Quasi-periodic planar metamaterial substrates

Hongqiang Li[a)]
Department of Physics, Tongji University, 200092, Shanghai, China

Zhihong Hang
Department of Physics, the Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Yaqin Qin and Zeyong Wei
Department of Physics, Tongji University, 200092, Shanghai, China

Lei Zhou
Department of Physics, Fudan University, 200433, Shanghai, China

Yewen Zhang and Hong Chen
Department of Physics, Tongji University, 200092, Shanghai, China

C. T. Chan
Department of Physics, the Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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We report our experimental and theoretical studies on a metamaterial substrate consisting of a quasi-periodic metallic planr pattern and a flat metal sheet, interconnected through metallic vias. We show that this structure possesses *multiple* in-phase reflection frequency regimes and spectral gaps for transverse-magnetic surface waves, whereas the transverse-electric surface waves are suppressed in *all* frequencies. In particular, an antenna put on top of this planar structure radiates with very high directivity ($D=240$) at some frequencies. This phenomenon is mainly governed by the inhomogeneity of the structure, which is a collective effect of perfect magnetic and electric conductors operating simultaneously at the frequency. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1887822]

Two-dimensional periodic mushroom structures[1] are a class of metamaterials that can reflect an electromagnetic (EM) wave without a phase reversal and suppress a surface wave (SW) at a certain frequency regime, both are desirable features as antenna substrates. It is known that the in-phase reflections originate from magnetic resonances and the SW gaps are derived from the Bragg scatterings.[1,2] Many recent efforts were devoted to making the resonance units more compact,[3,4] or generating multiband functionality.[5]

In this letter, the focus is on an entirely different system, consisting of a *quasi-periodic* (QP) metallic planar pattern and a flat metal sheet interconnected through metallic vias. Photonic quasi-crystals have many unique characteristics,[6,7] such as stop bands without translational invariance, and localized modes with extremely high density of states.[6] Here, our QP metamaterial substrate is found to exhibit some unusual EM wave characteristics. Being a structure with multiple unit elements, it is not surprising that our QP substrate possesses *multiple* frequency regimes where the EM wave reflection is in-phase and the SWs are forbidden. What is less intuitive is that a small antenna put on top of this planar structure radiates with very high directivity ($D=240$) at some frequencies, and the transverse-electric (TE) SWs are suppressed in *all* frequencies on the surface of such a structure. Finite difference time domain (FDTD) simulations[8] reveal the physics to be governed by the intrinsic geometric properties of the QP structure.

A top-view picture of part of our sample is shown in Fig. 1(a). The QP metallic pattern with octagonal symmetry[6] was fabricated and deposited on the front side of a 1.6 mm thick PCB substrate (RT/duroid 5880), which has a metal sheet attached on the back side. The metal patches inside the QP pattern are separated by 0.7 mm wide air gaps, and the side length of each metal patch is 7.6 mm. Via holes (with diameters 0.7 mm) were drilled through the substrate on every patch center, and were then metallized. The lateral size of the sample is 210 mm$\times$210 mm.

We first study the reflective properties of our metamaterial. Since the metal sheet on the back side of PCB substrate

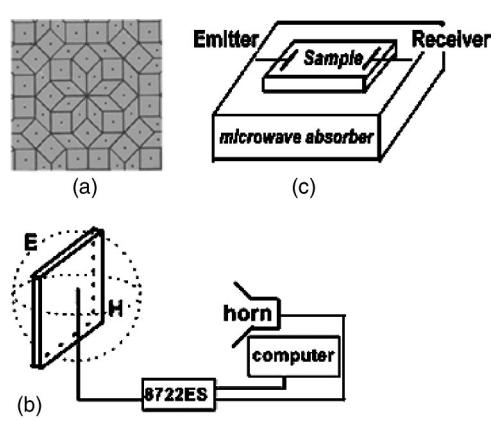

FIG. 1. (a) A top-view picture of part of our quasi-periodic metamaterial substrate. (b) Schematic picture of the experimental setup for in-phase reflection and antenna radiation measurements. (c) Schematic picture of the experimental setup for SW measurements.

[a)]Electronic mail: hqleek@online.sh.cn

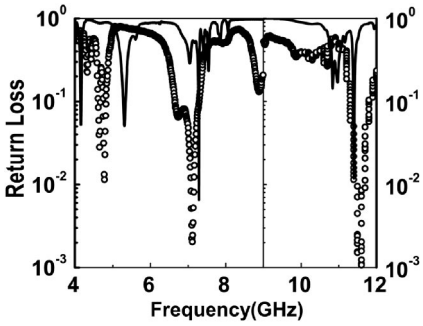

FIG. 2. Return loss of a 16 mm long dipole antenna (for 4–9 GHz) and an 8 mm long dipole antenna (for 9–12 GHz) put on top of our metamaterial substrate, obtained by measurements (symbols) and FDTD simulations (solid lines).

ensures a total reflection of EM waves on our plate at any frequency, only the reflection phase is of interest. As shown in Fig. 1(b), we put a small antenna just above the symmetry point of the QP structure and measure the forward radiation as well as the return loss ($|S11|^2$). The antenna is fed by a 50 Ω coaxial cable and the radiation power is measured by a horn receiver, both connected to a network analyzer 8722ES. If the reflection is out of phase like a metal, the reflected wave will interfere destructively with the source radiation so that little radiation will be detected and the return loss should be close to unity. On the other hand, at those frequencies where the reflection is in-phase, the interference will be constructive leading to strong forward radiations and dips in the return loss spectra.[1] Open symbols in Fig. 2 are the experimentally measured return loss spectra. We adopted a 16 mm long dipole antenna to measure the frequency regime 4–9 GHz and an 8 mm one for 9–12 GHz. Return loss spectra show three clear dips, centered at ~5, ~7.1, and ~11.5 GHz, implying the reflection is in phase in these frequencies.

We then perform the SW measurements under the setup shown in Fig. 1(c). We put our sample on a microwave absorber, and put two dipole (monopole) antennas parallelly (perpendicularly) on the surface, one as an emitter and another as a receiver, to measure the SW transmission spectra with TE [transverse magnetic (TM)] polarizations. Several pairs of monopoles or dipoles with different lengths were prepared, in order to cover a wider frequency range and to check the consistency of our results. The TM surface wave spectra for a metal plate of the same size serve as a reference since a flat metal surface supports the TM mode surface wave. Measured SW spectra are rather robust against varying emitter and receiver positions, indicating that our material is quite isotropic. This is understandable since our metamaterial has an eight-fold rotational symmetry, higher than any planar periodic system. Figure 3 shows the measured SW transmission spectra for different polarizations referenced by the TM surface wave spectra on metal plate. The emitter is about 100 mm away from the receiver in all measurements. Three SW gaps, centered at 5.0 GHz, 7 GHz, and 10.5 GHz, are observed in the TM spectra, reasonably consistent with the in-phase reflection regimes indicated in Fig. 2. However, the TE surface wave transmission is suppressed except for a narrow pass band at about 8.2 GHz. This is quite different from a periodic mushroom structure, where the TE surface wave is forbidden *only below the upper gap edge*.

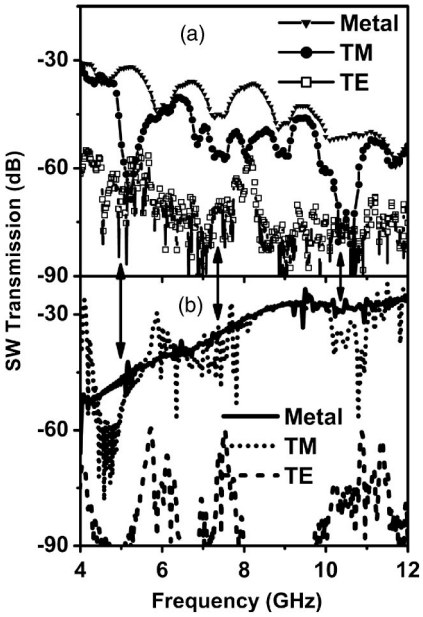

FIG. 3. SW transmission spectra of the QP metamaterial substrate for different polarizations, and for metal surface with TM polarization, both obtained by (a) measurements and (b) FDTD simulations, with arrowed line to mark the agreements.

The mechanism of the observed phenomena was understood through FDTD simulations. We simulate the experimental situations shown in Fig. 1. Starting from the symmetry point of our tiling pattern [see Fig. 1(a)], we define a *ring* composed by eight rotational equivalent elements (either a square or a rhombus). Limited by our computational power, a seven-*ring* QP structure sized ~85 mm × 85 mm is taken in the FDTD simulation. A basic mesh sized $0.6 \times 0.6 \times 0.6\ \mathrm{mm}^3$ is adopted to discretize our system (finer submeshes are adopted when required), and the convergence against the mesh size is carefully tested. We have also compared our seven-*ring* results with those of a four-*ring* system, and conclude that although our model system (seven-*ring*) is smaller than the true experimental sample, the results obtained are good enough to explain the main experimental findings qualitatively.

The FDTD results are shown in Figs. 2 and 3 as lines. While the agreement between theory and experiment is not quantitative due to the smaller size of the sample in the simulation, the salient features observed in the experiment are reproduced in the simulation. The FDTD results show that the in-phase reflection regimes (as well as SW gaps) actually consist of several fine dips. FDTD simulations revealed that the resonances at ~5 GHz are mainly due to rhombus-shaped metal patches and the resonances at ~7 GHz are due to square-shaped elements, while those at ~11 GHz are of higher-order resonances. However, as a natural consequence of quasi-periodicity, each element has a slightly *different* local environment causing the fine structures observed in the FDTD simulations on return loss and SW transmission spectra. In addition to the gap positions, FDTD simulations verified the experimental observation that the TE surface waves were substantially suppressed in all frequencies [see dotted line in Fig. 3(b)], and we trace this unique property to the inherent inhomogeneity of the QP structure. At resonance, the surface behaves as a magnetic conductor that can, in principle, support TE surface waves—but since the reso-

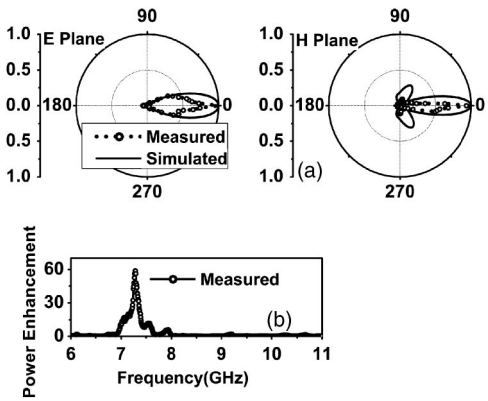

FIG. 4. (a) E- and H-plane radiation patterns of a dipole antenna (8 mm) put above the center of the QP plane at frequency of 7.29 GHz, obtained by experiments (symbols) and FDTD simulations (lines). (b) Measured power enhancement of the radiation compared to that of a dipole in free space.

nance frequencies of the square and rhombus elements are not the same, there does not exist any frequency in which the surface can support TE surface wave propagation. As the result, the overall TE transmission is greatly suppressed.

These unique properties may find many useful applications. For example, our QP structure naturally has a multiband response, and as a ground plane, our material can suppress the backward radiations. More interestingly, we show below that an antenna put on top of our material radiates with very high directivity at some particular frequency. Open circles in Fig. 4(a) are the measured radiation patterns of a 10 mm long dipole antenna at a frequency 7.29 GHz, corresponding to one of the magnetic resonances. The dipole antenna is put above the symmetry point of the QP pattern, along one air gap between two rhombus patterns. Both E- and H-plane radiation patterns were measured [see Fig. 1(b) for the experimental setup]. We see from Fig. 4(a) that the radiation is highly directive in both the E- and H-planes. The half-power width (3 dB width) is $\Delta\theta = 18°$ in the E-plane and is $\Delta\phi = 10°$ in the H-plane, which are translated to a directivity $D = 4\pi/\Delta\vartheta\Delta\phi = 240$. Figure 4(b) shows the measured forward radiation power scaled by that of a same dipole antenna in free space. We find an enhancement factor around 60 peaked at 7.3 GHz, indicating that the radiation is indeed strongly focused to the forward direction. Simulations [line in Fig. 4(a)] confirmed the directive emission around 7.3 GHz, although the calculated directivity ($D = 42$) is smaller than the measured one due to a smaller plate adopted in our simulations.

We note that previous implementations of directive radiation were obtained through placing a source inside a resonance cavity[9] or a metamaterial with a zero-refractive index.[10] Our directive radiation is obviously different since it is neither a bulk nor cavity effect. We find from both analytic theory and FDTD simulation that the directive emissions disappear when the present QP structure was replaced by a conventional periodic high-impedance surface (see also Fig. 6 in Ref. 3). In fact, at the resonance frequency, a conventional high-impedance surface can be represented by a perfect magnetic conductor (PMC). It is quite easy to show that an antenna put on a PMC surface radiates just like two parallel antennas close to each other, which does not show any appreciable directivity. The symmetry and the geometry of the QP structure are crucial to achieve this unusual phenomenon.

In short, we show by both experiments and theory that a metamaterial substrate with quasi-periodic geometry has many unusual EM wave characteristics. In particular, high directive emission was found by putting a small antenna on our metamaterial.

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