Enhancement of inductance along metallic mesh wires in three-dimensional quasi-isotropic metamaterials using high-$\varepsilon$ dielectric particles for impedance-matching with free space

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Abstract. In this paper, we consider cube-shaped unit cells including high-$\varepsilon$ dielectric cubes under magnetic dipole-like resonance placed at the center and metallic mesh wires for negative permittivity to construct three-dimensional quasi-isotropic metamaterials in the microwave region. Basically, such structures suffer from their low wave impedance due to inclusion of high-$\varepsilon$ materials. To reduce effective permittivity of the composite structures, we propose to insert additional inductance into the metallic mesh. For the insertion of lumped inductors along the wires, dispersion diagram and the Bloch-impedance are numerically estimated, and converted to effective permittivity and permeability. The numerical simulation results clearly show almost 3-D isotropic propagation characteristics in a specific frequency region and enhancement of the Bloch-impedance close to free space in the left-handed region. The lumped inductors are replaced by meander-line strip patterns for practical configurations. The metallic patterned structures also achieve the enhanced Bloch impedance that is well-matched to free space.

Keywords: Metamaterials / negative-refractive-index / dielectric cubes / impedance matching

1 Introduction

Negative-refractive-index (NRI) or left-handed (LH) metamaterials can be realized by making the effective permeability and permittivity negative simultaneously [1], and have been investigated for applications to super lenses, cloaking techniques, antennas, and so forth [2–5]. In the early days, most of bulky LH metamaterials were made of metallic patterns, such as a combination of split-ring resonators (SRRs) and thin metallic wires [6], lumped capacitors inserted in the metallic mesh wires [7], transmission line networks [8–10], and so forth. However, typical metallic pattern based metamaterials, such as SRRs, suffer from conductor loss near the resonance frequency and significantly anisotropic dependence on the polarization of incident waves.

On the other hand, dielectric particles with high dielectric constant, such as spheres or cubes, can be a good candidate for simple configuration for isotropic excitation of electric or magnetic dipole like resonances [11–14]. Dielectric-particle-based metamaterials have been investigated and classified into several schemes, such as all dielectric metamaterials based on combination of two different dielectric particles for electric and magnetic dipoles [15–23], and hybrid types with identical dielectric particles under magnetic dipole resonance that are embedded in the negative epsilon background using metallic structures [21–24]. Recently, silicon-based all-dielectric metamaterials have also been developed in optical regions [25–27]. Such dielectric-based metamaterials in the optical regions use dielectric materials with low relative permittivity at most 15. In those cases, the unit cell size becomes considerably large, typically, greater than a quarter wavelength. At low frequencies, in the microwave region, we can obtain materials with dielectric constant higher than several dozens or hundreds, but for the most cases, we suffer from significantly large loss tangent.

In our previous work, 3-D quasi-isotropic composite right/left-handed (CRLH) metamaterials including dielectric cubes with epsilon higher than one hundred and relatively low loss tangent and metallic mesh have been investigated [28,29]. However, due to high dielectric constant of dielectric particles, the composite structure seriously suffers from low wave impedance compared to that in free space. In order to efficiently transmit electromagnetic waves into the composite structures, additional films need to be inserted between air region

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outside and the structures for impedance-matching. Recently, we proposed dielectric-based 3-D left-handed metamaterials impedance-matched to free space and confirmed that backward wave propagation characteristics were observed without serious reflections and scatterings in the measurement [30]. However, it was focused mainly on the experimental demonstration and the detail design procedures for the metamaterials were not discussed there.

In this paper, we consider cube-shaped unit cells including a high-$\varepsilon$ dielectric cube under the magnetic dipole resonance placed at the center and metallic mesh wires wrapping the dielectric cubes for negative permittivity in order to construct 3-D quasi-isotropic left-handed metamaterials impedance-matched to free space. By increasing the value of inductance along the metallic mesh wires, the absolute value of effective permittivity can be reduced while the configuration does not affect the effective permeability. As a result, the wave impedance of the composite structure can be also increased. To enhance the inductance, we first consider composite structures loaded with lumped inductors along the metallic mesh wires. From the numerical simulation results, dispersion diagram and the Bloch impedance of the composite structures are estimated that are converted to effective permittivity and permeability. The lumped inductors are replaced by meander-line strip patterns for practical configurations to achieve the 3-D quasi-isotropic metamaterials impedance-matched to free space.

2 Geometry and numerical simulations

2.1 Composite structures loaded with lumped inductors

First of all, in order to enhance the inductance along the metallic mesh wires, lumped inductors are inserted in the wires. In Figure 1, geometry of the unit cell of 3-D quasi-isotropic metamaterials loaded with lumped inductors is shown. The structure is composed of three parts. First, a dielectric cube with high dielectric constant $\varepsilon_{\text{DR}}$ and the side length $d_{\text{DR}}$ is placed at the center of the unit cell. Second, a host medium with low dielectric constant $\varepsilon_{\text{H}}$ covers the dielectric cube forming the cubic shape with the side length $d_{\text{H}}$. Finally, the host medium is covered with a dielectric coating sheet with low dielectric constant $\varepsilon_{\text{C}}$ and thickness $t_c$ and printed metallic mesh wires loaded with lumped inductors on the inner side of the dielectric sheet. The length of a side of the cubic unit cell is $p = d_{\text{H}} + 2t_c$.

An equivalent circuit model describing the fundamental behavior of wave propagation along the unit cell is shown in Figure 2. The dielectric cube with high dielectric constant behaves as a magnetic dipole under the resonance and magnetically coupled with the magnetic field component of incident electromagnetic waves. The dipole resonance is expressed by a LC loop in terms of $L_{\text{DR}}$ and $C_{\text{DR}}$, and the loop is magnetically coupled with the series inductance $L_R$ through the mutual inductance $M$. The shunt inductance $L_{\text{L}}$ corresponds to the inductance of the metallic mesh wires parallel to the incident electric field. The shunt capacitance $C_{\text{K}}$ is determined by dielectric constants of the dielectric cube, host medium, and dielectric coating sheet, but is inevitably large due to high dielectric constant of the cube. In the equivalent circuit model, the effective permittivity $\varepsilon_{\text{eff}}$ of the whole structure is described by $L_{\text{L}}$ and $C_{\text{K}}$. As a result, the Bloch impedance can be considerably low.

The numerical simulations for wave propagation in the composite structures are performed by using HFSS ver.16 (ANSYS), based on the finite element method. The configuration parameters utilized in the numerical simulation are as follows; dielectric constant and side length of the dielectric cube are $\varepsilon_{\text{DR}} = 110$ and $d_{\text{DR}} = 6.0 \text{ mm}$, respectively. The dielectric constant of the host medium is $\varepsilon_{\text{H}} = 2.2$, and the dielectric coating sheet with dielectric constant $\varepsilon_{\text{C}} = 2.19$ has the thickness $t_c = 0.1 \text{ mm}$. The metallic strip in Figure 1 has the dimensions of $d_{\text{M1}} = 2.2 \text{ mm}$, $d_{\text{M2}} = 3.95 \text{ mm}$, and $w = 0.4 \text{ mm}$. Identical lumped inductors with the inductance $L$ and the dimension of $d_{\text{L1}} = 0.4 \text{ mm}$ and $d_{\text{L2}} = 0.4 \text{ mm}$ are inserted into the metallic strip. The strip thickness is $t = 0.018 \text{ mm}$. In the numerical simulation for eigen-mode solution, material losses have not been taken into account for simplicity.

In Figure 3, dispersion diagram of the designed metamaterial is shown for the lumped inductance $L = 1.5 \text{ nH}$. Periodic boundary condition is imposed on the unit cell in the $x$, $y$, and $z$ directions. The curves for $\Gamma X$, $\Gamma M$, $\Gamma R$ denote dispersion curves for three different propagation directions. The curves related to magnetic dipole resonance in the longitudinal direction have been
excluded due to negligible excitation for TEM wave incidence. As shown in Figure 3, almost 3-D isotropic propagation characteristics, defined in the paper as less than 10% differences of phase constants, are achieved in the vicinity of G point between 4.14 GHz and 4.37 GHz with the relative bandwidth of 5.4%.

In Figure 4, real part of the Bloch impedance $Z_B$ is shown as a function of lumped inductance varying from $L = 1.0$ nH to 2.2 nH. In the numerical simulation set-up, periodic boundary condition was applied to the side walls of the finite-cell structures with a normal incidence of TEM waves. The Bloch-impedance is extracted from the simulated transmission and reflection characteristics and normalized by the wave impedance of free space $Z_0 \approx 120 \pi \Omega$. It is found from Figure 4 that the Bloch impedance becomes higher in the left-handed frequency region as the value of the inserted lumped inductance increases. The impedance-matching to free-space was achieved at $Z_B / Z_0 = 1.0$ around at 4 GHz for $L = 2.2$ nH but with a narrow bandwidth, as shown in Figure 4. On the other hand, from an engineering point of view, when estimating bandwidths for impedance matching, we usually utilize magnitude of reflection coefficients, such as less than $-10$-dB or $-20$-dB. Of course, the criteria differ depending on practical applications. As is well-known, less than $-10$-dB reflection corresponds to $0.5 < Z_B / Z_0 < 2.0$, and less than $-20$-dB reflection corresponds to $0.8 < Z_B / Z_0 < 1.2$. As seen from Figure 4, for less than $-10$-dB reflection, the bandwidth for impedance matching takes the maximum with $L = 1.5$ nH covering the frequency region from 3.88 GHz to 4.42 GHz, whereas for less than $-20$-dB reflection, the bandwidth takes the maximum with $L = 2.0$ nH in the frequency region from 3.89 GHz to 4.18 GHz. Therefore, it is found from Figures 3 and 4 that for $L = 1.5$ nH, the band for less than $-10$-dB reflection successfully covers the whole band for the quasi-isotropy with the bandwidth of 5.4%.

To understand mechanism of the increase in the Bloch-impedance $Z_B$ with the inductance $L$ along the metallic wire, the effective permittivity $\varepsilon_{\text{eff}}$ and permeability $\mu_{\text{eff}}$ for the whole structure are obtained by converting the combination of the dispersion curves and Bloch impedance with the use of the following relation,

$$\varepsilon_{\text{eff}} = \frac{Z_0 \beta c}{\omega Z_B}, \quad \mu_{\text{eff}} = \frac{Z_B \beta c}{\omega Z_0},$$

where $c$ denotes the speed of light in vacuum.

In Figures 5 and 6, real parts of the effective permittivity and permeability are plotted as a function of the lumped inductance $L$. As found from Figure 5, the frequency at zero effective permittivity corresponding to the parallel resonance in shunt branch in Figure 2, decreases as the lumped inductance along the wires increases. The frequency dependences of the permittivity for three different inductances show similarity in the slope, but
with different operational frequencies. These results verify that the enhancement of inductance along the metallic wires directly contributes to the shunt inductance \( L \), as shown in Figure 2.

On the other hand, it is found from Figure 6 that the frequency dependence of effective permeability does not significantly vary with the inductance along the wires in the negative permeability frequency region from 4.0 GHz to 4.5 GHz. This result implies that the enhancement of inductance along the metallic wires does not contribute to the effective permeability under the magnetic dipole-like resonance of dielectric particles. Figure 6 also shows magnetic dipole resonance of dielectric cubes around at 3.95 GHz, as seen from the existence of singular points in the frequency dependence of the effective permeability.

Thus, it is confirmed that we can independently control the effective permittivity without changing effective permeability and enhance the Bloch-impedance, by increasing the inductance along the metallic mesh wires to achieve the impedance matching to free space.

### 2.2 Composite structure loaded with printed meander-line patterns

For practical configuration, the inductance along the mesh wires needs to be enhanced by designing distributed inductance in the metallic mesh patterns. The geometry of the unit cell for the 3-D quasi-isotropic metamaterial loaded with the distributed inductance along the metallic mesh wires is illustrated in Figure 7. The lumped inductors discussed in the previous section have been replaced by meander-line patterns printed in the metallic mesh. The effective value of \( L \) can be controlled by extending the length of metallic strips. In addition, the value of \( L \) can increase by magnetic coupling between the meander lines.

The configuration parameters utilized in the numerical simulation are the same as in Section 2.1, except for the dimensions of metallic mesh wires. The dimensions of meander metallic strip are \( d_{M1} = 1.8 \text{ mm} \), \( d_{M2} = 3.95 \text{ mm} \), \( g = 0.2 \text{ mm} \), and \( w = 0.4 \text{ mm} \).

In Figure 8, dispersion diagram is shown for the length of meander lines \( d = 1.5 \text{ mm} \). As seen from the dispersion curves, almost isotropic propagation characteristics are achieved in the left-handed frequency region between 4.17 GHz and 4.47 GHz with the bandwidth of 6.9 %.

In Figure 9, real part of the normalized Bloch impedance is plotted for the structure with printed meander-line patterns as a function of the length of meander line. It is found from Figure 9 that the Bloch impedance increases as the length of the meander lines is extended. As seen from Figure 9, for less than \(-10 \text{ dB} \) reflection, the bandwidth for impedance matching takes the maximum with \( d = 1.5 \text{ mm} \) in the frequency region from 3.95 GHz to 4.47 GHz, whereas for less than \(-20 \text{ dB} \) reflection, the bandwidth takes the maximum with \( d = 1.8 \text{ mm} \) in the frequency region from 3.96 GHz to 4.22 GHz. Therefore, it is found from Figures 8 and 9 that for \( d = 1.5 \text{ mm} \), the band for less than \(-10 \text{ dB} \) reflection covers the whole band for the quasi-isotropy with the bandwidth of 6.9 %. Therefore, the meander-line type could achieve the bandwidths greater than that for lumped inductor type.

The real parts of the effective permittivity and permeability are shown in Figures 10 and 11, respectively. As shown in Figure 10, when extending the length of the meander lines, the frequency at zero effective permittivity goes to lower frequencies. It is found from Figure 11 that the increase in the length of meander lines does not
significantly affect the frequency dependence of effective permeability but with the small shift of the singular points to the lower frequencies. This is due to shielding effect of meander-lines on the magnetic coupling between dielectric particles. Eventually, the frequency dependence of effective permittivity and permeability for insertion of meander-lines in Figures 10 and 11 are similar to the cases with the insertion of lumped inductances along the mesh wires in Figures 5 and 6.

Thus, it is confirmed that we can independently control effective permittivity without significant change in the permeability by adjusting appropriate length of meander lines along the mesh wires to achieve impedance-matching with free space.

Next, we will show the influence of material losses on the transmission characteristics in the proposed metamaterial. Based on the experimental set-up in the previous work [29,30], we have assumed that metallic strip is made of copper, and loss tangent of the dielectric cube, host medium and dielectric coating sheet are 0.002, 0.0009 and 0.0007, respectively. Figure 12 shows the extracted real and imaginary parts of the effective permittivity and permeability for the proposed structure with the meander-line patterns for $d = 1.5$ mm. It is found from Figure 12 that both imaginary parts of permittivity and permeability become large at the magnetic dipole resonance of dielectric cube at 3.95 GHz. Figure 13 shows classification of propagation losses per unit cell due to each material loss.

As seen from Figure 13, the loss of dielectric cube is dominant at 3.95 GHz in the vicinity of the magnetic dipole resonance, whereas the conductor loss in the metallic mesh becomes dominant at higher frequencies. It is desirable to select the operation frequency as far as possible away from the magnetic dipole like resonance. From Figure 13, the total material loss can be estimated to be about 0.3–0.5 dB per unit cell in the frequency range of interest. Thus, material losses do not seriously do harm to transmission characteristics of the proposed structures.

3 Conclusion

In this paper, we treated cube-shaped unit cells including high-ε dielectric cubes under the magnetic dipole-like resonance placed at the center and metallic mesh wires covering dielectric cube for negative permittivity in order to construct 3-D quasi-isotropic metamaterials in the microwave region. To reduce effective permittivity of the composite structures, we proposed to insert additional inductance into the metallic mesh. For the insertion of lumped inductors along the wires, dispersion diagram and the Bloch impedance were numerically estimated and converted to effective permittivity and permeability. The numerical simulation results clearly showed almost isotropic propagation characteristics in the specific frequency region.
and enhancement of the Bloch-impedance close to free space in the left-handed region. The lumped inductances were replaced by meander-like strip patterns for practical configurations. The metallic patterned structures also achieved the enhanced Bloch impedance that was well-matched to free space. In order to further enhance the bandwidths for quasi-isotropy and impedance matching, it is necessary to more precisely design the metamaterial unit cells by taking into account gradients of frequency dispersions of the effective permittivity and permeability.

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