Transformational optics of plasmonic metamaterials

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Abstract. Plasmonic metamaterials provide a convenient experimental platform for demonstration of principles of transformational optics. In this paper, negative index imaging and guiding of surface waves using layered plasmonic metamaterials has been demonstrated. Imaging experiments have been compared with numerical simulations. In addition, a two-dimensional $\varepsilon$ near zero metamaterial has been realized.

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1. Introduction

Recent observations of negative refraction of surface plasmon polaritons (SPPs) in the visible frequency range [1, 2] may soon bring about practical applications of the superlens concept originally introduced by Pendry [3]. It appears that regular dielectric materials deposited onto the metal film surface (such as gold or silver) may be perceived by SPPs as negative refractive index materials. It is important to note that the negative refractive index behavior in this case is omni-directional, and the figure of merit $\text{Re}(k)/\text{Im}(k)$ of these two-dimensional (2D) negative index materials may reach values of the order of 10 [4]. This relatively high value compared to the typical figures of merit of the 3D negative index metamaterials [5] makes it possible to utilize...
2D negative index materials in practically useful nano-optical devices. Negative refraction may find applications in novel linear and nonlinear nano-optical devices, which bypass the diffraction limit of conventional optics. While a very large number of theoretical papers on electromagnetic properties of negative index materials and devices exist (see for example an overview in [6]), experimental observations in the visible frequency range are limited to a few demonstrations of negative refraction at the positive–negative interface [2, 4], measurements of transmission and reflection from very thin layers of these materials (see [5] and the references therein), and rudimentary imaging experiments [1]. Much more experimental work is needed to firmly establish foundations and practical limitations of the novel and exciting theoretical ideas in this field. In this paper, we report the experimental observation of magnified negative index imaging, which occurs at the boundary between the negative and the positive index media, provide the experimental demonstration of surface wave guiding based on the transformational optics approach, and demonstrate an $\varepsilon$ near zero plasmonic metamaterial.

2. Negative refraction and imaging by plasmonic metamaterials

Our approach to fabrication of plasmonic metamaterials in the visible frequency range is based on 2D optics of SPPs [7]. The wave vector of SPPs propagating over a metal–dielectric interface is defined by the expression

$$k_p = \frac{\omega}{c} \left( \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} \right)^{1/2} = \frac{\omega}{c} \varepsilon^{1/2}_{2D},$$

(1)

where $\varepsilon_m(\omega)$ and $\varepsilon_d(\omega)$ are the frequency-dependent dielectric constants of the metal and dielectric, respectively. Above the resonant frequency described by the condition $\varepsilon_m(\omega) \sim -\varepsilon_d(\omega)$ the SPP group and phase velocities may have opposite signs, which leads to the negative refractive behavior of SPPs [1, 2]. This behavior is illustrated in figure 1(a), which shows the typical SPP dispersion law for a metal surface covered with a thin layer of dielectric (see for example [8]). Since in ambient conditions all surfaces are covered with a thin (a few nm thick) layer of adsorbed water (this layer is responsible for the shear force between the tip and the sample in a near-field optical microscope [9]) this behavior of the SPP dispersion is generic. In addition, when the metal film is not too thick, the SPPs which live at the top and at the bottom surfaces of the film interact with each other, which leads to the appearance of the so-called long-range surface plasmon polariton (LSPP) and short-range surface plasmon polariton (SSPP) modes [7], the latter ones typically exhibiting negative refractive behavior. Thus, regular optical materials deposited onto a gold film surface may be perceived by SPPs as negative refractive index materials. However, as illustrated in figure 1, in a typical situation a layer of such material would behave as a high-pass filter: the low-$k$ components of the SPP source field would perceive the deposited material as a positive index one, whereas the high-$k$ components of the SPP source field would see it as a negative index material. Nevertheless, as illustrated in figures 1(b)–(d) the loss of low-$k$ components of the field does not lead to deterioration of the spatial resolution.

An interface between two media with opposite signs and unequal magnitudes of refractive index must exhibit magnified ‘mirror’ imaging, as shown in figure 2(a). The magnitude of the expected magnification is equal to $M \sim n_2/n_1$. We were able to detect this effect by looking at the spatial distribution of SPP scattering inside a poly(methyl methacrylate) (PMMA) layer using a far-field optical microscope. The test sample geometry is shown schematically in figure 2(b). The triangular test patterns were formed near the edge of the PMMA layer using
Figure 1. (a) Typical SPP dispersion law for a metal surface covered with a thin layer of dielectric. The inset shows image formation by negative index SPP modes, whereas no image is formed by the positive index modes. (b)–(d) illustrate the imaging action of a high-pass filter formed by the dielectric layer. The image in (d) is formed by deleting contributions of the Fourier components from the source carried by positive index modes (the modes inside the circle in (c)).

e-beam lithography, as described in [1]. The triangles were made of PMMA bars formed on top of the gold film surface in such a way that the spacing between the PMMA bars would allow phase-matched excitation of SPPs on the gold/air interface under illumination with 532 nm laser light (see figure 1 from [1]). Figure 2(d) demonstrates that magnified ‘mirror’ images of the original triangular patterns were indeed formed inside the PMMA layer. These images were observed using a conventional far-field optical microscope due to SPP scattering into photons by the defects of the PMMA layer. The observed magnification was approximately equal to 1.6, which corresponds to the magnitude of the effective 2D refractive index of PMMA: $n_{\text{PMMA}} \sim -1.6$ [1]. The contrast in the images deteriorates away from the edge of the PMMA layer due to SPP losses. Numerical modeling of SPP propagation in this geometry, which is presented in figure 3(f), demonstrates good agreement with the experiment. On the other hand, no ‘mirror’ imaging has been observed when the test pattern was illuminated with 633 nm laser light (figure 3(e)), which is consistent with the absence of negative index SPP modes at this wavelength. This experiment provides additional strong evidence of negative refractive behavior of SPPs around the 500 nm wavelength.
Figure 2. (a) Image magnification at the interface between two media with opposite signs and unequal magnitudes of the refractive index. (b) Schematic view of the experimental geometry. (c) Image of the test sample obtained using a far-field microscope with white light illumination from the top. (d) Image of the test sample obtained using a far-field microscope with phase-matched 532 nm illumination. Due to SPP scattering, magnified plasmonic mirror images are visible inside the PMMA layer (on the right). (e) As expected, no imaging has been observed at 633 nm wavelength. (f) Numerical simulation of image formation inside the PMMA layer performed via numerical solution of Maxwell equations using COMSOL multiphysics 3.3a.
3. Transformational optics demonstration

The transformational optics approach [10]–[12] allows one to control the path of light by creating complex spatial distributions of dielectric permittivity $\varepsilon(r)$ and magnetic permeability $\mu(r)$, which emulate propagation of electromagnetic fields in some curvilinear space time. A practical approach to transformational optics may be based on multilayer stacks of positive and negative index materials. If the stack is compensated so that the optical width of the stack is approximately equal to zero, light rays propagate through the stack in the direction perpendicular to the layers [4]. Curving the stack allows one to redirect the light rays. This approach has been demonstrated experimentally in the design of a ‘magnifying superlens’ [1]. In this design a concentric pattern of PMMA rings formed on the gold film surface operated as a concentric pattern of positive and negative refractive index materials. This pattern guided SPP rays emitted by point sources in the radial directions. Our numerical simulations presented in figures 3(a) and (b) indicate that the same approach may be used to guide SPP rays along arbitrary curvilinear paths. The geometry of layers shown in figures 3(a) and (b) is obtained by stretching the ‘magnifying superlens’ geometry along the horizontal axis. This deformation leads to the curvilinear propagation of the rays from the point sources located near the internal rim of the structure. Experimental realization of this geometry is demonstrated.
in figures 3(c)–(e). A far-field optical image of the test structure obtained with white light illumination from the top demonstrates a pattern of PMMA photoresist produced on top of a 50 nm thick gold film using e-beam lithography. PMMA dots produced inside this pattern may act as point sources of SPPs under illumination with 532 nm laser light. The location of these dots is shown by arrows in figures 3(d) and (e). The curvilinear path of the plasmon ray in figure 3(d) is clearly visible.

4. Demonstration of \( \varepsilon \) near zero plasmonic metamaterial

Since both the effective refractive index and the effective 2D ‘dielectric constant’ \( \varepsilon_{2D} \) of PMMA from equation (1) may change sign near the frequency of surface plasmon resonance \( \varepsilon_m(\omega) \sim -\varepsilon_d(\omega) \), the effective average \( \varepsilon_{2D} \) of the layered plasmonic metamaterial may be made very close to zero by adjusting the widths \( d_1 \) and \( d_2 \) and the periodicity \( d_1 + d_2 \) of the multilayered structure. Figure 4 represents an experimental step in this direction.

The \( d_1 \) and \( d_2 \) parameters of the concentric PMMA ring structure shown in figure 4(a) were varied gradually to produce the \( \varepsilon \) near zero condition at some distance from the center. This experimental approach appears to work regardless of the theoretical model used to describe the plasmonic metamaterial. The structure was illuminated by an external laser operating at 532 nm, at an illumination angle which corresponds to the phase-matching excitation of SPPs at the top and bottom outer rims of the structure. Since the periodicity of the structure changes away from the outer rim, SPPs are excited with much less efficiency anywhere else, and the picture of light scattering presented in figure 4(b) corresponds to SPP propagation through the central region of the structure. SPPs are supposed to experience total internal reflection from the \( \varepsilon \) near zero boundary, as illustrated in figure 4(c), unless they propagate exactly through the center of the structure. Comparison of the experimentally measured figure 4(b) with our theoretical simulations shown in figure 4(c) and with results of numerical simulations of Alu et al. (figure 11 from [13]) strongly suggests that \( \varepsilon \) near zero conditions have been created. The similarity of these figures is quite compelling. Note that in simulations shown in figure 4(c) \( \varepsilon = 0.1 \) is used, which means that the phase and amplitude of the wave passing through the cylinder has not yet become completely uniform. The narrow beam passing through the center of the \( \varepsilon \) near zero structure may be used to produce efficient spatial directional filters. Figure 4(b) also demonstrates that most of the optical energy is trying to flow around the \( \varepsilon \) near zero area, in a manner which is similar to that described in [10]–[12]. Similar results can also be found in [14]. We should also note that theoretical simulations performed for a single dielectric step often indicate the strong coupling of 2D SPPs to radiating photons [15]. It should be noted that when multiple nearly periodic dielectric steps are involved, the interference of radiation from the steps may become either constructive or destructive. In the destructive interference case, the coupling of SPPs to 3D radiation should become suppressed. The experimental results presented in the paper can be explained by such destructive interference.

5. Conclusion

In conclusion, we have demonstrated that plasmonic metamaterials provide a convenient experimental platform for demonstration of the principles of transformational optics. In this
Figure 4. (a) Image of the test structure obtained using a far-field microscope with white light illumination from the top. (b) Plasmon propagation at 532 nm through the test structure. (c) Numerical simulation of the power flow through an $\varepsilon$ near zero cylinder. In this simulation an $\varepsilon = 0.1$ cylinder is considered.

In this paper, the negative index imaging and guiding of surface waves using layered plasmonic metamaterials has been demonstrated. Imaging experiments have been compared with numerical simulations, and a good match has been obtained. In addition, a 2D $\varepsilon$ near zero metamaterial has been demonstrated experimentally.

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