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Negative refractive index modified fishnet enhancement by wire shift

Antoine Wegrowski1, Wei-Chih Wang2,3,4, Chileung Tsui1 and Prabir Garu4

1 Department of Mechanical Engineering, University of Washington, 165 Stevens Way, Box 352600, Seattle, WA 98195, United States of America
2 Department of Electrical and Computer Engineering, University of Washington, 185 Stevens Way, 352500, Seattle WA. 98195, United States of America
3 Department of Power Mechanical Engineering, National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu, 30013, R.O.C, Taiwan
4 Institute of Nano Engineering and Microsystems, National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu, 30013, R.O.C, Taiwan

* Author to whom any correspondence should be addressed.
E-mail: abong@uw.edu

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Abstract

We propose a modification to the negative refractive index fishnet design and demonstrate numerically that this modification leads to an even lower refractive index resonance peak and higher gains compared to the fishnet design, this effect being sustained for design dimensions ranging from the nanometer up to the millimeter and for various materials. This modification, we called ‘bd design’, consists in a shift of the metallic arms to the extremities of the metallic slab, the structure remaining otherwise identical. We discuss the numerical comparison between the use of the fishnet design and the bd design, simulating three fishnet-based metamaterials presented in the literature and showing how a modification of these metamaterials to the bd design leads to improved performances. Finally, we present an explanation for the superior characteristics of the bd design.

1. Introduction

Metamaterials are composite structures, which, when considered at scales small enough that their structural features become minuscule compared to the wavelength they are subject to, display effective electromagnetic properties such as permeability, permittivity, refractive index akin to those of uniform materials. Metamaterials provide us the ability to create our own ‘atoms’ and so access new ground-breaking functions like invisibility and imaging with unlimited resolution. The development of active, programmable, and nonlinear metamaterials, which will transcend natural media as platforms for optical data processing and quantum information applications, will mark the next stage of this technological revolution. These kinds of materials earn the suffix meta, meaning ‘with, across, after,’ because their effective properties are unlike any other material found in nature. The most interesting of these effective properties, the negative refractive index, has been first postulated by Veselago [1] and aroused tremendous interest in the last 20 years following groundbreaking work by Pendry et al [2] and Smith et al [3]. Pendry et al first realized and proposed to build arrays of split-ring resonators demonstrated by Smith et al. Negative refraction has opened doors to the realization of exotic devices such as invisibility cloaks [4, 5] using optical conformal mapping, or superlenses [6] that make use of the evanescent waves enhancing properties of negative refractive index metamaterial (thereafter NIM). The most commonly used metamaterial design is that of the fishnet, consisting in a layer of dielectric sandwiched between two layers of metal (usually gold, silver or copper), with the sandwich being punctured in a square array. This design was studied by Kafesaki et al [7], who showed the mechanism behind its negative refractive property. Besides, several others group also proposed and demonstrated the negative refraction based on various fishnet structures. A fishnet structure metamaterial device exhibits two near infrared (NIR) negative index resonance was proposed by Dani et al [8]. Such device was studied by pump-probe spectroscopy, which can achieve ultrafast nonlinear optical response on both resonances. In 2013, Soemphol et all. have proposed and experimentally demonstrated
a modified fishnet structure to achieve near-zero refractive index with low loss in the microwave regime [9]. The near-zero index band was generated within the matching electric and magnetic resonances around the transition from a negative-n region to a positive-n region, which were adjusted via the continuous wires and slab. A cascaded 3-D fishnet structure with a negative refractive index (NRI) over a broad spectral range from 1200 nm to 1800 nm was proposed and experimentally demonstrated by Valentine et al [10]. The metafishnet structure exhibits both positive and negative refractive index within the operating frequency band. A positive refractive index of 0.63 at 1200 nm and a negative refractive index of −1.23 at 1775 nm were achieved by the structure. Besides, the fishnet structure also yielding an experimental figure of merit (FOM) of 3.5 at 1775 nm. Cheng et al have proposed and numerically demonstrated a 3-D broadband isotropic NIM composed of double periodic array fishnet structure which can achieve negative permittivity and permeability simultaneously [11]. The metastructure has a relative bandwidth of 63%, a negative index bandwidth of nearly 7 GHz, and is essentially independent of the polarization and incidence angle of incoming waves. The FOM of the proposed NIM structure achieved a maximum FOM value of 55.1 at 8.5 GHz. A low-loss feature of curled fishnet metamaterial integrated into a rolled-up tube (RUT) that consists of multi alternating layers of gold (Au) and silicon dioxide (SiO2) was proposed and experimentally demonstrated by Briukhanova et al [12]. The structure possesses a negative refractive index with a high FOM of 2.76 in the NIR region. In this design, the NIM response and the negative index region may both be tuned by carefully adjusting the hole size and the size of the fishnet metamaterial, respectively. A 3-D curved fishnet-type metamaterial consisting of six alternating layers of metal and III-V semiconductor (In)GaAs was proposed and experimentally demonstrated by Rottler et al [13]. The fabricated structure is a single negative material with a rather FOM of 0.8 at 292 THz. The refractive index can be tuned within the operating frequency band from 195 THz to 320 THz by nanometer-precise control of the individual layer thickness. The strained layers start to roll once the sacrificial layer is etched, making the process of successive depositions and producing fishnet metamaterials simper. However, the rolled-up structure’s circular shape makes it difficult to characterize the spectrum properties of fishnet metamaterials, particularly when the diameter is small. The NIM behavior of such curved fishnet structures has therefore not been realized, despite the fabrication of a fishnet metamaterial prototype. The fabrication of a multilayered negative index metamaterial that resembles a fishnet using a scalable approach based on soft nanoimprinting lithography and electrodeposition has been reported by Gómez-Castao et al [14]. The structure can achieve a strong NRI in the operating frequency band with minimum value of −1.2 at 700 nm and a maximum FOM of 1.4 nearly at 960 nm. Although, the aforementioned fishnet metamaterial structures can realize high and even ultrahigh refractive indexes FOM, they have limitations of narrowband. Moreover, the controllable characteristics of such fishnet metamaterials are crucial for manipulating electromagnetic radiation at THz frequencies, where the natural material response is sporadic.

2. Structure of the bd design

A typical fishnet design is presented in figure 1(a), consisting in a layer of dielectric (here, in blue) sandwiched between two layers of metal (here, in yellow), and punctured by a square array of holes. Another way to visualize this design is by considering two superimposed structural components, the first consisting in an array of metallic wires, the second consisting in an array of dielectric slabs sandwiched between metallic slabs (better seen when considering the modified fishnet design, see figure 1(b)).

The fishnet design has been demonstrated [2] to merge two properties which, combined, give rise to a negative refractive index: negative permittivity and negative permeability. Those properties do not necessarily emerge at the same frequencies, so that a NIM will need to have the magnetic and electric resonance frequency span match in order to display negative refraction.

The negative permittivity occurs when an incident electromagnetic wave incurs plasmonic resonance in the first structural component of the fishnet design, i.e. the array of metallic wires. The negative permeability occurs when surface currents generated by incident electromagnetic wave over the metallic slabs of the second structural component generate, in turn, a resonating oscillating magnetic field within the dielectric between the metallic slabs.

The fishnet design has been refined into the so-called modified fishnet design [7] (figure 1(b)), which has been used in a variety of scales and materials to create NIM operating at various frequencies [15–17].

The bd design we propose in this article is a modification of the so-called modified fishnet design. Instead of having the metallic wires crossing the metallic slabs at their center, we place those wires at the extremity of the slab, in a rotational symmetry fashion (figure 1(c)), conserving otherwise all dimensions and materials of the originally suggested fishnet. As will be shown in the following sections, such modification will have positive effects on both the frequency span where negative refraction occurs the resonant refractive index minimum as well as the gain of the material.
3. Numerical results

We compared the refractive indexes and FOM of three variations of the NIM based on the modified fishnet design and their corresponding bd design modification. We chose the following three designs in literature: Zhang et al’s original fishnet design [9], Kafesaki et al’s modified fishnet [7], and Ding et al’s fishnet structure [15]. These choices allow us to test the bd design over a variety of dimensions (from nanometer to millimeter), materials and resonant frequencies (from GHz to PHz).

Zhang et al’s design consists in two layers of gold sandwiching one layer of undefined dielectric with refractive index of 1.5. We’ll use Al₂O₃ as a reference, since it is the material used in the experimental study they reference in their article. Kafesaki et al’s design is built from two layers of copper and one layer of FR4 dielectric substrate. Finally, Ding et al’s fishnet structure is made of two layers of gold with, in between, one layer of benzocyclobutene.

As the bd design is more easily related to the modified fishnet suggested by Kafesaki et al, we modify the designs suggested by Zhang et al and Ding et al, adding a space between two adjacent unit cells in the former and losing the geometric isotropy of the latter by removing the horizontal wires, so as to have uniform comparisons.
between the modified fishnet and the bd design. Respective dimensions of the three designs are presented in table 1, with dimension definitions in figure 2.

To the exception of the unit cell’s width v, all the dimensions are described in the respective articles. In the case of the unit cell’s width, this dimension was either unspecified in the article, or inconsistent with Chen et al’s unit cell boundary determination procedure [18], so that in each case we produced or corrected the unit cell’s width using the above procedure. We thereafter noticed small discrepancies between our numerical values and those of he referred articles, as expected since a different value for the effective boundaries of the fishnet could drastically affect the value of the effective refractive index. Still, we were able to retrieve a similar trend in terms of effective parameters between the articles results and ours, so that we can consider the discrepancy between our results and those of the articles to be entirely due to a difference in effective boundary value.

The numerical values of the S-parameters are retrieved using the commercial software CST Microwave Studio. For the proposed structure, the finite integration technique (FIT)-based CST Microwave Studio has been used. In the simulation technique, the unit-cell structure is placed between two waveguide ports, and the electromagnetic waves (plane wave source) are set to propagate in the negative z-direction. The top and bottom boundaries normal to the z-direction are set as open, while the periodic boundary conditions (PBCs) were imposed to the x-direction and y-direction (E_t = 0, H_t = 0), shown in figure 1. To evaluate the EM performance of the structure, a frequency-domain solver (FDS) with a tetrahedral mesh is utilized for simulation from 0.6–2.0 THz. In the simulation, unit cell boundary condition is applied to the x and y boundaries on all of the designs and the unit cells are excited by TE (polarization perpendicular to the vertical wires) and TM waves (polarization parallel to the vertical wires) in the z-direction. From the S-parameter results of the simulation, Chen et al’s effective parameter retrieval procedure [18] is applied in order to produce the effective refractive index, permeability, permittivity and FOM.

FOM is a fundamental parameter to characterize the performance of negative-index metamaterials (NIMs). It describes the ability of electromagnetic (EM) wave propagation through the metamaterial. The FOM is the

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**Table 1.** Dimensions of the three fishnets studied.

| Fishnet | Dimensions (μm) |
|---------|----------------|
|         | u   | v   | a   | s   | m   | d   |
| Zhang   | 0.801 | 0.11 | 0.1 | 0.5 | 0.03 | 0.06 |
| Kafesaki | 9500 | 4500 | 1500 | 7000 | 30 | 1600 |
| Ding    | 150 | 30 | 10 | 115 | 0.4 | 9 |

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**Figure 2.** Dimension definitions used in table 1: u is the side length of the unit cell, s is the side length of the metallic and dielectric slab, a is the width of the arm, v is the thickness of the unit cell, m is the thickness of the metal layers and d is the thickness of the dielectric layer.
comparison of real and imaginary refractive index, and can be defined as $\text{FOM} = \frac{-n' }{n''}$. Where, $n'$ and $n''$ are the real and imaginary part of the effective refractive index of the metamaterial, respectively. Generally, a larger FOM, meaning a lower loss, and EM wave can propagate through the metamaterial, is usually wanted. On the other hand, EM wave attenuates while it propagates through the metamaterial in case of lower FOM value.

The results are presented in figure 3. The effective parameters for the fishnet design are drawn in figure 3 in red, those for the bd design in blue. The real values are represented by solid lines, the imaginary values in dashed lines. The anisotropy of the device is evident by comparing the first and the second column figure 3, where negative refractive index is only exhibited when the device is excited by TM wave. The third column of the figure shows the FOM when the device is excited by TM wave to evaluate the performance of the negative index metamaterial designs. In all of the examined design we observe a recession of the resonant frequency of about 10%. The refractive minimum index becomes lower by approximately a factor of two, while the FOM is itself multiplied by two, meaning a corresponding increase of gain. The numerical results are summed up in table 2. The numerical results indicate a two-fold increase in the FOM value of the bd design for each design dimensions and materials presented by Ding, Kafesaki, and Zhang. It is remarkable, that the highest observed FOM value of the bd design was 6.54 for a refractive index of $n' = -4.86$ at nearly 0.814 THz. This outcome attributes that the metamaterial based bd structure can achieve a high gain since the loss of EM waves is very less while it propagates through the metamaterial.

Figure 3. Comparison between the effective material parameters of the fishnet design (red) and the bd design (blue). Real parts are indicated by solid lines, imaginary parts by dashed lines. The comparison is done using the dimensions and materials presented by (a) Ding, (b) Kafesaki and (c) Zhang.
3.1. Mechanisms behind the improved performances

The mechanisms behind the improved performances of the bd design can be explained as a conjunction of two mechanisms supporting each other: the magnetic resonance within the dielectric layer; and the part of the fishnet leading to the negative permittivity, i.e. the array of metallic wires.

3.2. Magnetic resonance within the dielectric layer

Figure 4 shows a comparison of the surface currents on the front and back face of one unit cell of fishnet at resonance frequency in the fishnet design and the bd design.

As described by Kafesaki et al, we observe a combination of two current modes, in which the current flows in both faces either in the same topological direction or in opposite topological direction. The first mode is
associated with the plasma-like behavior of the metallic wires array, the second with the magnetic resonance in the dielectric layer. The combination of these modes leads to a periodic accumulation and depletion of charges in two precise areas of the metallic surface.

In the fishnet design, the strongest surface currents are observed in the metallic arms part of the structure. In contrast, the bd design shows a maximum current happening on the side of the metallic slab opposed to the metallic arm. This is an important change, as the strongest surface currents lead to the strongest magnetic currents within the dielectric. Since those surface currents are closer to the bulk of the dielectric, we expect a magnetic resonance of larger amplitude in the case of the bd design, which is clearly observed in part c) of figure 4. In addition, we notice that this reduction of intensity in the arm’s surface currents leads to a reduction of the magnetic field in the dielectric layer’s arms, which, running counter to the resonant magnetic field, hinders the latter. This allows, in the case of the bd design, a larger area where the magnetic resonance occurs.

3.3. Electric resonance through the metallic wires

Another cause of the increased performances of the bd design can be found in the metallic wire arrays component of this design. As a reminder, this part of the fishnet design is responsible for the electric resonance and negative permeability of the fishnet. Pendry et al originally demonstrated how a square array of wires leads to a plasma-like behavior [19]. In their investigation, Pendry et al mention how the exact geometry of the array does not matter for the plasmonic behavior to occur; indeed, the original fishnet material is composed not of metallic wires per se but of metallic bands, arranged what is more into a rectangular array instead of a square one.

One could question, however, what happens when a shear deformation is applied to the geometry of the metallic array described by Pendry et al, the same shear that leads to the transformation from the fishnet design to the bd design.

In figure 5 we show the difference of numerically retrieved real permittivity between an array with wires arranged face-to-face and an array with wires shifted from one another. This figure shows how shifting the wires pushes the resonant frequency of the plasmon to higher frequencies, leading, for a given plasmonic frequency, to a lower negative permittivity. This lower negative permittivity contributes to the reduced negative refractive index in the bd design.

4. Conclusion

In this article, we have presented a novel design based on the fishnet design, demonstrating numerically how this bd design presents lower negative refractive index and lower loss than the fishnet design, this effect being sustained for design dimensions ranging from the nanometer up to the millimeter and for various materials. We have investigated two explanations for these superior properties and have performed numerical simulations supporting those explanations. The only caveat the bd design presents compared to the regular fishnet is that of the challenges to convert it, at least as presented in the current frequencies, to an isotropic metamaterial akin to that of Ding et al; while the fishnet can be rendered isotropic by adding arms in both x and y direction while retaining its properties, allowing negative refraction regardless of the polarization of the incoming wave (as long as the latter reaches the metamaterial normally to its surface). However, as discussed in section 31, the enhanced value of the negative index and FOM in the bd design is mainly contributed from the change in metallic
geometry towards the edge of the device. The change in geometry shift the location of the strongest surface current away from the metallic arm to the metallic slab, which increases amplitude of the magnetic resonance and also it lowers the permittivity of the design further into the negative region. Since the new design focuses the magnetic current to the central of the device, the geometry of the dielectric pattern, especially, on the edges, can be varied to reduce the difficulty of the potential fabrication challenges without significant impact on the performance of the bd design. In addition, if arms are to be fabricated, it can be done by Electron-beam lithography (EBL) technique within the overlay tolerance ranges. The EBL overlay process can be applied to fabricate genuine suspended and connected nanostructures. Another technique can also be employed to fabricate such suspended nm structure called tip-based nanofabrication (TBN) technique. The advantages of TBN include total process time as well as process flexibility. First, the turnaround time of tip based nanofabrication can be shorter than when using EBL. The tip scanning speed reported by TBN achieved 100 mm s⁻¹ faster than the scanning speed of a commercial high-resolution Gaussian EBL system. Regardless, this addition in the bd design interferes with the mechanism that makes it otherwise a candidate of choice for applications such as invisibility systems and superlenses requiring ever lower negative refractive index and loss.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Wei-Chih Wang https://orcid.org/0000-0003-3571-4743

References

[1] Veselago V G 1968 Electrodynamics of substances with simultaneously negative electrical and magnetic permeabilities Sov. Phys. Usp. 10 504–9
[2] Pendry J B 2000 Negative refraction makes a perfect lens Phys. Rev. Lett. 85 3966
[3] Smith D R and Kroll N 2000 Negative refractive index in left-handed materials Phys. Rev. Lett. 85 2933
[4] Pendry J B, Schurig D and Smith D R 2006 Controlling electromagnetic fields Science 312 1780–2
[5] Leonhardt U 2006 Optical conformal mapping Science 317777–80
[6] Pendry J B and Smith D R 2006 The quest for the superlens Sci. Am. 295 60–7
[7] Kafesaki M, Tsiafi A, Katsaralts N, Koschyn T, Soukoulis C and Economou E 2007 Left-handed metamaterials: the fishnet structure and its variations Physical Review B 75 235114
[8] Dani K M, Ku Z, Upadhyya P C, Prasankumar R P, Taylor A J and Brueck S 2011 Ultrafast nonlinear optical spectroscopy of a dual-band negative index metamaterial all-optical switching device Opt. Express 19 3973–83
[9] Soemphol C, Sonsilphong A and Wongkasem N 2013 Metamaterials with near-zero refractive index produced using fishnet structures J. Opt. 16 015104
[10] Valentini J, Zhang S, Zentgraf T and Zhang X 2011 Development of bulk optical negative index fishnet metamaterials: Achieving a low-loss and broadband response through coupling Proc. IEEE 99 1682–90
[11] Cheng Y, Nie Y and Gong R 2012 Broadband 3D isotropic negative-index metamaterial based on fishnet structure The European Physical Journal B 85 1–6
[12] Brindabanova D, Habib M, Issah I and Caglayan H 2021 Low loss fishnet metamaterial via self-rolled nanotechnology Appl. Phys. Lett. 119 141101
[13] Rottler A, Harland M, Broll M, Schweiger S, Stickler D, Stemmann A, Heyn C, Heitmann D and Mendach S 2012 Rolled-up nanotechnology for the fabrication of three-dimensional fishnet-type GaAs metamaterials with negative refractive index at near-infrared frequencies Appl. Phys. Lett. 100 151104
[14] Gómez-Castiaño M, García-Pomar J L, Pérez L A, Shanmugathasan S, Ravaine S and Mihi A 2020 Electrodeposited negative index metamaterials with visible and near infrared response Adv. Opt. Mater. 8 2000865
[15] Ding P, Liang E, Hu W, Zhang L, Zhou Q and Xue Q 2009 Numerical simulations of terahertz double-negative metamaterial with isotropic-like fishnet structure Photonics and Nanostructures-Fundamentals and Applications 7 92–100
[16] Zhang S, Fan W, Malloy K, Brueck S, Panoiu N and Osgood R 2005 Near-infrared double negative metamaterials Opt. Express 13 4922–30
[17] Dolling G, Enkrich C, Wegener M, Soukoulis C M and Linden S 2006 Low-loss negative-index metamaterial at telecommunication wavelengths Opt. Lett. 31 1800–2
[18] Chen X, Grzegorczyk T M, Wu B J, Pacheco J Jr and Kong J A 2004 Robust method to retrieve the constitutive effective parameters of metamaterials Phys. Rev. E 70 016608
[19] Pendry J B, Holden A, Robbins D and Stewart W 1998 Low frequency plasmons in thin-wire structures J. Phys. Condens. Matter 10 4785