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Subwavelength electromagnetic shielding by resonant surface

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The authors studied the influence of a small resonant surface on the radiation pattern of a monopole wire antenna when the resonant surface was placed in proximity. By discussing both experiment and simulation results, the authors found that the small resonant surface can effectively block the electromagnetic wave with wavelength which is greater than its dimension. The underlying principle is attributed to the nature of resonance. Therefore, a small resonant surface may function as a subwavelength reflector and protect, to some degree, humans from exposure to electromagnetic radiation. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2385858]

The development of wireless communication technology has granted extra freedom to people's life, but at the same time also brings about unexpected threat to our health such as electromagnetic (EM) radiation. It has been shown that the current handset telephones radiate a tremendous amount of the emitted power into the user's head.[1] Recently, much effort has been invested into designing specific antenna and artificial EM material, especially photonic band gap crystals, to achieve minimum radiation from the handset telephones toward the user.[2–5] A type of mushroomlike EM surface is ingeniously developed to exhibit the property of isolating the radiating element from the nearby surroundings.[6] It has been studied that the frequency selective surfaces (FSSs) can selectively reflect the EM wave of a specified frequency and they operate on the principle of resonance intrinsic to their metallic units periodically arranged into one or two dimensional arrays.[7–9] In this letter, we demonstrate, through experiments and finite-difference–time-domain (FDTD) simulations, that a small frequency selective surface can reflect near-field EM wave emitted from a wire antenna when placed close to the antenna, even if its lateral size is much smaller compared to the wavelength of reflected EM waves. In contrast, a finite-sized conducting surface or a metal plate fails to shield the radiation from the antenna when its lateral dimension is less than half of the corresponding wavelength. The underlying distinction between the two surfaces is that FSSs exhibit resonant behavior at microwave frequencies while metal plates do not. Therefore, our results provide a possibility to realize subwavelength EM wave shielding at desired frequency and may also be employed for antenna design in telecommunication techniques.

Figure 1 illustrates the experimental setup and the FSS structure. The wire antenna is a 26 mm monopole mounted on the surface of a 74 mm diameter ground plane and is fed from a 50 Ω coaxial transmission line. The FSS structure measuring 36×36 mm^2 is placed on the ground plane, parallel to the y-z plane and with a distance of 19 mm from the monopole, to shield the electromagnetic radiation, delineated by semiloop lines, from the monopole. The FSS, fabricated on a dielectric slab with a thickness of 1.6 mm and permittivity 3.6 (measured by HP 85070B dielectric probe kit), is made up of a 3×6 array where each periodic unit of the FSS consists of a section of coil connected to a pair of paralleled metallic strips at each end. Comparing with a standard dipole array, the metallic element is inductively loaded at the middle and capacitively loaded at the ends.[7] In our experiments, the monopole antenna was connected to port 1 of an S-parameter network analyzer (Agilent 8720ES), while a horn antenna, connected to port 2 of the analyzer and placed approximately 40 cm from the monopole, is used to receive the radiation field. A primary measurement of $|S_{21}|$ at the frequency band of 1.5–3.5 GHz reveals that the resonant plate can effectively reflect EM waves at 2.60 GHz, where receiving in $+X$ direction shows a minimum and in $-X$ direction a maximum, as illustrated in Fig. 2. It should be noted that the situation is completely opposite when the frequency sweeps down to 2.25 GHz, which implies the antenna radiation towards $+X$ direction is reinforced to some extent at this frequency value, instead.

In order to confirm the effect of the resonant plate on the monopole radiation, we measured the pattern of the radiation

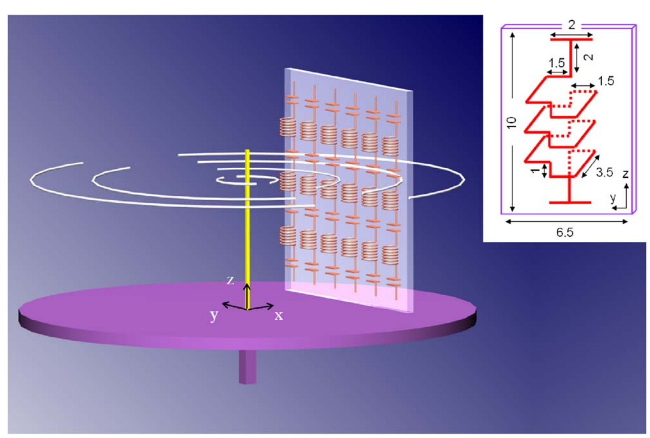

FIG. 1. (Color online) (a) Schematic illustration of the experimental setup. The inset shows a unit cell of the frequency selective surface modeled in simulation. The length denoted is in millimeter.

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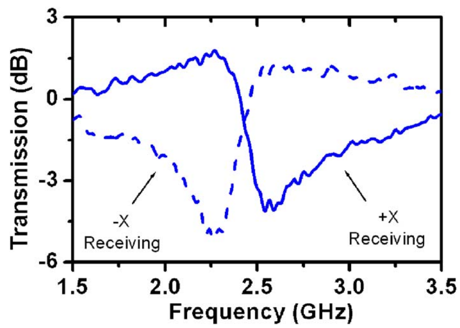

FIG. 2. (Color online) $|S_{21}|$ measurement when the receiving horn is located on the $+X$ and $-X$ directions, respectively. The spectra shown here have been normalized to the received signal without the presence of the frequency selective surface.

field (electric field) in $z=0$ plane for a single frequency. As shown in Fig. 3(a) bare monopole without the FSS radiates the EM wave omnidirectionally (open circles). For comparison, the experimental procedure was repeated to replace the resonant plate with a metal plate of the same size. Despite having the same dimension as 36×36 mm^2, the metal plate cannot block the EM waves at 2.60 GHz (see open triangles). This is because its lateral dimension is smaller than half of the corresponding wavelength (115 mm); however, in the case of the resonant plate, the radiation pattern denoted by open squares indicates that the radiation towards the FSS is significantly suppressed in spite of its subwavelength lateral dimension (36 mm).

FDTD simulation method was employed to study the FSS sample numerically.[10] For the purpose of simulation, the metal in the FSS was treated as perfect conductor, and the coil component in each identical element was approximated by a helix of wires with a rectangular cross section,[11] see the inset of Fig. 1. In the first place, we determine the resonance frequency for the FSS by simulating an array of resonant units with the same periodical spacing as the sample. The simulation of a plane EM wave transmission of such FSS structure shows a stop band with maximum rejection at 2.25 GHz, corresponding to a resonance where the high electrical field intensity appears at the capacitive ends and high magnetic field intensity inside the inductive coil.[12] Then we simulate the monopole shielded by the experimental samples. The solid and dashed lines in Fig. 3(a) showed the simulation results on $z=0$ plane for the monopole antenna near the resonant plate at 2.30 GHz and the metal plate at 2.60 GHz, respectively, which are in good agreement with the experiments.[13] Their corresponding radiation patterns calculated versus polar angle on $y=0$ plane were plotted in Fig. 3(b), which shows the subwavelength shielding ability of the resonant plate in contrast to the metal plate.

By simply measuring S_{21}, we know that the small resonant surface also significantly alters the radiation pattern of the antenna at the lower frequency, 2.25 GHz. For the frequency selective surface discussed above, Fig. 3(c) illustrates the measured and simulated radiation patterns on $z=0$ plane at 2.25 and 2.05 GHz, respectively, and the pattern on $y=0$ plane is shown in Fig. 3(d) calculated versus polar angle. The results show the intensified radiation towards the FSS while reduced away from it, which causes the radiation to become directional with respect to that of the bare monopole.

The formation of the unique radiation pattern at these two frequencies is attributed to the resonance nature of the

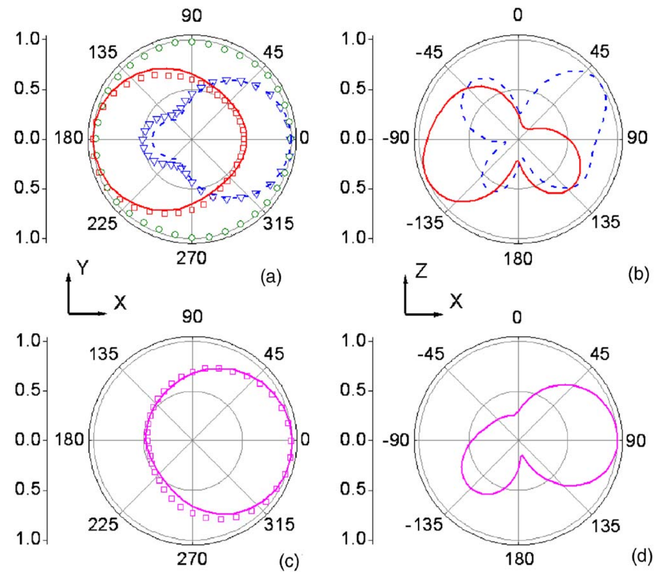

FIG. 3. (Color online) Measurements and simulations of radiation patterns of the electric field. (a) The symbols denote the measurements in $z=0$ plane for the monopole without any sample in place (open circle), with the resonant plate in place (open square), and with the metal plate in place (open triangle). The three cases are all measured at 2.60 GHz. The lines represent the corresponding simulations (the solid line for the resonant plate at 2.30 GHz and the dashed line for the metal plate at 2.60 GHz). (b) The simulations in $y=0$ plane for the resonant plate at 2.30 GHz (solid line) and the metal plate at 2.60 GHz (dashed line). (c) The measurement in $z=0$ plane for the monopole with the resonant plate in place at 2.25 GHz (open square) and the simulation (solid line) at 2.05 GHz. (d) The corresponding simulation in $y=0$ plane at 2.05 GHz. All field patterns are normalized to their maxima. The angle value shown in (a) and (c) is the azimuthal angle and that in (b) and (d) is the polar angle.

FSS. The unit in the FSS here can be equivalently viewed as a serial resonant circuit, consisting of a capacitance C and an inductance L.[7] Below the resonance frequency $f_0 = 1/2\pi\sqrt{LC}$, the circuit is capacitive, while above the frequency the circuit behaves inductively. Therefore, when the spectrum crosses f_0, the circuit experiences a phase shift of π. Considering that the monopole has a quite capacitive near field on the measurement frequencies, the EM energy stored inside the near field towards $+X$ direction should be enhanced at first and then weakened, because reactance of the antenna and the FSS are superimposed firstly in phase and then out of phase when the frequency sweeps across f_0. Consequently, the far-field radiations present similar characteristics as discussed above. It should be noted that although the resonance frequency f_0 is caused by the individual resonant unit, it will be modified somewhat depending on the coupling between these resonant units, if the array is changed.[7] Therefore, the subwavelength EM shielding might be degraded for some cases when the periodical array breaks down.

In conclusion, through both experiment and simulation we studied the influence of a small FSS on the radiation pattern of a monopole by placing the resonant surface near the antenna, and observed that the small FSS can effectively block the EM wave with wavelength larger than its lateral dimension at some frequencies. Additionally, the resonant surface may "shield" the radiation in the direction opposite to the FSS at another frequency by altering the radiation pattern. Therefore, a small FSS near the antenna can function as a subwavelength reflector and be utilized in application to protect people from the EM radiation exposure.

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[12] In simulation, we implemented the periodic boundary condition to the unit cell as plotted in Fig. 1 with the periodical spacings equal to the sample's values and let the plane wave to be normally incident upon the structure, and found that the resonance for the unit is at 2.25 GHz by searching for the position with the maximum rejection of the stop band.
[13] As the rectangular helix approximation of the coil was applied in simulation, the discrepancy between the simulations and the experiments would be expected. To compensate for such discrepancy, we picked up the frequencies where the simulated patterns match well with the measured ones. It is noted that for the metal plate the simulation, exactly the same as the experiment, produced a good agreement.