Recent Experimental Progress in 3D Optical Metamaterials and Transformation Optics

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Abstract

In this paper, we review our recent experimental progress regarding three-dimensional metamaterials and transformation-optics architectures. In particular, we present several variations of our previously introduced gold-helix metamaterials as compact broadband circular polarizer. Furthermore, we discuss our polarization-independent visible-frequency invisibility cloak that has been enabled by three-dimensional stimulated-emission-depletion direct-laser-writing optical lithography. Finally, we possibly also present our ongoing research on more “down-to-earth” three-dimensional transformation-optics devices based on spatially inhomogeneous linearly birefringent metamaterials.

1. Introduction

Metamaterials have come a long way from microwave frequencies to optical and even visible frequencies [1] and later from mere planar structures [1] to truly three-dimensional “materials” [2-4]. This combination has also enabled truly three-dimensional (3D) transformation-optics architectures [5], such as 3D invisibility cloaks. In this presentation, we will review our recent corresponding experimental progress.

2. Variations of 3D gold-helix metamaterials

Fabricating three-dimensional rather than just two-dimensional structures is more than just stacking planar layers: Some phenomena such as, *e.g.*, chirality only exist in three dimensions. Metal helices are *the* paradigm structure for optical activity and circular dichroism. In 2009, we have shown [4] that square arrays of three-dimensional gold helices can be used as compact circular polarizer with a bandwidth exceeding one octave in the 3-6 µm wavelength range. Following the wisdom of antenna textbooks (*e.g.*, J.D. Kraus, “Antennas”, McGraw-Hill), we were tempted to interpret this behaviour in terms of the properties of the individual helices. In fact, in his textbook, John D. Kraus, the inventor of the end-fire helical antenna, explicitly states in boldface on page 225: “*Not only does the helix have a nearly uniform resistive input over a wide bandwidth but it also operates as a ‘supergain’ end-fire array over the same bandwidth! Furthermore, it is noncritical with respect to conductor size and turn spacing. It is also very easy to use in arrays because of almost negligible mutual impedance.*”

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Inspired by corresponding dielectric helical structures [6], we have investigated different checkerboard arrangements of gold helices. For example, gold helices of the same handedness but rotated by 90 or 180 degrees with respect to each other are positioned onto the “white” and “black” squares on the checkerboard. We find very large differences in the optical properties of these structures – in sharp contrast to the expectation from the above wisdom. These results rather suggest a strong interaction among the different helices. As expected, racemic (mixed left-handed and right-handed) control structures show vanishing circular dichroism. Details [7] will be presented at the conference.

We have also fabricated and characterized helix arrays with helix axes parallel [7] rather than normal [4] to the substrate.

3. Polarization-independent visible-frequency invisibility cloaking

In 2010, we have fabricated and characterized the first 3D invisibility cloaking structure [5]. This structure was based on the carpet-cloak concept introduced by Jensen Li and John Pendry and exhibited excellent cloaking in the wavelength range from 1.5-3.0 µm. Smaller operation wavelength would have required smaller minimum feature sizes in the 3D direct-laser-writing (DLW) optical lithography, which were not available at that time.

More recently, we have succeeded in breaking Abbe’s diffraction barrier by adopting the concept of stimulated-emission-depletion (STED) invented by Stefan Hell for fluorescence microscopy. There, world-record lateral resolutions as small as 5.6 nm have been demonstrated at visible frequencies. However, in 3D STED-DLW optical lithography, not only the lateral [8] but also the axial resolution has to be improved. By solving this problem, we have been able to miniaturize our previous woodpile-photonic-crystal-based 3D invisibility cloak [5] by more than a factor of two in all three spatial directions leading to what we believe is still the only 3D polarization-independent (!) visible-frequency invisibility cloak [9]. Detailed optical characterization will be presented at the conference. Fig.1 gives a first flavor.

Invisibility cloaking is an impressive demonstration of the strength of the optics-design tool called transformation optics. However, we feel that invisibility cloaking will not be really useful in itself. Thus, we are working on designing particular polarization optics on the basis of transformation optics. These structures require spatially inhomogeneous linearly birefringent metamaterials that can be made by 3D DLW optical lithography. Details will be presented at the conference.

The above 3D transformation-optics structures were all purely dielectric structures. Using metals would add flexibility to the design possibilities. However, metals like gold or silver often have a way “too negative” electric permittivity, such that (smooth) metal films with thicknesses of just a very few nanometers may be required, which are very difficult to fabricate – especially in 3D architectures. Alexandra Boltasseva and Harry Atwater have recently emphasized that highly doped semiconductors or isolators may be an interesting alternative to usual metals [10]. Regarding 3D architectures, this requires deposition of such materials *via* techniques as, *e.g.*, atomic-layer deposition (ALD). Using ALD of highly Al-doped ZnO (“AZO”), we have achieved tunable (!) free-electron plasma frequencies, which can even reach the red end of the visible spectrum, together with smooth conformal coatings in 3D [11]. The determined free-electron damping (or collision frequency) is reasonable. This technological step opens further future experimental possibilities.

4. Conclusion

Using 3D direct laser writing (DLW) that can be enhanced by stimulated-emission-depletion (STED) approaches, combined with 3D infilling (*e.g.*, electroplating) or coating (*e.g.*, atomic-layer deposition) approaches, we have realized a variety of truly three-dimensional metamaterials and transformation-optics architectures at near-infrared or even at visible operation frequencies.

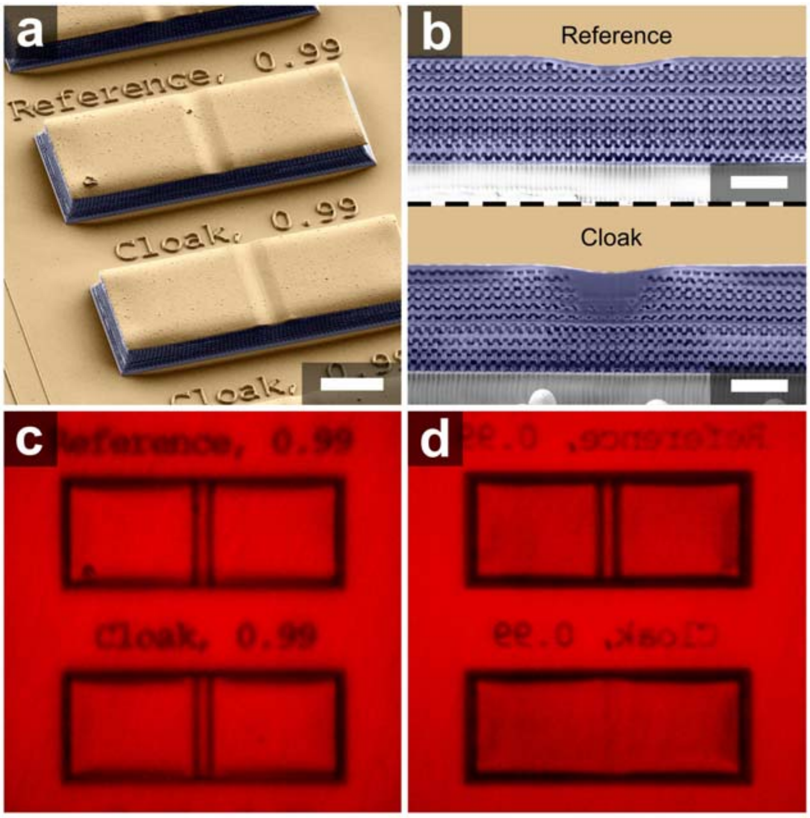

Fig. 1: Three-dimensional polarization-independent carpet-invisibility-cloaking structure operating at visible frequencies. (a) colored oblique-view electron micrograph (10-µm scale bar), (b) side-view electron micrograph (2-µm scale bar) taken after focused-ion-beam (FIB) milling to reveal the sample's interior, (c) control true-color optical micrograph taken from top (illumination at 700-nm wavelength), and (d) true-color optical micrographs through the reference structure (top) and the cloaking structure (bottom), respectively. Taken from Ref.[9].

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