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# A low loss semi H-shaped negative refractive index metamaterial at 4.725 THz

M. Askari[a,*], A. Zakery[b], A.S. Jahromi[c]

[a] Physics Department, College of Sciences, Salman Farsi University of Kazerun, Kazerun, Iran
[b] Physics Department, College of Sciences, Shiraz University, Shiraz, Iran
[c] Zarghan Branch, Islamic Azad university, Zarghan, Iran

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ABSTRACT

We numerically propose a negative refractive index metamaterial structure with a unit cell composed of only one semi H-shaped element. With this structure a very high transmission of −0.65 dB and a low reflection of −16.48 dB can be achieved at 4.725 THz, with the real part of the refractive index equal to −1.9. The FOM of the structure is 89.43, which warrants the quality of the proposed structure for negative refractive index applications.



## 1. Introduction

Interaction of electromagnetic waves with subwavelength metallic structures called metamaterials has attracted considerable attention in recent years. These metallic microstructures can be designed in such a way to provide novel electromagnetic properties, which are not naturally available. [1–11]. These novel properties give rise to potential applications in super-lensing, invisibility cloaking, molecular spectroscopy, and ultra-sensitive biochemical sensing [12–16], and therefore, researchers have made several attempts to realize metamaterials in the whole electromagnetic spectrum [11,17,18].

One of the features of metamaterials that has largely been studied is the negative refractive index, which was initially proposed by Veselago as an academic concept [19]. About three decades later, it was realized that magnetic response could be achieved by using artificial structures [20]. Later on, a composite structure based on split-ring resonators was realized, and it was shown that the real parts of permittivity $\Re(\epsilon)$ and permeability $\Re(\mu)$ were negative over a common frequency band, and therefore, the existence of negative refractive index was experimentally realized [21]. In addition to split-ring resonators, other metamaterial structures such as short wire pair structures, fishnet structures, and chiral metamaterials have been realized so far to represent negative refractive index [22–30].

One of the first structures designed to represent negative refractive index were those composed of split-ring resonators and metallic wires, in which split-ring resonators were exploited to provide negative real part of magnetic permeability $\Re(\mu)$, and continuous wires were exploited to provide a negative real part of electric permittivity $\Re(\epsilon)$. There have also been some metamaterial structures composed only of split ring resonators, which exhibit negative refractive index at microwave frequencies [31]. For infrared and optical frequencies, structures composed of U-shaped elements are more common than split-ring resonators. In addition to negative refractive index applications, U-shaped structures are widely used in designing chiral metamaterials and in structures suitable for biosensing applications [32–35].

In this paper, we propose a negative refractive index metamaterial structure with a unit cell composed of only one semi H-shaped resonator (SHR) element. With this structure, a very high transmission of −0.65 dB and a reflection of −16.48 dB can be achieved at 4.725 THz, with the real part of the refractive index equal to −1.9. The FOM of the structure is 89.43 which warrants the quality of the proposed structure for negative refractive index applications.

## 2. Proposed metamaterial structure

The proposed unit cell contains only a single SHR composed of a middle part and four arms made of gold (see Fig. 1). The thick-

* Corresponding author.
E-mail address: MehdiAskari@kazerunsfu.ac.ir (M. Askari).

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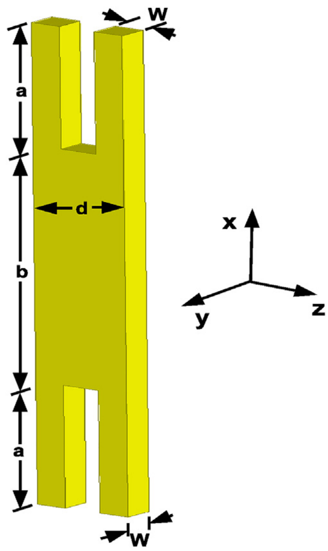


**Fig. 1.** Schematic of the unit cell of the proposed metamaterial with $d = 5.2\,\mu m$, $w = 1.6\,\mu m$, $b = 25\,\mu m$, and $a = 17\,\mu m$.

ness of this semi-H-shaped element is $w = 1.6\,\mu m$. The width of the middle part of the SHR is $d = 5.2\,\mu m$, and its height $b = 25\,\mu m$. Each arm has a width $w = 1.6\,\mu m$ and a height $a = 17\,\mu m$. For simplicity, we do not consider a dielectric substrate here, but in practice, this SHR can be embedded in a dielectric host medium. We take the lengths of the unit cell in the $x$- and $y$-directions as 65 and 15 μm respectively. Therefore, the gap width between adjacent H-shaped elements along the $x$-direction is considered as 6 μm. The structure is periodic along the $x$- and $y$-directions, while only a single layer is considered along the propagation direction. The propagation direction of the incident linearly polarized electromagnetic wave is along the $z$-direction, with the electric field polarization along the $x$-direction and the magnetic field component along the $y$-direction.

## 3. Numerical calculations and discussion

To investigate the electromagnetic response of the proposed metamaterial structure, we performed a set of finite element numerical method calculations using a commercial software package high frequency structure simulator (HFSS). We used only one unit cell of the structure, with appropriate periodic boundary conditions, in the $x$–$y$ plane and only one unit cell along the propagation direction. Perfect electric boundaries and perfect magnetic boundaries were used in the $x$-direction ($y$–$z$ plane) and the $y$-direction

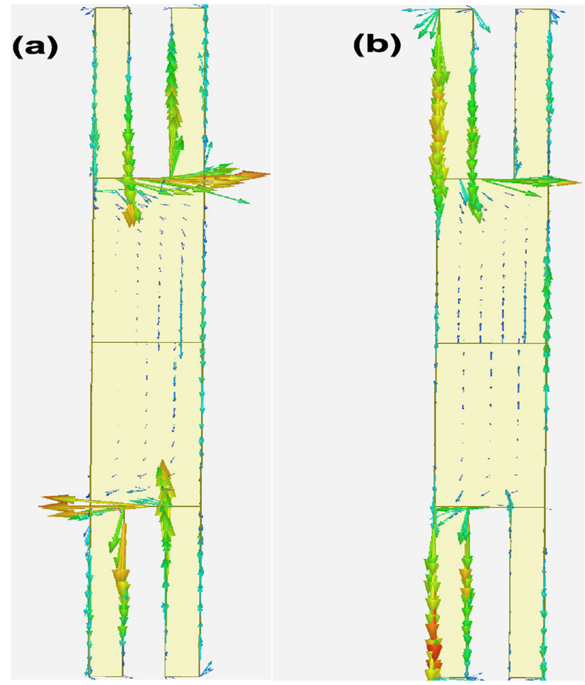


**Fig. 2.** (a) Surface current distribution at a negative refractive index frequency of 4.725 THz. The antiparallel surface currents in both arms of the semi H-shaped element reveal the existence of a magnetic resonance. (b) Surface current distribution at a positive refractive index of 5.17 THz.

($x$–$z$ plane), respectively, to warrant the polarization of electric field along the arms of the SHR (along the $x$ axis) and the polarization of magnetic field perpendicular to the plane containing the SHR (along the $y$ axis). An electromagnetic wave was incident normal to the $x$–$y$ plane, propagating in the $z$-direction. We used the Drude free electron model for the permittivity of gold

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

where $\omega_p$ is the plasma frequency and $\gamma$ is the collision frequency. The $\omega_p$ and $\gamma$ values for gold were considered $1.37 \times 10^{16}$ rad/s and $4.08 \times 10^{13}$ rad/s, respectively [36]. Although, at high frequencies, noble metals are not as good as graphene and high-$T_c$ superconductors, they are still the best candidates for conductors in metamaterials [36].

In the proposed structure, a negative real part of permittivity can be generated by the middle part and the arms of the semi H-shaped structure at frequencies below the plasma frequency, and a negative permeability can be generated by exciting a circular cur-

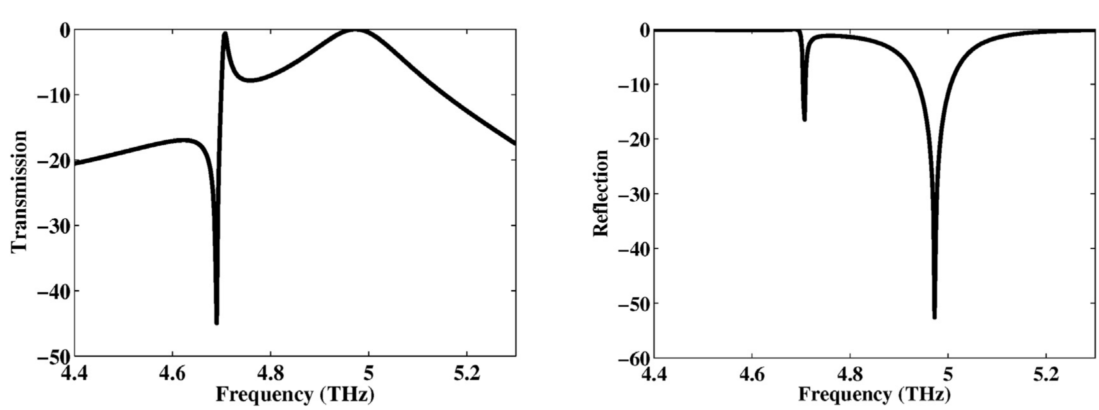


**Fig. 3.** Transmission and reflection amplitudes.