Surface plasmon polariton flat lenses

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Abstract

We extend designs of perfect lenses to the focussing of surface plasmon polaritons (SPPs) propagating at the interface between two anisotropic media of opposite permittivity sign. We identify the role played by the components of anisotropic and heterogeneous tensors of permittivity and permeability, deduced from a coordinate transformation, in the dispersion relation governing propagation of SPPs. We illustrate our theory with three-dimensional finite element computations for focussing of SPPs by perfect flat lense. Finally, we propose a design of a flat SPP lens consisting of metamaterial in a periodic fashion (hexagonal array) on a metal plate. This new design open the way to experiments.

1. Introduction

Focusing light using negative refraction (using the left hand (LH) metamaterials) is an emerging subject mixing fascinating and elusive features. It is now well known that one can reverse the flow of light with negative refractive index materials, within which light takes the "*wrong*" turn in accordance with inverted Snell-Descartes laws of refraction [1, 2, 3]. However, there has been a growing interest in a better control of light through transformational optics([4, 5] and plasmonics([10]).

However, there are other types of electromagnetic waves well worth controlling such as surface plasmon polaritons (SPPs) that allow for fascinating applications in the emerging field of nano-optics. Imaging and focussing [6] of SPPs based on two-dimensional plasmonic metamaterials consisting of alternating layers of positive and negative refractive indices, which are arranged in either layered or checkerboard fashion on the surface of a gold film have been further experimentally studied by the group of Davis in 2007 [7].

In the present paper, we extend the design of transformation based perfect lens to the focussing of surface plasmon polaritons (SPPs). Interestingly, Agranovich et al. have shown in 2004 that one can obtain negative refraction for exciton-plasmon waves in organic and gyrotropic material using a surface transition layer [8].

Our main contribution here is that we explain how one can manipulate SPPs in such a way that the electromagnetic space where they live is folded back onto itself, so that we can extend the proposal of Pendry and Ramakrishna to build generalized lenses using the original concept of complementary media [9] to the area of plasmonic waves. Importantly, we also perform full wave computations to exemplify the imaging effects of SPPs through negative refraction in a novel class of generalised plasmonic lenses.

2. Transformational plasmonics and generalized perfect lenses in Cartesian coordinates for SPPs

Let us consider two semi-infinite regions separated by a plane interface at $x_2 = 0$. The upper region ($x_2 > 0$) is filled with air i.e. with relative permittivity $\varepsilon_1 = 1$ (resp. relative permeability $\mu_1 = 1$), while the lower region ($x_2 < 0$) is filled with a Drude metal i.e. with relative permittivity

$$\varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2 + \imath\gamma\omega} \tag{1}$$

(resp. relative permeability $\mu_2 = 1$): here, some gold with the plasma frequency ($\omega_p = 2175$ THz) and characteristic collision frequency ($\gamma = 4.35$ THz).

The original perfect lens presupposed a slab of material with ϵ = -1 and μ = -1. Let us now derive the result using the powerful tool of transformational plasmonics [10]. In order to design generalized lenses for surface plasmon polaritons, we want to fold the plasmonic space back onto itself, and this leads to negative coefficients within the permittivity and permeability matrices. We end up finally with transformed media on both side of the interface(metal/dielectric)

$$\varepsilon_j' = \varepsilon_j \mathbf{T}^{-1}, \text{ and } \mu_j' = \mu_j \mathbf{T}^{-1} \, . \tag{2}$$

We note that there is no change in the impedance of the media, since the permittivity and permeability undergo the same geometric transformation: the perfect lens is impedance-matched with its surrounding medium (air, say) so that no reflection will occur at its interfaces.

where $\varepsilon_1 = 1$ and ε_2 are as in (1), and $j = 1$ for $x_2 > 0$ and $j = 2$ for $x < 0$. This is a generalization to transformational plasmonics of the result first derived in [9] and retrieved again using group theory (symmetries of Maxwell's equations) in [9].

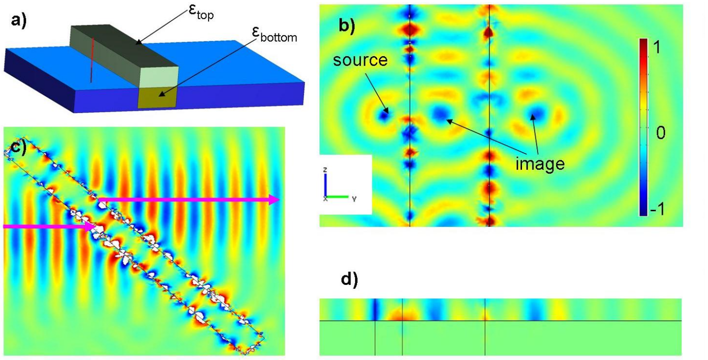

Fig. 1: Perfect plasmonic lens via negative refraction at 700 nanometers: (a) The medium $\varepsilon_1^1 = \mu_1^1 = 1$ in the yellow block and its Drude metal counterpart underneath $\varepsilon_1^2 = 1 - \frac{\omega_p^2}{\omega^2 + \imath\gamma\omega}$, $\mu_1^2 = 1$; (b) Top and side views of the computed field for a SPP line source; (c) Negatively refracted SPP beam making an angle of 45 degrees with the lens.

3. Proposal of experimental design for a flat SPP lens

The transformational plasmonics designs discussed above need still be implemented in structured metasurfaces. In order to do so, we looked at the vast literature on metamaterial and photonic crystal lenses via all-angle-negative refraction (AANR), as well as on focussing effects using the dispersion relation of metals [7, 11]. After a theoretical investigation, we propose a metamaterial, experimentaly realisable, to get a SPPs flat lens.

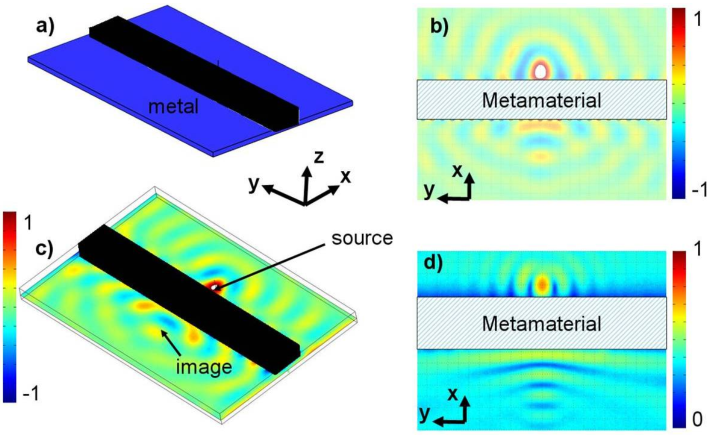

Fig. 2: Focussing through a flat plasmonic lens (of a thickness of 700nm) for a SPP line source at wavelength 700 nanometers placed at $300nm$ behide the lens : (a) Schematic diagram of the flat SPP lens with the LHD metamaterial; (b) 2D plot of the magnitude of the field;(c) 3D plot of the magnitude of the field; (d) 2D plot of the real part of the magnetic field;

4. Conclusion

Focusing SPP through a markedly enhanced control of their wave trajectories has been demonstrated. Complementary materials can be use to get negative refraction of SPPs. We propose also a numerically design that would alow experimental achievement of SPP flat lens. .

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