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Review

Implementation of optical dielectric metamaterials: A review

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A R T I C L E I N F O

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A B S T R A C T

Metamaterials are a class of man-made materials with exotic electromagnetic properties. The ability to fabricate three-dimensional macroscale metamaterials would enable embedding these structures in engineering applications and devices, to take advantage of their unique properties. This paper reviews the implementation of optical Mie resonance-based dielectric (MRD) metamaterials, as opposed to the more commonly used metallic-based metamaterials. Design constraints are derived based on Mie theory and related to fabrication specifications. Techniques to fabricate optical dielectric metamaterials are reviewed, including electron-beam lithography, focused ion beam lithography, nanoimprint lithography, and directed self-assembly. The limitations of each fabrication method are critically evaluated in light of the design constraints. The challenges that must be overcome to achieve fabrication and implementation of macro-scale three-dimensional MRD metamaterials are discussed.

Contents

1. Introduction

Electromagnetic metamaterials refer to a class of man-made materials consisting of sub-wavelength unit structures that display exotic properties such as negative magnetic

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permeability, negative electric permittivity and/or negative index of refraction [1–3]. The size of the unit structures, also referred to as “meta-atoms”, is significantly smaller than the operating wavelength, but larger than the atomic and molecular structure [1]. The electromagnetic response of a metamaterial is the result of complex interactions between incident electromagnetic waves and the sub-wavelength unit structures, and can be predicted via a homogenization approach based on the effective electric permittivity and magnetic permeability. The possibility of tailoring the electromagnetic properties of a material by designing the unit structure of the meta-atoms has paved the way to conceptualizing many novel devices and technologies such as superlenses [4–8], hyperlenses [9,10], and optical cloaking [11–13]. Metamaterials also find application in nanoantennas [14,15], radiative cooling [16], thermal radiative property control [17–20] as well as in energy harvesting and conversion devices [21,22] to only name a few.

Most metamaterials operating in the optical frequency band that are documented in the literature are made of metallic meta-atoms such as split-ring resonators, thin wires, rods or fishnet structures [1,23]. They require two types of meta-atoms to induce both electric and magnetic responses. For instance, split-ring resonators are employed for tailoring the effective permeability while wires enable control of the effective permittivity [24], thus offering flexibility to the metamaterial designer. However, metallic metamaterials also present several drawbacks. Fabrication of the intricate structures that form the meta-atoms typically requires sophisticated micromanufacturing techniques, which are time consuming and not easily scalable to manufacture macroscale three-dimensional (3D) specimens that can be integrated in engineering devices [25]. Additionally, large ohmic losses exist, and the effective electromagnetic response of the metamaterial is anisotropic as a result of the asymmetric geometry of the metallic split-ring and wire inclusions.

In contrast, Mie resonance-based dielectric (MRD) metamaterials consist of dielectric meta-atoms, such as spherical, cylindrical, or randomly shaped inclusions embedded in a dielectric host medium. The electric and magnetic resonances of the inclusions are the building blocks that dictate the effective electromagnetic properties of the metamaterial. Mie theory offers an exact solution of Maxwell's equations for electromagnetic wave scattering and absorption by a single spherical particle [26]. The term “Mie” is loosely used for MRD metamaterials to specify that the effective electromagnetic response of the metamaterial depends on the electric and magnetic resonances of the dielectric inclusions. However, these dielectric inclusions are not restricted to spheres and may take various shapes.

MRD metamaterials present potential advantages compared to metallic metamaterials. Since the electromagnetic response of MRD metamaterials relies on the electric and magnetic resonances of dielectric inclusions, only one type of inclusion can be used to induce both effective electric and magnetic resonances. Additionally, an isotropic electromagnetic response can be obtained with spherical inclusions or by using a large amount of randomly oriented, non-symmetric inclusions [27]. Losses for MRD metamaterials are expected to be smaller than for metallic metamaterials [25].

The electromagnetic response of MRD metamaterials can be engineered by varying the host medium and the shape, shape distribution, material, size, size distribution, spatial arrangement or concentration of the dielectric inclusions. The spatial arrangement of the inclusions can be adjusted from randomly dispersed to periodic, since the effective properties rely on the resonances of the dielectric inclusions, not the periodicity of the arrangement [1]. As a result, the role of fabrication imperfections in MRD metamaterials is less important than in the case of metallic metamaterials, where alignment and periodicity of the features is critical to obtaining the desired response.

MRD metamaterials operating in the microwave spectral band have been experimentally studied over the past few years [28–32]. The size of the inclusions and their separation distance can be as large as a few millimeters and, thus, fabrication is less challenging and can be accomplished with traditional, macroscale techniques. This review focuses on MRD metamaterials operating at optical wavelengths, which covers both the visible and the infrared spectral bands. Although several optical MRD metamaterials have been developed theoretically [33–42], few authors provide detailed information about possible fabrication methods, and even fewer published works documenting successful fabrication and implementation of optical MRD metamaterials [27,43–48]. In addition, the specimens fabricated in these studies are typically microscale two-dimensional (2D) specimens, with restrictions on the orientation of incident waves. Thus, they cannot easily be used in macroscale engineering applications. To take advantage of the exotic electromagnetic properties of MRD metamaterials in engineering systems and applications, fabrication of 3D macroscale metamaterial specimens is imperative. Hence, high-precision, high-throughput, and low-cost scalable manufacturing processes are needed to fabricate macroscale 3D MRD structures operating at optical frequencies. Furthermore, integration between metamaterial design and fabrication is critical to successfully implementing macrosale MRD metamaterials. Thus, the objective of this review is twofold. First, we establish the design and fabrication requirements needed to implement MRD metamaterials. Second, we review the manufacturing techniques that have been reported in the literature to successfully fabricate a proof-of-concept of all-dielectric optical metamaterials. Additionally, we discuss fabrication techniques that have been proposed, or are viable in principle, but have not yet been successfully implemented for MRD metamaterials. We point out that a review of fabrication techniques for metallic-based metamaterials has been provided by Boltasseva and Shalaev [23].

2. Design and fabrication requirements for engineering electric and magnetic resonances with MRD metamaterials

The effective electromagnetic response of MRD metamaterials depends on the interplay between the dielectric inclusions and the host medium, and can be engineered by