

Photonic Metamaterials: Science Meets Magic

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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 a decade ago. In this paper, we review some of the recent “almost magical” progress in the field of photonic metamaterials.

Starting in high school physics, we learn that light is made of a combination of electric and magnetic fields. As light propagates through matter, conventional materials only react to the electric field, and this interaction results in most of the optical effects that we know of, such as refraction, diffraction, lensing, imaging, etc. Forty years ago, Veselago asked the question “What if matter also interacts with the magnetic field of light?” [1]. He showed that when both electric and magnetic properties were negative ($\epsilon < 0$ and $\mu < 0$), the solution of the Maxwell equations resulted in an index of refraction with a negative sign.

The theoretical predictions of Veselago had to wait about 30 years for the first experimental realization of these engineered materials that are also called metamaterials. The seminal work of Pendry [2] provided the blueprints for the experimental realization of metallic-based resonant structures that are called split ring resonators (SRRs), which exhibit $\mu < 0$ at the resonance frequencies. Smith *et al.* [3] combined an array of SRRs ($\mu < 0$) and an array of metallic wires ($\epsilon < 0$) in order to create double negative composite metamaterials. In such a case, the famous “right-handed rule” between the electric and magnetic fields becomes left handed, in which these materials are known as left-handed materials (LHMs) or negative index materials (NIMs).

Besides negative refraction, scientists have shown that metamaterials can also be used to achieve “almost magical” applications such as subwavelength imaging, superlenses, perfect lenses, cloaking, chirality etc. Although the early experiments were performed at microwave frequencies, it took only a few years for the scientists to downscale these structures to optical frequencies [4]. These nanoscale metamaterials are now called photonic metamaterials.

As shown in Fig. 1, SRRs can be fabricated with dimensions reaching nanometer scales. The nanoscale SRR acts as an LC resonator with a resonance frequency at optical frequencies [5]. More importantly, the typical size of these resonant inclusions is approximately 10 times smaller than the vacuum wavelength of the light at the resonance frequency. Although a single-layer SRR structure can easily be fabricated on a dielectric surface, it is relatively difficult to stack these structures due to the tight alignment tolerance requirements. Giessen and his group have reported a new method where metamaterials in the near-infrared spectral region can be fabricated using a layer-by-layer technique [6].

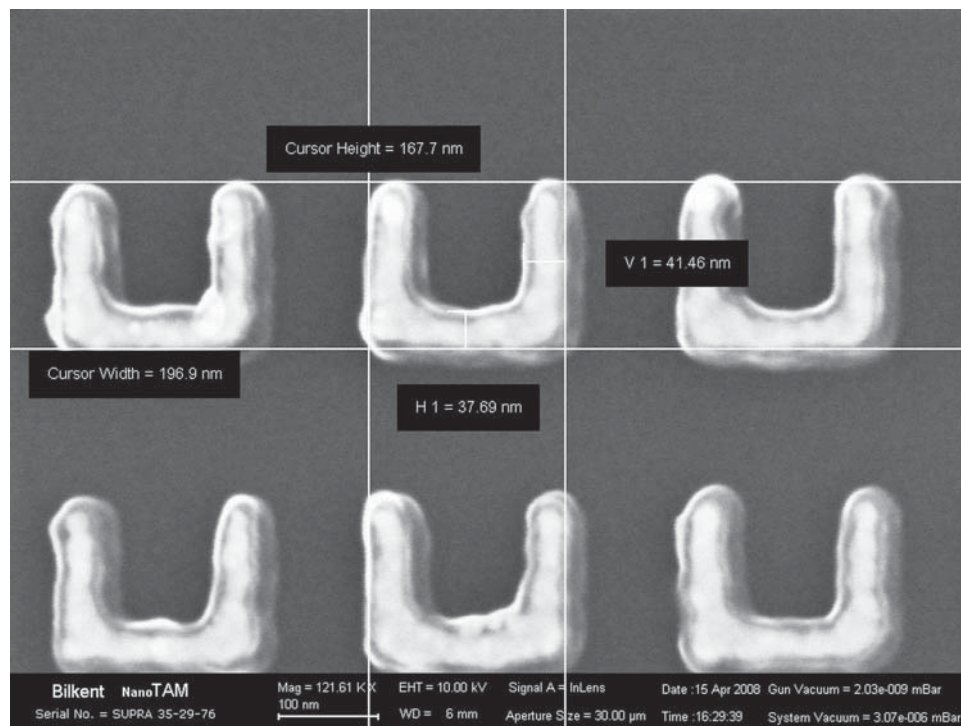


Fig. 1. Nanoscale SRR structures fabricated in Bilkent University.

Conventional SRRs provide a neat way to achieve magnetism at optical frequencies. In order to excite the magnetic resonance of the SRR, the incoming light should propagate in a direction that is parallel to the SRR plane. Shalaev *et al.* at Purdue University came up with a solution to this problem, where they modified the classical SRR into a coupled nanostructure [7]. Using the coupled nanostructures with various dimensions, the Purdue researchers were able to create metamaterials exhibiting optical magnetic responses across the entire visible spectrum: from red to blue.

Although the coupled nanostructure results in magnetism at even shorter wavelengths, they still do not possess the desired negative index behavior. If the metallic nanowires are fabricated on the same plane with the coupled nanorods, the structure resembles that of a fishnet. Professor Zhang's group at the University of California at Berkeley reported a 10-layer fishnet metamaterial structure [8]. Instead of relying on numerical retrieval methods, measurements of the refractive index of the structures were carried out by observing the refraction angle of the light passing through the prism by "Snell's Law." This method provides a direct and unambiguous determination of the refractive index [9], as the refraction angle depends solely on the phase gradient that the light beam experiences when refracted from the angled output face. The refractive index varied from $n = 0.63$ at 1200 nm to $n = -1.23$ at 1775 nm.

Photonic-crystal-based metamaterials also possess "almost magical" properties, including negative refraction and subwavelength imaging [10]. In a *Science* article, the Berkeley group reported observations of negative refraction in metallic-photonic-crystal-based metamaterials composed of silver nanowires embedded in alumina [11]. The group refractive indices of the metallic-photonic-crystal-based metamaterial are then shown to be -4.0 and 2.2 for TM and TE light, respectively. Similar to dielectric-based photonic crystals [12], metallic-photonic-crystal-based metamaterials can support propagating waves with large wave vectors that are evanescent in air or dielectrics, enabling the manipulation of visible light at the subwavelength scale. Such a property will be rather useful in various photonic applications including waveguiding, imaging, and optical communications.

Thanks to the popularity of the magic presented in the Harry Potter series of books and films, cloaking has also emerged as another “almost magical” application of metamaterials. The early experiments have shown that it is possible to design a metamaterial around an object such that an incoming wave can be totally reconstructed on the other side of the same object [13]. In a sense, the metamaterial acts like a cloak that makes the object inside invisible to the outside. Canonical spiral particles can also be used to achieve cloaking for both polarizations of the electromagnetic waves [14]. Spirals are optimized to exhibit equal permittivity and permeability response so that the cloak consisting of these spirals will work for both the TE and TM polarizations. Researchers at Berkeley have designed an optical “carpet” cloak using quasi-conformal mapping to conceal an object that is placed under a curved reflecting surface by imitating the reflection of a flat surface [15]. The cloak consists only of isotropic dielectric materials, which enables broadband and low-loss invisibility at a wavelength range of 1400–1800 nm. Another approach to obtain cloaking at optical frequencies is recently demonstrated by Cornell researchers [16]. The cloak operates in the near infrared at a wavelength of 1550 nm and it is composed of nanometer-size silicon structures with spatially varying densities across the cloak. The cloak conceals a deformation on a flat reflecting surface, under which an object can be hidden. The density variation is defined using transformation optics to define the effective index distribution of the cloak.

Although Chirality can be observed in nature, this effect is usually very weak, and to observe a significant polarization rotation effect, the light would have to propagate more than several centimeters (tens of thousands of visible wavelengths). Metamaterials can boost this effect by several orders of magnitude. In place of molecules, one can engineer tiny, subwavelength resonant electromagnets that act as magnetic dipoles [17]. Instead of using a resonant particle with a very narrow bandwidth, researchers at Karlsruhe University developed a uniaxial photonic metamaterial composed of 3-D gold helices arranged on a 2-D square lattice [18]. For propagation of light along the helix axis, the structure blocks the circular polarization with the same handedness as the helices, whereas it transmits the other, for a frequency range exceeding one octave. The structure is scalable to other frequency ranges and can be used as a compact broadband circular polarizer.

Photonic metamaterials are definitely one of the most active research areas within the photonics research community. Thanks to the recent experimental and theoretical demonstrations, the optical magic behind these structures has already been partially unveiled, in which we will definitely see more magic appear from photonic metamaterials in the coming years. The true magic behind photonic metamaterials is to create optical materials with new and unusual optical properties, and our imagination and creativity will continue to shape and advance this new research area.

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