Optical metamaterials with a negative index of refraction in the UV

R.C. Maas, J. Parsons, E. Verhagen and A. Polman

Center for Nanophotonics, FOM institute AMOLF, Science Park 104, 1098 XG Amsterdam, Tel. +31-20-7547 100, Fax +31-20-7547290, email: maas@amolf.nl

Abstract

Metamaterials composed of Ag/Si_3N_4 and Ag/TiO_2 multilayers were fabricated. Coupled plasmonic waveguide arrays were sculpted into miniature prisms using focussed ion beam (FIB) milling. Negative refraction is observed.

1. Introduction

Metamaterials are artificial materials structured on sub-wavelength scales which allow electromagnetic radiation to be manipulated in unprecedented ways. Such materials can yield a response not exhibited by natural materials, such as a negative index of refraction. First demonstrated at microwave frequencies, there has been considerable interest in recent years towards developing negative index metamaterials at optical frequencies. Previously, we have shown theoretically that a metamaterial comprised of coupled plasmonic waveguides can yield an isotropic negative index of refraction in the visible / near-UV [1], a schematic of the structure is shown in Fig. 1 (a). Here, we discuss recent progress towards the fabrication of negative index plasmonic waveguide arrays. Optical refraction measurements performed on miniature prisms are presented. We also compare our results with predictions from FDTD simulations. An example of such a simulation is shown in Fig. 1 (b).

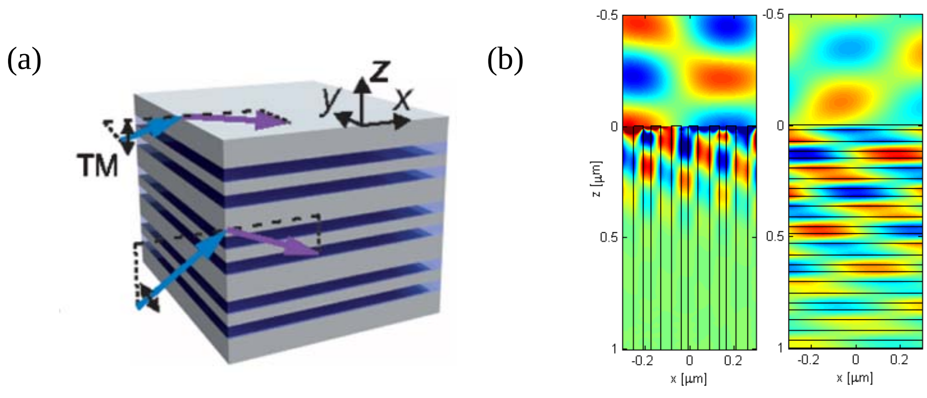

Fig. 1 (a) Schematical representation of an array of coupled waveguide pairs, illustrating negative refraction. (b) Snapshot of the H_y field distribution as a plane wave impinges on the interface perpendicular (left) and parallel (right) to the waveguides, with an angle of incidence of 30°.

2. Coupled plasmonic waveguides

Figure 2 shows the calculated mode wavevectors of metal dielectric metal (MDM) waveguides, $Re(k_x)$ is plotted as a function of free space wavevector for a semi-infinite Ag - 20 nm TiO_2 - semi-infinite Ag (MDM) waveguide (solid) and a semi-infinite Ag - 44 nm TiO_2 - 32 nm Ag - 44 nm TiO_2 - semi-infinite Ag (MDMDM) waveguide (dashed), assuming experimentally determined optical constants. A negative mode index, characterised by counter propagating energy and phase velocities, corresponds

ISBN 978-952-67611-0-7

to the shaded frequency range where the real part of k_x is negative and the slope $\partial k_0 / \partial \mathrm{Re}(k_x)$ is positive (see Fig. 2 (a)) [2]. Interestingly, in this regime the asymmetric mode has significantly lower losses when compared with the symmetric mode, making it the dominant propagating mode (Fig. 2 (b)). However, the planar geometry confines the negative refraction to the plane of the waveguide (*x-y* plane).

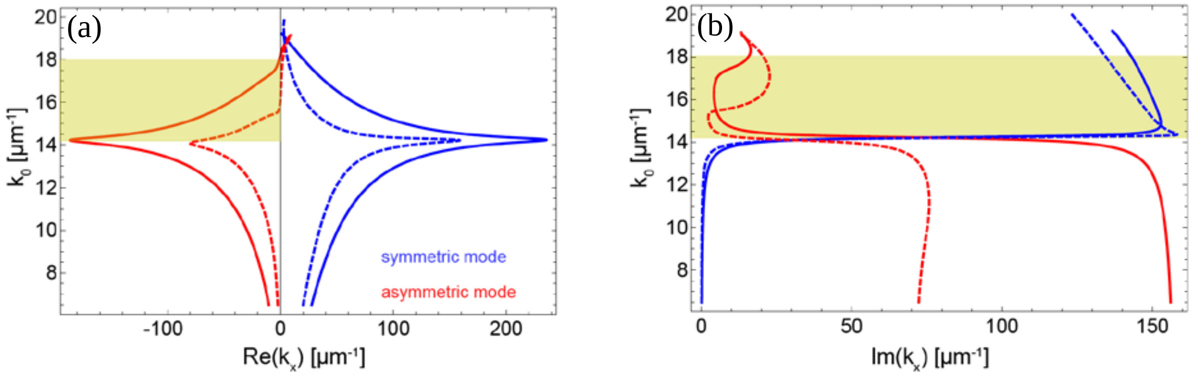

Fig. 2 Dispersion curves corresponding to the symmetric (blue) and asymmetric (red) waveguide modes. The solid lines denote the modes in an individual MDM waveguide, and the dashed lines denote modes in a coupled MDM waveguide pair

Stacking of single MDM waveguides into a waveguide array improves incoupling efficiency and presents the opportunity for negative refraction in both the *x-z* and *y-z* plane, which arises from coupling between neighbouring waveguides. The sign of the field overlap inside the dielectric determines the sign of the refraction angle [1]. The symmetric superposition of two asymmetric modes in a MDM waveguide pair has a negative field overlap with the adjacent MDM waveguide pair, resulting in negative refraction in the *x-z* and *y-z* plane.

3. Fabrication of coupled waveguide arrays and refraction of miniature prisms

A metamaterial consisting of two coupled MDM waveguide pairs was deposited by electron beam physical vapour deposition on a Si_3N_4 membrane (Fig. 3 (a)). Optical constants and layer thicknesses of individual layers were determined using variable angle spectroscopic ellipsometry. Using FIB milling, a freestanding prism was sculpted from the metamaterial (side length 6 μm, angle 4.1˚, see Fig. 3 (c)), accompanied by a reference hole where a section of membrane was removed. The SEM images of both the cross-section and the miniature prism clearly show the double periodic structure of our metamaterial. In a separate experiment, a FIB was used to mill linear slots into a Si_3N_4 membrane. The milled sections were filled with Ag by thermal evaporation, and the surface was polished by further milling (Fig. 3 (b)). In order to calibrate the angular distribution of transmitted light and verify sample alignment, a hole array was incorporated into the membrane, and the angular positions of the diffracted orders in Fourier space were recorded at each wavelength.

Refraction angles were measured as a function of wavelength for the prism depicted in Fig. 3 (c), and using Snell's law, this was converted to an effective index of refraction. Fig. 4 (a) shows a variation of index from 1.5 to 0.5 across the studied range. Interestingly, the effective index matches that of free space ($n_{eff} = 1$) at a wavelength of 450 nm.

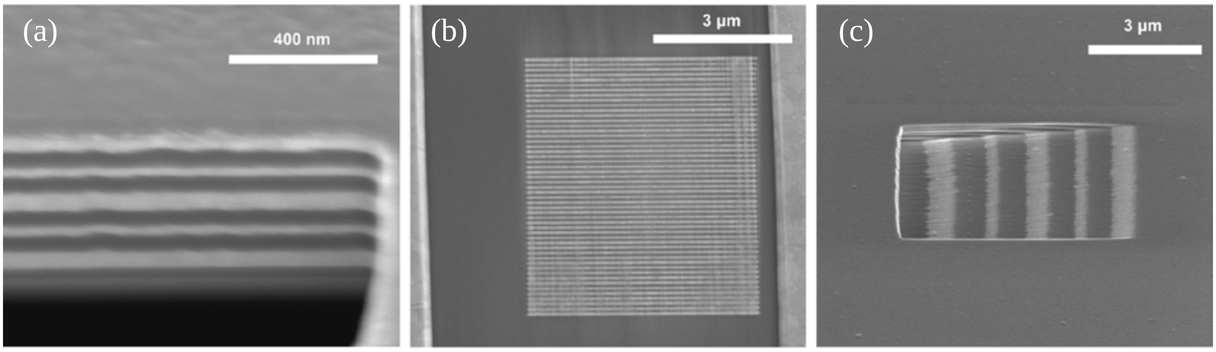

Fig. 3 SEM images of (a) a cross-section of a coupled waveguide metamaterial. The dark and light slabs are TiO_2 and Ag respectively (b) coupled waveguide metamaterial with waveguides perpendicular to the interface (c) a prism made by FIB milling

Far-field refraction angles obtained from FDTD simulations (see Fig. 4 (b)) are in good agreement with the measured values. Small discrepancies are attributed to variations in layer thickness and optical constants. The same measurement was also performed on the Si_3N_4 sample depicted in Fig. 3 (b), here the effective index of refraction was negative for a free-space wavelength of 380 nm.

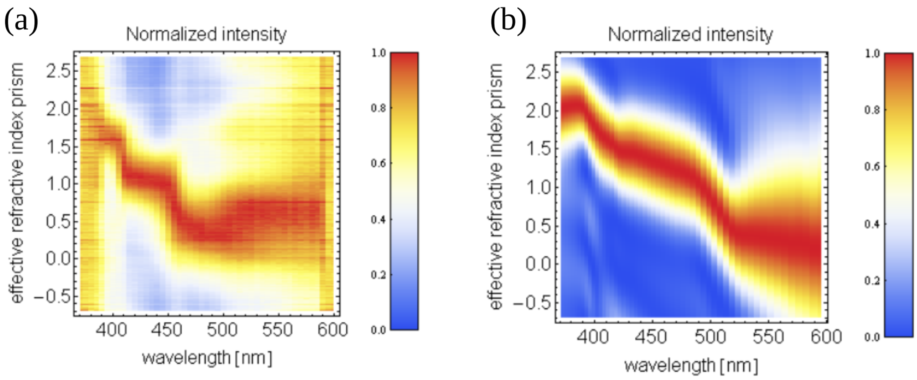

Fig. 4 (a) measured effective refractive index of the prism,
(b) simulated effective refractive index of the prism from (a).

4. Conclusion

The fabricated geometry shows highly dispersive behaviour across the visible spectrum. Negative refraction was observed for the geometry with waveguides perpendicular to the interface.

References

[1] E. Verhagen, R. de Waele, L. Kuipers and A. Polman, Three-dimensional negative index of refraction at optical frequencies by coupling plasmonic waveguides, *Physical Review Letters*, vol. 105, pp. 223901-223904, 2010

[2] J.A. Dionne, E. Verhagen, A. Polman and H.A. Atwater, Are negative index materials achievable with surface plasmon waveguides? A case study of three plasmonic geometries, *Optics Express*, vol. 16 no. 23 pp. 19001-19017, 2008