Mirror that does not change the phase of reflected waves

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We report that electromagnetic wave reflected from a flat metallic mirror superimposed with a planar wavy metallic structure with subwavelength features that resemble "fish scales" reflects like a conventional mirror without diffraction, but shows no phase change with respect to the incident wave. Such unusual behavior resembles a reflection from a hypothetical zero refractive index material, or "magnetic wall". We also discovered that the structure acts as a local field concentrator and a resonant "amplifier" of losses in the underlying dielectric. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2179615]

Wavelength sensitive transmission and reflection of a structured thin metal layers in the optical and microwave parts of the spectrum currently attract considerable attention. Such selectivity results from patterning the interface on a subwavelength scale in a way that makes electromagnetic excitation couple with the structure in a resonant fashion.[1–3] In this letter, we report on the first experimental observation of the "magnetic wall" property of novel structured metallic surfaces. The magnetic wall is a mirror that imposes extremely unusual electromagnetic boundary conditions [see Fig. 1(b)]: It does not change the phase of the electric field upon reflection, but reverses the phase of the magnetic field.[4] This property is in sharp contrast to the reflection from a dielectric interface or metal mirror, which reverses the phase of the electric field of the reflected electromagnetic wave and preserves the phase of the magnetic field instead [Fig. 1(a)]. The magnetic wall property is seen in a narrow spectral range near an isolated wavelength. Apart from this wavelength, the structure acts as a good broadband metallic reflecting surface. Zero-phase shift is a very unusual property of a reflective surface, because upon reflection from a conventional unstructured metal or dielectric surface with refractive index $n>1$, the electric field of the wave accrues a phase reversal (phase shift of 180°). Indeed $E_{\mathrm{reflected}}=-(n-1)/(n+1)E_{\mathrm{incident}}$ and therefore electric fields of incident and reflected waves have opposite signs.

For the experiments reported here, we manufactured a fish-scale structure with a square translation cell of 15 $\times$15 mm that was etched from a 35 μm copper film on one side of a flat 1.5 mm thick fiberglass substrate ($\epsilon=4.5$, tg$\delta=0.018$). The other side of the substrate was covered with a continuous copper sheet. The width of the strips was 0.8 mm. The overall size of the samples was approximately 220$\times$220 mm. We studied the reflection of electromagnetic radiation from the structure under nearly normal incidence conditions with the incident wave entering the sample at 6° to the normal. The measurements were performed in an anechoic chamber in the spectral range from 2 to 16 GHz using a vector network analyzer and linearly polarized horn antennas. The setup operated in a nondiffracting regime since this periodic structure does not diffract electromagnetic radiation for wavelengths λ longer than the translation cell size d, i.e., for frequencies lower than 20 GHz.

Without a fish-scale structure on top, one would expect a metallic sheet to be a very good reflector across the entire spectral range of interest, and that the reflected wave would have the opposite phase to the incident wave. What we found (see Fig. 2) is that with an x-polarized incident field the reflection losses are small everywhere apart from in a −40 dB trough at 8.77 GHz. Refection for the perpendicular y polarization is nearly perfect everywhere apart from in a smaller −35 dB trough at 4.22 GHz. For both polarizations, we observed that the reflected wave's phase change has a strong dispersion and that the phase difference between the incident and reflected wave passes zero in the proximity of the resonances, at 8.77 GHz and 4.22 GHz, correspondingly.

The origin of the array's resonant features for x-polarized incident radiation becomes apparent if one considers the structure as a sequence of straight-line strips periodically loaded with short-circuit sections of length $S/4$ where S is the full length of the strip within the elementary translational cell.[5,6] Coupling of the incident electromagnetic radiation to the strip line causes the resonant features of the structure. The resonant wavelength is determined by the length S of the folded strip, which is longer than the elemen-

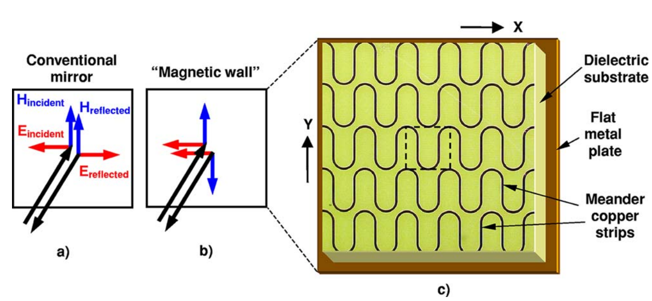

FIG. 1. (Color online) Field transformations upon reflection from a conventional mirror (a) and a magnetic wall mirror (b). Diagram (c) shows a fragment of the magnetic wall mirror consisting of the fish-scale pattern of copper strips on a dielectric substrate backed with a flat metal mirror. The dielectric substrate is much thinner than the wavelength. The dashed line box, whose sides d are smaller than the wavelength λ, indicates the elementary translational cell of the structure.

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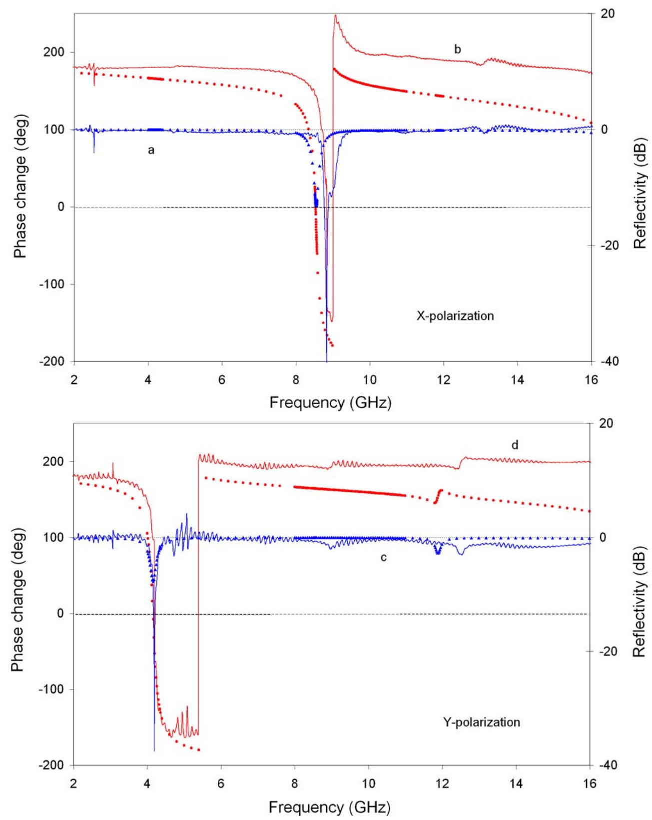

FIG. 2. (Color online) Normal incidence reflection of linearly polarized wave from the fish-scale metamaterial backed with a flat copper mirror, as presented in Fig. 1. Curves (a) and (c) show intensity of the reflected signal for x and y polarizations, accordingly. Curves (b) and (d) show phase difference between the incident and reflected waves for x and y polarizations. △ and ○ symbols denote the results of theoretical calculations using method of moments for the intensity and phase of the reflected wave, respectively.

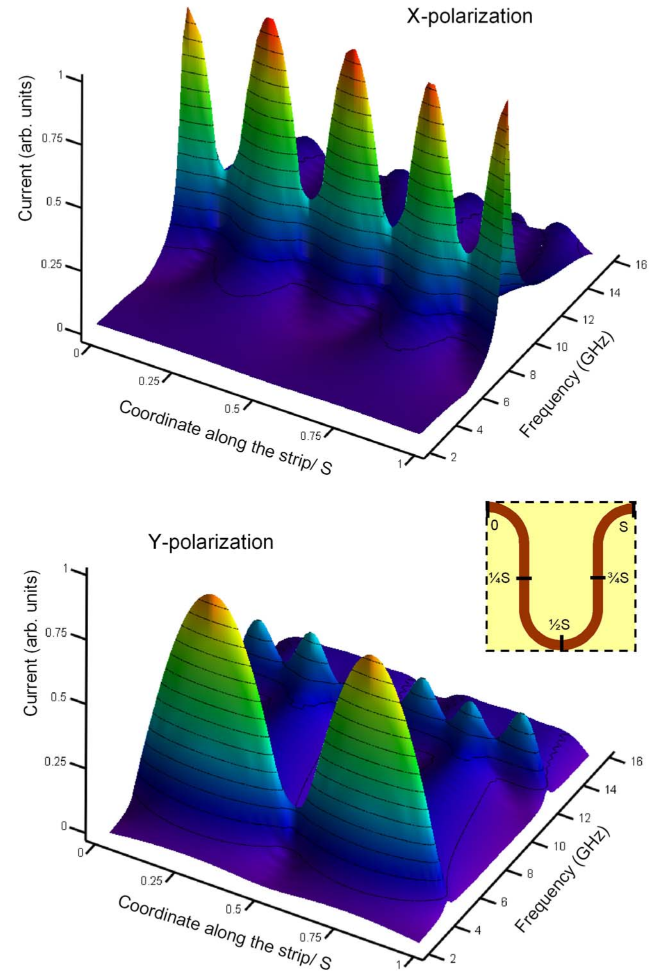

FIG. 3. (Color online) Distribution of the current induced in the strip by incident electromagnetic wave as a function of its frequency for the x polarization (upper graph) and y polarizations (lower graph). The inset shows the way the coordinate is measured along the strip inside the elementary translation cell of the structure.

tary translation cell d of the fish-scale structure. This creates resonances for nondiffracting wavelengths that are longer than d. Indeed, for the fish-scale structure on a metal-backed substrate the following formula can be used to estimate the wavelength of the excitation in the strips: $\lambda_g \approx (c/\nu)[(\epsilon+1)/2+(\epsilon-1)/2/\sqrt{1+5h/w}]^{-1/2}$,[7] where $2w$ is the width of the strip and h is the substrate thickness. Now, for the x polarization, the resonance occurs at a frequency where λ_g is close to one-half of the length S of the strip inside the elementary translation cell, i.e., $\lambda_g(\nu)\approx S/2$. This estimation gives a resonant frequency of 8.77 GHz which coincides with the experimentally measured value. A resonance for the y polarization shall occur when $\lambda_g(\nu)\approx S$, i.e., at frequency of 4.38 GHz, which is in a good agreement with the measured value of 4.22 GHz. Corresponding distributions of the current induced in the strip by incident electromagnetic wave as a function of its frequency is illustrated on Fig. 3.

These current distributions and the far-field responses of the fish-scale structure were modelled using the method of moments.[5] The numerical calculation that account for losses in the dielectric material on which the structure is fabricated accurately describes all characteristic trends seen in the reflection experiment and predicts the dramatic switching of the reflected signal phase at the resonances (see Fig. 2). Both the experimental results and calculations show the phase of the reflected wave changing sign and passing zero at about 8.77 GHz for x polarization and at approximately 4.22 GHz for y polarization. The calculations show that if the interface was lossless, which it could be in the case of an ideal metal and a nonabsorbing dielectric support, the zero phase change would correspond to reflection from an interface with a bulk homogeneous medium of zero refractive index, $n=0$.

The mirror, which does not reverse the sign of the electric field in the reflected wave, has a number of unusual properties. For instance, the mode structure in a laser-type Fabry–Perot resonator made out of normal mirrors has nods at the mirrors. In contrast, in a resonator made with fish-scale mirrors, the field maxima will appear at the mirrors. A circularly polarized wave reflected from the anisotropic fish-scale structure at resonance will retain handedness of its polarization state. This is in sharp contrast to the reflection from an unstructured metallic or dielectric mirror when the handedness of the wave is reversed upon reflection. Reflection from the fish-scale structure is extremely sensitive to the loss characteristics of the reflecting layer. Indeed, assuming that the structure and the mirror are made out of ideal metal and that the dielectric is loss-less, one would expect the reflected wave to have the same amplitude as the incident wave. Thus, the trough in the reflected signal, experimentally observed at the zero-phase frequency points, should not appear for lossless media. The only reason for such troughs to exist could be dissipative losses (other sources of losses, such as diffraction, are not present in this structure because the patterning

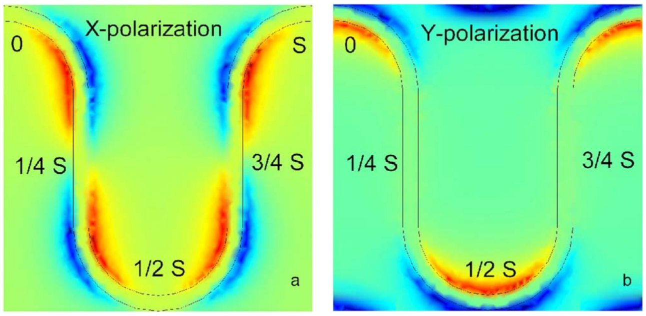

FIG. 4. (Color online) The color-coded maps (a) and (b) show the instantaneous values of the electric-field magnitude in the plane of the structure at resonant conditions for the x and y polarizations, respectively. Blue and red correspond to negative and positive values of the electric field, while green corresponds to zero value of the field.

period is smaller than the wavelength). However, in the microwave part of the spectrum, losses in copper are negligible; indeed, reflection losses for a free-standing copper mirror at 10 GHz are about 2.8×10^{-4}. For a copper mirror with a dielectric substrate in front of it, the losses related to the double pass of the wave through the substrate would only be a fraction of a decibel for the microwave material used in our experiment, and cannot explain the high losses (−40 dB and −35 dB) observed in the experiment at 8.77 GHz (x polarization) and 4.22 GHz (y polarization). In the case of a fish-scale structure, these strong resonant losses are related to the high concentration of the electric field between the strips of the fish scale design and the mirror plane. Such a high concentration of the electric field at the resonance was illustrated using three-dimensional finite element method for solving Maxwell's equations in the spectral presentation near the metal strips [see Figs. 4(a) and 4(b)]. This figure show instantaneous values of the electric field at the plane of the structure. When this field distribution is compared with the current distribution presented in Fig. 3, one can note that on the strip at resonance the current maxima are located at the minima of electric field which correspond to the maxima of magnetic field.

The unusual loss amplification property of the fish-scale structure may be used to improve photodetectors. The weak sensitivity of a photodetector outside its main frequency band may be enhanced if a fish-scale structure is used as a light-harvesting material to enhance small tail interband absorbtion. Here, a photosensitive material should replace the substrate dielectric of the structure. This approach may be particularly efficient in semiconductor detectors and for increasing the quantum efficiency of photomultipliers. A frequency-selective detector may also be created with help of this structure. The ongoing development of nanofabrication techniques may well lead to the use of the fish-scale structures in the optical part of the spectrum.

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