High figure of merit cylinder-shaped negative refractive index metamaterial based on paper as dielectric material

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Abstract
The design of unit cell metamaterial can tailor the permittivity and permeability. The negative refractive index was achieved while the negative real part of permittivity and negative real part of permeability simultaneously or \( \varepsilon_r \mu_r + \varepsilon_i \mu_i < 0 \) conditions were satisfied, where \( \varepsilon_r \), \( \varepsilon_i \), \( \mu_r \), and \( \mu_i \) are real part of permittivity, imaginary part of permittivity, real part of permeability, and imaginary part of permeability, respectively. Currently, the metamaterial based on paper is a fascinating issue. Additional, paper is used as dielectric due to its eco-friendly spacer. The unit cell design is the critical rule for achieving high figure of merit (FoM) of negative refractive index. This work aims to design the high FoM cylinder-shaped negative refractive index metamaterial based on paper as the dielectric material. The cylinder-shaped structure was simulated by CST microwave studio. The electromagnetic properties of the cylinder-shaped structure were estimated from the scattering parameter (S-parameter) result. The cylinder-shaped structure yields high FoM of negative refractive index performance. The negative refractive index was generated at 3.4–3.91 GHz. The above condition or negative real permittivity and negative real permeability simultaneously were satisfied at 3.4–3.91 GHz. The high FoM was achieved at 3.5–3.91 GHz.

1 | INTRODUCTION

The metamaterial is an artificial material that can tailor electromagnetic wave propagation on it. The electromagnetic properties of the metamaterial can be controlled by the structured unit cell. Many researchers have paid attention to study deeply about the unit cell of the metamaterial due to its unique characteristics. The tiny periodic metal structure as a unit cell was constructed on the dielectric material. The tiny periodic metal structure’s size has to be smaller than the wavelength of electromagnetic waves [1, 2]. The spectrum frequency of metamaterial performance can be adjusted by controlling the tiny periodic structure size. Adjusting the frequency performance is one of the uniqueness of metamaterial. Metamaterial yields several applications such as negative refractive index [3–5], high absorbance [6], energy harvesting [7–9], an invisible cloak [10, 11], and sensors [12–14].

The negative refractive index is one of the fascinating issues in metamaterial field. It can be implemented for perfect lenses. Veselago [15] proposed the theory of negative refractive index metamaterial in 1968. His concept is to generate simultaneously negative real permittivity (\( \varepsilon \)) and real permeability (\( \mu \)). The idea of negative refractive index metamaterial was first experimentally demonstrated in 2001 by Shelby et al. [16]. The basic idea of the negative refractive index metamaterial condition is the tailoring of unit cells to produce the negative real part of permittivity and negative real part of permeability simultaneously. However, Tung et al. [17] presented another basic mechanism for achieving negative refractive index metamaterial condition. They proposed that the condition is Equation (1) as below

\[
\varepsilon_r \mu_r + \varepsilon_i \mu_i < 0
\]

where \( \varepsilon_r \), \( \varepsilon_i \), \( \mu_r \), and \( \mu_i \) are real part of permittivity, imaginary part of permittivity, real part of permeability and imaginary part of permeability, respectively. They compared simulation and measured results. Boardman et al. [18] theoretically studied the negative refractive index mechanism. They agreed with Equation (1) condition that yield the negative refractive index performance. In previous studies [17, 18], the authors...
presented low figure of merit (FoM) of negative refractive index material.

Paper is a fascinating material due to inexpensive and environment-friendly nature [6]. A study of metamaterial-based on paper has been carried out in [6, 19]. Yudistira et al. [6] presented high absorbance metamaterial on paper as a spacer. They simulated the numerical and analytical performance of symmetrical split ring resonator (SRR) metamaterials. The symmetric SRR structure on paper yields high absorbance performance. Tao et al. [19] investigated paper-based metamaterial for biochemical detection. The metamaterial-based on paper presented an excellent performance for biochemical detection.

The negative refractive index metamaterials on paper is rare to observe. We consider to design negative refractive index metamaterials on paper and analyze its electromagnetic properties. In this work, we simulated numerically the high FoM cylinder-shaped negative refractive index metamaterials on paper as a dielectric material. Paper was used as dielectric material due to eco-friendly spacer. The high FoM defines that the electromagnetic wave can propagate through the metamaterial. The important rule for high FoM is the unit cell design. In this work, we presented the cylinder-shaped structure as a unit cell structure. The cylinder-shaped structure yields high FoM of negative refractive index performance. There is a fascinating issue to study the possibility of negative refractive index metamaterials based on paper. The electromagnetic properties such as impedance, refractive index, permittivity, and permeability were extracted from the scattering parameter (S-parameter) result.

2.1 SIMULATION METHOD AND DESIGN OF METAMATERIAL

Figure 1 presents the design of the cylinder-shaped negative refractive index metamaterial based on paper. The radius of cylinder \( r \), the gap of unit cell \( d \), conductor material thickness \( z_m \), and paper thickness \( z_d \) are 30 mm, 20 mm, 0.1 mm, and 0.1 mm, respectively. The numerical simulation work was done by using the software CST microwave studio, a commercial software, to solve the electromagnetic wave problem. CST microwave studio would solve the Maxwell equation by using the finite integration technique (FIT). The copper material is selected as conductor material on the CST microwave studio. The conductivity of copper material is \( 5.8 \times 10^7 \, \text{S/m} \). The permittivity and permeability of paper are 2.31 and 1, respectively. The unit cell condition is applied at the boundary of \( x \)- and \( y \)-direction. The open condition (add space condition) is applied at the boundary of the \( z \)-direction. We applied the tetrahedral mesh type on this numerical simulation. Finally, we run the numerical simulation by using a frequency-domain solver on CST microwave studio. The S-parameter was derived from the numerical simulation process by using CST microwave studio.

The numerical simulation result was presented as S-parameter result. The transmission \( S_{12} \) parameter and the reflection \( S_{11} \) parameter results are presented in Figure 2. There is a relationship between S-parameter with refractive
RESULT AND DISCUSSION

The numerical simulation results of cylinder-shaped metamaterials based on paper are presented in Figures 2a and b. The transmission and reflection are presented as a color line in Figure 2a, respectively. The magnitude of transmission or reflection and the phase of transmission or reflection are presented in Figures 2a and b, respectively. The lowest reflection and the highest transmission were performed at 3.9 GHz. The impedance and refractive index were estimated from the transmission and reflection result. Figures 3a and b show the impedance and the refractive index result, respectively. The real impedance and imaginary refractive index of cylinder-shaped metamaterial on paper have positive value at 3.4–4.6 GHz. It indicated that cylinder-shaped metamaterial on paper satisfied requirement as a passive medium. The real part of the refractive index has a jump around 3.9 GHz, which was reported as resonance frequency performance.

The lowest reflection would be presented when $R_1$ (in Equation 2) is close to zero ($R_1 = 0$). The impedance value of metamaterial should match air impedance (1+i0) to achieve $R_1 = 0$. The impedance value of cylinder-shaped metamaterial on paper at 3.9 GHz is 0.95+i0.01. It is close to the air impedance; therefore, the reflection result at 3.9 GHz presented the lowest result.

The transmission result would be low if $l[\alpha k_d/l] = (1/2S_{12}) (1 - S_{12}^2 + S_{12}^2)$ in Equation (3) is low or close to zero. The high imaginary refractive index is one of the conditions to achieve low $\varepsilon[\alpha k_d/l]$. The transmission result is low at around 3.4–3.52 GHz. The imaginary refractive index is relatively high at 3.4–3.52 GHz. The imaginary refractive index result showed close to zero along 3.52–4.6 GHz; thus, the transmission result yields more than 40% or 0.4 at this spectrum. The estimation of impedance and refractive index showed good agreement with S-parameter result through the model in Equations (2) and (3).

The impressive refractive index result (Figure 2d) is at 3.4–3.91 GHz spectrum (grey color area). The negative refractive index is presented on this spectrum. There are two basic mechanisms to explain the negative refractive index metamaterial:

\[
\varepsilon = \frac{\mu}{\varepsilon_n} \quad \text{and} \quad \mu = n\varepsilon,
\]

where $\mu = n\varepsilon = \mu_1 + \mu_2$ includes permittivity and permeability, and $\varepsilon = \varepsilon_1 = \varepsilon_2$ is sample thickness ($l = k_0 l = \varepsilon_0 + \mu_0$) or the total of conductor material thickness and paper thickness. The real part of the refractive index has a low or close to zero. The high imaginary refractive index is relatively high at 3.4–3.52 GHz. The imaginary refractive index is relatively high at 3.4–4.6 GHz. It indicated that cylinder-shaped metamaterial on paper satisfied requirement as

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3 | RESULT AND DISCUSSION

index ($n$) and impedance by [20]

\[
S_{11} = \frac{R_1 (1 - e^{j2\alpha k_d/l})}{1 - (R_1)^2 e^{j2\alpha k_d/l}}, \quad (2)
\]

\[
S_{12} = \frac{(1 - (R_1)^2)^{-1} + S_{12}}{1 - S_{12}}, \quad (3)
\]

where $R_1 = (\varepsilon - 1)/(\varepsilon + 1)$, $k_0$ is wave number in free space, and $l$ is sample thickness ($l = k_0 l = \varepsilon_0 + \mu_0$) or the total of conductor material thickness and paper thickness. The impedance ($\varepsilon$) and refractive index ($\mu$) can be estimated by inverting Equations (2) and (3) as $[1, 2, 20, 21]$

\[
\varepsilon = \pm \sqrt{(1 + S_{11})^2 - S_{12}^2} \quad (4)
\]

\[
\varepsilon[\alpha k_d/l] = X \pm \sqrt{1 - X^2} \quad (5)
\]

where $X = (1/2S_{12}) (1 - S_{12}^2 + S_{12}^2)$.

The cylinder-shaped metamaterial was modeled as a passive medium; thus, the real impedance ($\varepsilon$) and the imaginary refractive index ($\mu$) have to be a positive value. The sign on Equations (4) and (5) should be calculated based on the requirement as a passive medium ($\varepsilon \geq 0$ and $\mu \geq 0$) [1, 2, 20, 21]. The perturbation of S-parameter may alter the sign of real impedance and imaginary refractive index. Therefore, the estimation of the refractive index may be derived from another model that is not required to specify the sign in the equation. The refractive index ($\mu$) can be derived from Equations (2) and (3) that was dependant on S-parameter and impedance from Equation (4) [20]:

\[
\varepsilon[\alpha k_d/l] = \frac{S_{12}}{1 - S_{11} R_1} \quad (6)
\]

Equation (4) can obtain the value of the refractive index and can avoid the sign ambiguity in Equation (5). The permittivity and permeability can be calculated by $\varepsilon = \frac{\mu}{\varepsilon_n}$ and $\mu = n\varepsilon$. The impressive refractive index result (Figure 2d) is at 3.4–3.91 GHz spectrum (grey color area). The negative refractive index is presented on this spectrum. There are two basic mechanisms to explain the negative refractive index metamaterial:

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negative real part of permittivity and negative real part of permeability simultaneously or fulfill Equation (1) condition. The permittivity and permeability were estimated from impedance and refractive index results. Figures 4a and b present the permittivity and permeability of cylinder-shaped metamaterial based on paper. The negative real part of permittivity and negative real part of permeability are presented simultaneously at 3.5–3.91 GHz. The electrical and magnetic responses come from the cumulative charge on the gap of the unit cell and current on the surface of the unit cell, respectively. Figures 5a and b present the magnitude electric field distribution and the surface current on the cylinder-shaped metamaterial at 3.8 GHz. The high electric field on the gap (Figure 5a) described high cumulative charge on the gap. The loop surface current on cylinder-shaped metamaterial (Figure 5b) would yield the magnetic response.

A major question arises for the negative refractive index at 3.4–3.5 GHz. There is positive real permittivity at 3.4–3.5 GHz; however, there is a negative result on this spectrum. How does the existing negative refractive index at 3.4–3.5 GHz without the negative real part of permittivity and negative real part of permeability simultaneously exist? This phenomena could be explained well by the basic mechanism of negative refractive index from Tung et al. [17]. The satisfying Equation (1) condition could yield the negative refractive index. Figure 6a presents the calculation of $\varepsilon_r \mu_r + \varepsilon_i \mu_i$. The calculation of $\varepsilon_r \mu_r + \varepsilon_i \mu_i$ yields negative value at 3.4–3.5 GHz; thus, this spectrum could generate a negative refractive index even when the real permittivity value is not negative. Overall, Equation (1) condition or negative real permittivity and negative real permeability simultaneously were satisfied at 3.4–3.91 GHz.

The absolute FoM was calculated in Figure 6b. The FoM is the comparison of the real refractive index and imaginary refractive index (FoM = $n_r / n_i$). The FoM describes the ability of electromagnetic wave propagation through the metamaterial. The higher value of FoM defines that the electromagnetic wave can propagate through the metamaterial. On the other hand, the lower value of FoM describes that the electromagnetic wave was attenuated while it propagates the material. The FoM at 3.4–3.5 GHz is low. At this spectrum, the electromagnetic wave has high attenuation; thus, it could not propagate through the metamaterial. The FoM from Figure 6b is much higher than the results of previous studies [17, 18].
FIGURE 6  (a) The calculation of $\varepsilon r\mu i + \varepsilon i\mu r$ and (b) figure of merit refractive index magnitude of cylinder-shaped metamaterial based on paper

4 I SUMMARY

In summary, we simulated successfully the high FoM cylinder-shaped negative refractive index metamaterial based on paper as dielectric material. The negative refractive index was achieved at 3.4–3.91 GHz. Equation (1) condition or negative real permittivity and negative real permeability simultaneously were satisfied at 3.4–3.91 GHz. The FoM at 3.4–3.5 GHz is around 0.01. The high FoM was achieved up to $10^5$ (maximum) at 3.5–3.91 GHz. Overall, the high FoM of cylinder-shaped negative refractive index metamaterial on paper was yielded at 3.5–3.91 GHz.

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