative \( \mu \) meta-material that has very low loss with application to left-handed or double-negative media.