## Multiband subwavelength magnetic reflectors based on fractals

Lei Zhou,<sup>a)</sup> Weijia Wen, C. T. Chan, and Ping Sheng

Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

(Received 27 May 2003; accepted 5 September 2003)

We use theory and experiment to demonstrate that a composite material, consisting of a metallic planar fractal and a metal sheet separated by a thin dielectric layer, can reflect electromagnetic wave in-phase at a series of frequencies, with some of the corresponding wavelengths much longer than the reflector's own size. We show that the physics is governed by a series of intrinsic magnetic resonances and can be well described by an effective-media of frequency-dependent permeability. © 2003 American Institute of Physics. [DOI: 10.1063/1.1622122]

It is well known that metals reflect electromagnetic (EM) wave with a phase reversal, due to the boundary condition requirement that the tangential component of the electric field  $(E_{II})$  should be zero for a good metal.<sup>1</sup> When a metal plate is placed very close to a source to reflect its EM wave radiations, the power received in the far field will be strongly diminished  $(S_{11} \sim 1)$  because of the cancellation of the outof-phase reflected wave with the radiation from the source. In addition, a finite-sized metal plate cannot reflect EM wave whose half-wavelength is larger than plate's lateral dimension. Some frequency selective surfaces<sup>2</sup> and metallic fractal-like structures<sup>3,4</sup> can reflect EM waves with long wavelengths, but they share metal's characteristic of reflecting with a phase reversal. It is known that high impedance surface can reflect without a phase reversal. Recently, a type of structures,<sup>5</sup> consisting of periodically arranged hexagonal metal patches connected to a metal sheet by conducting vias, has been fabricated which can reflect EM waves without a phase reversal at a specific frequency regime. Split ring structures,<sup>6</sup> recently proposed for constructing negative index materials,<sup>7</sup> could also reflect EM wave in-phase at some specified frequency. Both structures were characterized by high surface impedance  $Z = \sqrt{\mu/\epsilon}$  at some particular frequencies, in contrast to low surface impedance of a metal. However, they typically operate at one single frequency.<sup>6,7</sup> Here, we show by using finite-difference-time-domain (FDTD) simulations<sup>8</sup> that a simple sandwich structure, combining a planner metallic fractal-like structure with a metal sheet separated by a thin dielectric layer (without connecting vias), could reflect EM waves in-phase at a series of frequencies, with some wavelengths much longer than the reflector's lateral dimension. By putting a simple dipole antenna on the top surface of the composite, we find that the antenna's forward radiations are strongly enhanced at those predicted inphase reflecting frequencies, and diminished at other frequencies. In contrast, a metal plate of the same size diminishes the antenna's forward radiations at all frequencies. FDTD simulations revealed that the physics of in-phase reflectivity is dictated by a series of "magnetic resonances" inside the composite, and the FDTD results can be well described by an effective-media model.

Figure 1 shows schematically the structure of our composite and the experimental setup. A 12-level copper fractal pattern<sup>3</sup> was deposited on a 0.8 mm thick dielectric substrate  $(\varepsilon = 4.0)$ , made by the shadowing/masking/etching technique. We have previously shown that such a metallic fractal possesses multiple stop and pass bands for EM waves,<sup>3</sup> and the fractal reflects like a perfect metal inside the stop bands. We now show that attaching a flat copper sheet of the same size to the opposite side of the dielectric substrate changes the boundary condition to that of a magnetic reflector for those band gap frequencies. We calculated the transmission/ reflection properties of the composite through FDTD simulations.<sup>8,9</sup> As absorption is negligible in the microwave regime, perfect conducting boundary conditions are adopted for the metallic surfaces. No transmission is found through the composite in our simulations, since there is a flat metal plate on the back. The phase of the reflected beam as a function of frequency is shown in Figs. 2(a) and 2(b) for the normally incident x-polarized wave (E field perpendicular to the first level of the fractal) and in Figs. 3(a) and 3(b) for the y-polarized one, respectively. While the reflected wave has a  $\pi$  phase change in most frequency regimes like the case of a metal, we find multiple frequency regimes where the reflection phase varies continuously from  $180^{\circ}$  to  $-180^{\circ}$ , indicating that the reflection becomes in-phase at some specific frequencies.

In our experiment, we put a center-fed dipole antenna directly on the top surface of the composite and measured



FIG. 1. A schematic picture of the composite structure and the experiment setup. Fractal details: 12 levels, first level line length 128 mm, linewidth 1 mm, film thickness 0.1 mm. Metal sheet size:  $25 \text{ cm} \times 25 \text{ cm}$ , thickness 0.1 mm.

3257

Downloaded 22 Oct 2003 to 202.40.139.165. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp

<sup>© 2003</sup> American Institute of Physics



FIG. 2. (a),(b) Reflection phase change on the surface of our composite, calculated by FDTD simulation (solid symbols) and an effective medium model (solid lines), for x-polarized incident wave. (c),(d) Measured forward radiation spectra for free antennas (solid line), antennas on the surface of a metal sheet (solid squares), and on the surface of the composite (open circles). The fractal's first level line is perpendicular to the antennas' wires.

the forward radiation power as a function of frequency. We also show the radiation spectra for the free antenna and that on a metal sheet of the same size for comparison. All samples were tested by a network analyzer (Agilent 8720ES), where the distance between the dipole antenna and a receiver horn was fixed at 30 cm and both were connected to the two terminals of the analyzer. We used a longer antenna (12 mm) for 1-5 GHz, and a shorter antenna (6 mm) for 5-14 GHz. The measured results are shown in Figs. 2(c), 2(d), 3(c), and 3(d) for two different polarizations. As shown in the figures, under a constant input power, radiations from the free antennas are increasing functions of frequency before reaching their quarter-wavelength maxima. When put on the surface of a metal sheet, forward radiations are significantly lower than free antenna because of destructive interference between reflected and source waves. Replacing the metal sheet by the composite, we find the antenna's forward radiations are strongly enhanced at frequency regimes centered at 1.6, 4.3 GHz for the x-polarization case, and at 2.6, 5.4, 9.8, and 12.8 GHz for the other polarization, implying



FIG. 3. Theoretical (a),(b) and experimental results (c),(d) for the *y*-polarization case. Other details are the same as those described in the caption of Fig. 2.

the interference between reflected and source waves to be constructive at these frequencies. Out of these frequency bands, we find the forward radiations to be clearly lower than those of a free antenna, similar to the metal case. The peaks in the radiation spectra coincide well with the in-phase reflection frequencies found from the simulation. However, our experiments failed to detect two narrow in-phase reflection bands centered at 7.83 GHz for x polarization and 12.1 GHz for y polarization, which were found by the FDTD simulations. These two bands are too narrow so that the integrated resonance strength is too weak to be detectable by our experiment where noises are always present.

We find from the FDTD simulations that the in-phase reflectivity originates from a series of "magnetic" resonances intrinsic to the composite material. A single metallic fractal possesses multiple local resonances which respond to the *E* field of the incoming wave.<sup>3</sup> When a metal sheet is placed on the back, each resonance couples to the metal sheet to generate a resonance that corresponses to the H field response. According to Farady's law  $\nabla \times \mathbf{E} = -\mathbf{B}/c$ , surface currents of opposite signs on the metal and on the fractal will be induced in response to the time varying B field sandwiched between the fractal and the metal. FDTD simulations revealed that such induced currents had typical resonance responses at a series of frequencies, characterized by the current amplitude reaching a maximum while its phase undergoing a  $\pi$  jump across the resonance frequency. For example, at one resonance frequency of 4.21 GHz, the FDTD simulation showed that the currents were mainly excited on the 10th levels of the fractal, and flow to higher level structures. At the same time, currents with almost the same amplitude but opposite signs were induced on the surface of the metallic sheet. In fact, we can model the resonance response of our composite by a 0.9-mm-thick (thickness of the fractal plus the dielectric layer) homogeneous magnetic material put on a perfect metal surface. The solid lines in Figs. 2(a), 2(b), 3(a), and 3(b) are the result calculated by such a model with the permeability of the magnetic material taken as

$$\begin{split} \mu_{yy}(f) &= 1 + \frac{0.2}{1.22^2 - f^2} + \frac{4.8}{4.21^2 - f^2} + \frac{0.3}{7.83^2 - f^2}, \\ \mu_{xx}(f) &= 1 + \frac{0.8}{2.51^2 - f^2} + \frac{0.5}{5.17^2 - f^2} + \frac{28}{9.66^2 - f^2} \\ &+ \frac{0.2}{12.08^2 - f^2} + \frac{1.2}{12.63^2 - f^2}, \end{split}$$

where f is the frequency measured in gigahertz. Excellent agreement is noted between the model and the true FDTD results. Such a model permeability exhibits resonant frequencies at which  $\mu_{\text{eff}}$  diverges, which in turn gives a very large impedance (Z) and a very large effective index (n). A large Z gives in-phase reflectance, and a large n ensures that the effect manifests itself in a thin layer with thickness much smaller than the free-space wavelength.

Besides the multiband functionality, the present structure has an additional characteristic that it can reflect in-phase at wavelengths that are much longer than the reflector's lateral dimension. Figure 4 shows the FDTD calculated radiation patterns (see Fig. 1 for the definition of angles and the H

Downloaded 22 Oct 2003 to 202.40.139.165. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp



FIG. 4. (a) *H*-plane and *E*-plane radiation patterns of a 24 mm long centralfed dipole antenna on our magnetic reflector (solid squares) and of the same bare antenna (open circles) at f = 3.73 GHz. The magnetic reflector includes a seven-level fractal (first level length=16 mm, linewidth=1 mm, thickness=0.2 mm, total size 30 mm×29 mm×0.2 mm) and a 0.2-mmthick metal sheet separated by a 1.6-mm-thick dielectric substrate ( $\varepsilon$ =4), and the dipole antenna is orientated perpendicular to the fractal's first level line. The patterns are normalized such that the total radiated powers are the same in the two cases (see Ref. 10).

plane and *E* plane) of a dipole antenna put on a small piece of the fractal high-impedance reflector. The working frequency is 3.73 GHz, coinciding with one of the resonance frequencies of the magnetic reflector. We note that 3.73 GHz corresponds to a wavelength of  $\sim 80$  mm, while the reflector's size is only  $\sim 30$  mm. In contrast to the free antenna patterns, we find that the reflector shields the antenna's radiation (in the backward direction) while at the same time increases the forward radiation power. The combined system thus serves as a subwavelength directional antenna. It is noted that a metal sheet of the same size cannot reflect at this frequency, because the corresponding half-wavelength is longer than the metal plate's own size.<sup>4</sup> Although the standalone fractal pattern can serve as a subwavelength reflector,<sup>4</sup> the antenna does not radiate efficiently when it is too close to the reflector.

In conclusion, we have demonstrated by both simulation and experiment that a multiband subwavelength magnetic reflector can be made based on fractal geometry. The multiband functionality and the subwavelength characteristic of the present structure present many potentially useful applications.

This work is supported by Hong Kong RGC through CA02/03.SC01.

- <sup>1</sup>J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975).
- <sup>2</sup>B. A. Munk, *Frequency Selective Surfaces, Theory and Design* (Wiley, New York, 2000).
- <sup>3</sup>W. Wen, L. Zhou, J. Li, W. Ge, C. Chan, and P. Sheng, Phys. Rev. Lett. **89**, 223901 (2002).
- <sup>4</sup>L. Zhou, W. Wen, C. Chan, and P. Sheng, Appl. Phys. Lett. **82**, 1012 (2003).
- <sup>5</sup>D. Sievenpiper, L. Zhang, R. Broas, N. G. Alexopolous, and E. Yablonovitch, IEEE Trans. Microwave Theory Tech. **47**, 2059 (1999).
- <sup>6</sup>J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).
- <sup>7</sup>R. A. Shelby, D. R. Smith, and S. Schultz, Science (Washington, DC, U.S.) **292**, 77 (2001).
- <sup>8</sup>K. S. Yee, IEEE Trans. Antennas Propag. 14, 302 (1966).
- <sup>9</sup>Simulations were performed using the package CONCERTO 3.1, developed by Vector Fields Limited, England, 2001. A basic cell size of 0.5  $\times 0.5 \times 0.5$  mm is adopted to discretize the space. Finer submesh was adopted in space regions where strong inhomogeneity exists.
- <sup>10</sup> In practice, the total radiated power depends on the impedance matching of a real device which should be carefully considered.