Science Meets Magic: Metamaterials

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Abstract

The word "magic" is usually associated with movies, fiction, children stories, etc. but seldom with the natural sciences. Recent advances in metamaterials have changed this notion, in which we can now speak of "almost magical" properties that scientists could only dream about only a decade ago. In this article, we review some of the recent "almost magical" progress in the field of metamaterials.

1. Introduction

In recent years, there has been a burgeoning interest in rapidly growing field of metamaterials due to their unprecedented properties unattainable from ordinary materials. Veselago pointed out that a material exhibiting negative values of dielectric permittivity (ε) and magnetic permeability (μ) would have a negative refractive index [1]. Generally speaking, the dielectric permittivity (ε) and the magnetic permeability (μ) are both positive for natural materials. In fact, it is possible to obtain negative values for ε and μ by utilizing proper designs of metamaterials. Left-handed electromagnetism and negative refraction are achievable with artificially structured metamaterials exhibiting negative values of permittivity and permeability simultaneously at a certain frequency region. The first steps to realize these novel type of materials were taken by Smith et al., where they were able to observe a left-handed propagation band at frequencies where both dielectric permittivity and magnetic permeability of the composite metamaterial are negative [2].

2. Subwavelength Resolution

Pendry conceived that a negative index material could be a potential candidate for imaging beyond the diffraction limit [3]. Negative index materials can restore the amplitude of evanescent waves and therefore enable subwavelength focusing [4]. Here, we employ the LHM under investigation in imaging measurement. In the imaging experiments, we used monopole antennae to imitate the point source. The exposed center conductor acts as the transmitter and receiver and has a length of 4 cm (~λ/2). The full width at half maximum (FWHM) of the beam is 8.2 cm (1.03λ). Then, we inserted LHM superlens, and measured the spot size of the beam as 0.13λ, which is well below the diffraction limit [5]. Since we were able to image a single point source with a subwavelength spot size, we used two point sources separated by distances smaller than a wavelength to obtain subwavelength resolution. The sources are driven by two independent signal generators and the power distribution is detected by using a microwave spectrum analyzer. The frequencies of the sources differed by 1 MHz to ensure that the sources are entirely incoherent. The imaging experiments are performed for two different separation distances between the sources. The imaged peaks were easily resolved when the sources were separated by λ/8. We then increased the separation of the sources to a distance of λ/5 and the peaks were resolved better. When the sources were λ/3 apart, we were able to resolve two peaks entirely.

3. Enhanced Transmission

We obtained enhanced transmission of electromagnetic waves through a single subwavelength aperture by making use of the resonance behavior of a split ring resonator (SRR) at microwave frequencies. By placing a single SRR at the near-field of the aperture, strongly localized electromagnetic

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fields were effectively coupled to the aperture with a radius that is twenty times smaller than the resonance wavelength ($r/\lambda = 0.05$). We obtained 740-fold transmission enhancement by exciting the electric resonance of SRR [6].

We have recently extended this transmission enhancement performance to even higher values [7]. The respective design parameters of the connected SRRs (Sample A&B) as depicted in Figure 1. The distinct SRR samples are deposited on a dielectric printed circuit board (PCB). We drilled an opening on a large metal plate. The dimensions of the metal plate were intentionally picked to be large in order to minimize the diffraction effects at the edges. The opening on our metal screen constituted the subwavelength aperture. The connected SRRs are inserted inside the aperture. We tried to manually align the samples to the midpoint of the aperture while leaving equal portions on both half planes. Transmission measurements were performed with conventional horn antennas operating around the frequency band of our interest. Transmission peaks that appeared in the simulation results suggested transmission enhancement. We also verified the transmission enhancement phenomenon experimentally. Our experiments indicated a transmission improvement factor above 70000 through a subwavelength aperture with a width of $\lambda/31$ and a height of $\lambda/12$ in terms of the operational wavelength. We tried to emphasize the role of the connecting bars during this process. We numerically showed that the connecting bars linked the otherwise isolated SRRs to each other and guided the incoming wave through the subwavelength hole. The highly localized fields around the aperture, owing to the magnetic resonance of the SRRs, efficiently coupled the input wave to the exit side. This approach brings in the opportunity of attaining even higher transmission improvement factors by minimizing the dependence on the aperture geometry.

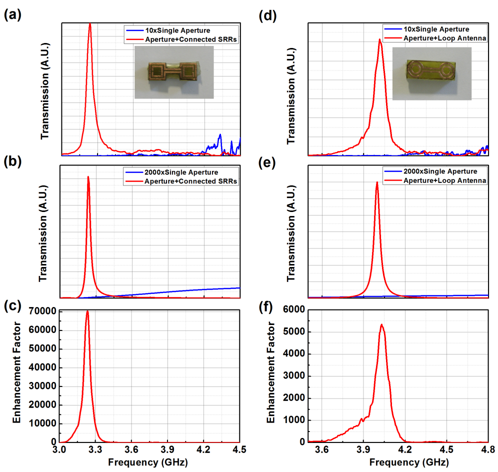

Fig. 1: (a) Measured, (b) simulated transmission results for Sample A (solid red lines) and the aperture (solid blue lines). (c) Experimentally validated enhancement factor for Sample A. (d) Measured, (e) simulated transmission results for Sample B (solid red lines) and the aperture (solid blue lines). (f) Experimentally validated enhancement factor for Sample B.

4. Complementary Chiral Metamaterials

Recently, chiral metamaterials (CMMs) have attracted much attention due to their exotic properties, e.g. giant optical activity, circular dichroism, and negative refraction [9-10]. A CMM lacks any mirror symmetry so that the cross-coupling between the electric and magnetic fields exists at the resonance. We experimentally and numerically report a complementary bilayer cross-wire chiral metamaterial. It exhibits giant optical activity and a small circular dichroism. Figure 2 shows the retrieved effective parameters of the chiral metamaterials based on the simulation (left) and experimental (right) data. The retrieval results reveal that a negative refractive index is realized for right circularly polarized waves due to the strong chirality. Our numerical results show that the mechanism of the chiral behavior at the resonance of lower frequency can be interpreted as the coupling effects between two sets of

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mutually twisted virtual magnetic dipoles, while the resonance of higher frequency shows complicated nonlocal features. This demonstrates both experimentally and numerically, the chiral properties of a CCMM. Like its counterpart (the cross-wire CMM), the CCMM also shows giant optical activity, and due to the strong chirality, the frequency bands of negative index are obtained for RCP waves. Our numerical results show that the mechanism of the chiral behavior at the resonance of lower frequency can be interpreted as the coupling effects between two sets of mutually twisted virtual magnetic dipoles, but the resonance of higher frequency shows complicated nonlocal features.

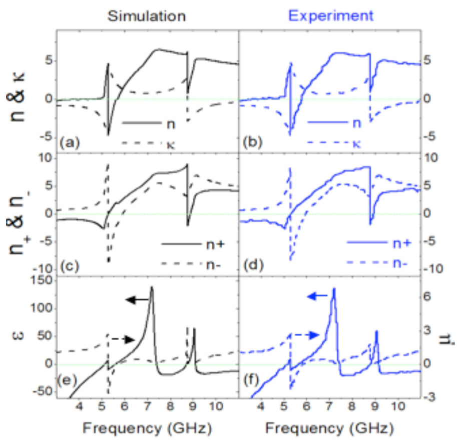

Fig. 2: The retrieved effective parameters of the chiral metamaterials based on the simulation (left) and experimental (right) data. (a) and (b) show the real parts of the refractive index n and chirality κ. (c) and (d) show the real parts of the refractive indices for RCP and LCP waves. (e) and (f) show the real parts of the permittivity ε and permeability μ.

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