

Metallic Coil-Polymer Braid Composites: I. The Numerical Modeling and Chirality

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ABSTRACT

Incorporation of metallic inductive elements into composites introduces a new opportunity to tune the overall electromagnetic (EM) properties of such materials over certain frequency ranges. The design can incorporate arrays of straight wire or coiled wire conductors. The straight wires must be very thin in order to tune the composite to operate within microwave regimes. Coil arrays, on the other hand, can use relatively thick wires. The coiled wires are integrated into the composite within reinforcing braids, where one or more metallic wires are woven with necessary polymer fiber bundles. The coils however introduce chirality in the EM response of the material. In this study we consider two approaches to cancel this chirality effect. One is to use a 1- or 2-D grid of left- and right-handed coils. This does not alter the frequency characteristics of the material, but requires more effort in the arrangement of the two types of coils during manufacturing. Another approach is to use a double coil, with the outer and the inner coils having opposite handedness. This method does not require the extra effort for the arrangement however needs more complex braids. It also shows interesting effects in the dispersion behavior of the material. Both methods will be discussed and some of the simulation results will be presented.

Keywords: *Electromagnetic Scattering, Multifunctional Composites, Braided Composites, Chiral Media, Numerical Simulations, Effective Medium Theory.*

INTRODUCTION: THE STRAIGHT WIRE MEDIUM

This work is concerned with design, analysis, and manufacturing of multifunctional composites. The idea is to develop materials that are not mere load-bearing elements, but also have other functionalities such as enhanced electromagnetic response and thermal management [7]. The main focus of this paper is to tune index of refraction and dielectric constant in bounded frequency ranges, specifically microwave band. Same principles can be applied to alter magnetic properties of a composite. We design the composites using electromagnetic scattering elements to modify the overall dielectric constant in the effective medium regime [1-3]. It can be reduced to negative values. Similarly the magnetic permeability can be modified and reduced to negative values [4]. Furthermore when both the permittivity and permeability become simultaneously negative, the index of refraction will be also real and negative. This class of artificial materials shows many interesting properties that are discussed elsewhere [5, 6].

A *plasmonic medium* is defined to have plenty of free electric charges. These charges depending on the inductance of the medium can freely vibrate with external excitations. Electromagnetic waves below a certain frequency do not propagate in this medium. This frequency is called the *plasmon frequency* of the medium, at which the dielectric constant changes sign. Below it, the index of refraction is imaginary as it is equal to $\sqrt{\mu\varepsilon} / \sqrt{\mu_0\varepsilon_0}$ where μ and ε denote respectively the permeability and permittivity and the

subscript 0 identifies the base values of the free space. Note that the magnetic response of the material is not usually altered very much by the free charges that are vibrating linearly. Therefore the plane waves of frequencies lower than the resonance are attenuated as they travel through this medium. Above the plasmon frequency, the index of refraction becomes positive and dispersive such that a plane wave is a propagating mode. The enhanced composites that show tuned dielectric constant have various electromagnetic scattering elements embedded in a periodic array to introduce the free charges. The inductance of these elements determines the resonant frequency of the charges which is the same as the plasmon frequency. The simplest elements are long straight thin conductive wires. Based on the geometric and material parameters the composite shows different behavior and can be tuned to the desired values of the turn-on frequency. Note that if the embedded wires are unidirectional, only the component of the wave with electric field parallel to the wires would be affected since the free charges in the conductors can mainly vibrate in this direction. This is also true for other designs such as loop-wires and coils. In-plane bi-directional arrangements and tri-directional arrangements in space can be used to partially deal with this anisotropy [7].

Pendry et al. [1, 2] derived the following analytical result for the plasmon frequency of thin perfectly conducting wires in vacuum:

$$f_p^2 = \frac{1}{2\pi} \left(\frac{c_0^2/d^2}{\ln\left(\frac{d}{r}\right) - \frac{1}{2}(1 + \ln \pi)} \right)$$

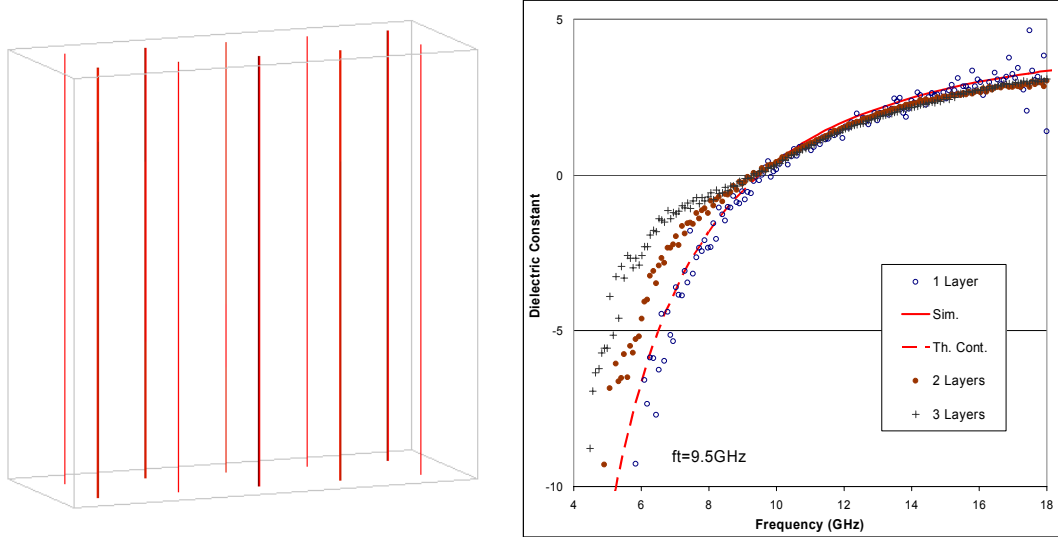


Figure 1. Straight wire medium. [Left] A slab of material with embedded straight wire array. [Right] Theoretical, numerical and experimental results for effective dielectric constant of an Epoxy/E-glass composite with embedded 50 micron wires in a quarter inch lattice. The solid line is the simulations results from an eigendomain finite element solver (ANSOFT-HFSS) while the dashed line is its theoretical extension to lower frequencies. The other 3 sets of data are extracted from transmission measurements taken from samples with 1, 2, and 3 layers of wires through the thickness. In the chart ft is the turn-on frequency of the medium, below which the medium is opaque to EM waves. The dielectric constant of the medium approaches to the value of it for only the composite without the wires at large enough frequencies.

In this formula, c_0 is the speed of light in vacuum and d and r are respectively the lattice spacing and the radius of the wires. In his paper, Pendry et al. neglected the constant term in the denominator as this is derived by assuming that $d/r \gg 1$. However for all engineering purposes, the constant term should be kept. For a plasmonic medium, the effective dielectric constant takes the following dispersive form:

$$\kappa = \frac{\epsilon}{\epsilon_0} = 1 - \left(\frac{f_p^2}{f^2} \right).$$

In this formula κ is the effective dielectric constant as a function of frequency f and f_p is the plasmon frequency. Moreover, if the wires are embedded in a matrix with a dielectric constant $\kappa_0 \neq 1$, this formula must be changed to [7] (see Figure 1):

$$\kappa = \kappa_0 - \left(\frac{f_p^2}{f^2} \right).$$

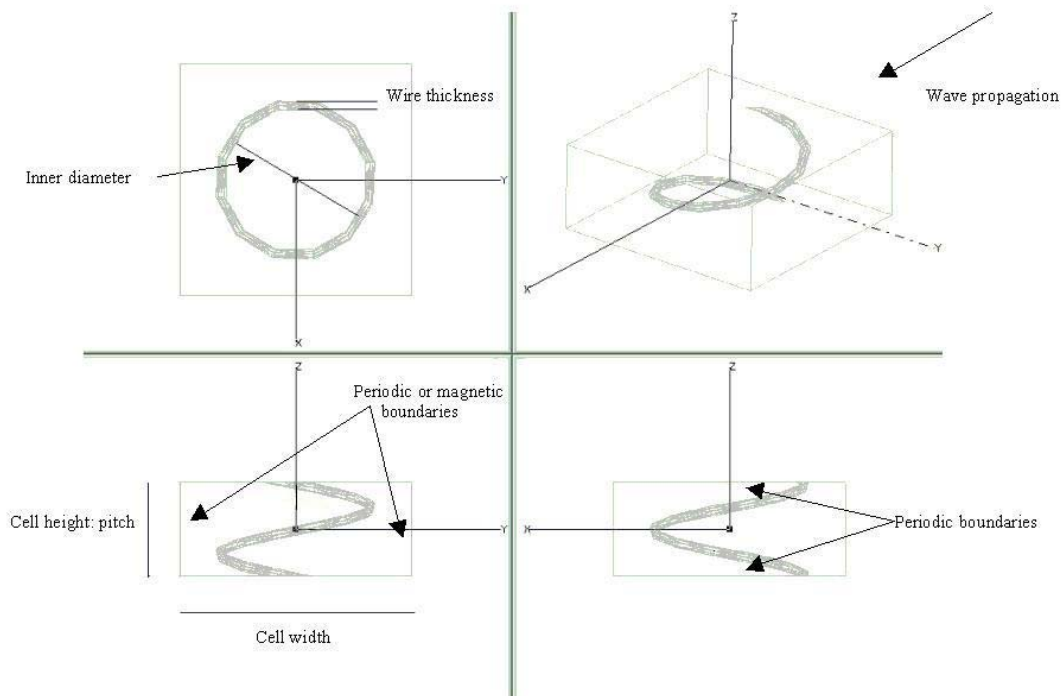


Figure 2. Geometry of a unit cell of a coiled medium, generated using ANSOFT-HFSS for eigendomain finite element numerical calculations. This is a right-handed coil.

THE COIL MEDIUM

The value of r must not only be small compared to d so that the medium behaves like dilute plasma but also the thicker wires are less inductive. This causes the turn-on frequency (below which the material is not transparent to electromagnetic waves) to increase and the wavelengths to decrease. In order for the effective medium theory to be applicable to the composites and overall values for material properties to

be meaningfully defined, the wavelength must be much larger than the lattice spacing of the array ($\lambda/d \gg 1$). Otherwise the small-scale structure can not be neglected in favor of a homogenized description of the material.

At the same time, from a manufacturing point of view, incorporation of thin wires to be effective in microwave regime is not very easy. In order to use thicker wires, one has to apply other means to enhance the inductance of the medium. One method is to increase the length of conductors per unit volume of composite by introducing loop-wire elements or changing the geometry from straight wires to coils. This is shown in Figure 2. The processing and manufacturing techniques used to incorporate coils in fiber reinforced composites are discussed in detail in the second part of this paper presented in this conference: *Metallic Coil-Polymer Braid Composites: II. Material Processing and Characterization*. Also to avoid repetition a dispersion curve of such medium is only included in the second part, see Figure 4 there. Also look at Figure 3 in the present paper for partial results of a parametric study on the geometrical specifications of the medium.

The introduction of coil geometry or loop-wires not only affects the inductance of the medium and consequently the overall dielectric constant, but also introduces different capacitive response than mere straight wires. This capacitive response usually changes the overall magnetic properties of the medium. We have not yet completely studied the magnetic behavior as the electric response is the dominant effect. Part of this response is included in the chirality effect which is discussed presently. However a more careful and thorough study is needed since the techniques that can be used to eliminate chirality do not necessarily affect the axial magnetic effects.

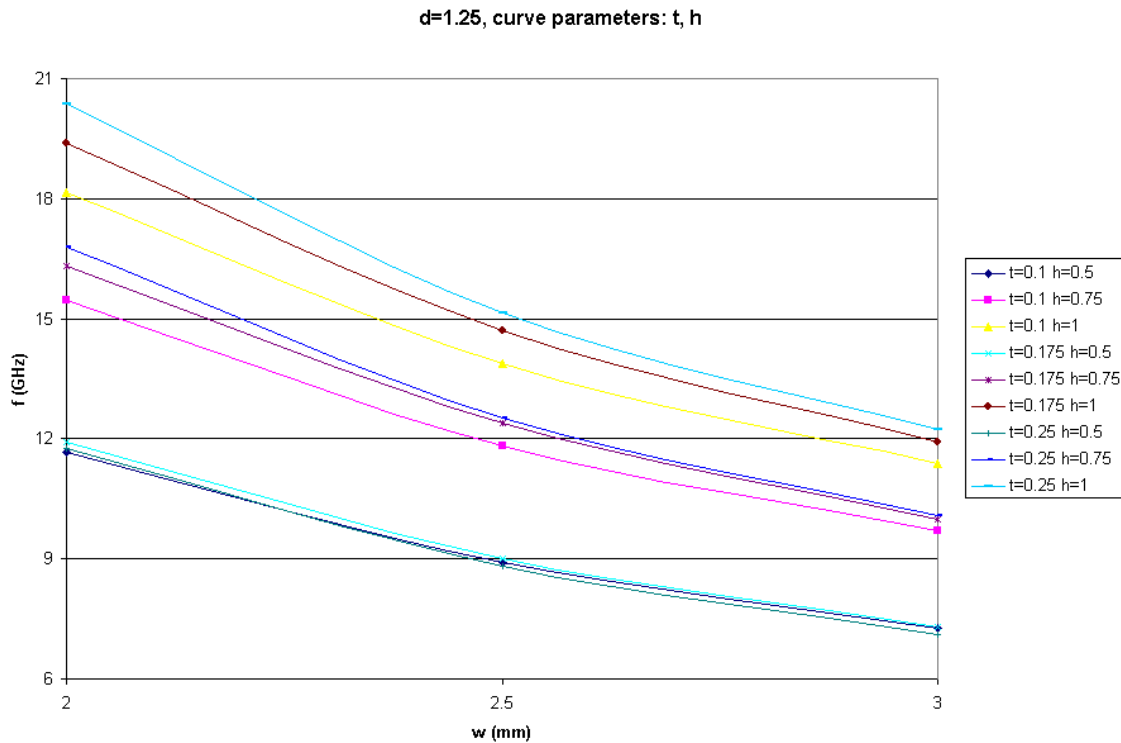


Figure 3. Partial results of a parametric study on coiled media. The curves represent the dependence of the plasmon frequency of the medium on width of the unit cell. The parameters are defined as follows (more detail in Figure 2); w: cell width (only square lattices were considered in this case), d: coil diameter, t: wire thickness, h: cell height.

More important is the effect of the handedness of the coils on the field vectors. The geometry of the coils (and also the loop-wires) requires that the current density in the conductors have a circumferential component in addition to the axial component which is the only one present in the case of the straight wires. The oscillating circumferential component of the current enhances the magnetic field of the propagating wave with a component parallel to the axis of the coils. Note that as the active component of the electric field is parallel to the axis of the coils, the accompanying magnetic field is normal to it. Therefore the enhanced magnetic field is normal to the external excitation.

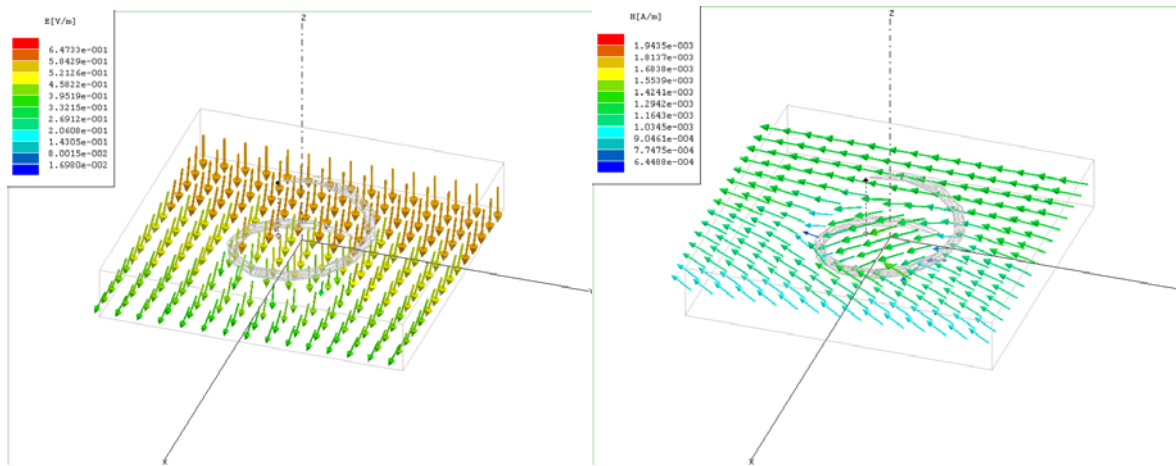


Figure 4. Field patterns calculated for a unit cell of a coiled medium using ANSOFT-HFSS. The wave is propagating in x -direction and the fields on the two yz faces have 50° phase difference. In other words the wavelength is $360/50$ times the length of the cell in x -direction. The graph on the left shows the electric field and the one on the right shows the magnetic field. The incoming wave (electric field) from the far yz face is at this time polarized parallel to the axis of the coil. However the effect of the coil adds an out of phase normal component. Therefore the field vectors of both electric and magnetic fields are rotated as the wave travels through the cell.

Moreover the new component is in phase with the current density and in turn with the external electric field, whereas the external magnetic field and electric field are out of phase by a quarter of a cycle. If the created magnetic component was in phase with the external excitation, the superposed field would be slightly skewed from the original field. This would have meant that one could still define principal axes for the material property tensors, although they are slightly angled compared to the structural axes. However the phase incompatibility creates rotating magnetic fields which in turn create rotating electric fields. The principal propagating polarizations are not linear any more, but rather have elliptical polarization, see Figure 4. This effect is called *chirality* in the literature [8]. The material property tensors, when written in linear polarization bases have imaginary (complex if it the material is lossy) off-diagonal components.

ALTERNATING ARRAYS AND DOUBLE COILS

The effect of chirality can be used to benefit some applications. However in most cases it may introduce unwanted complexity. In order to eliminate this behavior two methods have been proposed. The first method is to include alternating coils in the array so that every right-handed coil should be adjacent to left-handed coils. We considered this solution only for regular arrays as will be discussed but we conjecture that for effective media the wavelength is much larger than the spacing between coils, a randomly homogenous and statistically equal distribution of the right-handed and left-handed coils should also do the trick. Note that for an irregular medium the size of the volume that is randomly homogeneous must be considerably smaller than the wavelength as compared with a regular array. Another way to

eliminate the chirality effect is to use double coils instead of simple single coils. If two concentric coils with the opposite handedness are together, most of the magnetic field created by the circumferential electric current is effectively canceled.

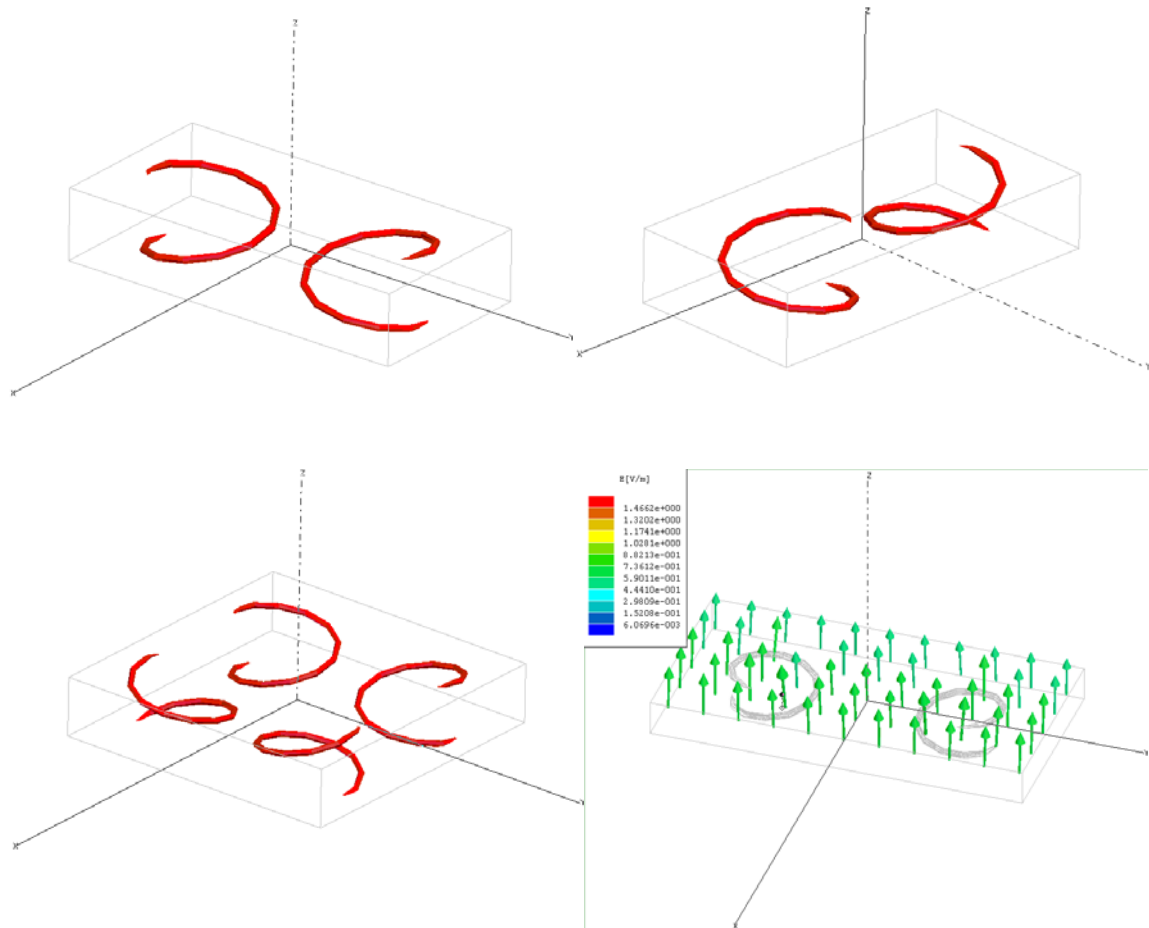


Figure 5. Alternating arrays of left-handed and right-handed coils. Considering an EM wave is propagating through the medium in x -direction, each of the above sets can be used to cancel the polarization rotation effect. To envision the whole array, imagine these as blocks and fill the 3D space with similar blocks in each case (only translated by the size of the block in each direction). Top Left: Each layer through the thickness consists of alternating coils. The layers are then stacked such that traveling normal to the thickness the coils are similar. Top right: Layers of uniform right-handed and left-handed coils are stacked through the thickness. Bottom Left: Checker board configuration. All four adjacent coils to any single one are of opposite handedness. Bottom right: The effect of the field rotation is canceled. All the parameters are the same as Figure 3. However the linear polarization of the electric field parallel to the axis of the coils is maintained through the medium. Note that the periodic length of the medium for the top right and bottom left cases is twice as much as it for the top left case, hence they have a smaller diffraction frequency limit. The dispersion relation and plasmon frequency for the principal propagating modes remain essentially unaltered compared to the uniform arrays. However, the modes are dramatically different.

In the first method, one can stack alternating layers of right handed and left handed coils together. The traveling wave undergoes the opposite effects of the two layers and therefore the polarization of the fields will not be rotated. Another arrangement that has the same effect is to design each layer to have alternating coils. In other words, instead of having alternating layers in the thickness direction, one has alternating layers in the normal direction. Moreover by shifting these layers by one lattice spacing, one can achieve a 2D checker board design. All these 3 designs have similar behavior and they don't affect the plasmon frequency by much, compared to the original chiral medium. In all equal circumstances, the

design with alternating layers normal to the propagation direction is better to use, as the length period in the propagation direction is smallest and therefore the diffraction frequency limit is higher (Figure 5.)

		single	double 1:1	double 1:2	double 2:3
spacing (mm)		6.35	6.35	6.35	6.35
cell height (mm)		1.1	1.1	1.1	1.1
outer coil	inner diameter (mm)	2.6	2.6	2.6	2.6
	turns in one cell	1	1	2	3
inner coil	inner diameter (mm)	-	2.2	2.2	2.2
	turns in one cell	-	1	1	2
wire thickness (mm)		0.1	0.1	0.1	0.1
plasma frequency (GHz)		3.26	7.59	6.73	5.35

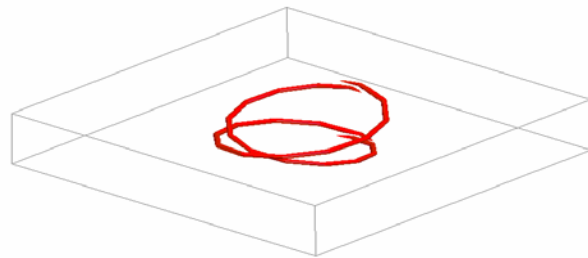
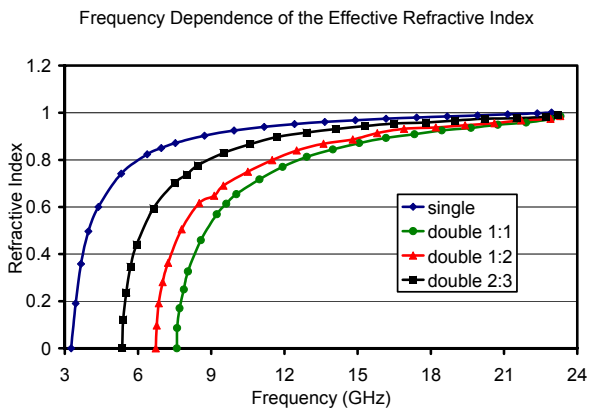


Figure 6. Double coils (bottom right: 1:1 case) can also be used to cancel the effect of chirality. However they also modify the plasmon frequency of the medium as the effective inductance and capacitance per unit volume is being changed. The other two configurations that are not shown here, have all other geometric parameters similar to this, except for the number of turns of the outer and inner coils in one cell.

In the second method, the effect of clockwise or counter-clockwise circumferential current is not cancelled by adjacent coils, but by a local and concentric coil of the opposite handedness. The attraction of this method lies in the fact that no special ordering or arrangement at the time of manufacturing of the composite is required. The double coils can either be made by a 2-stage braiding scheme or a similar design can even be achieved by braiding the conducting coils of insulated wires at the same time in opposite orientations. More detail on the manufacturing techniques and methods can be found in the second part of this paper. The double coils may have an advantage in mass production of composites. However the additional inside loop pushes up the plasmon frequency and reduces the effective range of pass band. Numerical studies show that higher pitch values can overcome this difficulty (Figure 6.)

SUMMARY

Incorporation of metallic scattering elements into composites provides the opportunity to design and manufacture structural materials with controlled and desired electromagnetic properties. Different schemes are being investigated for this purpose, including straight wire arrays and coiled media. The advantage of the coiled media lies in the possibility of using thicker wires. However one may have to deal with the chiral effects caused by the coils. Two different remedies are introduced here. One is to use alternating arrays of left-handed and right-handed coils. Another method is to use concentric double coils

of opposite handedness instead of single coils. Based on the objective of a design and manufacturing limitations either method can be used.

Acknowledgements

The authors would like to thank David R. Smith from Department of Physics of UCSD for many helpful discussions and sharing his insight. This research is supported by ARO DAAD19-00-1-0525 to the University of California, San Diego. All simulation results presented in this paper are run using ANSOFT-HFSS and Optimetircs electromagnetic numerical analysis software.

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