Resonance-based metamaterial in the shallow sub-wavelength regime: negative refractive index and nearly perfect absorption

Thi Trang Pham\textsuperscript{1,2}, Hoang Tung Nguyen\textsuperscript{1}, Dac Tuyen Le\textsuperscript{2}, Ba Tuan Tong\textsuperscript{2}, Thi Giang Trinh, Van Tuong Pham\textsuperscript{1} and Dinh Lam Vu\textsuperscript{1}

\textsuperscript{1}Institute of Materials Science, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Hanoi, Vietnam
\textsuperscript{2}Hanoi University of Mining and Geology, 18 Pho Vien, Hanoi, Vietnam

E-mail: lamvd@ims.vast.ac.vn

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Abstract
The research on magnetic resonances in typical meta-atoms has led to the discovery of electromagnetic metamaterials (MMs). These new materials played a crucial role in achieving extraordinary phenomena as well as promised potential applications. In this paper, we numerically and experimentally investigated two different MM effects: the absorption and the negative refraction, which induced by magnetic resonances in a symmetric structure. The meta-atom sandwich model that includes two parallel flat rings separated by an insulating slab was designed. Firstly, three resonances in sub-wavelength range were demonstrated, revealing the negative permittivity and permeability effects. Notably, negative refractive index (NRI) was gained at the third-gap resonance, resulting from superposition of the rest of the electric resonance and the magnetic one accompanied by multi-plasmon. Moreover, the manipulation of the structural parameters could control the NRI behavior and, interestingly, a nearly perfect absorption peak arises in shallow sub-wavelength regime.

Keywords: metamaterials, magnetic resonance, negative refractive index, perfect absorption

Classification numbers: 2.01, 5.17

1. Introduction

Recently, artificial sub-wavelength material, so-called metamaterial (MM), which possesses extraordinary effects or phenomena such as simultaneously negative permittivity \cite{1} and permeability \cite{2} leading to negative refractive index (NRI) \cite{3–5}, perfect absorption (PA) \cite{6,7}, electromagnetic (EM) induced transparency \cite{8} and so on, has been of great interest in the fields of plasmonics and optics \cite{6,7}. In 1999, the first realization of the negative permeability created by Pendry \textit{et al} \cite{2} and based on the magnetic resonance in split ring (C-shape) has opened the field of MM research by experimentally observing the well-known NRI effect \cite{1,4}. Almost all of the extraordinary MM effects were indeed produced by exploiting the resonance. Hence, it has been become a fundamental key to the evolution of the MM concept.

The first known effect, thanks to the magnetic resonance, is the NRI produced by the negative values of the permeability and permittivity in the same range \cite{3}. This is combination of the magnetic and the electric meta-atoms responding to simultaneously negative permeability and permittivity, respectively. Recently, the manifestation of the
NRI in a single symmetric atom gives a simple structure could be possible. It is known that the spectra of the typical simple meta-atoms, for examples split-ring resonator (SRR) \cite{4, 5} and cut-wire pair (CWP) \cite{9}, produce not only magnetic but also an electric resonance in the sub-wavelength range. However, the superposition of them to obtain NRI still remains a challenge in the symmetric MMs. Large efforts have been devoted to observe the NRI in a single meta-atom, the third-gap resonance that is accompanied by the multi-plasmon \cite{10} has been considered in previous works \cite{10, 11}. The third resonance is able to be produced in the sub-wavelength range. However, the clear observation of the expected effects, especially, the NRI behavior at the third resonance, is not always possible, so its confirmation in specific MM structures is significantly demanded.

The magnetic resonances in the MMs are not only applicable to produce NRI but also exploited to create black bodies in view of the MM concept, perfect absorbers \cite{6, 7, 12}. A PA slab, no reflection and transmission, is obtained when the effective impedance matches to the environment \cite{13, 14} and consume the EM energy by the high intrinsic losses of the wave-matter interaction at the resonance.

In this work, the magnetic and electric resonances in MMs which are designed based on a ring pattern were exploited to investigate both the classical NRI and the absorption effect. We designed a meta-atom to demonstrate the three resonances in GHz regime. The third one was tamed to yield NRI effect by combining with the electric resonance at the second gap. Similar to the first resonance, this also shows the magnetic response but supporting by multi-plasmon \cite{10}. The manipulation of MM in the shallow sub-wavelength range could be controlled the NRI and more interestingly, which produce a PA peak exploiting multi-plasmonic resonance.

2. Simulations and experiments

As schematically depicted in figure 1(a), a unit cell of the 2D structure of dual-ring MM consists of three layers, simply two metallic rings separated by a dielectric layer. The copper which conductivity of 5.8 × 10^{7} S m^{-1} was defined as metallic layer. The material parameters of the printed-circuit-board (PCB) were used as in our previous works \cite{12, 15, 16}. Thickness of copper layers, \( t_c \) is 36 \mu m and one of the PCB slab, \( t \) is 0.4 mm. The radius and the width of the rings are varied in the study. This structure of the unit cell was known as basic meta-atom and could use to investigate the key effect in MM research, magnetic and electric resonances.

As shown in figure 1(b), the fabricated sample was made by lithography method combining with the chemical etching. The PCB slabs were employed, whose parameters were coincided with the simulated definitions. The samples were measured in free space by using a Hewlett-Packard E8362B network analyzer connected to microwave standard-gain horn antennas. The operation range of EM wave is from 12 to 18 GHz.

The numerical simulations were performed using commercial software, CST MICROWAVE STUDIO \cite{17}, which is based on the finite integration technique \cite{18}. The EM incidence was transverse wave and propagating perpendicularly to 2D lattice MM with transversal \( \mathbf{H} \)-field and vertical \( \mathbf{E} \)-field directions. The calculations of the effective permittivity, permeability and refractive index were used the home code developed based on the work of Smith et al and Chen et al \cite{19, 20}. The expression of absorption is simply as \( A(\omega) = 1 – R(\omega) – T(\omega) = 1 – [S_{11}]^2 – [S_{21}]^2 \) where \( A(\omega), R(\omega), T(\omega), S_{11} \) and \( S_{21} \) denote absorption, reflectance, transmittance, reflection scattering and transmission scattering, respectively.

3. Results and discussions

Firstly, in this work, a typical single meta-atom which produces all three gap resonances was examined on model of dual-ring MM (figure 1(a)). A demonstration spectrum of three basic resonances of a typical EM MM as same as CWP and SRR meta-atoms \cite{4, 5, 21–23} in previous works is plotted in figure 2(a). The first magnetic resonance gap at 4.9 GHz, the second electric one at 13.7 GHz and the third magnetic one at 17.0 GHz correspond to antiparallel single-plasmon, parallel
single-plasmon and antiparallel multi-plasmon, respectively, illustrated by current density as shown in figure 2(b).

We have more interest in the multi-plasmon, which is possible to exhibit the resonance-tunable property and then expected to realize the extraordinary MM effect. One of them is NRI, whereas the resonance takes place in the range of electric mode influence. The multi-plasmonic NRI results are shown in figure 3(a), a plot of the simulation spectrum together with the experimental result. It demonstrates full NRI as shown in combined structures of single-NRI in the range of 14.1–15.1 GHz and double-NRI or left-handed (LH) behavior in the range of 15.1–16.4 GHz. Note that the LH range is more transparent than single-NRI range because of the results of the optical propagation (the real parts) and the other responses of the dissipation (imagine parts). We clarified the third range of 16.4–16.7 GHz which also exhibits the single-NRI results. However, it is different from the first single NRI range, which is the positive permeability and negative permittivity. The third range occurs with the positive permittivity and negative permeability. Note that it also results of the dissipation effect. The NRI behavior was tamed to be at the sub-wavelength range of MM medium.

A difficulty of MM manipulation in multi-plasmon magnetic gap is that it drifts out of the sub-wavelength range, but it is an advantage in seeking the MM effects influenced by dimension of the unit cell. NRI is firstly switchable at the third gap resonance and secondly merging a new dynamic resonance in the third gap band with the conventional electric resonance in the second gap, thus the perfect absorption effect has been manifested.

As in the above discussion, it is not always possible to get the superposition of the negative range of the electrical permittivity and the magnetic resonance. In the following, the switchable NRI has been demonstrated in figure 3(b) as the
plots of the refractive index in the range of the third gap resonance. The width of the metallic rings is manipulated. The amplitude of the refractive index is strongly depended on the superposition at the rest of the second electric resonance and the multi-plasmonic magnetic one. While the electric resonance is persistent with the width of the rings, the magnetic one is sensitive. The very long blue-shift of the resonance frequency, \( f_3 \), beside the short red shift of the electric response resonance \( f_\varepsilon \) (at which \( \varepsilon = 0 \)) according to the reduction of \( w \) in figure 3(c) is well relied as an evidence. The NRI behavior is degraded and switched to positive when the resonances are de-overlapped.

In figure 4(a), a perfect absorption peak is gained in the regime of the third gap resonance. The numerical simulation and experimental spectra were plotted and showed well agreement. It is results of matching impedance when new resonance appears at the same frequency with the magnetic one. The impedance matching result is plotted in figure 4(b) responding to the manipulation of the width of the rings. In other words, thanks to the sensitivity of resonances in shallow sub-wavelength regime, the PA could be achieved by manipulating the effective parameters: the permittivity and the permeability. The obtained result is in a good agreement with our previous work on achieving isotropic MMPA by overlapping the losses induced by both magnetic and electric resonances on each other [24]. However, taking one step further, we are now able to create isotropic MMPA employing multi-plasmonic resonance which is rarely observed to date. These innovative results could be helpful for the studies approaching towards multi-dimensional MMPA.

**Figure 3.** NRI in the shallow sub-wavelength regime. (a) The transmission spectrum around resonance frequency is verified by experimental measurement at the ring width of 5.3 mm, (b) the retrieval of the effective parameters shows well the NRI behavior, and (c) the NRI can be switched by varying the width of the rings.
4. Conclusions

The MMs have been investigated, showing the extraordinary effects relying on the resonances in the single symmetric MM atom. The typical 2D MMs of the dual-ring structures produced fully three gap resonances to the incident EM wave. Manipulation of parameters could gain both switchable NRI and PA in symmetric MM in the shallow sub-wavelength range. Moreover, the high absorption peak is observed at the multi-plasmon regime of the symmetric structures. Both NRI and MMPA are experimentally verified at the multi-plasmon resonance. This work is adding a confirmation for the evolution of the MMs in full sub-wavelength EM range.

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