

Reflectivity of planar metallic fractal patterns

Lei Zhou,^{a)} 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

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We studied the reflective properties of a small dielectric plate covered with a fractal-like metallic pattern generated by a particular type of space-filling curves. We found, both experimentally and theoretically, that the plate can reflect electromagnetic waves in a multitude of frequencies, generated from a near-field monopole antenna. Some of the reflected waves have wavelengths much larger than the lateral dimension of the plate. In comparison, a metal plate of the same size failed to reflect when its lateral size was smaller than half of the corresponding wavelength. © 2003 American Institute of Physics. [DOI: 10.1063/1.1553993]

Many materials can provide nearly total reflection for electromagnetic (EM) waves. Metals reflect EM waves with frequencies lower than their plasmon frequency. Frequency-selective surfaces¹ can provide frequency-selective reflectivity, and so do photonic crystals.² While these materials have their own useful characteristics, they have their intrinsic limitations. Take a photonic crystal as an example: Since it operates on the principle of Bragg scattering, both the thickness and the lateral dimensions must be a few times that of the reflection wavelength. Hence, to reflect EM waves at 1 GHz would require a photonic crystal on the order of $1\text{ m} \times 1\text{ m} \times 1\text{ m}$. Metal sheets can be very thin, but a finite-sized metal plate cannot reflect EM waves when its lateral size is smaller than half of the corresponding wavelength. For example, a metallic sheet has to be larger than a mobile phone in order to effectively shield its near-field radiation.

Frequency-selective surfaces with periodic units can reflect at low frequencies, particularly for those with multilayer structures that are ingeniously designed,³ but they typically operate at one single frequency. Here, we show that very compact frequency-selective reflectors, functional at multiple frequencies, can be achieved with a specific class of planar fractal-like geometry based on space-filling curves.⁴ Through both finite-difference-time-domain (FDTD) simulations⁵ and experiments, we demonstrate that a small plate containing such metallic patterns can reflect near-field EM waves in a multitude of frequencies radiated from a monopole antenna, with some wavelengths much larger than the lateral size of the fractal plate. For comparison, a metal plate of exactly the same size failed to reflect when its lateral dimension is less than half of the corresponding wavelength. The FDTD simulations revealed that the subwavelength reflectivity originates from a series of resonances intrinsic to the metallic fractal structure.

The generator of our fractal is a horizontal H-shaped metallic structure with equal height and breadth (inset of Fig. 1). In the subsequent generation, four (generator) elements, scaled in size by a factor of 0.5, are attached to the free ends of the mother element. This procedure is then iterated, with each set of parallel metallic lines defined to be one “level.”

With an increasing number of levels, the pattern approaches a space-filling curve that tiles a two-dimensional square.

Figure 1 schematically illustrates the experimental setup and a six-level fractal structure studied both theoretically and experimentally. The metallic fractal pattern shown in Fig. 1 was deposited on a 1.6 mm thick dielectric substrate,⁶ made by the shadowing/masking/etching technique. Such a fractal plate was perpendicularly put on a 60 mm \times 60 mm metallic ground plane, and a monopole antenna was fed from a 50 Ω coaxial line (see Fig. 1). The radiation patterns for both the H plane and E plane (see Fig. 1 for the definition of the angle origins for the two planes) were calculated by FDTD simulations.⁷ As absorption loss inside the metal is very small and is negligible in the present microwave regime, we have adopted perfect conducting boundary conditions for the metal surfaces in our calculations. We find that the fractal plate can effectively reflect EM waves at four frequency ranges centered at 2.25 GHz, 3.85 GHz, 7.0 GHz, and 10.5 GHz, with gap/midgap ratios 6.7%, 6.1%, 10.6%, and 4.7%, respectively.⁸ For comparison, we have also calculated the radiation pattern with the fractal plate replaced by a perfect metallic plate of exactly the same size, under the same conditions.

In our experiments, the monopole antenna was excited by a function generator (HP83711B). The radiation power

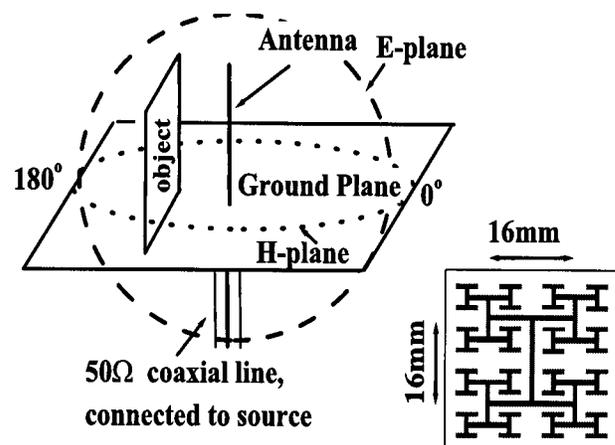


FIG. 1. Schematic picture of the experimental setup. Inset shows the six-level fractal structure: First-level line length 16 mm, linewidth=1 mm, thickness=0.5 mm. The plate measures 28 \times 29 mm.

^{a)}Electronic mail: phzhou@ust.hk

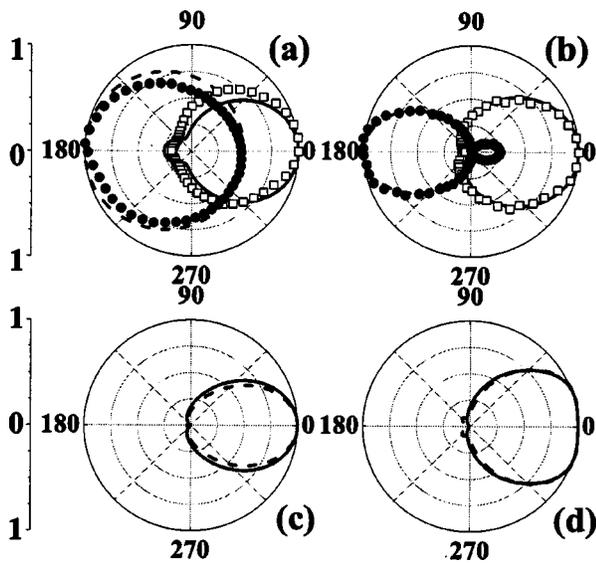


FIG. 2. FDTD calculated and experimentally measured H-plane radiation patterns for a monopole antenna of length L under an operation frequency f , with a fractal plate (FDTD: solid lines; experimental: open squares) or a metal plate (FDTD: dashed lines; experimental: solid circles) placed at a distance d from the antenna. (a) $f=2.25$ GHz, $L=24$ mm, and $d=15$ mm, (b) $f=3.85$ GHz, $L=24$ mm, and $d=9$ mm, (c) $f=7.0$ GHz, $L=8$ mm, and $d=9$ mm, and (d) $f=10.5$ GHz, $L=8$ mm, and $d=9$ mm.

was measured by a receiver horn (HP11966E) placed 20–25 cm from the antenna, connected to a power meter (Agilent E4418B). In Fig. 2, the solid and dotted lines denote the calculated H-plane radiation patterns for the case of fractal plate and the metal (copper) plate, respectively. Open (fractal) and solid (metal) symbols denote the experiment.⁹ Good agreement between theory and experiment is noted. It is clear from Figs. 2(a) and 2(b) that the metallic plate cannot block EM waves at 2.25 GHz and 3.85 GHz. At these frequencies, the corresponding half wavelengths (~ 67 mm and ~ 39 mm) are larger than the lateral dimension of the plate (~ 29 mm). In contrast, the fractal plate can effectively reflect at these two frequencies (the reflectivity is a bit worse for the lower-frequency case). For some particular frequencies, the forward radiation for the metallic plate can be stronger than the backward radiation. At the two higher frequencies [Figs. 2(c) and 2(d)], where half wavelengths are smaller than the plate size, both the fractal and the metallic plates reflect the EM waves effectively, with similar radiation patterns.

The calculated E-plane radiation patterns are shown in Fig. 3. We again note the differences in the reflectivity of fractal and metallic plates at low frequencies. Furthermore, we observe considerable forward energy leakage in the metallic case for frequencies up to at least 7 GHz [Fig. 3(c)], owing to re-radiation from the edges of a finite-sized metallic plate. In contrast, no forward energy leakage was found in the fractal case [Fig. 3(c)].

FDTD simulations revealed that the fractal pattern exhibits multiple resonances which are (approximately) log periodic in frequency. These resonances give strong reflections. At each resonance, currents are excited mainly along the metallic lines of a particular level, flowing toward higher levels of the structure. The current density distribution¹⁰ on the fractal surface is shown in Fig. 4 for the case of 3.85 GHz.

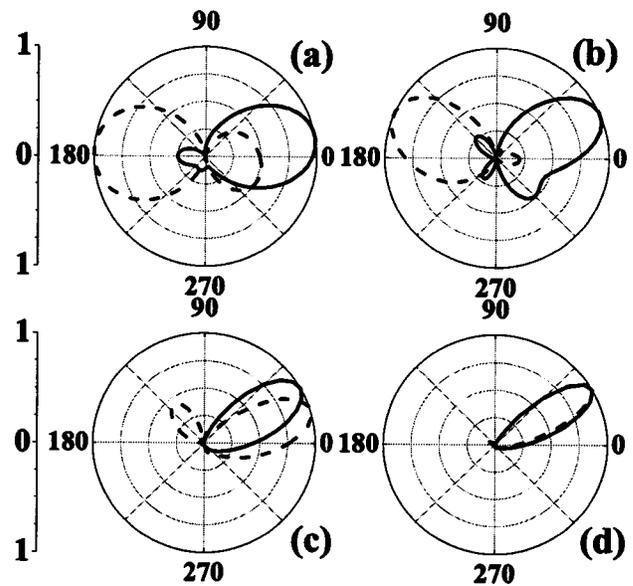


FIG. 3. FDTD calculated E-plane radiation patterns for a monopole antenna with a fractal plate (solid lines) or a metal plate (dashed lines) placed nearby, with the same details as described in the caption of Fig. 2.

GHz. The surface currents are excited mainly along the third-level lines, flowing toward the sixth-level lines.¹¹ Similarly, at 2.25 GHz, the currents are mainly excited along the second-level lines. Since the second-level lines are perpendicular to the third-level ones, the fractal has to be rotated by 90° (with respect to that shown in Fig. 1) in order to shield an EM wave of 2.25 GHz. A rotationally invariant structure can easily be obtained by stacking two fractal plates together with the second one rotated by 90° and separated by a thin dielectric spacer. The resultant structure will be effective in reflecting radiation at arbitrary orientations.

A unique property of a fractal structure is the existence of continuous paths much longer than the linear dimensions of the fractal plate. Since the resonance wavelength is roughly proportional to the length of a particular conductive path on which the surface currents flow, the resonance wave-

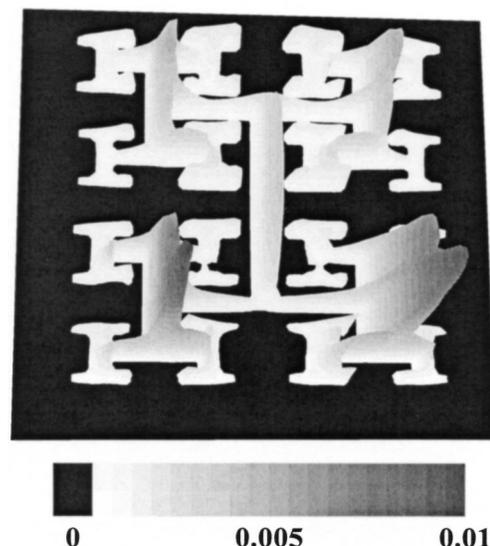


FIG. 4. Excited surface current density (in unit of A/mm) distribution on the fractal surface at 3.85 GHz.

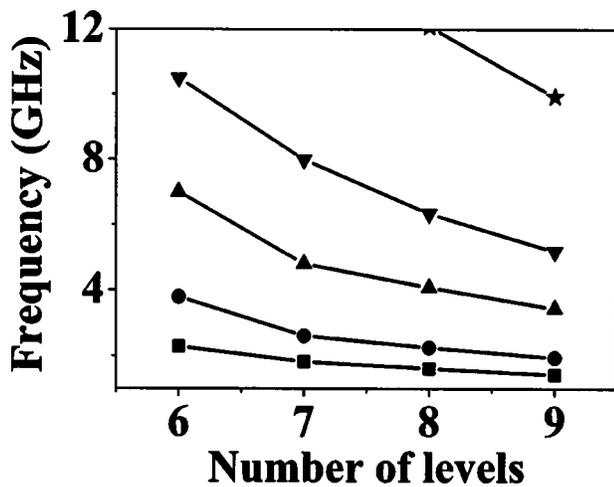


FIG. 5. FDTD calculated resonance frequencies as a function of the number of levels inside the fractal pattern, confined in an area of $32\text{ mm} \times 32\text{ mm}$.

length can be significantly longer than the square root of the plate area. Hence, if we add more levels to the fractal structure shown in Fig. 1 while keeping the plate area unchanged, each resonance will be shifted to a lower frequency since the relevant metallic path is increased in length. At the same time, more resonances will appear. Figure 5 shows the development of those resonances as the number of levels inside the fractal pattern is increased from six to nine.¹²

In short, we have demonstrated through both theory and experiment that a specific kind of metallic fractal pattern can serve as a multiband subwavelength reflector. We emphasize here that the effect is not tied to the selected geometry but is an intrinsic property of the fractal pattern. Similar effects will be observed for other geometries (say, without the

ground plane). However, the resonance frequency may shift if other objects are placed in the near field. For example, the resonance frequency will downshift if we apply a dielectric coating on the fractal surface. Such effects are common to all frequency selective reflectors operating on the principle of resonance.¹

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³See, e.g., D. Sievenpiper, L. Zhang, R. Broas, N. G. Alexopolous, and E. Yablonovitch, *IEEE Trans. Microwave Theory Tech.* **47**, 2059 (1999).

⁴See, e.g., M. Barnsley, *Fractal Everywhere* (Academic, San Diego, 1988).

⁵K. S. Yee, *IEEE Trans. Antennas Propag.* **14**, 302 (1966).

⁶With $\epsilon_r = 6.5$ adopted in FDTD simulations, fixed by a comparison with our experiment data.

⁷Simulations were performed using the package CONCERTO 2.0, developed by Vector Fields Limited, England, 2001. A basic cell size of $0.5 \times 0.5 \times 1\text{ mm}$ is adopted to discretize the space. The grid size has been improved to achieve convergent results in the calculated frequency regime. Finer submesh is adopted in space regions where strong inhomogeneity exists.

⁸The fractal plate should be rotated 90° with respect to that shown in Fig. 1 in order to reflect EM waves at 2.25 GHz and 7.0 GHz. The gap edges are defined by the 20 dB positions in the transmission spectra for a plane wave input.

⁹The experimental and calculated patterns are normalized so that the maximum in each pattern equals 1.

¹⁰Calculated from the curl of tangential magnetic fields on the metal surfaces.

¹¹Since the input wave is not a plane wave, the excited current amplitudes are not the same on different third-level metal lines.

¹²For fractals with seven, eight, and nine levels, the linewidth has been set as 0.2 mm.