A Novel Resonant Metallo-Dielectric Structure for Design of High Performance ε-μ Meta-Materials

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1. Abstract: The goal of this paper is to address a magneto-dielectric (ε-μ) meta-material with improved material properties. To accomplish this, a meta-material with periodic configuration constructed of small size metallo-dielectric transmission-line resonators is proposed. At the resonance the metallo-dielectric inclusions are equivalent to parallel LC circuits magnetically coupled to transmission line model of the medium. It is demonstrated that the permeability of proposed structure has a relatively larger bandwidth compared to the conventional resonant loop circuit design. A larger quality factor (*Q*) and smaller loss tangent for the new design is predicted.

2. ε-μ Meta-Materials: In recent years there have been significant amount of research in the area of functional meta-materials. The aim of meta-material development is to propose novel periodic configurations of available materials for achieving new media with desired figures of merit. Different material properties such as Double Negative (DNG), Double Positive (DPS), Epsilon Negative (ENG), and Mu Negative (MNG) parameters have been investigated and many novel applications for them in the areas of RF and optical systems have been proposed [1]-[6].

However, most of the designs are still in the stage of theory and there is a big challenge to integrate them in real applications. The building block unit cells of so far designed meta-materials are constructed of metallic loop circuits and in order to obtain a desired magnetic property the structures must operate near their resonance. This generates two problems, one is narrow permeability bandwidth, and the other is significant conduction loss in metallic loops. Therefore, the meta-material development utilizing resonant loop circuits are kind of impractical.

The objective in this work is to present a new meta-material design with enhanced characteristics. This will be achieved with the use of periodic array of small resonant transmission line sectors. Compared to the loop circuit configuration, the inclusions (metalo-dielectrics) occupy more volume and the magnetic property is accomplished using quarter-wavelength short-circuit transmission lines. Therefore, an efficient permeability with higher bandwidth and less loss tangent is achieved.

In what follows, first the design of a meta-material constructed of embedded-loop circuits is reviewed. Next the concept of metallo-dielectric resonant structures, and application of them for the design of high performance meta-materials is investigated.

3. Loop Circuit Inclusions: The conventional method for providing artificial magnetism is based on the use of resonant loop circuits. Basically, this idea was introduced for the first time by Schelkunoff [7] where he showed how a permeability property can be achieved utilizing a loop circuit inclusion with inductance L terminated to a series capacitor C. The Schelkunoff geometry is shown in Fig. 1. An impressed magnetic field along the axis of the loop induces a current on the loop that changes the flux density of the medium and consequently creates an effective permeability μ_{eff}.

To obtain a material with artificial magnetic property a periodic array of resonant loop circuits is depicted in Fig. 2(a). A unit cell transmission line model of the structure is shown in Fig. 2(b). The magnetic flux linking the transmission line induces a current in the loops in a direction so that the magnetic flux generated by the loops would oppose the transmission line magnetic flux and thus presents an effective magnetic behavior. In addition, the coupling capacitors existing between the wire loops and the conductor of transmission line significantly affect the dielectric property of the background material and produce an effective permittivity. The equivalent circuit model of the transmission line analogy of embedded-circuit structure is shown

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in Fig. 2(c) (the metallic loss is ignored). It is obtained from the circuit model that the designed meta-material in Fig. 2(a) offers the effective permeability [1]:

$$\mu_{eff} = \mu_0 \left(1 - (0.47)^2 \frac{1}{1 - (1.05)^2 / f^2_{(GHz)}} \right), \tag{1}$$

and effective permittivity $\varepsilon_{eff} = 1.8\,\varepsilon_0$. The effective ε_r-μ_r of the medium is plotted in Fig. 3.

Transmission coefficient for a plane wave propagating through a magneto-dielectric slab with the above ε_{eff}-μ_{eff} parameters is determined in Fig. 4. A Finite Difference Time Domain (FDTD) technique with Periodic Boundary Conditions/Perfectly Matched Layered (PBC/PML) walls [8] is also applied to characterize the complex resonant loop circuit meta-material (shown in Fig. 2(a)). A very good agreement between the transmission line analysis and FDTD approach is demonstrated. This verifies the complex meta-material is in fact equivalent to a uniform medium with ε_{eff}-μ_{eff}.

From Fig. 3 it is observed that the developed meta-material has a permeability with very narrow bandwidth around its resonance. In addition, although here for simplicity the loss is ignored, from practical point of views it has a major impact. At the resonance, a very strong current is circulated in the loops and generates a considerable conduction loss. These are the issues that have to be resolved for practical purposes.

4. Metallo-Dielectric Inclusions: The focus in this section is to investigate a meta-material with building block unit cells made up of resonant transmission line sections (metallo-dielectric structures) demonstrating improved magnetic characteristics. Fig. 5(a) shows a periodic array of quarter-wavelength metallo-dielectric sectors. The metallic sections are basically parallel strip transmission lines loaded with high permittivity dielectrics. Their physical size in fact is small fraction of wavelength in free space ($< \lambda_0/15$). At resonance short circuit transmission lines represent parallel LC circuits. Thus the meta-material has the similar circuit equivalent as Fig. 2(a). However, compared to the loop circuits, the metallo-dielectrics occupy more space and one can expect to provide permeability with higher value, larger bandwidth, and smaller loss tangent.

The meta-material has effective permittivity $\varepsilon_{eff} = 7\,\varepsilon_0$, and permeability given by

$$\mu_{eff} = \mu_0 \left(1 - (0.72)^2 \frac{1}{1 - (0.98)^2 / f^2_{(GHz)}} \right). \tag{2}$$

Fig. 5(b) shows ε_r-μ_r of the medium. Transmission coefficients for a plane wave propagating through a slab of the above materials and original complex meta-material (shown in Fig. 5(a)) are determined in Fig. 6. Note that inside the stop band region some differences between the results obtained from the FDTD and circuit model are observed. This is because that in this region the transmission magnitude is bellow $-70\,dB$ that is outside the accuracy range of the PML. A more accurate FDTD result can be obtained with the use of a PML with larger dynamic range.

It is shown in Fig. 5(b) that the permeability of the new meta-material design has larger value and wider bandwidth. It is anticipated that this design can also provide a higher Q with lower loss tangent, which is currently under investigation.

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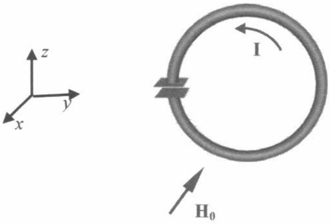


Fig. 1: A loop with inductance L terminated to series capacitor C for realizing artificial magnetism (Schelkunoff model).

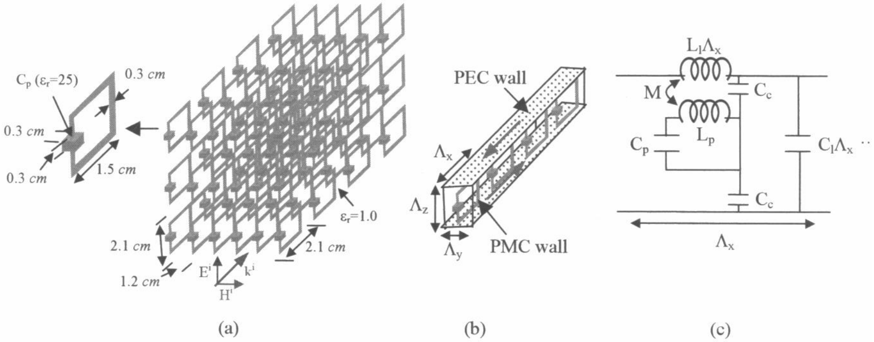


Fig. 2. Meta-Material constructed of resonant loop circuits. (a) Periodic structure, (b) Building block unit cell, (c) Equivalent circuit model.

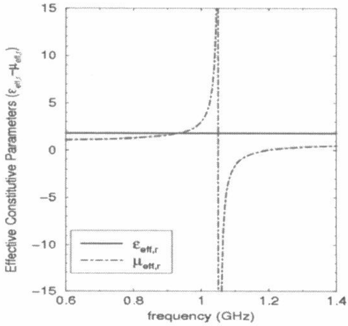
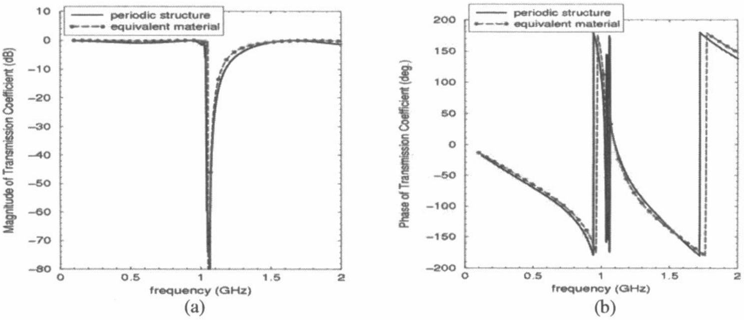
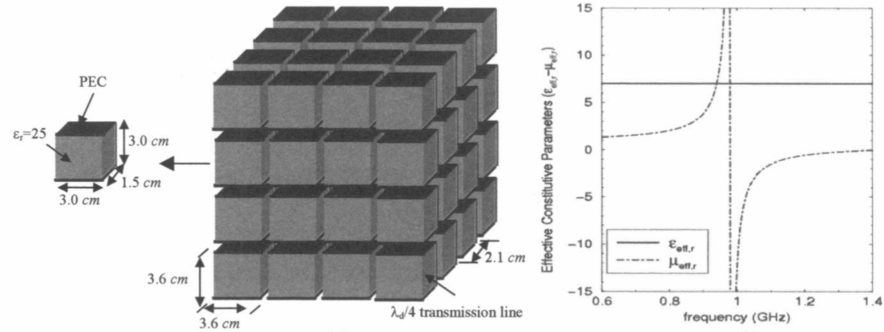


Fig. 3. Effective constitutive parameters of resonant loops meta-material (Fig. 2(a)).



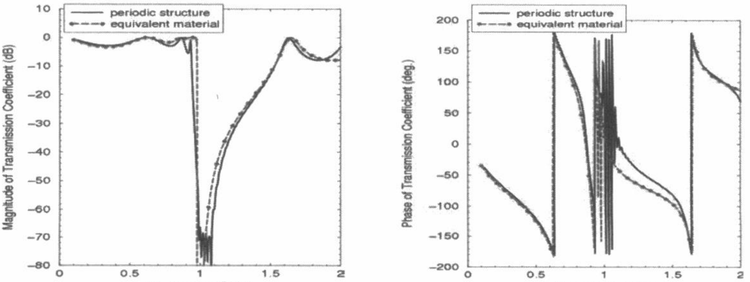
(a) (b)

Fig. 4. (a) Transmission amplitude and (b) phase of the resonant loops meta-material.



(a) (b)

Fig. 5. (a) Resonant metallo-dielectrics meta-material and its (b) effective constitutive parameters.



(a) (b)

Fig. 6. (a) Transmission amplitude and (b) phase of the resonant metallo-dielectrics meta-material.