INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS

J. Opt. A: Pure Appl. Opt. **9** (2007) L1–L2 doi:10.1088/1464-4258/9/1/L01

RAPID COMMUNICATION

Optical magnetic mirrors

A S Schwanecke[1], V A Fedotov[1], V V Khardikov[2], S L Prosvirnin[2], Y Chen[3] and N I Zheludev[1]

[1] EPSRC NanoPhotonics Portfolio Centre, School of Physics and Astronomy,
University of Southampton, UK
[2] Institute of Radio Astronomy and Kharkov National University, Kharkov, Ukraine
[3] Rutherford Appleton Laboratory, Didcot, Oxon, UK

E-mail: A.S.Schwanecke@soton.ac.uk

Received 19 October 2006, accepted for publication 7 November 2006
Published 22 November 2006
Online at stacks.iop.org/JOptA/9/L1

Abstract
We report the first demonstration of an optical magnetic mirror achieved by nanostructuring a metal surface. It reverses the magnetic field of an incident wave upon reflection, acting as an 'optical frequency superconductor'.

Keywords: magnetic wall, nano-structured surface, meta-material

Optical properties of materials result from the individual responses of molecules smoothed over the wavelength of light. In the past the only way of engineering these properties was by changing a material's chemical composition. Electronic and optical band engineering achieved through structuring of natural solids on a scale smaller or comparable with the wavelength has opened new ways of tailoring optical responses.

However, it is only recently that fabrication techniques have allowed the assembly of large numbers of individual subwavelength elements as 'artificial molecules'. For instance, metal nanowires can be arranged in configurations exhibiting magnetic response at optical frequencies, resulting in a negative refraction index [1, 2], while purposely designed subwavelength structures may become highly transparent [3] or even completely 'invisible' [4, 5] at certain wavelengths. Here we report the first demonstration of an entirely new type of optical functionality achieved through nanostructuring of metal surfaces, an optical magnetic mirror.

A *magnetic mirror* imposes extremely unusual electromagnetic boundary conditions: it does not reverse the electric field of a light wave upon reflection, but reverses the magnetic field. This property renders it distinctly different from a normal mirror, which instead reverses the electric field of a reflected wave, see figure 1. The former property can be directly concluded from observation of a transverse-electromagnetic wave. If zero phase change upon reflection is found for the electric field component and the wave can only form the right-handed $\boldsymbol{k}$–$\boldsymbol{E}$–$\boldsymbol{H}$ triade, as required by the Maxwell equation, the magnetic field has to be reversed simultaneously. The magnetic field is therefore cancelled in the plane of the magnetic mirror. This makes it similar to a superconductor that will repel any external magnetic field by creating an oppositely directed magnetization, known as the Meissner effect. We therefore can speak of a magnetic mirror as a 'superconductor at optical frequency'.

Due to the mirror image dipole, emission of an electric dipole quenches at a normal mirror. In contrast, radiation of the dipole at a magnetic mirror enhances, providing interesting opportunities for molecular spectroscopy. Owing to its unusual boundary conditions, a magnetic mirror is extremely sensitive to losses at the surface, a property which may be used for enhancing photodetector sensitivity.

The concept of a magnetic mirror emerged through research in the microwave part of the spectrum on high-impedance structured interfaces [6]. Here, for the first time, we show that planar 'fish-scale' nanostructures exhibit magnetic mirror properties in the *optical* part of the spectrum. The structure, patterned by electron-beam lithography, was fabricated on a silicon wafer in three layers: a flat 150 nm aluminium backing-mirror, covered with a 50 nm dielectric (silicon dioxide) and 50 nm-thick fish-scale shaped aluminium nanowires on top. It is patterned in a periodic fashion (unit cell 440×440 nm^2) on a subwavelength scale and, hence, does not diffract. With an overall size of the mirror of 500×500 μm^2, it contains about 10^6 fish-scale elements. The absolute phase change on reflection was measured using an interferometric arrangement with a super-continuum photonic-crystal fibre laser.

1464-4258/07/010001+02$30.00

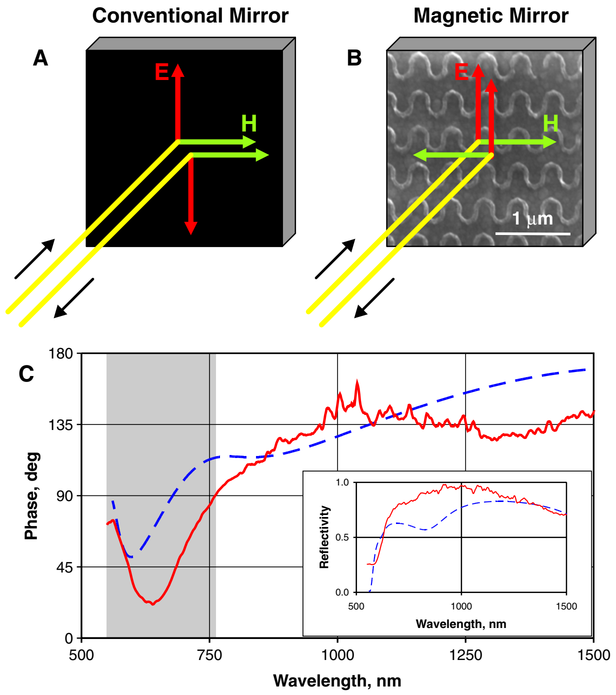

Figure 1. The field changes upon reflection from a *conventional* mirror (A) and a *magnetic* mirror (B) are distinctly different with respect to their effect on electric and magnetic fields respectively. A scanning-electron micrograph depicts the investigated 'fish-scale' nanostructure. (C) Wavelength dependencies of intensity and phase shift for a reflected wave (solid line—experiment, dashed line—theory). The shaded area indicates a range of frequencies where the structure manifests magnetic mirror behaviour.

(This figure is in colour only in the electronic version)

Figure 1 shows reflectivity R and phase change $\Delta\phi$ inflicted by the structure upon reflection for visible and near-infrared wavelengths of an incident linearly polarized wave. Here, magnetic mirror behaviour corresponds to phase shift $|\Delta\phi| < \pi/2$, with a perfect magnetic mirror corresponding to $\Delta\phi = 0$. Magnetic mirror behaviour was therefore seen in the spectral range from 550 to 760 nm. At wavelengths around $\lambda = 560$ nm we saw a dramatic reduction of the phase shift $\Delta\phi$ reaching a low value of 20°. Magnetic mirror properties were also seen for light polarized along the perpendicular direction with $\Delta\phi$ reaching 30° near $\lambda = 630$ nm, matching with a corresponding shift to higher frequencies as seen for the similar microwave structure [4]. Results of pseudo-spectral time-domain (PSTD) [7] calculations, implementing the finite-difference time-domain (FDTD) method, confirm the experiments. Remaining differences can be partly attributed to the employed bulk dielectric coefficients for the granulated aluminium wires. Our calculations also indicate that a perfect magnetic mirror ($\Delta\phi = 0$) should be achievable in correspondingly scaled structures for longer wavelengths, where losses are smaller. For longer wavelengths it will also be easier to achieve a smaller ratio between the strip width and pitch of the structure, which will make the resonant phase change sharper.

In conclusion we have demonstrated that fish-scale nanostructures act as magnetic mirrors in the optical part of the spectrum.

Acknowledgments

The authors gratefully acknowledge the support of the Engineering and Physical Sciences Research Council, UK and the EU Network of Excellence 'Metamorphose'.

References

[1] Shalaev V M *et al* 2005 Negative index of refraction in optical metamaterials *Opt. Lett.* **30** 3356–8
[2] Dolling G *et al* 2006 Simultaneous negative phase and group velocity of light in a metamaterial *Science* **312** 892–4
[3] Alu A and Engheta N 2005 Achieving transparency with plasmonic and metamaterial coatings *Phys. Rev.* E **72** 016623
[4] Fedotov V A *et al* 2005 Planar electromagnetic metamaterial with a fish scale structure *Phys. Rev.* E **72** 056613
[5] Pendry J B, Schurig D and Smith D R 2006 Controlling electromagnetic fields *Science* **312** 1780–2
[6] Sievenpiper D *et al* 1999 High-impedance electromagnetic surfaces with a forbidden frequency band *IEEE Trans. Microw. Theory Tech.* **47** 2059–74
[7] Gao X *et al* 2004 Applying a mapped pseudospectral time-domain method in simulating diffractive optical elements *J. Opt. Soc. Am.* A **21** 777