Optical Negative-Index Metamaterials: from Low to no Loss

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Abstract: Practical optical negative index materials based on coupled plasmon resonances must overcome reflection and absorption. Simulations show that matched impedance and compensated losses due to optimized design and gain material lead to 100% transmission.

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, and materials with negative index have some remarkable properties. For example, vectors $\vec{E}$, $\vec{H}$, and $\vec{k}$ form a left-handed system and such materials are synonymously called "left-handed" or negative-index materials (NIMs). No naturally existing NIM is known so far in the optical range and it is necessary to create artificial materials (metamaterials) in which the effective refractive index (n'_{eff}) is negative. A truly negative index $n'_{eff} < 0$ can only be achieved in metamaterials with structural dimensions far below the wavelength; for optical wavelengths such materials must be nanocrafted. A possible approach to create a NIM is to design a material where the effective isotropic properties (permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ and permeability $\mu = \mu' + i\mu''$) obey the equation $\varepsilon'|\mu| + \mu'|\varepsilon| < 0$, which is always satisfied, if $\varepsilon' < 0$ and $\mu' < 0$.

The first conceptual design of a magnetically active metamaterial arranged of two split ring resonantors (SRRs) of subwavelength dimensions was predicted to give $\mu' < 0$ [1]. The SRRs have been further combined with metallic wires with a negative electric response in the 10 GHz range [2]. The outcome was the first-ever NIM with $\varepsilon' < 0$ and $\mu' < 0$ at ~10 GHz [3]. Further downsizing led to higher frequency responses, and the resonance was pushed up to 1THz [4]. An alternative to double SRRs is a single SRR facing a metallic mirror, where the resonance frequency was shifted to 50 THz [5]. But further downscaling becomes uncertain due to localized plasmonic effects, which nonetheless open yet another design opportunities. Thus, a double SRR is not required any more [6]. The electric resonance of single SRRs has even been pushed to the important telecom wavelength of 1.5 µm [7] and it was concluded that the magnetic response of single SRRs should be found at the same frequency [8]. In [9], it was shown experimentally that a sample containing pairs of gold nanopillars show transmission spectra that can be explained if a negative permeability is assumed. However, an experimental proof of a negative refractive index was not given in that work.

Here we discuss NIMs with magnetic activity at optical wavelengths that use localized plasmonic resonances and abandon the SRR completely. In [10] it was first predicted, that materials containing pairs of coupled metal rods can show a negative n' even for visible wavelengths. Two gold rods are separated by a distance far less than the wavelength. The diameter of the cross section of the rods is also much less than the wavelength and the length of the rods may be, but does not need to be in the range of half of the wavelength. An AC electric field parallel to both rods will induce parallel currents in both rods which are in phase or out of phase with the original electric field, depending on whether the wavelength of the electric field is longer or shorter than the wavelength of the dipolar eigen-resonance of the electrodynamically coupled rods. An alternative way of looking at this is that the anti-parallel currents in the rods and the displacement currents at the ends of the two rods form a current loop or an inductance, while the gaps at the ends form two capacitors. The result is a resonant LC-circuit. It is important that the dipolar electric and the dipolar magnetic resonance are at the same wavelengths. This requires that the coupling between the two rods should not be too strong, because otherwise the two resonances split further apart.

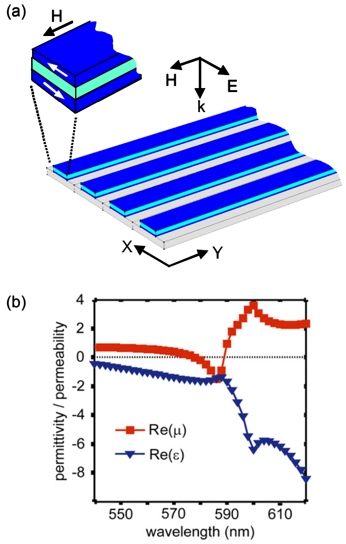

Fig. 1: (a) Double silver strips, separated by Al_2O_3. The strips are infinitely long in y-direction and periodically repeated in x-direction. The H field is oriented in y-direction. Currents in the both strips are anti-parallel (white arrows in the magnified inset) if the H-field is polarized in y-direction. (b) Real parts of the permittivity and permeability as simulated with FEMFD.

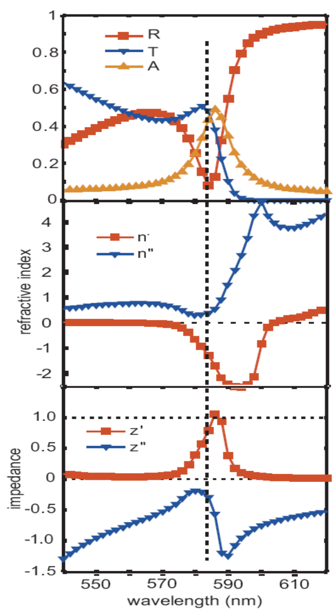

Fig. 2 Spectra of several optical constants of the structure shown in Fig. 1. Upper panel: Reflection R, transmission T, and absorption A spectra; middle panel: real and imaginary part of the refractive index; lower panel: real and imaginary part of the impedance. The vertical dashed line at 584 nm indicates a spectral region where the reflection is minimal, the transmission is high, the refractive index is n = - 1.30 + 0.39i and the real part of the impedance is close to 1, indicating impedance matching to air.

The unambiguous measurement of a negative refractive index in the optical range (specifically, at the optical telecom wavelength of 1.5 μm) was reported in [11]. Pairs of nanorods were fabricated on a glass substrate using electron beam lithography. A full description of the sample and its preparation is given in [12,13]. According to experimental and simulation results obtained in [11] for our NIM, the refractive index becomes negative in the wavelength range from approximately 1400 nm to 1600 nm, which includes the important telecommunication band at 1500 nm. The experimental data proving that $n' = -0.3 \pm 0.1$ has been obtained.

A negative refractive index has been also obtained for the inverted system of paired dielectric voids in a metal [14,15]. We note that inverted NIMs, i.e. elliptical or rectangular dielectric voids in metal films, are physically equivalent to paired metal rods in a dielectric host, in accordance with the Babinet principle.

As discussed in [11-13], NIMs using plasmon resonant metallic elements have two distinct problems: high reflection and absorptive losses, both reducing the overall transmission through the metamaterial. The reflection can be suppressed by an optimized design with matched impedance. We show an example of optimized NIM where the conditions $Z \to 1 + 0 \cdot i$, $n' < -1$, and $|n''| < 1$ hold simultaneously for a visible wavelength. The NIM is arranged of coupled silver strips separated by a dielectric spacer (see Figs. 1 and 2). For this NIM, the simulated transmission has a local maximum of 51% at 582 nm. The impedance is matched quite well from 582 to 589 nm, i.e. $Z' > 0.5$ and reaching 1 at 586 nm with $|Z''| < 0.5$ in the range 570 - 585 nm. We have shown that a given design can be optimized to an impedance-matched NIM for the visible light. The transmission is limited to 50% almost solely due to absorption.

These absorptive losses (in terms of a large n'') are the second major difficulty, since the ohmic losses are generally large due to localized plasmon resonances. To overcome this difficulty we propose supplying energy from gain material in NIMs using stimulated emission.

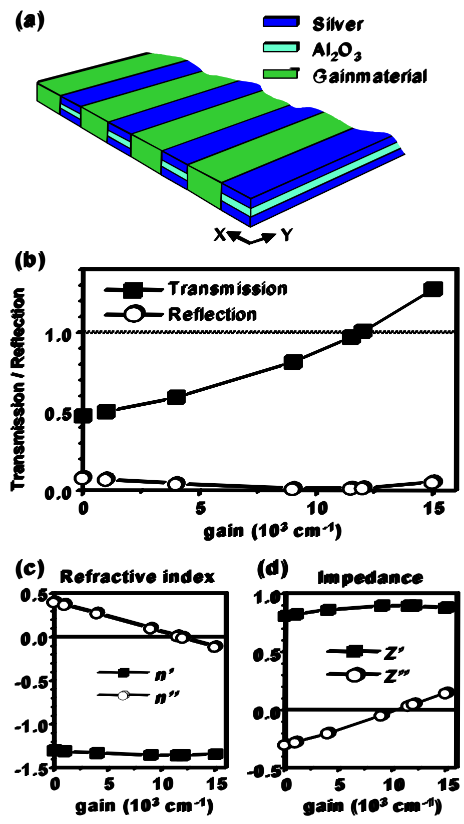

Fig. 3: (a) Same sample as in fig. 1a, but with gain providing material in between the double silver strips. Air is assumed above and below the layer, and the layer is irradiated wit a plain wave (584 nm) from above, H-field polarized along the y-direction. (b) Transmission and reflection as a function of the gain. At g = 12 000 1/cm gain and losses cancel each other. Interestingly, the reflection shows also a minimum at g = 12 000 1/cm. (c,d) refractive index and impedance as a function of gain. $n' \approx -1.3$, for all investigated gain levels.

We simulated the same impedance-matched structure, but now we embedded a material that provides a fixed amount of gain between 0 and $15\cdot10^{3}$ cm^{-1} (see Fig. 3). We found that at a gain of $12\cdot10^{3}$ cm^{-1} the structure becomes transparent, while the real part of the refractive index n' is almost unaffected by the gain material. Moreover, the impedance which has already been matched quite well without the gain medium improves further when gain is applied, i.e. $Z'\approx 1$ and $Z''\approx 0$ for $g=12\cdot10^{-3}\mathrm{cm}^{-1}$. The exact results for a gain of $g=12\cdot10^{-3}\mathrm{cm}^{-1}$ are $n'=-1.355$, $n''=-0.008$, $Z'=0.89$, $Z''=0.05$, $T=100.5\%$, and $R=1.6\%$.

In summary, we have shown that two key remedies are now available to overcome major obstacles that currently limit the development of optical negative-index materials (1) impedance matching designs are capable to suppress high reflectance, and (2) gain materials embedded in metallic nanostructures can fully compensate for absorptive losses while still retaining the negative refractive index.

References

[1] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from Conductors and Enhanced Nonlinear Phenomena," IEEE Transactions on Microwave Theory, **47**, 2075-2084 (1999).

[2] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, "Extremely Low Frequency Plasmons in Metallic Mesostructures," Physical Review Letters, **76**, 4773-4776 (1996).

[3] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a Negative Index of Refraction," Science **292**, 77-79 (2001).

[4] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, "Terahertz Magnetic Response from Artificial Materials," Science **303**, 1494-1496 (2004).

[5] Z. Zhang, W. Fan, B. K. Minhas, A. Frauenglass, K. J. Malloy, and S. R. J. Brueck, "Midinfrared Resonant Magnetic Nanostructures Exhibiting a Negative Permeability," Physical Review Letters, **94**, 037402 (2005).

[6] L. V. Panina, A. N. Grigorenko, and D. P. Makhnovskiy, "Optomagnetic composite medium with conducting nanoelements," Physical Review B **66**, 155411 (2002).

[7] C. Enkrich, M. Wegener, F. Perez-Willard, S. Linden, J. Zhou, T. Koschny, and C. M. Soukoulis, "Optimizing the design parameters for split-ring resonators at telecommunication wavelengths," presented at International Conference on Quantum Electronics and Laser Science (QELS), Baltimore (USA), 2005.

[8] S. Linden, C. Enkrich, M. Wegener, J. Zhou, T. Koschny, and C. M. Soukoulis, "Magnetic Response of Metamaterials at 100 Terahertz," Science, **306**, 1351-1353 (2004).

[9] A. N. Grigorenko, A. K. Geim, H. F. Gleeson, Y. Zhang, A. A. Firsov, I. Y. Khrushchev, and J. Petrovic, "Nanofabricated Media with negative permeability at visible frequencies," *Nature*, vol. 438, pp. 335-338 (2005).

[10] V. A. Podolskiy, A. K. Sarychev, and V. M. Shalaev, "Plasmon Modes in Metal Nanowires and Left-Handed Materials," *Journal of Nonlinear Optical Physics & Materials*, vol. 11, pp. 65-74 (2002).

[11] V. M. Shalaev, W. Cai, U. K. Chettiar, H. K. Yuan, A. K. Sarychev, V. P. Drachev, and A. V. Kildishev, "Negative index of refraction in optical metamaterials," *Optics Letters*, vol. 30, pp. 3356-3358 (2005). This work was first posted in http://www.arxiv.org/abs/physics/0504091, Apr. 13, 2005.

[12] V. P. Drachev, W. Cai, U. Chettiar, H. K. Yuan, A. K. Sarychev, A. V. Kildishev, G. Klimeck, and V. M. Shalaev, "Experimental verification of an optical negative-index material," *Laser Physics Letters*, v. 3, 49-55 (2006).

[13] A. V. Kildishev, W. Cai, U. K. Chettiar, H. K. Yuan, A. K. Sarychev, V. P. Drachev, and V. M. Shalaev, "Negative Refractive Index in Optics of Metal-Dielectric Composites," *Journal of the Optical Society of America B*, March (2006)

[14] S. Zhang, W. Fan, N. C. Panoiu, K. J. Malloy, R. M. Osgood, and S. R. J. Brueck, "Experimental Demonstration of Near-Infrared Negative-Index Metamaterials," *Physical Review Letters*, vol. 95, pp. 137404 (2005).

[15] S. Zhang, W. Fan, K. J. Malloy, S. R. J. Brueck, N. C. Panoiu, and R. M. Osgood, "Demonstration of metal-dielectric negative-index metamaterials with improved performance at optical frequencies," *Journal of the Optical Society of America B*, March (2006).