Optical metamaterials with a negative index of refraction in the UV

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Abstract

Metamaterials composed of Ag/Si_3N_4 multilayers were fabricated using focussed ion beam milling and reactive ion etching. The coupled plasmonic waveguide arrays were experimentally studied using UV interferometry. A -132 degree phase retardation was observed at a freespace wavelength of 363 nm, corresponding to a negative effective index.

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. Previous negative index metamaterial designs have utilized subwavelength resonant elements such as split rings to engineer the electromagnetic response. Due to their resonant properties these structures show poor performance in the visible regime, caused by increased ohmic losses when operating close to the plasma frequency. 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], with significantly reduced losses when compared to other resonator based geometries. Here we present a new method to fabricate this UV metamaterial and demonstrate its negative index using interferometry.

2. Coupled plasmonic waveguides

Using waveguides as a building block for a metamaterial structure relies on the principle that light transmitted through a waveguide adopts the properties of the mode supported by the waveguide. Here, waveguide dimensions are chosen such that the structure supports a negative index mode at a specific frequency range. Figure 1 (a) shows the calculated mode profile of the negative index mode in red, which consists of a superposition of two asymmetric surface plasmon polariton (SPP) waveguide modes strongly coupled by a thin metal layer. The corresponding dispersion relation is shown in red in figure 1 (b-c). The waveguide mode index is negative above the surface plasmon resonance frequency, when the slope $\partial\omega / \partial \mathrm{Re}(k_x)$ becomes positive [2].

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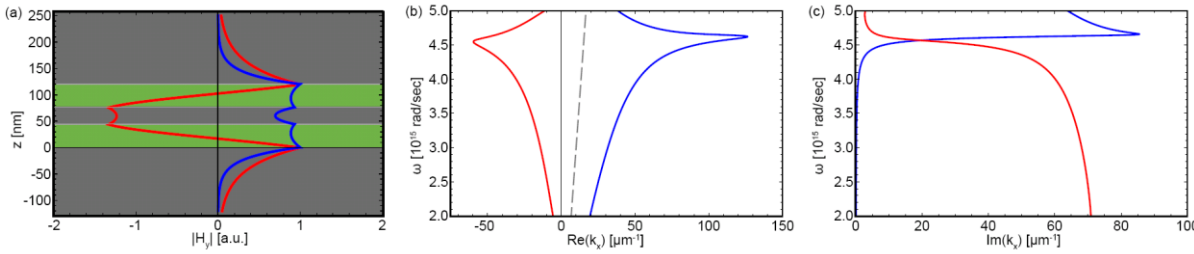

Fig. 1: (a) Calculated field distribution of the symmetric (blue) and asymmetric (red) waveguide mode. The green and gray regions correspond to Si_3N_4 and Ag layers respectively. (b-c) Dispersion curves corresponding to the symmetric (blue) and asymmetric (red) waveguide mode.

Isolated waveguides with a negative mode index only facilitate negative refraction in the plane of the waveguide. Stacking single metal-dielectric-metal (MDM) waveguides into a waveguide array improves incoupling efficiency and presents the opportunity for negative refraction out of the plane of the waveguide due to 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 (as shown in fig 1 (a)) has a negative field overlap with the adjacent MDM waveguide pair, resulting in an isotropic negative index.

3. Fabrication of coupled waveguide arrays

Thin (100-300 nm) freestanding Si_3N_4 membranes supported by a Si frame are covered by a 20 nm Cr masking layer. High resolution, low beam current FIB milling was used to pattern slots in this Cr masking layer. This pattern was subsequently transferred into the Si_3N_4 layer using a CHF3/O2 anisotropic reactive ion etch recipe. The slots in the membrane were infilled with Ag using thermal evaporation, and the surface of the structure was polished using FIB milling at grazing angles to ensure optical access to the metamaterial. A schematical overview of the fabrication steps with corresponding scanning electron microscope (SEM) images is shown in figure 2.

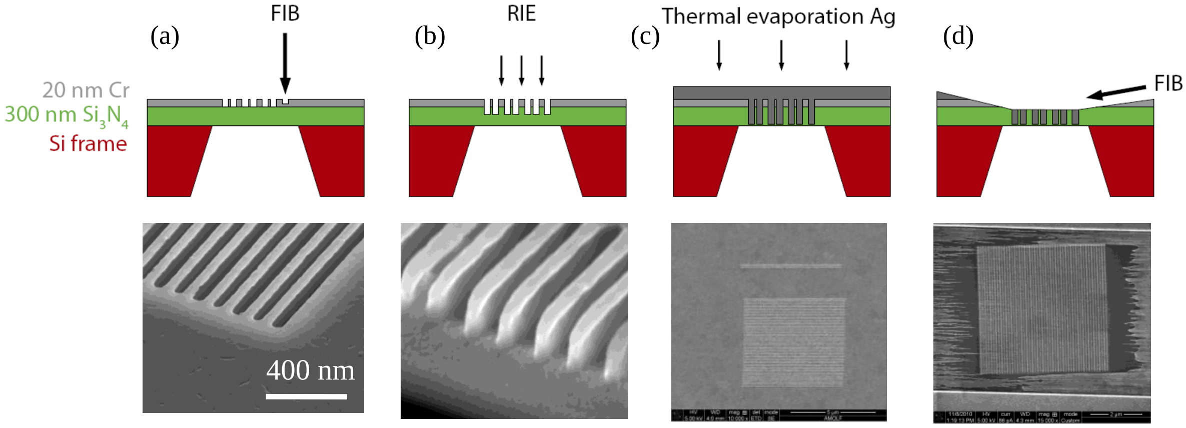

Fig. 2: (a) Selective removal of the Cr masking layer. (b) The exposed Si_3N_4 is etched, a SEM image of a cross-section is shown below. (c) Thermal evaporation coats the structure conformally. (d) The underlying structure is exposed after polishing the surface

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4. Interferometric measurements

In order to determine the optical response of the metamaterial, interferometry was used to measure the sign and magnitude of the phase shift of light transmitted through the structure. At UV wavelength a clear negative phase shift was observed for TM polarized light, whereas at longer wavelength a positive phase shift was observed, see figure 3. This is in good agreement with theory, which predicts a positive index mode to be dominant at frequencies below the surface plasmon resonance frequency (blue lines in figure 1).

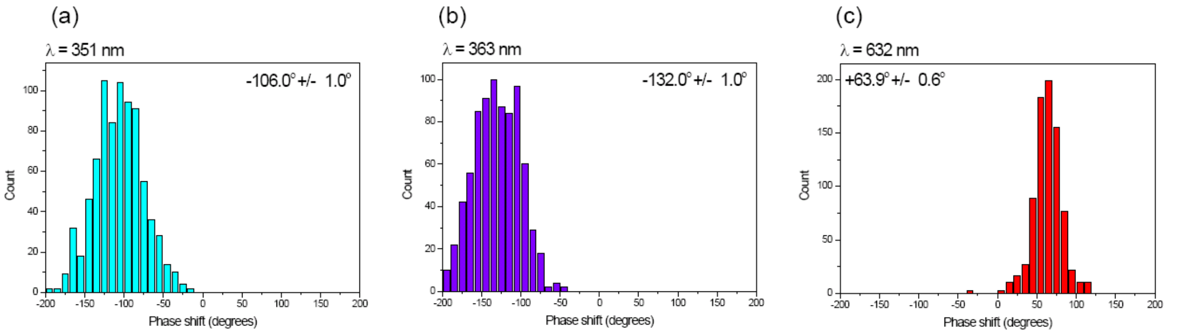

Fig. 3: Phase shifts recorded during the interferometric measurement for TM polarized light. (a-c) show histograms of measurements for a freespace wavelength of 351, 363 and 632 nm respectively.

The interferometric measurements were repeated for TE polarized light. For this polarization, light is unable to couple to SPP waveguide modes, but the dielectric waveguides do support a (positive index) TE waveguide mode above their cut-off frequency. Indeed, the observed phase shift agrees well with the expected phase shift. Light below cut-off is not allowed to propagate through the structure, and low transmission is observed.

5. Conclusion

We fabricate a Si_3N_4-Ag multilayer metamaterial using a combination of focussed ion beam milling and reactive ion etching. Interferometry shows a negative phase shift at 351 and 363 nm freespace wavelength, and a positive phase shift at 632 nm for TM polarized light. This is in agreement with calculations.

References

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