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A new direct retrieval method of refractive index for the metamaterial

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With the advent of metamaterial the approaches of automated extraction of effective parameters for a metamaterial have recently attracted considerable attention among researchers. Evaluation of refractive index has received huge importance especially for the left-handed metamaterial. This communication presents a new simplified equation for the direct retrieval of refractive index from the transmission and reflection co-efficient. Refractive index is calculated from the new equation for two recently published metamaterials. The resultant curve for the proposed method shows good conformity with the classical NRW-method and shows a result closer to that achieved using the TR-method. In addition, a comparative study of the three methods is presented.

Keywords: Metamaterials, Nicolson–Rose–Weir method, transmission–reflection method.

METAMATERIAL is an artificially engineered material which exhibit some extraordinary electromagnetic properties; it does not exist naturally. These extraordinary electromagnetic properties of the metamaterials have extended their demand in many important applications like antenna design, electromagnetic cloaking, electromagnetic absorption reduction, etc.[1–3]. A metamaterial may be either single-negative (SNG) or double-negative (DNG). A DNG or left-handed (LHM) or negative refractive index metamaterial is one that is characterized by its effective parameters, i.e. permeability and permittivity. For the left-handed material or negative-refractive index metamaterial the effective parameters have to be negative simultaneously, which never happens naturally. Parameter extraction is one of the important tasks for characterizing the metamaterial. Due to the growing interest on metamaterial research, the effective parameter extractions as well as direct calculation technique of refractive index have received much attention by the researchers.

Different methods for effective parameter extraction of metamaterials are available[4–14]. Among them, a class exist based on the transmission and reflection parameters, like TR (transmission–reflection) method, direct-retrieval method, Nicolson–Ross–Weir (NRW) method, etc.

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However, very few of them focus on the direct retrieval of refractive index from reflection and transmission parameters (i.e. *S*-parameters), although it is one of the important issues for claiming a metamaterial as DNG or LHM. The reflection and transmission parameters are important, especially for microwave and optical engineering. These parameters refer to the effect on travelling currents and voltages in a transmission line when they meet any impedance caused by the insertion of a network into the transmission line. In most of the electromagnetic experimental analysis, it is easy to measure directly the reflection and transmission parameters rather than other parameters. Moreover, most of the commercially available simulation software that use finite-difference time domain (FDTD) method, finite element method (FEM) or method of moment (MOM) can calculate the reflection and transmission coefficient directly. Hence direct calculation of refractive index from reflection and transmission parameters is highly intended. The TR method is one of the promising methods used for the direct retrieval of refractive index for a planar material sample from the reflection and transmission parameters. The direct retrieval of refractive index using the TR method involves determination of correct branch index, which entails a lengthy process[15]. The NRW method is popular for its simplicity[4]. The retrieval of refractive index from the NRW method depends on the extraction of effective permittivity and permeability, and not on the reflection and transmission parameter. This method does not involve any such determination of cosine branch index or any other complexity. It is a promising method for its simplicity. However, Choi *et al.*[16] have recently proposed an extraction method of refractive index applicable for their proposed metamaterial design for THz application. Li-Ming *et al.*[17] have proposed an extraction method of refractive index, but it still includes the cosine branch index. Kim and Baker-Jarvis[18] presented an equation of refractive index, which is applicable for guided waves and dependent on the waveguide length. However, a simple method to determine the refractive index directly from the reflection and transmission parameters is still in demand.

We report here a simplified equation for the direct retrieval of refractive index from the transmission and reflection coefficient. For validation of the proposed equation, the *S*-parameters are first calculated for the two recently published samples mentioned in the literature[19,20], using the commercially available computer simulation technology (CST) software and then they are used to evaluate the refractive index for the above three methods – the TR method, the NRW method and the proposed method. As a reference structure, a double-negative metamaterial is considered. The calculated refractive index from the new equation shows good conformity with the classical NRW method and also shows similar result of TR-method. Moreover, a comparative study is done among the methods.

The NRW method is a popular method of metamaterial effective medium parameter extraction. The equation used for the extraction of effective medium parameter according to the NRW method is given below.

$$V_1 = S_{21} + S_{11}, \tag{1}$$

$$V_2 = S_{21} - S_{11}, \tag{2}$$

$$\mu_r \approx \frac{2}{jk_0 d}\frac{1-V_2}{1+V_2}, \tag{3}$$

$$\varepsilon_r \approx \frac{2}{jk_0 d}\frac{1-V_1}{1+V_1}, \tag{4}$$

$$\eta = \sqrt{\varepsilon_r \mu_r}, \tag{5}$$

where ε_r is the effective permittivity, μ_r the effective permeability, d the thickness of the substrate, k_0 the wave number and η is the refractive index. Although the NRW-method is good for the calculation of effective permittivity and permeability using *S*-parameter, calculation of refractive index is still dependent on calculation of permittivity and permeability. However, this technique does not include any branch index complexity or impedance calculation.

The TR method is popular for direct refractive index calculation for metamaterial samples. The simplified equations that are used in the TR method are given below.

$$\eta = \frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}(1 - S_{11}^2 + S_{21}^2)\right] \pm \frac{2m\pi}{kd}, \tag{6}$$

$$z = \pm\sqrt{\frac{(1+S_{11})^2 + S_{21}^2}{(1-S_{11})^2 + S_{21}^2}}, \tag{7}$$

$$\varepsilon = \frac{n}{z}, \tag{8}$$

$$\mu = nz. \tag{9}$$

Here S_{11} and S_{21} are the *S*-parameters for reflection and transmission through the structure respectively, m is an integer and k is the wave vector in free space, which accounts for the different possible branches of the inverse cosine function.

This method is better for the calculation of effective parameters of those metamaterials which are composed of arrays of metallic inclusions with complex shapes. Using this method the refractive index can be directly calculated from the *S*-parameters using eq. (6). However, this method includes determination of impedance of the material and correct branch index of the inverse cosine function. The

n, z and therefore ε and μ are frequency-dependent. Depending on certain issues, they satisfy certain requirements for characterizing metamaterials. Generally, the real impedance (z) and imaginary refractive index (n) must be greater than zero for passive materials. The impedance z is strongly dependent on the overall size of the material and surface termination. That is why it is not possible to assign normalized impedance to non-continuous materials. It is possible to get non-ambiguous z only in the case of continuous material that depends on certain criteria. The determination of correct branch index (m) is another problem in this method, which can be resolved using some complex ways mentioned in the literature[8,21].

A simple direct retrieval method for the extraction of refractive index from the transmission and reflection parameters is still in demand due to the growing demand of DNG metamaterial applications.

When a wave socks an air-sample interface, the partial transmission and reflection occur. The summarized reflections that arise at the first sample interface can be expressed as

$$R_{\text{in}} = R_1 + T_{12}T_{21}R_3\text{e}^{-j2\zeta d} + T_{12}T_{21}R_3^2R_2\text{e}^{-j4\zeta d} + \ldots$$

$$= R_1 + T_{12}T_{21}R_3\text{e}^{-j2\theta}\sum_{n=0}^{\infty} R_2^n R_3^n \text{e}^{-2jn\theta}. \tag{10}$$

Using

$$\sum_{n=0}^{\infty} r^n = \frac{1}{1-r},$$

where $r = R_2R_3\text{e}^{-2jn\theta}$,

$$R_{\text{in}} = R_1 + \frac{T_{12}T_{21}R_3\text{e}^{-2j\theta}}{1-R_2R_3\text{e}^{-2j\theta}}, \tag{11}$$

$T_{12} = 1 + R_2$ and $T_{21} = 1 + R_1$; considering $R_2 = R_3 = -R_1$

$$S_{11} = R_{\text{in}} = \frac{R_1(1-\text{e}^{-2j\theta})}{1-R_1^2\text{e}^{-2j\theta}}, \tag{12}$$

where $\theta = \zeta d$ and ζ is propagation constant of the material.

Similarly,

$$S_{21} = \frac{\text{e}^{-2j\theta}(1-R_1^2)}{1-R_1^2\text{e}^{-2j\theta}}. \tag{13}$$

From eqs (12) and (13),

$$T = \text{e}^{-2j\theta} = \frac{S_{21}+S_{11}-R_1}{1-R_1(S_{21}+S_{11})}, \tag{14}$$

where T is defined as the exponential transmission term.

Similarly,

$$R_1 = \frac{T-S_{21}+S_{11}}{1-T(S_{21}-S_{11})}. \tag{15}$$

Now,

$$1-\text{e}^{-2j\theta} = \frac{(1-S_{21}-S_{11})(1+R_1)}{1-R_1(S_{21}+S_{11})}. \tag{16}$$

Considering the finite slab thickness, the complex exponential transmission term between the two faces of the slab can be expressed as[4]

$$T = \text{e}^{-jkd}, \tag{17}$$

where k is the wave vector.

According to the Taylor series definition and neglecting the higher order terms, eq. (17) can be rewritten as

$$T \approx 1 - jkd. \tag{18}$$

Now, from eqs (16) and (18)

$$k \approx \frac{1}{jd}\frac{(1-S_{21}-S_{11})(1+R_1)}{1-R_1(S_{21}+S_{11})}. \tag{19}$$

The complex wave vector can be written as[6]

$$k \approx \frac{2\pi f}{c}\sqrt{\varepsilon_{\text{r}}\mu_{\text{r}}} \approx k_0\sqrt{\varepsilon_{\text{r}}\mu_{\text{r}}}.$$

According to Ziolkowski[22], refractive index is defined as

$$\eta \approx \frac{k}{k_0}. \tag{20}$$

Now from eqs (14), (15), (19) and (20), the direct refractive index (DRI) can be expressed by a simple equation that is approximated as

$$\eta \approx \frac{c}{j\pi fd}\left\{\frac{(S_{21}-1)^2 - S_{11}^2}{(S_{21}+1)^2 - S_{11}^2}\right\}^{1/2}, \tag{21}$$

where S_{11} and S_{21} are the S-parameters for reflection and transmission for a metamaterial structure respectively, c the velocity of light in the free space, $c = 3 \times 10^8$ m/s, $\pi = 3.14$, f the frequency and d is the thickness of the substrate.

For verifying the proposed method, two published DNG metamaterial samples were considered. For the first sample in Figure 1 a and b, the electromagnetic waves

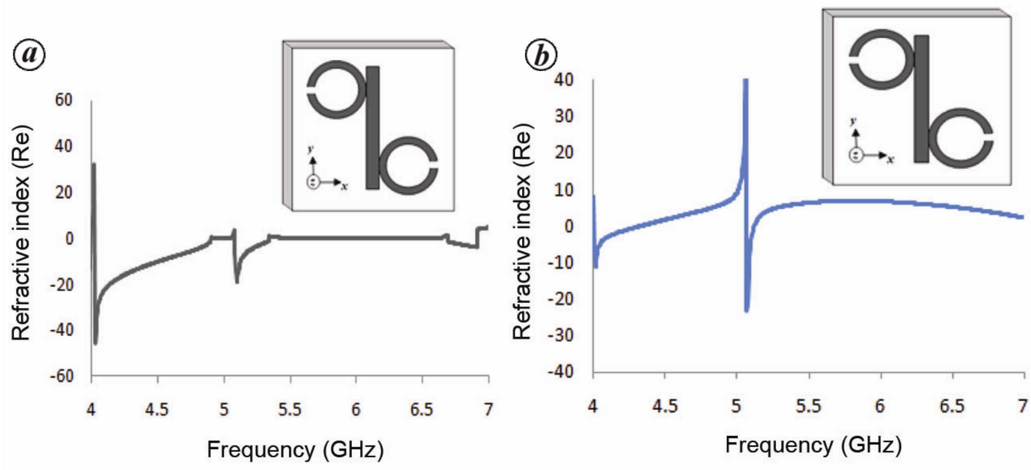

Figure 1. Real magnitude of refractive index for (***a***) classical NRW method and (***b***) TR-method.

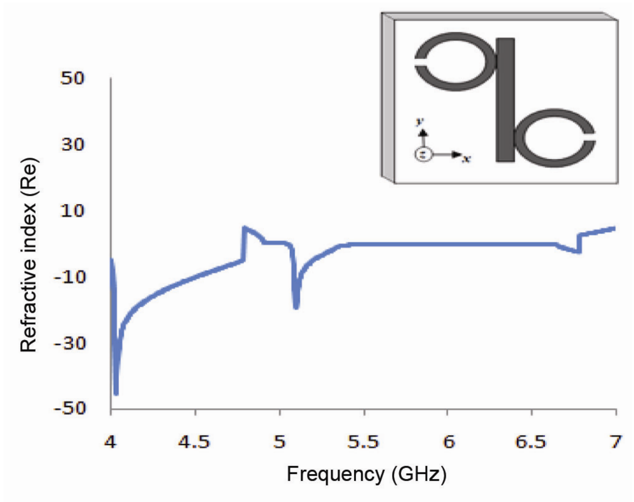

Figure 2. Real magnitude of refractive index for the same sample for the proposed DRI method.

were considered to pass through the structure across the *z*-axis and simulation was done for 4–7 GHz to get the transmission and reflection parameters. Then these parameters were used to calculate the refractive index for the three methods – NRW, TR and DRI and for this, eqs (5), (6) and (21) respectively were considered. However, further simulation was done after replacing the second sample and transverse electromagnetic (TEM) wave was passed through the sample across the *x*-axis. The same methodology has been used to get the values of *S*-parameters as mentioned in ref. 19 and simulation was done for 2–15 GHz. For the ease of usual calculation of refractive index from the TR method, the cosine branch index was considered zero for both cases.

Figure 1 *a* shows the real magnitude of refractive index for the classical NRW method and Figure 1 *b* shows the real magnitude of refractive index for the TR method. Figure 2 shows the real magnitude of the refractive index for the same sample which has been constructed from the proposed DRI method. All the figures are generated based on the *S*-parameter, which has been calculated for the first sample and all three plots depict that the sample is double-negative at frequencies 4.03 and 5.13 GHz. It can be seen from the above figures that according to the resonance point of view, the plot generated from the proposed DRI method agrees well with that generated for classical NRW method. The plot for the TR method also matches well with the plot for the proposed DRI-method according to the resonance position. However, disparity is seen in the magnitude level. At the frequency 4.03 GHz, the highest magnitude of the graph of refractive index is seen near $\eta = 30$ to -45 for NRW method, but in case of TR method it remains within ± 10. However, for the proposed method the highest magnitude starts from $\eta = -6$ and ends near $\eta = -48$. At the resonance point of 5.09 GHz a positive, sharp peak is seen for the plot of TR method compared to the NRW and DRI methods. This disparity may be due to improper selection of branch index.

Figure 3 *a* depicts the real magnitude of refractive index for the classical NRW method for the second sample. Figure 3 *b* shows the real magnitude of refractive index for the TR method for the same sample. Figure 4 reveals the real magnitude of the refractive index for the second sample, which has been constructed from the proposed DRI method. There are some differences among the three graphs. It is apparent that the refractive index curve constructed from the proposed DRI method shows good conformity with the curve obtained from the classical NRW method for the second sample in this case. However, it shows similar result of refractive index with the TR method for the second sample.

In case of the second sample, the NRW and DRI methods show sharp resonance at 5.21 GHz, whereas in case of the TR method it has slightly shifted at 5.80 GHz. At 7.12 GHz, the magnitude of refractive index for the NRW

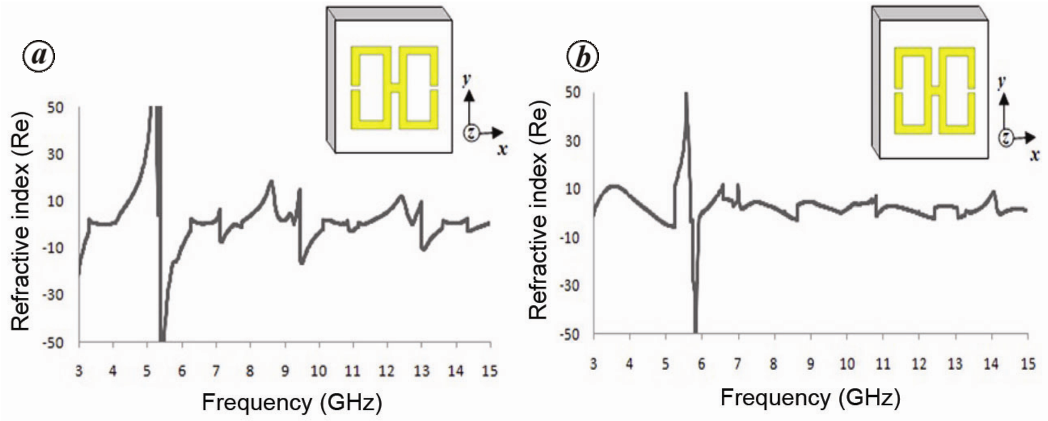

Figure 3. Real magnitude of refractive index for the second sample (*a*) classical NRW method and (*b*) TR method.

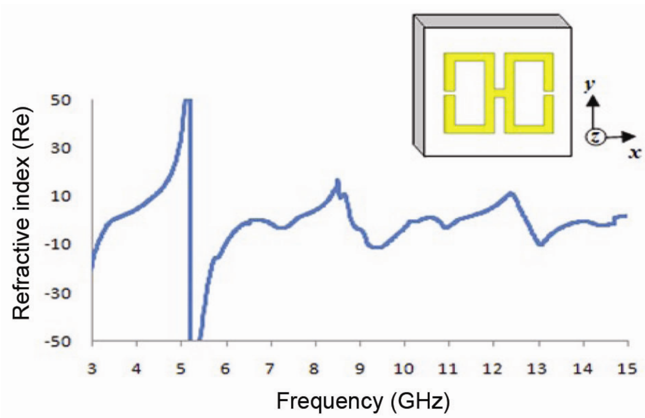

Figure 4. Real magnitude of refractive index for the second sample for the proposed DRI method.

method is $\eta = -7.07$, while for DRI method it is $\eta = -2.59$, but for the TR method it is positive magnitude with the value of $\eta = 1.94$. At 9.46 GHz, the magnitude of refractive index for the NRW method is $\eta = -16.17$ and for DRI method it is $\eta = -11.24$, whereas for the TR method it is positive magnitude with the value of $\eta = 2.05$. Similarly, resonance is seen for both the NRW and DRI methods at the point of 13.07 GHz; the magnitude of refractive index for the NRW method is $\eta = -10.05$ and for the DRI method it is $\eta = -9.87$, while for the TR method it is $\eta = -1.98$. Thus, it is evident that for the second sample the curve for the TR method in Figure 3 *b* shows some clear differences than the curves for the NRW and DRI methods which may be due to improper selection of branch index. Moreover, it is apparent that a good agreement (approximately 90% perfect result) is seen between the classical NRW method and the proposed DRI method according to resonance and magnitude point of view than the TR method.

In this paper, a new method has been introduced for the direct retrieval of refractive index from the transmission and reflection parameters. For verification of the proposed method, two published samples have been considered and the result for the proposed method has been compared with two popular DRI calculation methods; the NRW and TR. It is evident that the proposed method agrees well with the classical NRW method and it also shows almost similar result of the TR method. In addition, it is also clear that due to the incorrect selection of branch index of the TR method, it can show dissimilarities with results from the other methods.

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Impacts of rice intensification system on two C. D. blocks of Barddhaman district, West Bengal

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Rice is an important cereal crop of West Bengal and in many of the Indian states. There is a compelling need to increase rice productivity vertically in West Bengal due to less availability of land and greater dependency of the population on the productivity of the land. For this reason, the economic and ecological potentiality of the system of rice intensification (SRI) has been evaluated by several researchers. In the present study, Monteswar and Memari-II C. D. blocks of Barddhaman district, West Bengal have been selected to analyse the impacts of SRI on economic and ecological aspects of rice-growing. Results show that benefit–cost (B : C) ratio in SRI practice is significantly higher than the conventional method of rice cultivation. Under SRI B : C ratio varies from 5.06 : 1 to 3 : 1, but in the conventional method it varies from 2.18 : 1 to 1.78 : 1. Therefore, SRI farmers are experiencing multiple benefits in terms of both economics and ecology.

Keywords: Agro-ecology, benefit–cost ratio, economic and ecological potentiality, system of rice intensification.

WATER shortage appears to be one of the major limitations affecting rice production[1]. The Food and Agriculture Organization (FAO) of the United Nations estimates that rice crop consumes about 4000–5000 litres of water/kg of grain produced. Since water for rice production has become increasingly deficit, water saving sustaining the high productivity has become a priority in rice research[2].

The system of rice intensification (SRI) was developed in 1980s in Madagascar[3], as a water-saving practice with many-fold increase in crop yield[4]. This method is also ecologically beneficial and is applicable for wheat, sugarcane and several other crops. Also it is more suitable for the small farmers because they can manage their land using this method by their own innovation[5].

Analysing the potentiality of SRI remains a continuing concern among many researchers[6–16] due to an agro-ecologically imbalanced condition in paddy fields. Pandey[17] has studied the relation of different weed control methods with different variables of rice cultivation under SRI in an experimental field in Nepal and found that three mechanical weeding methods under SRI gave the best result with respect to the number of effective tillers/sq. m, grain number, grain weight, yield/ha and benefit–cost (B : C) ratio. Rajitha and Reddy[18] have found that SRI with integrated nutrient management (50% Farm Yard Manure (FYM) + 50% RD of NPK) and SRI with 100% organic manuring saved 28.63% and 34.25% input cost respectively, compared to conventional method of transplanting with recommended fertilizer and cultural practices.

The key elements of SRI practice are discussed below. Young seedlings (not more than 15 days, preferably 8–12 days) are transplanted in SRI practice to achieve the potential of getting higher yield. Transplantation is done by careful removing of the seedlings from the nursery bed and putting them vertically at a shallow depth (1–2 cm) in the soil within 15 min of their removal from the nursery bed. Careful handling of seedlings avoids trauma to the roots, with little or no interruption of plant growth and no transplant shock. Also, transplantation should be done in a square pattern of at least 25 × 25 cm distance between rows and hills in order to give the roots of a single plant enough space to collect nutrients from the soil (Figure 1).

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