Negative index metamaterial combining magnetic resonators with metal films

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Abstract: We present simulation results of a design for negative index materials that uses magnetic resonators to provide negative permeability and metal films for negative permittivity. We also discuss the possibility of using semicontinuous metal films to achieve better manufacturability and enhanced impedance matching.

OCIS codes: (160.4760) Optical properties; (260.5740) Resonance

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1. Introduction

The refractive index ($n = n' + in''$) is a key parameter describing the interaction of light with matter, where the real part n' is usually considered to be positive, which is in fact true for all naturally existing materials. However, a case with $n' < 0$ does not violate any physical laws; indeed such materials will have some very interesting properties making them good candidates for a plethora of valuable applications. Since such materials do not exist in nature they have to be artificially fabricated. In a material with a permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ and permeability $\mu = \mu' + i\mu''$, the condition $\varepsilon' < 0$ and $\mu' < 0$ is sufficient for $n' < 0$ [1]. But the condition $\varepsilon''\mu' + \mu''\varepsilon' < 0$ represents the necessary condition for a negative refractive index in a passive medium [2], where for example, a material with a large loss can have $n' < 0$ even if ε' and μ' are not negative simultaneously. Such a material will undoubtedly have a large loss preventing any useful application.

The first experimental demonstration of a negative index material (NIM) was given in the microwave frequency range using an array of metal lines and split ring resonators [3]. Negative index of refraction was demonstrated in optical frequencies using an array of paired nanorods [4], an array of elliptic voids in a multilayered structure [5,6] and a fishnet structure [7]. In this paper we present a simpler and intuitive 2D geometry which shows a pronounced negative refractive index.

2. Magnetic resonator based on a pair of metal nanostrips

It was predicted that a pair of metal rods separated by a dielectric can give rise to artificial permeability due to a localized plasmonic resonance [8-10]. In fact a pair of nanorods can have two kinds of resonance: a symmetric resonance, which results in an artificial permittivity and an asymmetric resonance, which gives rise to an artificial permeability; the two resonances make it possible to have a negative refractive index as was first predicted in [9]. In general, these two resonances occur at different wavelengths. We use a simplified 2D version of a nanorod pair as a magnetic resonator. This structure consists of two nanostrips separated by a dielectric as shown in Fig. 1(a). The strips are infinite in the direction perpendicular to the plane of the page (*y*-direction). The sample consists of an array of nanostrip pairs distributed periodically along the *x* direction. The incoming field is oriented in TM polarization as shown in Fig. 1(a). Similar to the nanorod pair, the nanostrip pair has two different principal resonances (the magnetic and electric resonance respectively). The metal nanostrips are assumed to be made of silver because of its low losses. The dielectric spacer between the nanostrips is taken to be alumina because the relatively large refractive index of alumina is confining the field between the nanostrips. The space between adjacent pairs of nanostrips is filled with silica providing mechanical support for further lamellar stacking.

The complex transmission and reflection coefficients of this structure were calculated using a spatial harmonic analysis based code and verified with a commercial FEM solver. The permittivity of silver was taken from tabulated experimental values [11]. The transmission and reflection coefficients were then used to retrieve the effective refractive index and impedance for the nanostrip composite [12, 13]. Figure 1(c) and (d) show the effective permeability and permittivity for the following design parameters, t = 30 nm, d = 40 nm, w = 300 nm, p = 600 nm (refer Fig. 1(a) for the key to the symbols). We note that there are two distinct resonances: a magnetic resonance around 1700 nm and an electric resonance around 900 nm. The spatial field distribution is plotted as insets at two different wavelengths (1720 nm in Fig. 1(c) and 910 nm in Fig. 1(d)). The field maps are shown for only half of the nanostrip pair to preserve space. In the field maps, the arrows represent electric displacement, whereas the
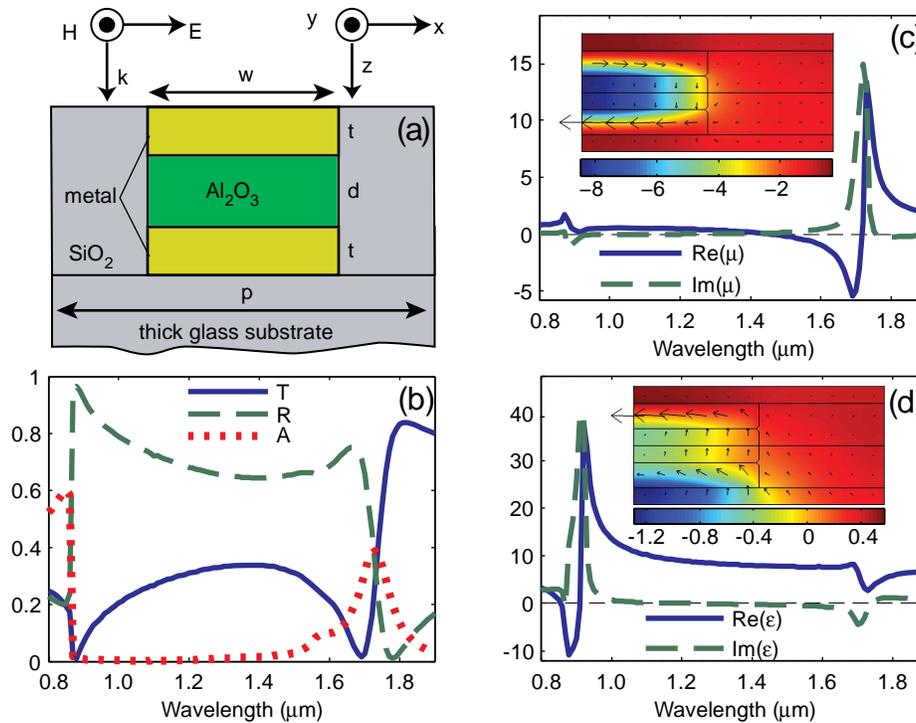
Fig. 1. (a) Unit cell for the array of nanostrip pairs; (b) Transmittance (T), reflectance (R) and absorbance (A) for the nanostrip pair array; (c) Effective permeability and field map at 1720 nm; (d) Effective permittivity and field map at 910 nm. In the field maps the arrows represent the electric displacement and the colormap represents the magnetic field.

color represents the value of the magnetic field. We can clearly see the origin of the effective permittivity and permeability. At 910 nm the electric displacement vectors in both nanostrips are aligned and yield a symmetric resonance which gives rise to an effective permittivity. However, at 1720 nm the electric displacement vectors in both nanostrips are opposite to each other. This creates a strong magnetic field between the two nanostrips which gives rise to an effective permeability. The wavelengths of these two resonances depend largely on the width and aspect ratio of the nanostrips. In order to obtain a strong resonance, the periodicity and the thickness of dielectric layer have been optimized. We also note the presence of an electric and a magnetic anti-resonance at 1700 nm and 900 nm, respectively. This is the result of the periodicity in the structure and has been studied extensively [14]. Because of the presence of the anti-resonances it is hard to overlap the magnetic and electric resonances, since as the electric and magnetic resonances get closer to each other the anti-resonances increase in strength, nullifying the resonance for one of the two quantities (permittivity or permeability).

The transmittance and reflectance spectra are shown in Fig. 1(b). We note the relations between the Fig. 1(b) and Fig. 1(c,d). The real and imaginary parts of the permeability around 1700 nm show good correspondence with the transmittance and absorbance as expected. On the other hand the real part of the permittivity around 900 nm shows good correspondence with the transmittance, but there is no absorption corresponding to the electric resonance. There is an absorption band below 860 nm, but that corresponds to the radiation loss due to diffraction. Hence, the electric resonance does not result in any appreciable absorbance.

In case of a transverse electric (TE) excitation the structure acts like a diluted metal with the plasma wavelength shifted to a higher value with respect to bulk metal [15].

3. NIM using a magnetic resonator and continuous metallic films

In the previous section we saw that a pair of nanostrips can generate a strong magnetic resonance resulting in a negative permeability. Now all we need for creating a negative index
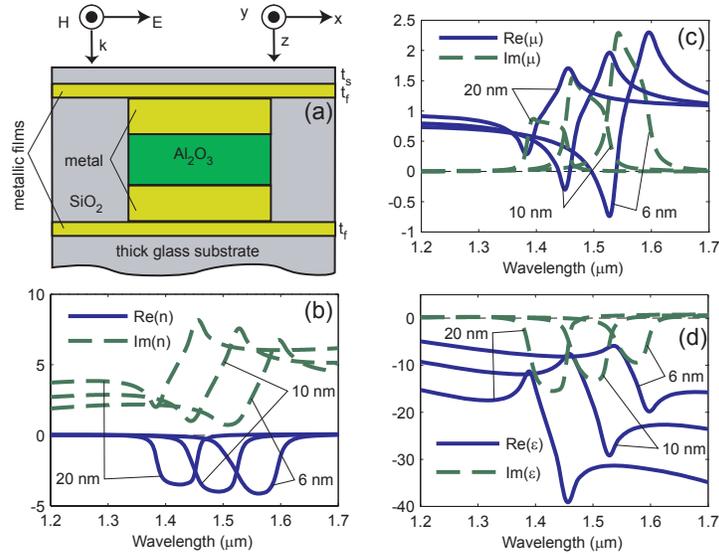
Fig. 2. (a) Unit cell with a magnetic resonator and metallic (silver) films on top and bottom; (b) Effective refractive index with t_f = 6 nm, 10 nm and 20 nm. For all cases t_s = 20 nm; (c) Effective permeability; (d) Effective permittivity.

material is a negative permittivity. This is easy to achieve since noble metals like gold and silver have negative permittivity at optical frequencies. Hence adding a metal film above and below the magnetic resonator as shown in Fig. 2(a) should be sufficient to provide a negative permittivity. We note that an alternative way to provide negative permittivity is to use continuous wires [16]. In our design the films are brought in contact with the strips to avoid additional resonances due to the interaction between the strips and the films. Our simulations have shown that such additional resonances are detrimental to the magnetic properties of the nanostrip pair. The additional layer of silica on the top functions as a seal preventing the silver from being oxidized or sulfurized due to exposure to air. Intuitively, only one metal film should suffice since we can use a single thick film instead of two thin films to provide similar permittivity. However, using two films ensures that the structure is symmetric and justifies the use of the retrieval formula to extract the effective optical parameters of the structure. The retrieval procedure assumes that the structure is symmetric. Furthermore, using a single film would also generate additional resonances due to the interaction between the isolated strip and the film. This interaction is suppressed through the use of two films.

The dimensions of the nanostrips were taken from the previous section and simulated for 6, 10 and 20 nm silver films. The structure is assumed to be coated with a 20 nm thick silica layer. The effective refractive index, permeability and permittivity are shown in Fig. 2. Here $n' < 0$ in all cases, but the real part of the permeability is negative only for 6-nm or 10-nm metal films (note that n'' is also much lower when $\mu' < 0$). The sample with 6-nm films has a maximum transmittance of 27% and $n' < 0$ at a wavelength of 1520 nm. The refractive index at this wavelength is −2.38 + 0.84i. However it should be remembered that it is barely possible to fabricate a continuous 6 nm silver film (the film would be essentially semi-continuous). Typically, the film thickness should be at least 20 nm to ensure that the silver is continuous, but as it is clear from Fig. 2, the performance is much worse with 20-nm film. For example the minimum of n'' is about 2.5 times as large for the 20 nm thick silver films as compared to the 6 nm thick films (Fig. 2(b)). This is a direct effect of $\mu' > 0$ (Fig. 2(c)).

We also notice that the magnetic resonance is at shorter wavelengths for the thicker films. The addition of the metal films causes the currents in the nanostrips to leak into the metal films, especially towards the ends of the nanostrips. This reduces the effective width (w) of
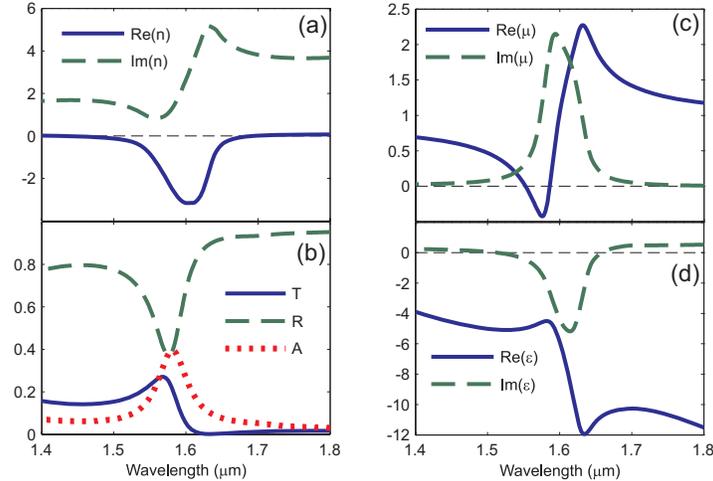
Fig. 3. Effective parameters and spectrum for the structure with semicontinuous silver films (metal filling fraction = 65%, thickness = 20 nm). (a) Effective refractive index, (b) Transmittance, reflectance and absorbance spectra, (c) Effective permeability, (d) Effective permittivity.

the nanostrips which results in a shorter resonance wavelength. This leakage of current also has the effect of diminishing the resonance in permeability.

4. NIM using a magnetic resonator and semicontinuous metallic films

So far, our simulations have shown that combining continuous metal films with nanostrip magnetic resonators can easily yield a negative index metamaterial. Unfortunately, that requires unrealistically thin metal films. The problem arises because silver has a highly negative ε' around 1.5 µm, but the magnetic resonator can not provide a comparable value of negative μ'. This results in a huge impedance mismatch and a subsequent large reflection which degrades the magnetism of the entire structure. Furthermore, a thick film would shield the incoming field more efficiently, thus suppressing the performance of the magnetic resonator. A possible way to circumvent this problem is to use a thinner metal film, except the minimum thickness is limited by the material properties and fabrication tolerances.

Instead of bulk metal, the films can be formed with a mixture of silica and metal (semicontinuous metal films, SMF). Such films can be fabricated using very basic techniques like sub-monolayer evaporation. The permittivity of a SMF can be well described by the effective medium theory (EMT) [17]. According to EMT, the effective permittivity (ε_e) of a d-dimensional metal-dielectric composite consisting of a metal with permittivity ε_m and a filling fraction of f, and a dielectric with permittivity ε_d and filling fraction of $1-f$ is given by Eq. (1). This is a quadratic equation which has two solutions for ε_e. We select the solution that has a positive imaginary part ($\varepsilon_e'' \geq 0$).

$$ f\left(\varepsilon_m - \varepsilon_e\right)/\left[\varepsilon_m + (d-1)\varepsilon_e\right] + (1-f)\left(\varepsilon_d - \varepsilon_e\right)/\left[\varepsilon_d + (d-1)\varepsilon_e\right] = 0 \qquad (1) $$

The performance of EMT has been tested against an enhanced formulation solved numerically using block elimination method [18] and it has been confirmed that EMT provides good agreement with the numerical method except for some minor differences. It can be concluded that the EMT describes the optical properties of semicontinuous metal films quite accurately for typical sizes of metal grains (10 to 50 nm), film mass thicknesses between 5 and 15 nm, and for the broad range of metal filling factors, from roughly 0.2 to 0.8.

According to EMT, the permittivity of a SMF is much less negative as compared to bulk metal films. Hence we can have a SMF that is thick enough to be fabricated easily while having a real part of the permittivity which can be matched with the permeability created by magnetic resonators. This is critical for impedance matching.

For example, consider a structure similar to that of Fig. 2. This time, semicontinuous silver films are used instead of the continuous silver films. We assume the SMF to have a metal filling fraction of 65%. The physical thickness of the SMF is 20 nm, which is quite easy to achieve. The permittivity of the SMF was calculated using two dimensional EMT. The results of the simulation are shown in Fig. 3. The real part of the refractive index is negative between 1500 nm and 1650 nm. The transmittance spectrum has a maximum value of 27% at 1570 nm. The refractive index has a value of $-1.85 + 0.93i$ at the wavelength of maximum transmittance. We note that the transmittance is better than in the case with 10 nm continuous silver films although the SMF contains more metal than a 10 nm continuous silver film.

5. Conclusions

We examined the magnetic behavior of nanostrip pair arrays that was found to posses a strong magnetic resonance, which results in a negative permeability. By changing the dimensions of the nanostrip, the region of negative permeability is wavelength tunable. The nanostrip pair array can be modified without difficulty to exhibit a negative refractive index by fusing metal films on the top and bottom of the nanostrip pair. The fusing of the films with the nanostrips is essential to avoid additional resonances due to the interaction of the nanostrips with the films.

A homogeneous silver film provides a highly negative permittivity, which can not be matched with the permeability provided by the magnetic resonator. The resulting impedance mismatch significantly deteriorates the properties of the complete structure. Hence we use semicontinuous metal films (SMF) to take this problem into account. The use of SMFs provides an additional degree of freedom in optimizing the behavior of such metamaterials.

Certainly, there are other ways to achieving the same goal, using for example an array of elliptical voids [5, 6] or a fishnet geometry [7]. The fishnet geometry is typically fabricated using E-beam lithography, which severely limits the size of the sample. In contrast, a larger array of elliptical voids can be fabricated with interference lithography, though such a sample has the possible disadvantage of variable width of the magnetic resonators, since both the shape and dimensions of the voids are limited by the resolution of the fabrication process. In our geometry a large array of magnetic resonators can be fabricated with a high fidelity using interference lithography, since only two interfering beams are required for fabricating the magnetic substructure. The semicontinuous films can be deposited efficiently using a standard E-beam or thermal evaporation. Thus our strategy allows for the fabrication of larger structures through relatively inexpensive means.

The structure can also be easily stacked on top of each other since the top metal film can be made reasonably flat (with roughness on the order of a few nanometers) using current technology. The top metal film can then act as an ideal platform for further layers. Aligning the different layers can be challenging, but the difficulties are comparable to the stacking of other structures currently in use such as elliptical voids or fishnets. Nevertheless the properties of the metamaterial will definitely change on stacking multiple layers due to the interaction between the different layers. This is a problem that needs to be studied in detail taking into account the specific application that is being targeted with the metamaterial. An approach similar to the one presented in [19] could be used to study the effect of stacking.

We could also extend the idea and fabricate the nanostrips using semicontinuous metal instead of bulk metal. This will provide us with more flexible means of making manufacturable resonant metallic elements and adjusting their properties.