

Optical Negative-Index Metamaterial Using CSRR by Incidenting the Light Horizontally at Near-Infrared Domain

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Abstract

Metamaterial structure based on cascaded split ring resonators (CSRR) is proposed in order to produce a negative refractive index in terahertz regime at near-infrared range. We have incident light horizontally instead of incidenting it perpendicular. We have measured the negative refractive index, permeability and permittivity by using the S-parameter analysis. Furthermore, it is found out that negative refractive index, permeability and permittivity are dependent upon the width of the wire and the gap between resonators at near-infrared range. This work will be helpful for the fabrication and design of double negative metamaterials structure having negative permeability, permittivity and negative refractive index for in plane applications.

Keywords

Metamaterials, Negative Refractive Index, Left Handed Material, Scattering Parameters

1. Introduction

Negative refractive index (NRI) is the main focus point of current research. Within five years after Smith's proposal, the field of NRI has seen development at optical range by using different structures like paired nano-rods [1], nano-fishnet with circular voids [2], nano-fishnet with elliptical voids [3], and nano-fishnet with rectangular voids [4].

As compared to photonic crystals, which retain a periodicity in the order of the wavelength, the size and the distance of the distinct presence in metamaterials are subwavelength. This permits to define the optical response

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of metamaterials by effective material parameters. This is an equivalence to wave propagation in conventional materials, where the interaction of an electromagnetic wave with a group of atoms or molecules is defined by permittivity ϵ and the permeability μ . Effective permittivity ϵ_{eff} and an effective permeability μ_{eff} define the electromagnetic response of the metamaterial. The effective refractive index n_{eff} and the effective wave impedance z_{eff} can be calculated from the effective permittivity ϵ_{eff} and an effective permeability μ_{eff} is used to describe the propagation of a wave through the metamaterial.

An array of thin conducting wires, showing an effective plasmonic response at GHz frequencies [5] and the material composed of split-ring resonators (SRRs) which had a magnetic response [6], was the two basic metamaterial designs that were explained in late 1990s. In 2006, the electric LC-resonator (ELC) with an electric resonance was presented as a third basic metamaterial element [7]. Nowadays, the metamaterial structures evolved on the variations in these three designs. Subsequently for the implementation of optical components, metamaterials have appeared as a flexible device. As compared with conventional materials, the advantage of metamaterials is that the optical response of a metamaterial can be effortlessly designed to the desired values for an application by altering the size and shape of the subwavelength elements. Metamaterials in THz regime are being used as absorbers [8], quarter waveplates [9], switches and modulators [10]-[15]. Metamaterial negative refractive index has numerous applications such as M-NRI for antennas [16], Superlens [17], and wireless power transfer [18] and for biomedical applications [19] [20].

Since Smith *et al.* [21] experimentally confirmed the presence of corresponding negative index materials. In the last decade, negative indexed materials (NIMs) or double negative materials (DNG) or left-handed materials (LHMs) with simultaneously negative permittivity ϵ and negative permeability μ have attracted considerable attention. The terahertz (THz) and optical metamaterials fascinated some devotion in recent years. In numerous design techniques of THz and optical metamaterials, though, the resonant cells should be made much smaller than the operation wavelength. Consequently, problems in fabrication of such small resonant elements and material loss turn out to be big challenges in reality. Furthermore, most of the metamaterials designs are restricted by narrow bandwidths, so tunability of operating frequencies becomes an important issue in the metamaterials research, which motivates the present work.

Most of the current metamaterials research is that light incident on the normal direction. But, many researchers are trying to integrate devices with different functions on a single chip. Therefore, metamaterials to work with light in plane propagation direction is necessary for on-chip integration at near-infrared regime. However, few research of in plane light propagation is reported in case of metamaterials. In this paper, we have studied a metamaterial structure for an in plane light propagation and studied its optical properties at near-infrared range.

2. Design and Simulation

Different kinds of techniques have been developed in the past few years for extraction of S-parameters. In our simulation we are using the S-parameters extraction technique discussed by Smith *et al.* [22]. The structure was simulated by FDTD method. Choosing the frequency unit in THz, S-parameter analysis tool was used to extract the S-parameters. Each calculation is based on 100 frequency samples. The unit cell is shown in **Figure 1**. It consists of three materials: SiO_2 as a substrate, Si as waveguide and split ring resonator made of gold. This structure was simulated for 216 THz frequency range. The thickness of the substrate is 340 nm, the thickness of the waveguide is 220 nm, width of metal wires is 40 nm, length of the metal wires of the outer ring is 230 nm and the gap between the inner ring and the outer ring is 40 nm.

3. Results and Discussion

The calculated wavelength spectra of the structure are shown in **Figure 2(a)**, where the width of the wires is kept at 40 nm. The appearance of the LH behavior can be confirmed by using the extracted effective parameters of the structure, as presented in **Figures 2(b)-(d)**. Obviously, both the effective permeability and permittivity are negative. Consequently, the refractive index has a negative value ($n < 0$). Moreover, there is a dependence of the structural parameters of the metal wire on the LH behavior. We found that the electromagnetic response of the structure is significantly affected by the width of the continuous wire. **Figure 3** shows spectra's of the compound structure by varying the width of the continuous wire. For this purpose, the width of the wire pairs is kept at 40 nm while the width of the continuous wire is varied from 20 to 40 nm.

As can be seen, resonance is shifted with an increase in width of the continuous wire. To confirm this pheno-

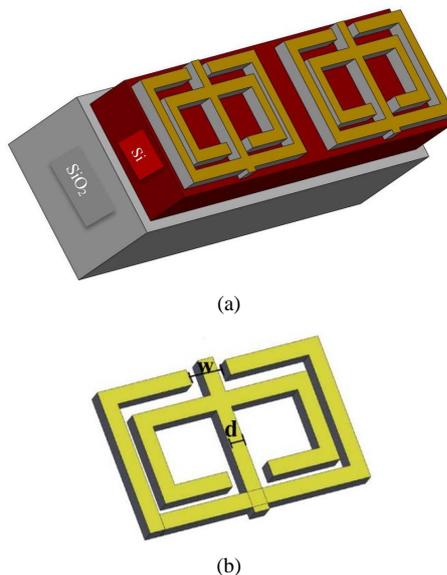


Figure 1. (a) 3D design of the structure, bottom layer is the SiO₂, on top of it is Silicon waveguide and cascaded split ring resonators are placed on the top of the waveguide and (b) shows the parameters width w and the distance d of the cascaded split ring resonators.

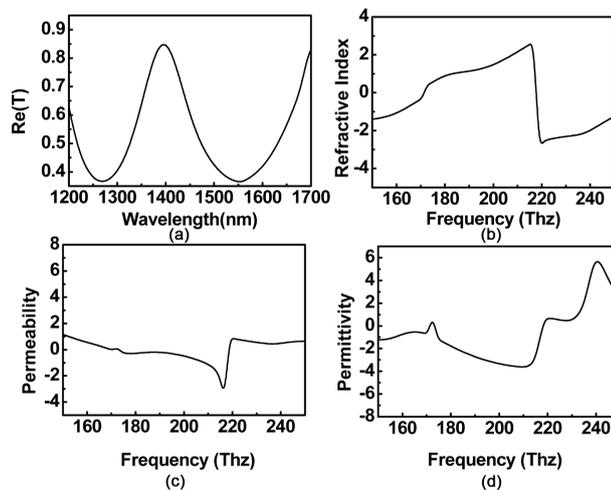


Figure 2. (a) Simulated wavelength spectra of the structure, where the width of the wires are kept at 40 nm; ((b)-(d)) real part of the permittivity, permeability and refractive index extracted from the simulation data, respectively.

menon, the effective permittivity, permeability and also refractive index of the structures are extracted from the scattering parameters, as shown in **Figures 3(a)-(c)**, respectively. As expected, the magnetic response shifts towards a lower frequency by decrease in width of the continuous wire, while the plasma frequency remains unchanged. Thus, this explains the reason for the dependence of resonance peak on width of the continuous wire. As **Figure 3(a)** shows, the refractive index is decreasing with the decrease in width of the continuous wire.

Another interesting result is shown in **Figure 4**, where the LH behavior of the structure is also intensely affected by varying the gap d between the centers of the continuous wires. To study this phenomenon, the gap d was varied from 30 to 160 nm. The effective permittivity, permeability and refractive index are extracted from simulation results. As it can be seen in the figure, the resonance in the right is shifted by varying the gap d between the centers of the continuous wire. A reduction of negative refractive index appears when decreasing the gap size.

In **Table 1**, we have compared our results with the other structures near-infrared range that are using perpendicular

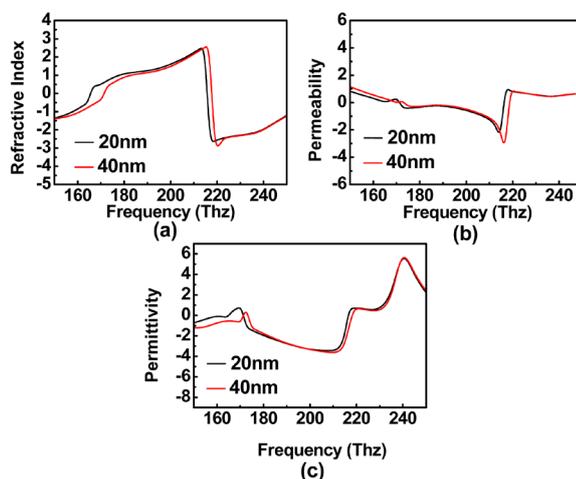


Figure 3. Simulated spectra of the structure with different widths of the continuous wires. ((a)-(c)) Real part of the refractive index, permeability and permittivity respectively.

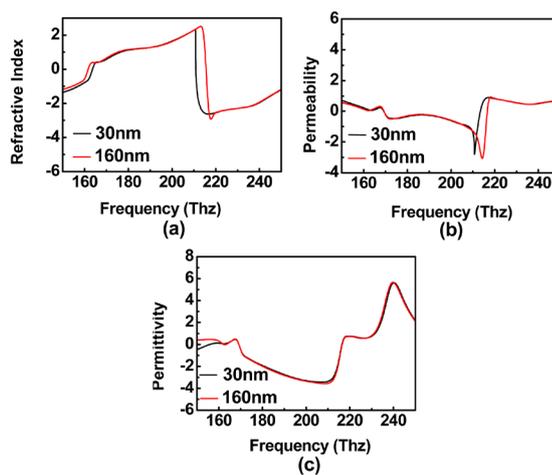


Figure 4. Extracted effective parameters of structure from the calculated scattering parameters: (a), (b) and (c) are the refractive index, permeability and permittivity, respectively.

Table 1. Comparison between different structures.

References	Structures	Refractive index	Wavelength	Direction of pump
[1]	Paired nanorods	-0.3	1.5 μm	Perpendicular
[23]	Nano-fishnet with circular rods	-2	2.0 μm	Perpendicular
[4]	Nano-fishnet with rectangular rods	-1	1.4 μm	Perpendicular
[24]	Metal-dielectric-metal	-1.05	780 nm	Perpendicular
[25]	Multishell nanowires	-2.0	690 nm	Perpendicular
Our design [26]	Cascaded split ring resonators	-2.8	1.5 μm	Horizontally

direction of the incident light, where as in our design we are using the horizontal direction of incident light and achieve the refractive index of -2.8 at optical wavelength. The results by using the horizontal direction of incident light are useful for designing novel devices for on chip integration by utilizing the optical properties of metamaterials.

4. Conclusion

Simulation studies have been conducted on ring-type cascaded split ring resonators (SRR) to understand the properties of metamaterial structure with horizontally incident source at near-infrared range. By incidenting the light along x-axis, the proposed structure shows a negative refractive index indicating the properties of double negative material and left-handed material at near-infrared range. Moreover, it is observed that the width of the continuous wire as well as distance between the centers affects the left-handed behavior of the structure. The search results in our paper are useful for designing novel devices for on chip integration by utilizing the optical properties of metamaterials.

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