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Towards Experimental Verification of Permeability Upgrading Using Metamaterial Inserts

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Abstract

A concept is being developed to upgrade the permeability of a homogenous, isotropic magneto dielectric material by inserting metamaterial macro-cells to produce a hybrid composite material of much higher permeability than that of the host material. The new material will be anisotropic or bi-anisotropic. The analysis and simulation show the multiplicative effect of the hybrid structure, operating at high frequencies using specially designed host materials. In this paper, we take the first step in proving the concept of permeability upgrading by performing experimental verification of a hybrid structure that uses commercially available host material at low frequency. Measuring the *S*-parameters of thin layers of the host material, followed by using documented parameter retrieval algorithms, we calculate the host material's permeability, permittivity, and loss tangent versus frequency. The measurements are repeated for the metamaterial-inserted hybrid structure to obtain the same parameters and observe the permeability upgrading, or multiplication.

1. Introduction

Producing a thin, flexible, high permeability, reasonably low loss surface at high frequencies has been a challenge that attracted the attention of electromagnetic researchers and antenna engineers. Such materials would have applications as high impedance surfaces for low-profile antennas, and shielding surfaces at selected frequency bands, to mention a few. The insertion of ultra-thin metamaterial cells in an already high-permeability, low loss material, is sought to produce much higher permeability in the hybrid structure of host-plus-metamaterial composition. The two elements of this concept, high permeability host material [1] and metamaterial insertion [2]-[3], have been analyzed and simulated using electromagnetic-solver algorithms, and chemical-analysis tools. The analysis and simulation tools have to handle multiple-parameter optimizations and simulations with a high mesh density in order to calculate the right polarizability functions for both elements of the hybrid structure. This challenging task is both time-consuming and memory intensive. The loss tangent analysis and results of the hybrid structure is particularly of interest, especially at high frequencies. In parallel to the analysis and simulation path, experimental verification, or prototyping, of commercially available host materials with metamaterial insertions would be an alternate and faster path to prove the permeability upgrading concept [4]. This experimental, or synthesis, path is explained in the next sections.

2. Permeability Upgrading Concept

There are no known magnetic materials having high permeability at high frequencies. This is due to the relationship between the static permeability, μ_s, and the ferromagnetic resonant frequency, ω_{res}, as given by Snoek's law [1]. In other words, higher μ_s leads to lower ω_{res} and vice versa. For instance, in hexagonal ferrites, the static permeability can be as high as 20 with the resonant frequency 3GHz. The complex permeability can be calculated using the Lorentzian dispersion law.

Another class of magnetic materials are known as artificial magnetic materials. They can be constructed by embedding arrays of high dielectric inclusions or conducting inclusions with complex shapes [2]-[3]. The inclusions can be designed to resonate at any frequency. This adds more degrees of freedom than natural magnetic constituents.

In this work, we explore the idea of inserting metamaterial inclusions in magnetic material containing natural magnetic constituents to enhance magnetic properties. The key concept is to match the metamaterial inclusions' resonance with the ferromagnetic resonant frequency. If the metamaterial inclusions' resonance is lower or higher than the ferromagnetic resonant frequency, the combined magnetic effects are dominated by the metamaterial inclusions or the ferromagnetic particles respectively. This is due to the well-known fact that effective magnetism quickly vanishes when the frequency deviates from the inclusion or particle resonance.

3. Experimental and Simulation Setup

The waveguide measurement system is used to test the host material with and without the metamaterial inserts [5]. The measurement setup is depicted in Figure 1. The system consists of two coaxial waveguide adapters, material under test (MUT), or sample, and network analyzer. The MUTs are RT/Duroid 5880 (4.30 in. x 2.15 in. x 125 mils), FR4 (4.30 in. x 2.15 in. x 62 mils) and metamaterial cells embedded in RT/Duroid 5870 (4.30 in. x 2.15 in. x 125 mils) block. The waveguide measurements without MUT in place were taken to establish the reference. The material block is then inserted at the center between two waveguides. All of the *S*-parameter measurements are carried out using the network analyzer. It should be noted that we need to de-embed the electrical length from the measurement port to the surface of MUT to match with simulation results. In this setup, it is the adapter's length that is extracted from the phase information of measured data.

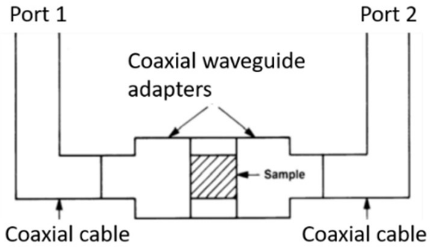

Figure 1. Waveguide measurement setup

For the simulation analysis, we use the commercial electromagnetic software, FEKO. The unit cell has dimensions of 125 mils x 125 mils x 125 mils for RT/Duroid 5880, 125 mils x 125 mils x 62 mils for FR4, and 840 mils x 840 mils x 125mils for metamaterial cells embedded in RT/Duroid 5870, as demonstrated in Figure 2 and Figure 3, respectively. It is placed at the origin and excited by a x-polarized electric field in a plane wave traveling along the z-axis. The periods along the *x* and *y* axis are 125 mils for RT/Duroid 5880 and FR4, and 840 mils for metamaterial-embedded cells. The material extends to infinity in the *x* and *y* directions, with thickness of one cell in the *z* direction using two-dimensional periodic boundary conditions. It should be noted that the simulated *S*-parameters are also de-embedded to the surface of the unit cell in the z axis.

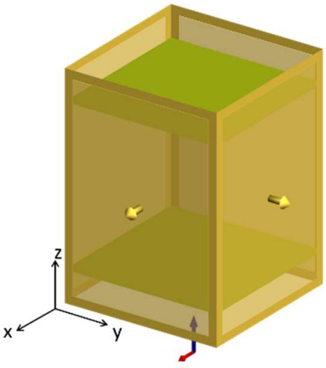

Figure 2. Unit cell of RT/Duroid 5880 or FR4 in FEKO.

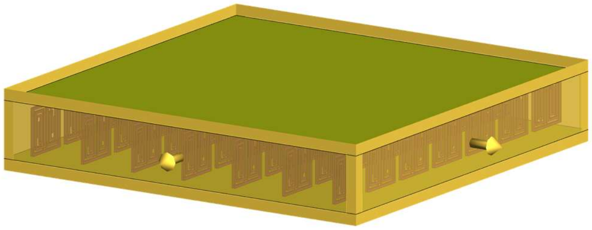

Figure 3. Unit cell of metamaterial embedded in RT/Duroid 5870.

4. Measurements vs. Simulations

The comparisons between simulated and measured *S*-parameters for RT/Duroid 5880 and FR4 are shown in Figure 4 and Figure 5, respectively. As we can see, there is a strong correspondence between measured data and simulated data. The slight difference between measured and simulated magnitudes of S_{11} is due to calibration errors resulting from using coaxial calibration in the waveguide set up. Since the relative permittivity, ε_r, of both RT/Duroid 5880 and FR4 are constant versus frequency, we would expect the *S*-parameters to respond the same way.

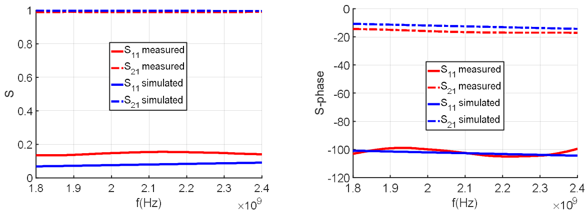

Figure 4. Comparison between simulated and measured *S*-parameters (magnitude and phase) for RT/Duroid 5880.

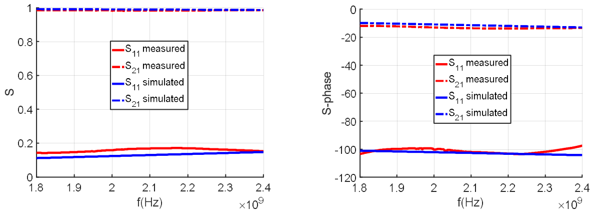

Figure 5. Comparison between simulated and measured *S*-parameters (magnitude and phase) for FR4.

The metamaterial cell chosen to design an artificial magnetic material is a U-spiral pair (USP) resonator. It has been demonstrated that the USP resonator can obtain much better miniaturization at microwave frequencies in comparison to conventional spit-ring resonator (SRR) for a given physical cell size [6].

The comparisons between simulated and measured *S*-parameters for metamaterial cells embedded in RT/Duroid 5870 are shown in Figure 6.

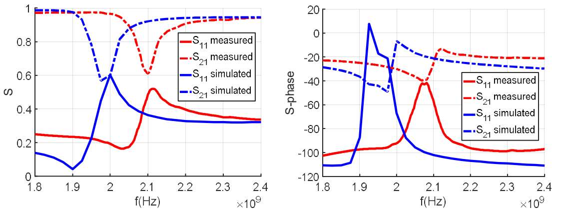

Figure 6. Comparison between simulated and measured *S*-parameters (magnitude and phase) for metamaterial cells embedded in RT/Duroid 5870.

Both measured and simulated results show the same trend with a notable frequency shift and slight differences between the levels around the resonances. The frequency shifts are due to the small air gap, around 2 mils thick on each side of the metamaterial inserts as shown in Figure 7.

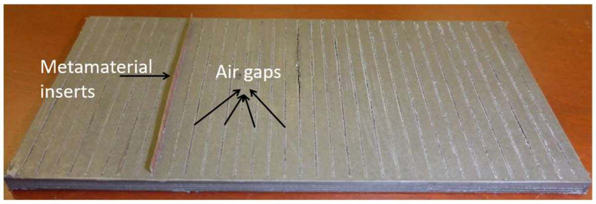

Figure 7. Fabricated prototype, showing the small air gaps around the metamaterial inserts.

Repeating the simulation to include the effects of the air gaps results in agreement between measured and simulated results. This is shown in Figure 8.

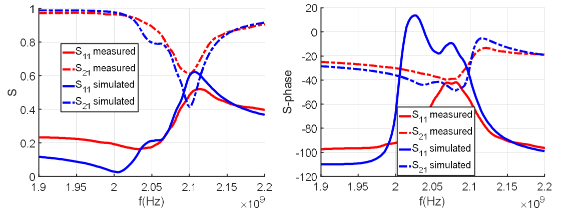

Figure 8. Comparison between simulated (accounted effects of the air gaps) and measured *S*-parameters (magnitude and phase) for metamaterial cells embedded in RT/Duroid 5870.

The peak in S_{11} and the dip in S_{21} indicate the resonance behavior in the structure. The phase of S_{11} is near zero which indicates a magnetic resonance. In other words, the structure has high permeability, which comes from inserting the USP cells.

5. Conclusions

In this work, we present a concept of upgrading the permeability of a homogenous, isotropic magneto dielectric material by inserting metamaterial macro-cells. We perform experimental verification of a hybrid structure, where metamaterial cells are inserted into dielectric material (RT/Duroid 5870), as the first step towards proving the concept of permeability upgrading. The measured and simulated data are matched. This will be followed by proving the concept using commercial magnetic material as the host material for metamaterial inserts.

6. References

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