Frequency selective reflectors, magnetic walls and perfect optical absorbers based on new classes of metal and dielectric-loaded relief metamaterials

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Abstract

New classes of continuously metallic and 'dielectric-loaded' relief metamaterials (raised or indented sub-wavelength patterns on continuous, non-perforated metal surfaces) enable manipulation of reflected light intensity and phase in the visible-infrared range. Perfect absorption, colour control, field enhancement and optical magnetic mirror effects can be achieved and controlled through structural design.

1. Introduction

Engineering metamaterials for functionality in the photonic domain is of great significance for both fundamental research and practical applications. We have reported recently on continuously metallic 'bas-relief' (raised, Fig. 1a) and 'intaglio' (indented, Fig. 1b) metamaterial designs providing control over the perceived colour of pure metals [1]. Here, we further describe the ability of such structures to control the intensity and phase of reflected light in the visible range and illustrate their application to 'perfect absorption' and optical magnetic conductor effects. We also extended the family of relief metamaterials to include 'dielectric-loaded' metamaterials, wherein nanoscale dielectric patterns are located on planar metal substrates (Fig. 1c). These structures provide for the strong localization of light and associated field enhancements, thereby again facilitating control over the intensity and phase of reflected light. Dielectric-loaded metamaterials function well at visible and offer great versatility and flexibility for a range of photonic applications.

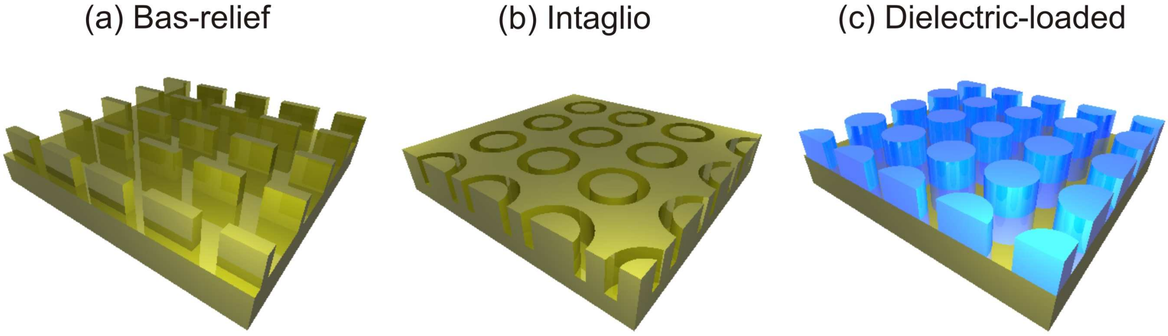

Fig. 1: Artistic impressions of assorted relief metamaterial types.

2. Metal relief metamaterials for perfect absorption and optical magnetic conductor

Fig. 2a shows spectra for square arrays of intaglio rings milled (by focused ion beam) to varying depths in a gold film, alongside the reflection spectrum for the unstructured gold surface. The plasmonic resonances of the structure red shift and grow in strength increasing etch depth, giving rise to the dramatic colour variations seen in the inset optical microscope images. Note that nearly 86% of incident light is absorbed by sample *D* at 610 nm. Fig. 2b shows spectra for an anisotropic intaglio design of asymmetric split rings, again inscribed into a gold surface. In this case absorption is polarization-dependent and reaches 85% for the y-polarization at 603 nm.

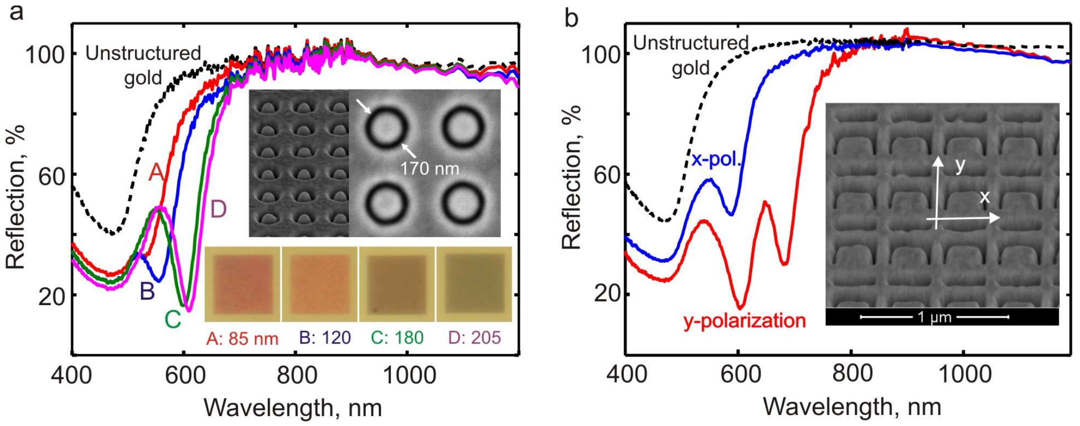

Fig. 2: Resonant absorption in gold relief metamaterials. (a) Reflection spectra for unstructured gold and for gold patterned with arrays of 170 nm diameter rings cut to varying depths (as labelled). Insets show electron microscope images of the intaglio design and optical microscope images of the patterned domains; (b) Reflection spectra for flat gold and for gold patterned with an intaglio design of asymmetric split rings [depth ~150nm], for incident polarizations parallel and perpendicular to the split.

As well as modifying the intensity of reflected light, plasmonic relief metamaterials can dramatically change the phase. Fig. 3 presents numerical simulations of an intaglio design in gold, comprising rectangular grooves (with a length of 200 nm in the x-direction, width of 50 nm and depth of 100 nm) arranged in a square array with a period of 300 nm. These sub-wavelength grooves have little interaction with x-polarized incident light and for this polarization present reflection spectra (intensity and phase) almost identical to those of flat gold. However, for the y-polarization, near-perfect absorption is achieved at ~650 nm.

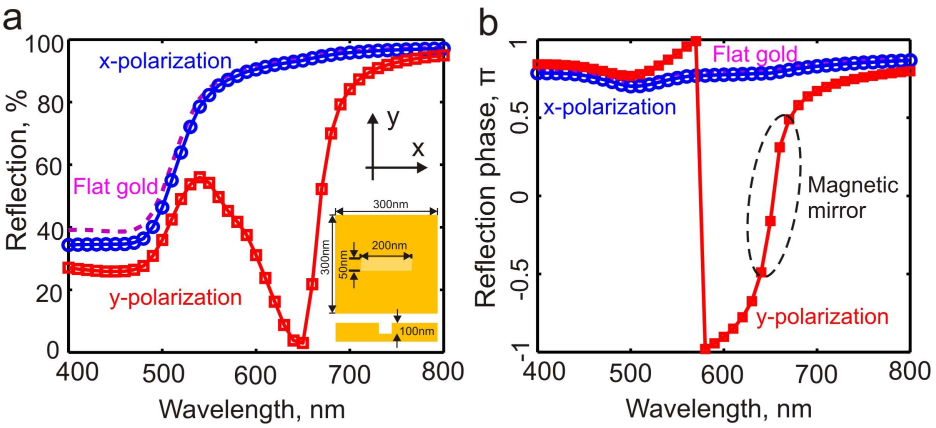

Fig. 3: Reflection intensity and phase modification by relief metamaterials. (a) Reflection spectrum of flat gold [pink curve] and intaglio slot metamaterial [geometry and dimensions shown inset] for x- [blue] and y- polarizations [red] at normal incidence; (b) Corresponding reflection phase spectra.

And around this absorption resonance, the reflection phase (Fig. 3b) departs radically from the behaviour of flat gold – crossing zero at the resonance. Exotic 'magnetic mirror' responses of this kind may be employed, for example, to enhance the efficiency of optical antennas or to manipulate the emission characteristics of gain media such as quantum dots coupled to the metamaterial.

3. Dielectric-loaded relief metamaterials

The introduction of ‘dielectric loaded’ structured (sub-wavelength patterns of thin film dielectrics on a metallic back-plane) brings additional variety to the relief metamaterials family. Fig. 4 illustrates the significant changes in the reflection spectrum of gold that may be brought about by the application of a patterned dielectric layer only 50 nm thick. As Fig. 4b shows, a continuous dielectric layer of this thickness (assumed to be lossless, with a refractive index of 2.5) has relatively little effect. But a nanostructured layer (in the present case an array of 200 nm diameter disks), supporting localized surface plasmon modes with strong field enhancement at the metal/nanodisk interface as shown in Fig. 4c, can substantially modify the reflection spectrum of the metal.

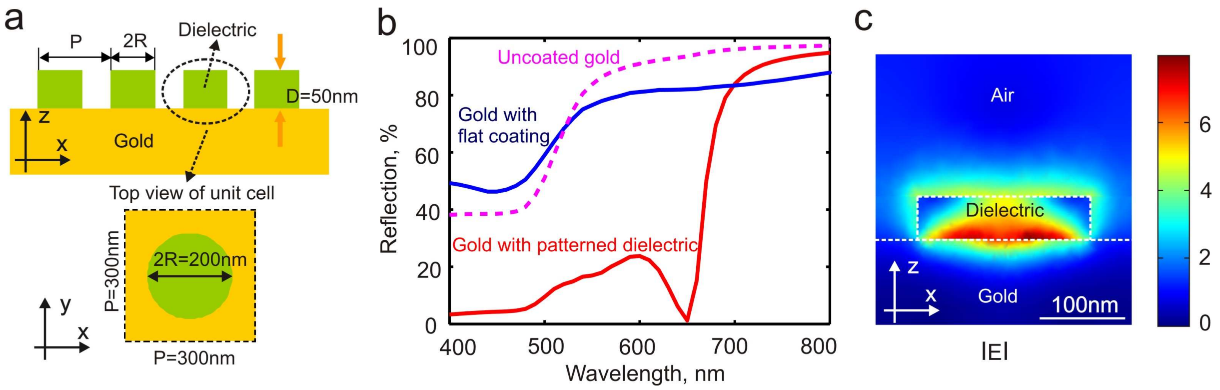

Fig. 4: Dielectric-loaded relief metamaterials. (a) Structural geometry and dimensions - a flat gold surface loaded with a 300 nm period square array of 200 nm diameter, 50 nm thick dielectric disks; (b) Numerically simulated reflection spectrum of the structure in (a) alongside the spectra for unstructured, uncoated gold and gold with a continuous thin film dielectric coating; (c) Cross-sectional map of electric field intensity in the y symmetry plane of a nanodisk. The structure is illuminated at normal incidence with x-polarized plane waves.

4. Conclusion

New classes of continuously metallic and dielectric-loaded relief metamaterials have been introduced. The excitation of structurally dependent plasmonic resonances in the constituent sub-wavelength meta-molecules provides wide ranging control over the intensity and phase of reflected light and allows for spectral tuning of phenomena including perfect absorption, localized field enhancement optical magnetic mirror functionality in the visible to near-infrared range. These in turn present opportunities in the engineering of enhanced linear and nonlinear optical properties and nanoscale functional devices for the generation, switching and detection of light

References

[1] J. Zhang, J.Y. Ou, N. Papasimakis, K.F. MacDonald and N.I. Zheludev. Controlling the Colour of Metals: Intaglio and Bas-Relief Metamaterials, arXiv 1011.1977v1, 2010