Double Negative Index Metamaterial: Simultaneous Negative Permeability and Permittivity at 812 nm

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Abstract: A negative index metamaterial demonstrating $n = -1.0 + 0.8i$ with both negative effective permittivity and permeability at 813 nm of linearly polarized light is fabricated. It also exhibits a negative refractive index at 772 nm for orthogonal polarization.

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The refractive index ($n = n' + in''$) is the key parameter in the interaction of light with matter. While n' has generally been considered to be positive, the condition $n' < 0$ does not violate any fundamental physical law. Negative index metamaterials (NIMs) with $n' < 0$ have some remarkable properties that promises a number of novel applications. Typically a NIM consists of an artificially engineered material which has a negative n' for a certain range of wavelengths. A material with simultaneously negative real parts of its effective permeability and permittivity ($\varepsilon' < 0$ and $\mu' < 0$), always has a negative real part of its refractive index. However, $\varepsilon' < 0$ and $\mu' < 0$ is a sufficient condition, but not a necessary condition. A material can have a negative refractive index if its effective permeability and permittivity satisfy the following 'necessary' condition, $\varepsilon'\mu'' + \varepsilon''\mu' < 0$. Hence, its refractive index can be negative even if only permeability (or permittivity) has a negative real part, provided that the imaginary part of permittivity (or permeability) is large enough to make $\varepsilon'\mu'' + \varepsilon''\mu'$ negative. The 'necessary' condition implies that a passive material can not have $n' < 0$ with $\mu = 1 + 0i$, indicating the necessity of a magnetic response.

From the above discussion it follows that there are two types of NIMs. A "Double-negative NIM" (DN-NIM) is a material with simultaneously negative real parts of permittivity and permeability. In contrast, a "Single negative NIM" (SN-NIM) is a material that has a negative refractive index with either ε' or μ' (but not both) being negative. In all the optical SN-NIM reported in literature to date, the real part of permittivity is negative whereas the real part of permeability is positive ($\varepsilon' < 0$, $\mu' > 0$). This is the case since it is much easier to get a negative permittivity as compared to a negative permeability at optical wavelengths. For example, noble metals have a negative permittivity at optical wavelengths longer than the plasma wavelength.

The figure of merit (FOM) for a negative index material is usually considered to be represented by the ratio $-n'/n''$, since low-loss NIMs are desired for practical applications. The FOM can be written as $|n'/n''| = |\varepsilon'|\mu| + |\varepsilon|\mu'|/|\varepsilon''|\mu| + |\varepsilon|\mu''|$. From this relation it is clear that a DN-NIM gives a better FOM as compared to a SN-NIM with the same n' but with a positive μ'. In other words, a DN-NIM will have a lower n'' when compared to a SN-NIM with the same value for n' ; in addition, DN-NIMs can provide better impedance matching as compared to SN-NIMs.

Substantial progress has been achieved recently in the field of NIMs. The first experimental demonstration was given in 2001 at microwave frequencies [1] NIMs in the optical range were studied theoretically by many researchers [2,3]. The first NIMs in the optical range were demonstrated in 2005 at 1.5 µm [4] and 2 µm [5]. In both of these cases a SN-NIM was demonstrated, with FOMs of about 0.1 and 0.5, respectively. The first DN-NIMs in the optical range were demonstrated at 1.4 µm with a FOM of about 3 [6] and at 1.8 µm with a FOM above 1 [7]. Most recently, negative refraction was pushed into the visible with a negative index at 780 nm [8]. This was a SN-NIM with a maximum FOM of about 0.5. This paper presents the results for a DN-NIM at the shortest wavelength to date. The DN-NIM has a maximum FOM of 1.3 at a wavelength of 813 nm. Also, the same structure exhibits SN-NIM behaviour at 772 nm, thus showing negative n' at the shortest visible wavelength thus far.

The structure of our DN-NIM was based on the fishnet geometry suggested in [5]. The structure consisted of two layers of silver separated by a layer of alumina. The sample was fabricated using E-beam lithography followed by E-beam evaporation and lift-off. A 10 nm thick layer of alumina was deposited on top and below the structure to help maintain the integrity of the structure during lift-off process. It also protects the silver layer from deterioration due to oxidation (or sulfuration) and improves adhesion to the substrate. Fig. 1(a) shows a FE-SEM image of the fabricated sample. The figure also depicts the "primary" polarization of incident light at which the sample shows double

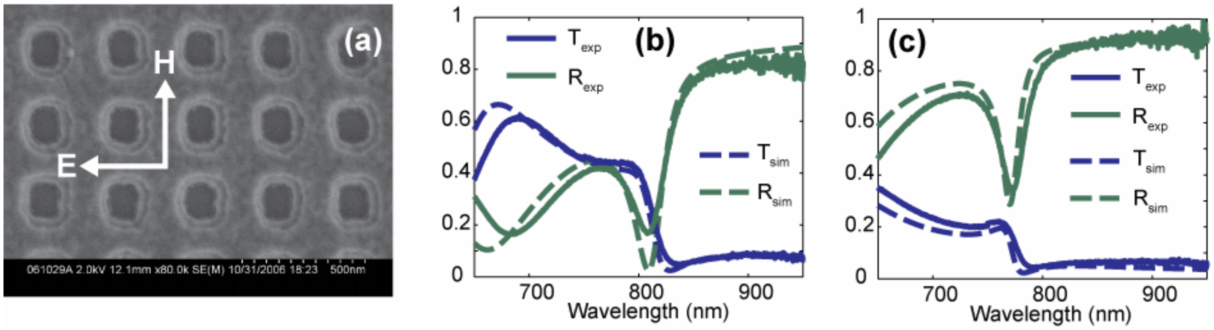

Fig. 1: (a) FE-SEM image of the fabricated sample indicating the primary polarization. (b) Experimental and simulated spectra of the sample for the primary polarization. Continuous lines show the experimental spectra and dashed lines show the simulated spectra. (c) Experimental and simulated spectra of the sample for the secondary polarization.

negative behaviour. The “secondary” polarization is orthogonal to the primary polarization. At either polarization, the strips aligned with the magnetic field (magnetic strips) provide an artificial permeability through a magnetic resonance. In an optimized structure the resonance can be sufficiently strong to yield a negative permeability. On the other hand the strips aligned with the electric field (electric strips) acts like a dilute metal and provide a negative permittivity through plasmonic response [9]. As a result the structure can exhibit simultaneous negative permeability and permittivity, demonstrating DN-NIM behaviour.

The sample was optically characterized to obtain the transmittance and reflectance for both polarizations. The structure was simulated using a commercial FEM software (COMSOL). The permittivity of silver was taken from experimental data [10], with the exception that the collision frequency was assumed to be three times that of bulk silver. This was done to match the experimental results. This additional damping corresponds to the additional losses in silver due to imperfections in silver including roughness, granularity and size effect. The details of the simulation and geometry are shown elsewhere [11].

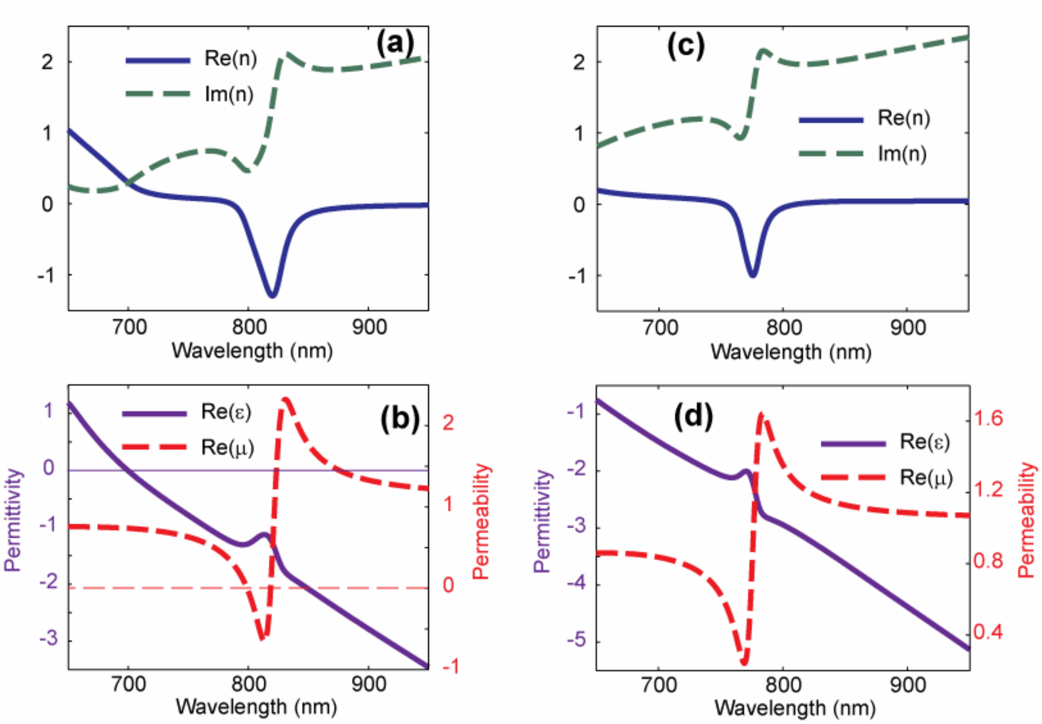

Fig. 2: (a) Real and imaginary part of effective refractive index at the primary polarization. (b) Real parts of effective permittivity (purple solid line) and effective permeability (red dashed line) at the primary polarization. Note that both permeability and permittivity are simultaneously negative from 799 to 818 nm. (c) Real and imaginary part of effective refractive index at the secondary polarization. (d) Real parts of effective permittivity and permeability at secondary polarization.

Fig. 1(b) and (c) shows the experimental and simulated spectra for the primary and secondary polarization respectively. There is excellent agreement between simulation and experiment including the sharp resonant features due to a magnetic resonance around 800 nm for the primary polarization and 780 nm for the secondary polarization. The strips responsible for the magnetic resonance (magnetic strips) are narrower in case of the secondary polarization and consequently the magnetic resonance is blue shifted.

The good agreement between the spectroscopic measurements and numerical simulations over a wide wavelength range for two different linear polarizations is a good indication of the validity of the numerical model. The effective refractive index of the sample was calculated from the simulated transmission and reflection coefficients using a standard retrieval procedure [12]. Fig. 2(a) shows the effective refractive index for the primary polarization with the real part of the refractive index being negative between 785 nm and 860 nm. Fig. 2(b) shows the real part of permeability and permittivity for the primary polarization. We note that ε' is negative over a broad range of wavelengths and μ' is negative between 799 nm and 818 nm. This band is the DN-NIM regime. The maximum FOM($-n'/n''$) is about 1.3 at 813 nm, where the refractive index is $-1.0 + 0.8i$. From Fig. 1(a) we can see that the widths of the horizontal and vertical strips are very close to each other. Hence we would expect the secondary polarization to show similar results, albeit at a different wavelength and with different resonance strength. Fig. 2(c) shows the effective refractive index for the secondary polarization. In this case the real part of refractive index is negative between 753 nm and 810 nm. Fig. 2(d) shows the real part of permeability and permittivity for the secondary polarization, where in contrast to the primary polarization the real part of permeability is always positive. Its minimal value ($\mu' \approx 0.2$) is obtained at a wavelength of 769 nm along with $\varepsilon' \approx -2.0$. Hence for the secondary polarization the sample is a SN-NIM with a maximum FOM of about 0.7 at 772 nm. The refractive index at the point of maximum FOM is $-0.9+1.2i$. In conclusion, we have demonstrated DN-NIM and SN-NIM behaviour in the same sample in two different polarizations at wavelength of 813 nm and 772 nm respectively.

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