Realization of broadband polarization-insensitive negative refraction using water-based metamaterial

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1. Introduction

In 1968, a concept of negative refractive index, not existed in natural materials, was theoretically proposed by Veselago, he predicted that a material with negative permittivity and the permeability simultaneously will produce a left-handed medium in which light travels at opposite phase and energy velocities [1]. More than thirty years later, researchers realized the negative refraction experimentally using metamaterials (MMs) whose equivalent electromagnetic (EM) parameter (\(\varepsilon\), \(\mu\)) can be tailored at will through their geometries [2, 3]. From then on, MMs have become of enormous interests since new physics and exotic EM phenomena are illustrated which are not existed in natural materials including negative refraction [4–8]. Negative refraction responses have typically been implemented using planar or tridimensional metal-dielectric isotropic MMs with periodic unit cells providing electric and/or magnetic resonances ranging from microwave to optical frequencies [9–13], and even ultraviolet [14]. All kinds of metal-dielectric MMs were successfully used to fabricate the MMs with negative refractive index [15–18]. Besides the ohmic loss, however, the two impediments of the metal-dielectric MMs with negative refraction are narrow bands from the electric and/or magnetic resonances and polarization-sensitivity from the isotropic geometry. Recently, non-metal MMs offer a possible solution to reduce the ohmic loss, which can support an electric and magnetic dipole response due to Mie resonances [19–21]. Specifically, the great advantages of all-dielectric MMs have been manifested because of the high ohmic loss of the metal-dielectric MMs in optical frequency [19, 22–25], while performances of bandwidth and polarization-sensitivity are still not further improved to some extent. It is known that water has been used as a metal substitute for MMs in the microwave frequency due to the superior properties of the abundant reserves and pollution-free
environment [26–33], what’s more, countless structural pipes with injectable water can be designed and easily fabricated using 3D printing techniques.

The purpose of this paper is to realize a broadband and polarization insensitive MM with negative refractive index using water-based MM. Therefore, we present the design, numerical simulation, and measurement of water-based MM whose effective permittivity and permeability are negative at the same time in a broadband region. Different from the single electric and/or magnetic resonances excited by the metal-dielectric MMs, the proposed MMs exhibits the multiple resonances and exhibits two separated wide bandwidths of 12.5–22.7 GHz, and 26.2–28.0 GHz with negative refractive index. The designed MM has the same response to both transverse electric (TE) and transverse magnetic (TM) waves because the structure is symmetric along the x- and y-axis. Both numerical calculations of beam shifting and microwave measurement are carried out to evaluate our design, and the results are consistent with each other. The proposed design using water-based all-dielectric MM open an additional way to achieve the negative refractive index using all-dielectric materials. It has promising applications in the fields of electromagnetic stealth, information storage, and mobile communication.

2. Design and simulation method

Figure 1 illustrates the structure of our design using water-based all-dielectric MM. The perspective view of the designed structure is demonstrated in figure 1(a), the UV-light photosensitive resin (UV-PSR) is perforated by cross shaped channel, and the water is poured into this cross shaped channel, which is shown in figure 1(b). The overall structure of the designed MM is shown in figure 1(c), we can see the designed MM is enclosed in UV-PR all around, and the water can be conveniently injected and removed through the reserved inlet and outlet. The permittivity of UV-PR is 3.35 and the tangent loss is 0.001. The thickness of the MM along z axis is $T = t_1 + t_2 + t_3 = 5.6$ mm. Numerical simulations are carried out using the CST Microwave Studio by applying the frequency domain solver. The directions of x- and y-axis are set as unit cell boundary conditions, and the open (add space) boundary is applied in the z direction. Because of the symmetric design along x- and y-axis, the proposed MM is polarization insensitive to the TE and TM waves. The permittivity of water is obtained from Debye equation [34], and the calculated results of permittivity and refractive index for water with the temperature of 20 °C are shown in figure 2.
3. Results and discussion

Figure 3 shows the simulation magnitude of reflectance and transmittance of the designed MM. From figure 3, we can see that several resonances at different frequencies are excited when EM waves pass through the designed MM, which are listed in table 1. Because of the different thickness of the front and bottom layer, the reflections from different incident ports along -z, and z axis (S11 and S22) are slightly different. The reflection along z axis (S11) has six resonant points, and the reflection along -z axis (S22) has five resonant points, shown in table 1. The transmittions along -z, and z axis (S12 and S21) are the same trends and have four resonant points. It is known that the properties of the resonances are supported by the magnetic and electric fields (H-field and E-field), and electric dipole and magnetic dipole are two basic resonance models. The magnetic dipole mode is usually expressed as circulating electric displacement current which excites a magnetic dipole moment across to the current loop. The electric dipolar resonance excitation requires the mass polarization of the E-field component of the incident wave in the resonators [35, 36].

Figure 4 shows the E-field and H-field intensities at the resonant frequencies of transmission (the resonances of the reflection are not shown). To identify the magnetic dipole and electric dipole modes, the H-field intensity in y-z plane and the E-field intensity in x-z plane are plotted in figure 4. The lines inside the fields represent the E-

![Figure 2](image1.png)  
(a) ε_water and (b) n_water at 20 °C.

![Figure 3](image2.png)  
Simulated results. (a) reflectance, (b) transmittance.

|       | f₁  | f₂  | f₃  | f₄  | f₅  | f₆  |
|-------|-----|-----|-----|-----|-----|-----|
| S₁₁   | 7.8 | 17.4| 20.2| 22.5| 25  | 27.7|
| S₂₂   | 7.8 | 16.3| 20.5| 23  | 27  | —   |
| S₁₂ (S₂₁) | 5.5 | 15.5| 22  | 28.7| —   | —   |

Table 1. Resonant frequencies of S₁₁, S₂₂, and S₁₂ (S₂₁). (Unit: GHz).
or H-field lines for recognizing the current loops. From figures 4(a) and (b), one can see that the current loop formed by the H-field induces the electric dipole of the electric dipole mode at the frequency of 5.5 GHz. It is clearly shown in figures 4(c) and (d) that two current loops with enhanced H-fields at the center of the loops at 15.5 GHz. In addition, the E-field lines have two centers, which are located at the junction of water and UV-PR with the E-field maxima. It means a coupled magnetic mode is excited and the H-fields are distributed on the two sides of water. Accordingly, we can conclude that the electric dipole and magnetic dipole mode are excited at the frequencies of 22 and 28.7 GHz, which are shown in figures 4(e)–(h), respectively. From the electric and H-field lines, we can see multiple electric dipole and magnetic dipole are excited at the higher frequencies. We can explain the physical natures of reflection resonances in the same way.

In the following section, we calculate the effective EM parameters from the simulated reflectance and transmittance using the formula in references [37–41]. Figure 5(a) shows the real and image magnitudes of the effective permittivity ($\varepsilon_{\text{eff}}$) against the frequency, it can be seen clearly that the real part of effective permittivity curve has three negative regions of $<7.6 \text{ GHz}$, 12.5–22.7 GHz, 26.2–28.0 GHz, which covers almost C-band, Ku-band, 4.5 GHz bandwidth from K-band, and a nearly 2 GHz bandwidth from Ka-band. Similarly, the real and image magnitudes of permeability ($\mu_{\text{eff}}$) are shown in figure 5(b), which displays a negative region of 12.5–30 GHz that totally covers bandwidth of Ku- and K-bands. Figure 5(c) illustrates the real and image magnitudes of the refractive index ($n_{\text{eff}}$), from figure 5(c), it is apparent that the real part of the refractive index

![Figure 4. The E-field intensities in x-z plane and H-field intensities in y-z plane at the resonances. (a), (b) 5.5 GHz, (c), (d) 15.5 GHz, (e), (f) 22 GHz, (g), (h) 28.7 GHz. The lines inside the fields represent the E- or H-field lines for recognizing the current loops.](image-url)
exhibits the negative magnitude from 12.5 GHz to 30 GHz. Herein, we need to clarify that the refractive index of the material is negative when its permittivity and permeability are negative simultaneously. Therefore, it is notable that two wide bandwidths of negative refractive index are formed at 12.5–22.7 GHz, and 26.2–28.0 GHz, respectively.

The simulation platform of beam shifting depicted in figure 6 is established to further investigate our retrieved effective negative refractive index, which can monitor the shift of incident beam. The simulation setup can be regarded as two combined prisms; thus, the refraction occurs twice at the interfaces of the air and MM. The shift $d$ of the refractive beam can be calculated by the formula [37, 38]:

$$d = w \cdot \sin \theta_1 \cdot \cos \theta_1 \left[ 1 - \frac{\cos \theta_1}{n_2 \sqrt{1 - \left( \frac{\sin \theta_1}{n_2} \right)^2}} \right]$$  \hspace{1cm} (1)

where $\theta_1$ and $n_2$ represent the incident angle and the refraction index of the MM, respectively. The maximum shift of the refractive beam for a non-negative refractive index material is

$$d_{\text{max}} = w \cdot \sin \theta_1 \cdot \cos \theta_1$$  \hspace{1cm} (2)

In the simulation, six layers of the designed structure with the thickness of $T = 33.6$ mm are stacked along the z-axis, and the incident angle of $\theta_1$ is set to be $15^\circ$, as shown in figure 4. The width of MM along z-axis is $w = T / \cos \theta_1$. Therefore, the maximum shift of $d_{\text{max}}$ is about 8.70 mm calculated from formula (2) when the incident angle is $15^\circ$. We monitor the transmittances with different positions along x-axis at three frequencies of 13.5, 15.5, and 16.5 GHz. The corresponding effective refractive indices and the shift of refractive beam at these three frequencies are shown in table 2. At these three frequencies, the effective refractive indices are $-1.836$, $-1.836$, and $-1.836$, respectively.

**Figure 5.** Retrieved effective EM parameters. (a) $\varepsilon_{\text{eff}}$, (b) $\mu_{\text{eff}}$, (c) $n_{\text{eff}}$.

**Figure 6.** Schematic diagram of simulation platform for monitoring the beam shifting.
−1.448, and −1.70, and the corresponding shifts of the refractive beam at these three frequencies are 13.317, 14.429, and 13 mm obtained from formula (1) at θ₁ = 15°, respectively.

We monitor the normalize magnitudes (NM) of the transmittance at the three frequencies of 13.5, 15.5, and 16.5 GHz at positions from 10 to 18 mm along -x axis. Firstly, we fix the input port of Port 1 at the center of the MM, and we move the output port of Port 2 from 10 to 18 mm by the step of 1 mm along -x axis, which is shown in figure 6. The normalize magnitudes of the transmittance at these three frequencies of 13.5, 15.5, and 16.5 GHz are sketched in figure 7. We can clearly see that the maximum of the NM of the transmittance appears when x = −13 mm at the frequency of 13.5 GHz, which is coincide with the calculated result of d = 13.32 mm from formula (2) shown in table 2. In addition, the maximum shift of x = −15 mm at the frequencies of 15.5 and 16.0 GHz are also agreed well with the calculated results of −14.43 and −15.03 mm from formula (1) shown in table 2. Therefore, we can firmly conclude that the negative refractive index is achieved from our designed MM.

4. Experimental verification

The microwave experiments using free space method are carried out to test our simulations. The sample with the same geometry in the simulations is fabricated by using 3D printing technology, and the dimension of the sample is 250 × 250 mm², which is shown in figure 1(d). We firstly measure the temperature of the water using a thermometer and keep the temperature of the water at about 20 °C; after that, the water is injected from the inlet and the outlet is closed. Due to the limitations of our existing experimental conditions, we can only carry out the experimental tests below 18 GHz in our chamber. Therefore, we just test the reflectance and transmittance at 5–18 GHz. In measuring the reflectance (S11, S22), two identical horn antennas connected to the vector network analyzer (Agilent E8362B) are placed on the same side of the sample. Before the measurement, the reflectance was normalized by a metal plate with the same geometrical size as the sample. After that, the corresponding reflectance can be obtained by replacing the metal plate with the fabricated sample. In measuring the transmittance (S12, S21), a metal plate of 1.5*1.5 m² is placed in the middle, and the center of which was hollowed with the same size of the fabricated sample. Two horn antennas are placed on both sides of the metal plate; and the fabricated sample is embedded in the center of the metal plate. The sample was firstly removed for normalization of the transmittance. After that, the transmittance can be obtained by embedding the sample in the center. The tested results are shown in figure 8, we plot the simulated reflectance and transmittance again in figure 8 for better comparison. Obviously, it can be seen that the simulated and tested results are consistent in a comparable range of 5–18 GHz. Therefore, we can confidently speculate that the simulated and tested results

| Table 2. Effective refractive index and shift. |
|---------------------------------------------|
| Frequency (GHZ) | f₁ = 13.5 | f₂ = 15.5 | f₃ = 16.0 |
| nₑff          | −1.836   | −1.488   | −1.17     |
| d (mm)        | −13.32   | −14.43   | −15.03    |

Figure 7. Normalized Magnitude of the transmittance versus the distance along -x axis.
should be consistent in the absence of testing range. Herein, we also can observe that the measured reflection spectra is slight different with the simulated results. Except for some intrinsic discrepancies of loss of the substrate and the fabrication tolerance in the simulation and experiment. The differences of the reflection spectra between simulation and experiment are mainly caused by the following reasons. Firstly, the unit-cell boundary is applied in the simulation, therefore the physical size of the proposed MM is infinite, while the size of the sample in the experiment is limited, which will lead to edge diffraction. Secondly, the incident angle for the measurement is nearly 5°, so the angle between the incident antenna and the reflected antenna is about 10°, but the vertical incident wave is used in the simulations. We cannot ignore this reason leading to the discrepancies between the simulated and measured spectra. Although these differences, the simulated and tested results are basically consistent in the whole frequency range.

5. Conclusion

In conclusion, we have demonstrated a water-based all-dielectric polarization insensitive MM with broadband negative refractive index at 12.5–22.7 GHz, and 26.2–28.0 GHz, respectively. The simulated and measured results show that our designed MM exhibits two excellent properties of broadband bandwidth and polarization-insensitivity due to the excellent structural design. The design using water-based all-dielectric MM offers an optional chance to achieve the negative refractive index based on all-dielectric materials.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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