Session 0A1b
Metamaterials with Negative Index and Related Phenomena

THz Metamaterials

W. J. Padilla and R. Averitt
Los Alamos National Laboratory, USA

THz time domain spectroscopy (TDS) is used to characterize the frequency dependent electromagnetic behavior of both electric and magnetic metamaterials. Time dependent response and dynamical tunable electromagnetic behavior is studied throughout the terahertz frequency regime.

The Positive and Negative Goos-Hänchen Shifts with Left-handed Slabs

J. B. J. Chen, **T. M. Grzegorczyk**, **B.-I. Wu**, **and J. A. Kong**
Massachusetts Institute of Technology, USA

A generalized analytic formulation for analyzing the Goos-Hänchen (GH) lateral shift direction is provided, from which we show that the phenomenon of both positive and negative GH shifts at different incident angles can be observed with left-handed material (LHM) slabs. The formulation also reveals that this unique phenomenon is related to the relative amplitudes of the evanescent waves inside the LHM slabs, which is confirmed by the study of energy flux patterns.

By introducing the analytical equation for the GH shift direction

$$sign\{S\} = sign\left\{-\frac{\mu_{1r}}{\mu_{2r}}\,[C - C_1][C - C_2]\right\} \tag{1}$$

where C is ratio of the growing and decaying evanescent wave amplitudes inside the slab, while C_1 and C_2 are functions of slabs parameters and the beam's incident angle, we are able to analyze the GH shift direction change and its dependence on the incident angles and the slab's thickness. Although the well-known equation $S = -\,\partial\Phi(k_x)/\partial k_x|_{k_x=k_{ix}}$ can also be used for the parametric study of GH shifts, Eq. 1 has the advantage of directly relating GH shift directions to the slab's parameters and the electromagnetic waves in the system. More importantly, the physical meaning of the value of C is the ratio of the growing and decaying evanescent wave amplitudes inside the slab. Hence Eq. 1 reveals the connections between the GH lateral shift direction change and the variations of the ratio of the evanescent wave amplitudes inside the slab.

It can be shown that the existence of a *simultaneous* positive and negative GH shift at different angles is due to the fact that the GH shifts can change directions as the LHM slab thickness becomes smaller. The changes of GH shift directions at different slab thicknesses can be understood intuitively. For a very thin LHM slab (relative to the wavelength), the presence of the slab has little effect on the waves and the total internal reflections are mainly due to the third medium resulting in positive GH shifts. For an electrically thick LHM slab, however, the total internal reflections are mainly due to the LHM slab, yielding a negative GH shift. In between these two extremes, there exist a certain slab thickness in which *simultaneous* positive and negative shifts occur. In addition, a unique property of the LHM slab is that depending on the constitutive parameters, a slab can be electrically thick but still yield a positive GH shift as if the slab were electrically thin. As an extreme example, when the LHM slab is exactly matched to the third medium, the GH shift is always positive regardless of the slab thickness. The physical reason for this effect is related to the energy flux pattern inside the slab, which is also addressed.

Sensitivity Analysis of the Full Wave Solution of a Near-Perfect Lens with $n = -1$

O. E. French, **K. I. Hopcraft**, **and E. Jakeman**
University of Nottingham, UK

Smith et al., in their 2003 paper [1], consider the resolution achievable by a single evanescent mode in the case of a nearly perfect lens for which $\epsilon = -1$ but for which $\mu = -1 + \delta_\mu$, and note that there is a deviation from perfect resolution in the case of such material parameters.

We generalise this result by presenting the full wave solution for a dipole source above a slab of left-handed medium (LHM) of refractive index $n = -1$, but with ϵ and μ differing from those ideal values that create the perfect lens through taking

$$\epsilon = -\frac{1}{1+\delta}, \tag{1}$$

$$\mu = -(1+\delta), \tag{2}$$

where δ is real, as in the 2004 paper by Lu et al [2]. It should be noted that depite their deviations from the ideal case, the permittivity and permeability of the slab remain real and so any modifications in resolution are not due to loss effects within the lens. Solutions for the form of the fields throughout all space are obtained using the method of Hertz potentials. The imperfection modelled by the presence of a non-zero value of δ creates a single resonance, rather than the infinity of resonances that is the defining characteristic of the ideal LHM lens, with the effect that the perfect lensing properties are compromised (see in addition Chew [3]).

Using an appropriately defined resolution criterion, we examine the sensitivity of the lens as a function of the material imperfection δ.

REFERENCES

1. Smith, D. R., D. Schurig, M. Rosenbluth, S. Schultz, S. A. Ramakrishna, and J. B. Pendry, *Appl. Phys. Letts.*, Vol. 82, No. 10, 1506, 2003.
2. Lu, J., T. M. Grzegorczyk, B.-I. Wu, J. Pacheco, M. Chen, and J. A. Kong, *Opt. Tech. Letts.*, Vol. 45, No. 1, 49, 2005.
3. Chew, W. C., *Opt. Tech. Letts.*, Vol. 42, No. 5, 49, 2004.

Existence of Negative Refraction Index in Periodic Semiconductor-ferrite Composite in Microwave Frequencies

R. X. Wu
Nanjing University, China

J. Q. Xiao
University of Delaware, USA

Taking the advantage of negative permeability of certain ferrites, a new type of negative index materials (NIMs) with only-mu-negative (MNG) materials based on semiconductor-ferrite multi-layers has been proposed. We have studied the effective refraction of index of the film composite in microwave frequencies using transfer matrix method. We have found negative index of refraction could be realized in this kind of composite. For the given ferrite with negative permeability, the effects of material parameters of n-type silicon on negative index have been studied. We have found that the effective negative index and power loss depend on the layer thickness ratio between semiconductor and ferrite, and the impurity concentration in semiconductor. In comparison with other existing NIMs in microwave frequencies, the composite has advantages of low power loss and small in size.

Electric Metamaterials

D. Schurig, **D. R. Smith**, **and J. J. Mock**
Duke University, USA

J. B. Pendry
Imperial College, England

T. F. Starr
Sensor Metrix, USA

Since the arrival of negative index, an array of wires has been the standard metamaterial design for achieving negative permittivity. Recently a number of issues have arisen demonstrating that this media is more complex than initially assumed, for example, the behavior of wires terminating on an interface, the importance of continuity between orthogonal wires in multidimensional media, and the transmission of longitudinal modes. Some of these issues point to the desirability of an alternative to wire media. We will discuss some of the recent findings for wire media as well as present an alternative design for achieving electric responding metamaterials.