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Characterization and tilted response of a fishnet metamaterial operating at 100 GHz

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Abstract
We numerically and experimentally investigate a fishnet metamaterial operating at around 100 GHz. Qualitative effective medium theory and standard retrieval characterization methods are performed to demonstrate the double negative nature of the fishnet structure. This study is extended to include the effects of a finite number of unit cells at each layer and the number of layers in the propagation direction. Finally, we study the response of the metamaterial layer when the metamaterial plane normal and the propagation vector are not parallel.

(Some figures in this article are in colour only in the electronic version)

By introducing artificial periodic structures, the so-called metamaterials, the naturally available range of matter–wave interactions can be extended. In the electromagnetic domain, the parameters permittivity (ε) and permeability (μ) of the material specify its response to the incident electromagnetic wave. By determining the shape and content of the unit cell of an electromagnetic metamaterial we can control the permittivity and permeability values and thereby obtain values including the negative ones at any desired frequency. The resulting unusual properties such as negative refraction, negative phase velocity and the reversal of Cherenkov radiation and Doppler shift were first predicted by Veselago in 1968 [1]. For the physical realization of metamaterials, the currently available planar substrate based technologies such as printed circuit board technology as well as optical and e-beam lithography techniques were used. One can obtain a double negative medium by superposing ε-negative ($\varepsilon < 0$) and μ-negative ($\mu < 0$) media. Negative media were demonstrated by using ferroelectric [2,3], ferromagnetic [4–6], ferrimagnetic [7] materials and nonmagnetic metal-dielectric structures [8] in the content of the metamaterial unit cell.

We can use cylindrically shaped ferroelectric ceramics with very high permittivity as the unit cell of metamaterials [2]. Large displacement current occurs due to the high permittivity of the ferroelectric rods and creates a subwavelength resonance at around 7 GHz [2]. Moreover, dense displacement currents of the periodic structure help the medium to act like a plasma [2]. In another study, by arranging subwavelength ferroelectric cubes in a three-dimensional array, a negative permeability medium with a tunable operation frequency (13.65–19.65 GHz) was obtained [3]. The cubes showed strong subwavelength magnetic resonance at the first Mie resonance mode, which was tuned by changing the temperature from −15 to 35 °C [3]. The possibility of a double negative medium, in which metallic ferromagnetic nanoparticles were arranged in an insulated matrix, was discussed theoretically [4]. Negative permittivity was automatically obtained when the operation frequency was less than the plasma frequency of the system and in the vicinity of ferromagnetic resonance (FMR), in which the effective permeability of the ferromagnetic materials can be negative [4]. Double negative media utilizing FMR were demonstrated experimentally at around 10 GHz [5] and 90 GHz [6]. Construction of an artificial double negative medium is also possible by using an array of wires cladded in a nonmagnetic dielectric and embedded in a ferrimagnetic host [7]. The results on the experimental demonstration of ferroelectric- and ferromagnetic-based metamaterials are rare and are still being developed.

The most common way to obtain a double negative medium is the usage of nonmagnetic metallic resonators [8] and wire mesh [9]. The proposition of electrically small resonators as the unit cell of μ-negative media [10] is followed by pushing the magnetic resonance frequency to higher [11, 12] and lower [13, 14] frequencies, while keeping the physical size of the resonator fixed. In these studies, the saturation of the magnetic resonance frequency due to metallic losses is observed. As the period of the incident wave becomes smaller, the electrons cannot complete the full necessary path in the resonator. The critical parameters here are the Fermi velocity (v_F) and the electron relaxation time (τ), which are relatively fixed by the metal type and environment temperature [15]. Instead of patterning resonators on one face of the planar substrate and stacking many layers in order to cover the incident electromagnetic wave, the cut-wire pair resonators that were introduced [16] use both faces of the planar substrate while designing the μ-negative medium. Cut-wire pair based metamaterials removed several technological challenges; however, their rather large electrical size is a drawback. The connected cut-wire and wire mesh media on both faces of a planar substrate are called fishnet metamaterials. Fishnet metamaterials operating at GHz, [17, 18] near-IR [19] and IR [20] regimes have been demonstrated experimentally. In this paper, the characterization of a fishnet metamaterial operating at 100 GHz is described.

There are two well-developed methods to determine whether a metamaterial slab is double negative for the particular polarization and frequency of the incident electromagnetic wave. The first one is the qualitative effective medium theory [21–23]. We begin by considering the transmission data of the μ-negative medium, which is composed of periodically arranged subwavelength resonators. The magnetic resonance of each resonator originates from the circular currents induced on it. By shorting the resonators we compose another medium and thereby expect different transmission characteristics. In order to obtain the double negative medium we superpose the ε-negative wire mesh and μ-negative periodic resonator media. Even though the wire mesh might have a negative ε below its plasma frequency, the composite medium shows a different plasmonic behaviour. Therefore, in addition to the transmission data of the double negative medium, we also obtain the transmission data of composite wire mesh and shorted resonator media. In total, by measuring the transmission characteristics of four different media we qualitatively conclude as to whether the slab is double negative or not.

A rather robust method is the standard retrieval analysis, in which instead of four different structures, only the double negative metamaterial is measured. However, complex transmission and reflection parameters are necessary. The electrically small nature of the metamaterial unit cell enables us to assign an effective index (n) and impedance (z) values to the slab that can be extracted from the complex scattering parameters. Effective permittivity and permeability are found via the formulae $\mu = nz$, $\varepsilon = n/z$. There are many studies on the retrieval analysis of metamaterials in the literature; in this work we follow the formulation of [24, 25].

In our numerical calculations we utilize CST-Microwave Studio, which is a full wave commercial code based on the finite integration technique. We insert the unit cell of the medium in a hollow waveguide and choose the boundary conditions in such a way that the waveguide supports a transverse electromagnetic mode with a vertically polarized electric field (E_y) and a horizontally polarized magnetic field (H_x). The boundary conditions at the top and bottom walls are perfect electric conductor (PEC) and at the left and right walls are perfect magnetic conductor (PMC). By this method we obtain the scattering parameters of the infinitely periodic unit cell in the lateral directions, if the unit cell is symmetric with respect to the x–z and y–z planes.

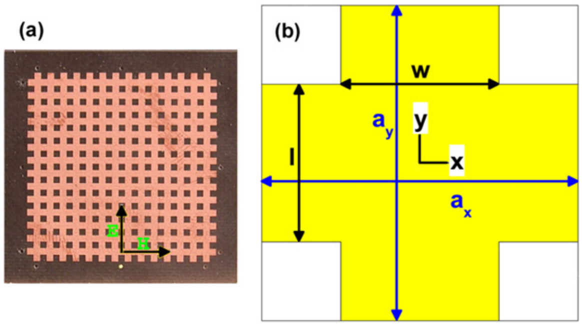

Figure 1. (a) A front view photograph of the fabricated fishnet metamaterial layer. The electromagnetic wave propagates in the $-z$-direction, in which the E-field and B-field are along the y- and z-directions. (b) The geometry of one unit cell of the fishnet metamaterial.

The front view photograph of the fishnet metamaterial and unit cell are shown in figure 1. There are 14 unit cells in the lateral directions, the incident E-field is in the y-direction, the B-field is in the x-direction and the propagation vector is in the $-z$-direction. The periods in the x- and y-directions are $a_x = a_y = 2$ mm, the cut-wire pair length is $l = 1$ mm and the wire width is $w = 1$ mm. The relative permittivity of the substrate is $\varepsilon_r = 2.2 + i0.0009$ and the substrate thickness is 254 μm. The coated copper thickness and conductivity are 9 μm and 5.8×10^7 S m^{-1}, respectively.

The results of the qualitative effective medium theory are shown in figures 2 and 3. The electrically small cut-wire pair resonator geometry and induced surface current at the resonant frequency are shown in figure 2(a). The circulating currents that are driven by the capacitance between the cut wires resemble a magnetic dipole response. When we short the capacitance, as shown in figure 2(b), the circulating currents disappear and the response becomes similar to an electric dipole. The corresponding effect on the transmission spectra is the disappearance of the stop band, as shown in figure 3(a). We can thereby infer merely by considering the transmission spectra as to whether the stop band was magnetically originated. In figures 2(c) and (d) we exhibit the fishnet metamaterial unit cell and its shorted version. The fishnet metamaterial is composed of cut-wire pairs that are connected to long continuous wires along the vertical (y) direction. The long continuous wires act as a low frequency plasmon system with a plasma frequency that is larger than the metamaterial operation frequency. The plasma response of the fishnet structure is expected to be very similar to the shorted version. Therefore, from the transmission data shown in figure 3(b) we infer that the medium is ε-negative for

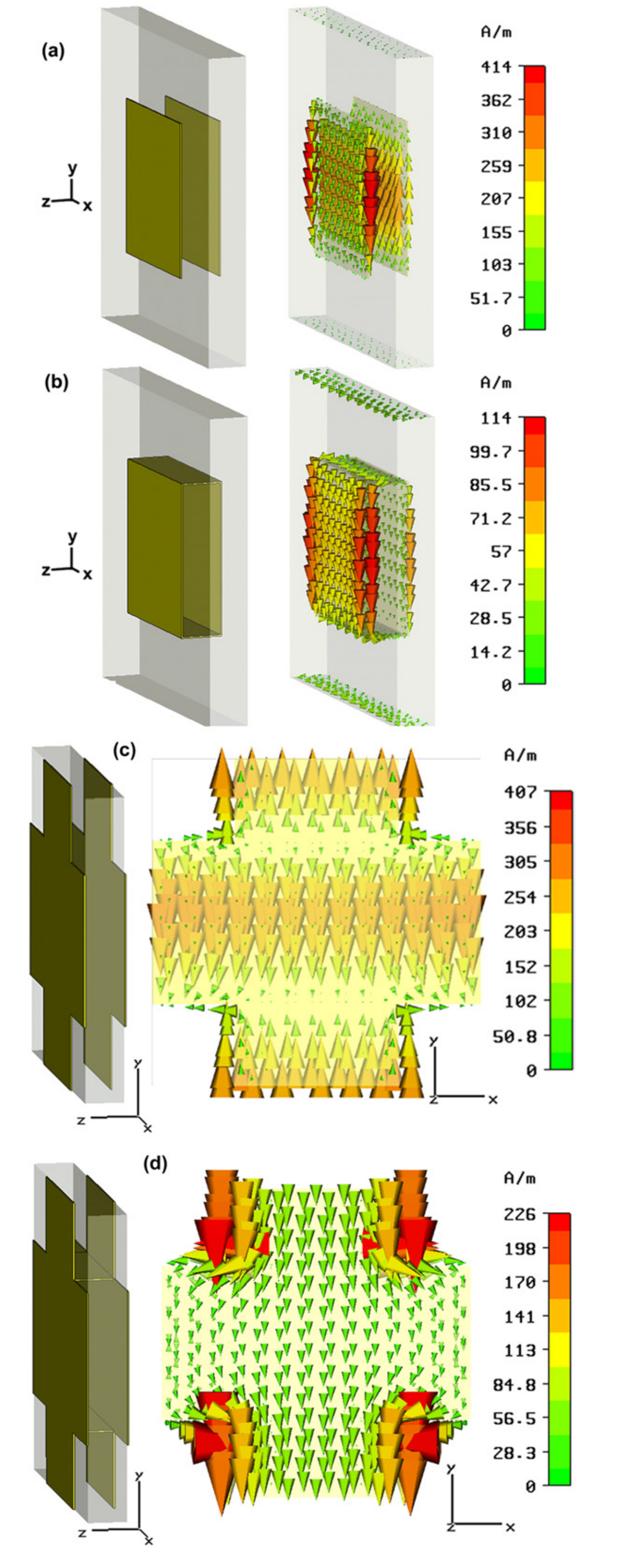

Figure 2. The schematic view and surface current: (*a*) the cut-wire pair (cwp), (*b*) shorted cut-wire pair (sh-cwp), (*c*) fishnet (fn) and (*d*) shorted fishnet (sh-fn).

$f < 120$ GHz and the transmission peak at $\sim$100 GHz is the result of the double negative nature of the fishnet metamaterial.

Finally, we present the standard retrieval analysis results. By using the complex scattering parameters we extract the

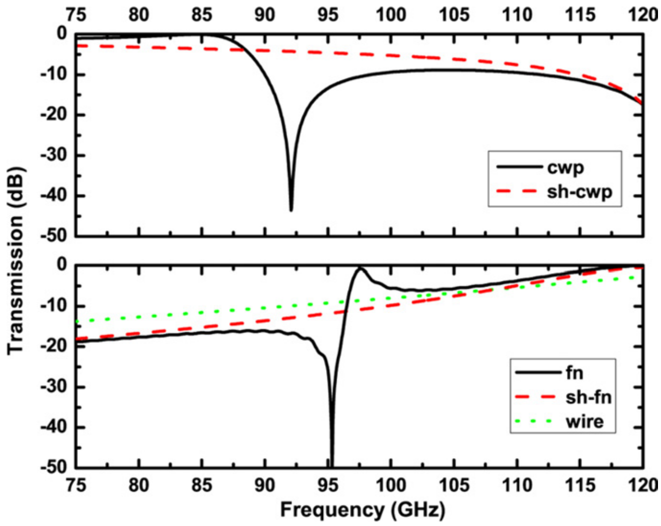

Figure 3. Transmission spectrum magnitude for one layer of structures in the propagation direction: (*a*) the cut-wire pair (cwp) and its shorted version. (*b*) fishnet (fn), shorted fishnet (sh-fn) and the wire mesh medium.

index and impedance of the one layer fishnet metamaterial. The real part of the refractive index, permeability and permittivity are negative at around the transmission peak, figure 4. The resonant nature leads to the narrow bandwidth of metamaterials. The fractional bandwidth of the negative region is calculated via FBW $= \Delta f/f_0$, where Δf is the half power bandwidth and f_0 is the centre frequency. Here we obtain $\Delta f = 1.57$ GHz, $f_0 = 97.7$ GHz and FBW is 1.6%, which is a typical value for a fishnet medium [18]. We would like to emphasize that for any arbitrary polarization of the plane perpendicular incident wave the response of the metamaterial is the same because the unit cell of the fishnet metamaterial is symmetric with respect to the x–z and y–z planes.

For the experimental demonstration we use a millimetre-wave network analyzer that has a 50 dB dynamic range at the 75–115 GHz band. The experiments are performed in free space and room temperature by using two standard gain horn antennas. We kept the distance between (16 mm) and orientation of the antennae fixed and used the free space transmission data as calibration data. We stacked several layers in the propagation direction with a layer to layer separation of 250 μm. Spacers are placed at the very edges of the metamaterial layers so that the medium between the layers is air. In figure 5 the experiment and corresponding simulation data are shown. We see a narrow transmission band at around 100 GHz. The experiment and simulation results are in good agreement in terms of the operation frequencies; however, the transmission magnitude in the experiment is rather low. At this point we would like to investigate the possible reasons for the discrepancies between the experiment and simulations in two groups: the fabrication-based and alignment-based discrepancies. At the fabrication step, there may be small deviations of the material parameters from the intended values in terms of the size of the metallic features and misalignment of the features at the front and back faces of the substrate. However, our fabrication is a very well-controlled process wherein the accuracy of the feature size is less than

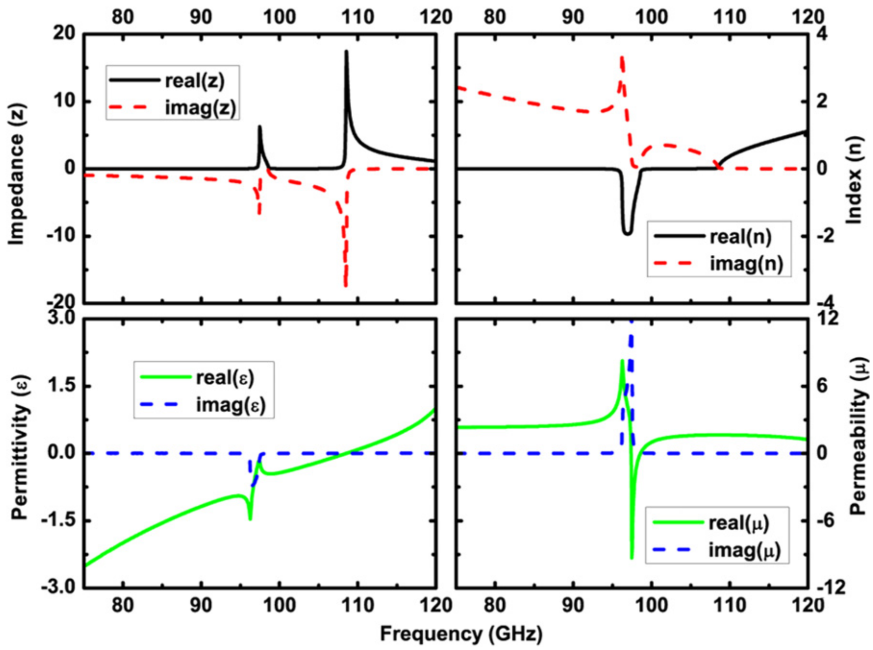

Figure 4. Extracted parameters as a function of frequency for the fishnet metamaterial medium.

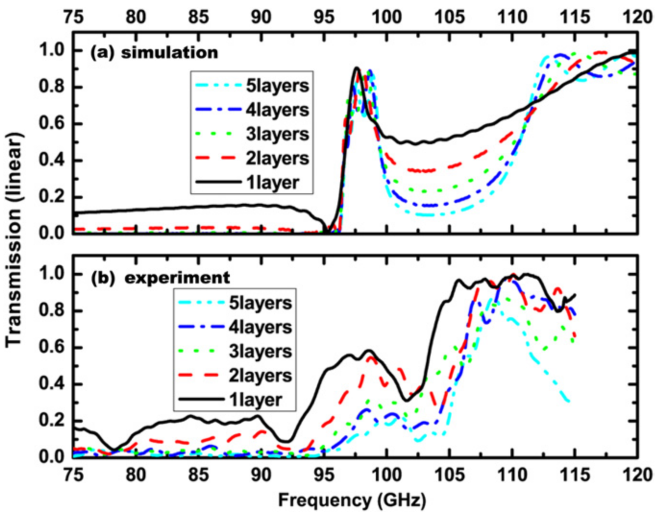

Figure 5. Transmission spectra in linear scale for several number of fishnet layers in the propagation direction. (*a*) Simulations and (*b*) experiments.

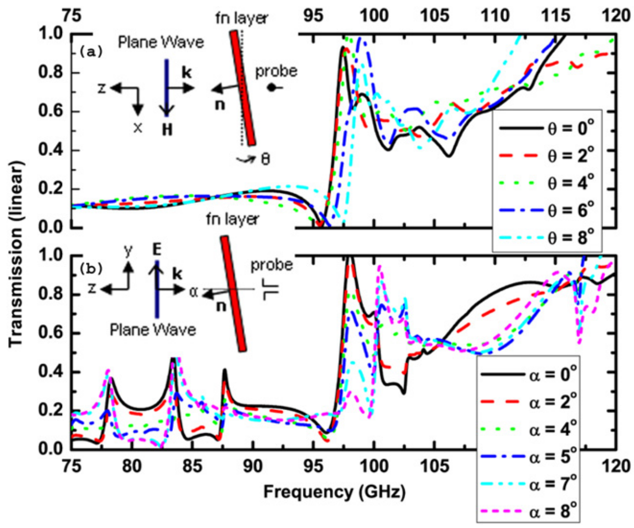

Figure 6. Transmission spectra for a number of incidence angles in a linear scale. The metamaterial layer is tilted, and the insets show the simulation configurations: (*a*) *H*-field makes a 2α angle. (*b*) *E*-field makes a θ angle with the metamaterial plane normal. The probes measure the *E*-field.

a micrometre. Therefore, we do not expect any significant fabrication-based discrepancies. On the other hand, as the operation frequency increases the alignment of the several stacked layers keeping the angle between the antenna emission normal and the metamaterial plane normal as zero becomes rather difficult. This difficulty encourages us to investigate the tilted response of the fishnet metamaterial layer.

We numerically studied the response of the fishnet metamaterial medium to an incident plane wave with a nonzero angle of incidence. In the simulations, we first fixed the number of unit cells to 14 in the horizontal direction (x) and the infinitely periodic state remains in the vertical direction (y), as shown in the inset of figure 6. As we rotate the metamaterial layer with respect to the y-direction with a rotation angle θ, we see a shift in the resonance frequency. Therefore, the narrow-band metamaterial does not operate at the same frequency any more, as shown in figure 6(*a*). Next, we fixed the number of unit cells in the vertical direction while keeping the infinite periodic condition in the horizontal direction. When the angle of incidence (α) increases, we observe that the negative transmission peak dies out at the operation frequency, which is shown in figure 6(*b*). From these results we can also see the effect of the finite number of unit cells in one of the lateral directions. The possible reason for the low transmission peaks in the experiment was the nonzero angle of incidence. At this point we would like to emphasize that planar metamaterials are not suitable for superlens [26] applications since their response is very sensitive to the angle of incidence.

To sum up, the characterization of a planar metamaterial operating at 100 GHz is demonstrated in terms of the qualitative effective medium theory and the standard retrieval analysis. The structure layers are produced via printed circuit board technology and then the transmission response for the increasing number of layers is analysed. When the linear polarization of the incident field changes, the transmission data remain the same if the angle between the structure plane and the propagation vector is kept fixed. This is due to the x–y plane symmetric design of the metamaterial. On the other hand, we also demonstrate the case for which the incidence angle is nonzero. The response of the medium changes very quickly as we increase the angle of incidence. We demonstrated that planar metamaterials are sensitive to the angle of incidence and this is a major drawback for superlens applications.

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