Slanted Layered Superlenses for Subwavelength Light Manipulation

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ABSTRACT
We demonstrate numerically the operation of optical microelements consisting of metal-dielectric multilayers with slanted edges. We show examples of optical devices for imaging with sub-wavelength resolution, for focusing in a sub-wavelength-sized area, for manipulation of the state of polarisation, and for cross-coupling between the propagating and evanescent parts of the spatial spectrum. The multilayers that are used by us consist of silver and a high refractive index dielectric and may be regarded as optimised low-loss metamaterials with a large effective anisotropy, with reduced Fabry-Perot resonances, with impedance matched to the host medium and with diffraction-free properties. The metamaterials are designed by us with the transfer matrix method and with use of the framework of linear-shift-invariant systems, while the device as a whole is analysed using the finite difference time domain method.
Keywords: superlens; super-resolution; metal-dielectric multilayer; skin depth.

1. INTRODUCTION

The development of emerging plasmonic-based devices opens novel perspectives for nano-optics. In this paper we review the properties of diffraction-free layered metal-dielectric periodic stacks and look to their possible applications. Since the suggestion of using a silver slab for projecting evanescent waves at sub-wavelength distances [1], the experimental demonstration of an asymmetric superlens [2,3] and the proposal of improving the performance of the structure by using a multilayer operating within the approximation of an effective medium [4], there exists an ongoing effort to design diffraction-free structures with low losses, a large total thickness, and sub-wavelength resolution [5-15].

In a recent work [11] we have optimised Ag-TiO_2, Ag-GaP and Ag-$SrTiO_3$ multilayers in terms of the resolution and transmission coefficient. Apparently, the optimised structures are dissimilar to those designed using the effective medium theory in terms of both the filling fraction and the internal distribution of the field. This is a strong argument for using numerical optimisation instead of simplified theoretical models when designing layered superlenses for practical applications. In [12] we have proposed a low-loss layered metamaterial for the construction of shaped (slanted or prism-shaped) diffraction-free structures with limited reflections, and with impedance matched to air. In [13] it is shown how to use the framework of linear shift-invariant (LSI) systems, widely used in the past within Fourier optics, to construct a polarisation-dependent point spread function (in a matrix form), which enables to express the layered system in an easily tractable form. This formalism has been also used to propose and study a diffraction-free non-planar imaging device. In [14], an analysis of the sensitivity of the superlens towards the fabrication uncertainties is presented, with the main conclusion that the imaging properties are extremely sensitive to the values of material permittivities as well as layer thicknesses of particular layers. Therefore, it remains a challenge to fabricate a super-resolving multilayers with an overall large thickness. Although it is convenient to treat a multilayer as an LSI, the analogy to classical imaging systems may be misleading in some respects. For instance, its point spread function (PSF) is not always similar to a Gaussian function and may include a strong phase modulation. In such a case the width of PSF can not be simply interpreted as a measure of resolution. Instead, the actual resolution depends on the feature size of the object and may be even better than the width of PSF [8]. Another issue is that due to reflections, a near-field source and the LSI stack can not be regarded as completely independent systems. Nevertheless, in the two limiting cases of tight coupling (a hard source model) and no coupling (a soft source) the LSI model remains valid [15], and in practice it proves to be an efficient tool for the design of multilayers.

2. DIFFRACTION-FREE IMAGING THROUGH LAYERED SUPERLENSES, PRISMS, AND COMPOUND OPTICAL NANO-DEVICES

In Fig. 1, we present the field profile inside an optimised [11] diffraction-free Ag-GaP superlens operating at a wavelength of 490nm. The multilayer contains no materials with optical gain, and the conductivity of silver is taken into account. We notice that on average the field decays slowly while it propagates throughout the structure, still its shape is not regular, and does not resemble that of coupled cavities or an effective Fabry-Perot etalon of any order. At the same time, the layers are relatively thick, and therefore simple to fabricate, with the period equal to 60nm. However, the effective medium theory can not be used to determine the transmission coefficient or resolution, except for a rough estimation.

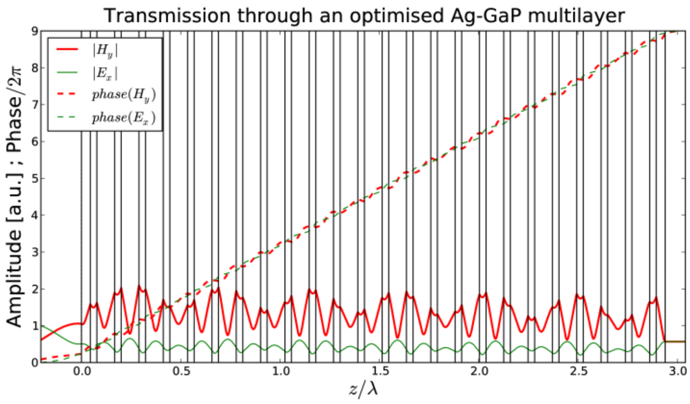


Figure 1. Propagation of a normally incident plane-wave through an optimised diffraction-free super-resolving multilayer with a high-transmission. Optimisation of the structure is presented in Ref [11].

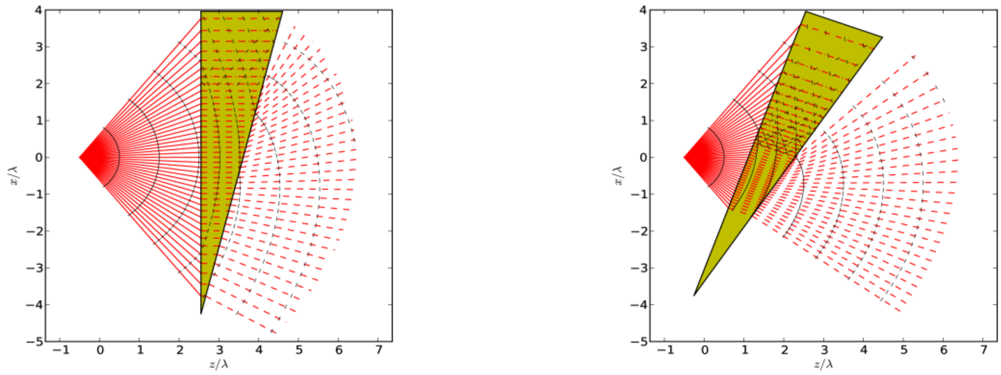


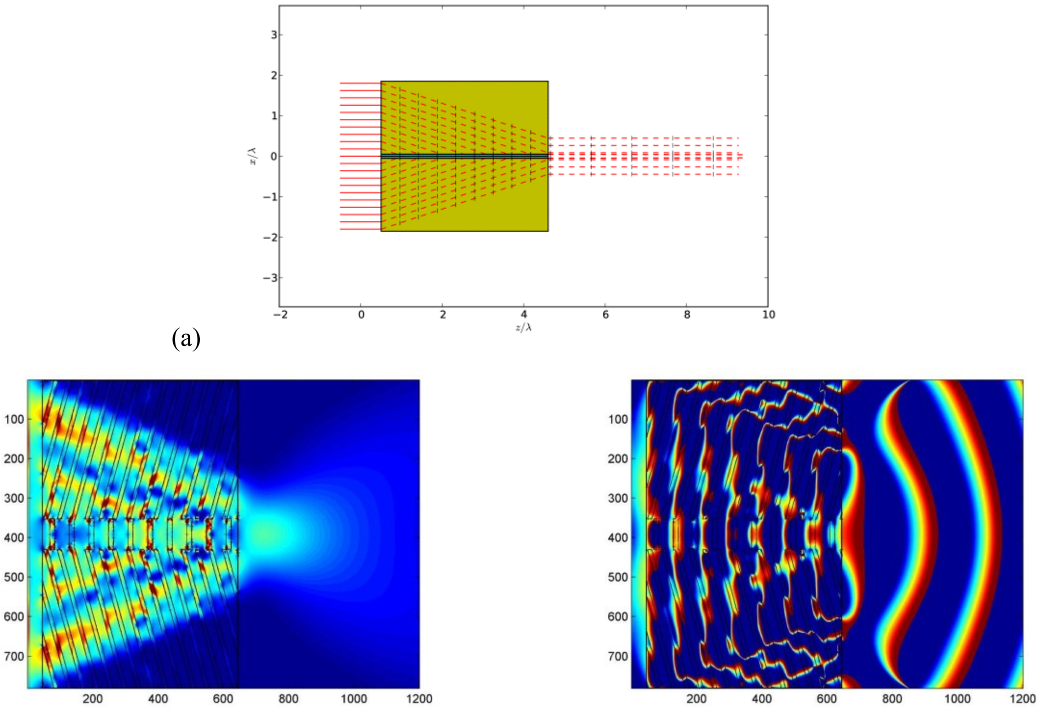
Figure 2. Ray-tracing based modelling of the transmission through a slanted layered superlens. In the simulation, we assume an effective medium model of the superlens.

To some extent light exhibits a ray-like behaviour in diffraction-free multilayers. This comes in spite of the fact that the typical feature-sizes of interest in nano-optics are smaller than the wavelength, and the description of propagation is certainly out of scope of geometrical optics. FDTD simulations of a beam coupled to a layered superlens through a small aperture in a metallic mask [8,11,12] reveal that such ray-like modes may propagate at distances of several wavelengths, and at the same time remain confined within a width of one tenth of a wavelength. An anisotropic uni-axial model of the multilayer with an extremely large axial permittivity in fact allows to represent a wavefront as a bundle of rays propagating along the axis with a phase velocity dependent on the permittivity in the perpendicular direction. Using the framework of ray-optics we are able to trace the wavefronts in the multilayer-based device, determine the direction of refraction, and check for the condition of total internal reflection. As an example, in Fig. 2 we present the transmission of a wavefront through differently oriented diffraction-free prisms. This simplified approach to the modelling of a sub-wavelength device has also significant limitations - for instance the evanescent waves in the host medium can not be clearly identified, and coupling to surface modes is neglected. Nonetheless, the approach facilitates the design of a device, prior to its computationally intensive rigorous analysis.

In Fig. 3 we show an energy concentrator composed of three diffraction-free multilayers, designed using ray-optics and later investigated with FDTD. Although the multilayers are differently oriented, the wavefronts remain parallel to the incidence plane and are continuous within the entire cross-profile of the structure. This property is correctly predicted with the ray-optics model.

In Fig. 4 we present a similar device. However, in this example we obtain a sub-diffraction-limited focal spot. As compared to the device shown in Fig. 3, this one is smaller, and the layers are narrower (in the order of 10nm) - therefore, the effective medium approximation is better justified.

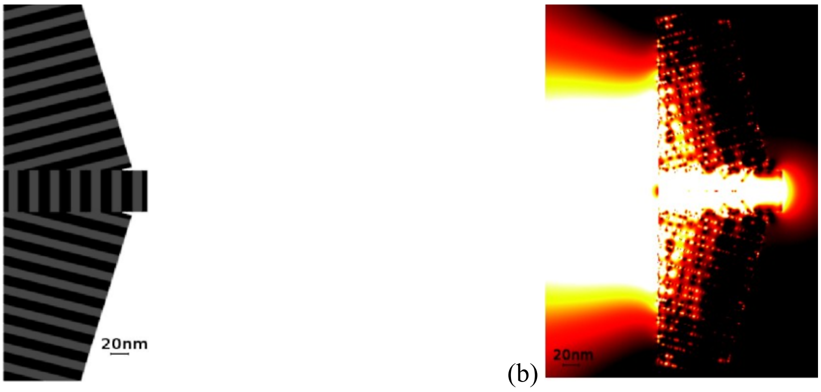
Two more architectures of focusing elements are presented in Fig. 5, including a hyperlens-like (a), and a focusing array of cylindrically shaped multilayers.



(a)

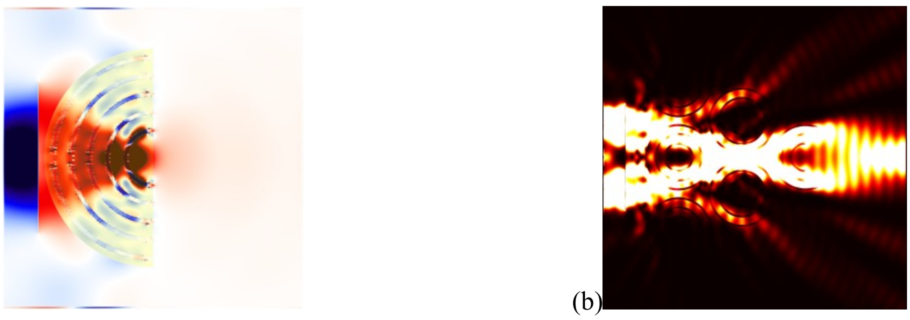
(b) (c)

Figure 3. Sub-wavelength focusing element. The upper, lower and central parts of the structure consist of diffraction-free uni-axial anisotropic metamaterials [11] with three orientations of the axis. a) Ray-tracing based design of the device; b) FDTD simulation – Poynting vector (the axis are in nm) and (c) phase isolines.



(a) (b)

Figure 4. a) Schematic of a sub-wavelength focusing nano-device composed of three diffraction-free multilayers; b) FDTD simulation. The definition of the metamaterial is taken from Ref. [12].



(a) (b)

Figure 5. Sub-wavelength focusing nano-devices locally consisting of layered metal-dielectric superlens-type materials (FDTD simulation). The definition of the metamaterial is taken from Ref. [12].

3. CONCLUSIONS

We have reviewed the properties of diffraction-free layered metal-dielectric periodic stacks for super-resolving imaging. We propose to use a simplified geometric optics approach for the design of compound nano-optical devices. While this technique is a powerful tool for working out new architectures, still it can not replace rigorous modelling such as that based on the FDTD method. We have discussed the operation of several devices for imaging, and for energy focusing, where the geometric and rigorous modelling play complementary roles.

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