DOUBLE-NEGATIVE AND SINGLE-NEGATIVE METAMATERIALS AT OPTICAL FREQUENCIES

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STATEMENT OF THE PROBLEM

The topic of metamaterials, as specially engineered media with unconventional response functions not readily found in natural materials, has received ever increasing attention in recent years. In particular, media in which one or both of the material parameters, permittivity and permeability, can attain negative real parts in a certain frequency band, have been the subject of study by numerous groups. When both material parameters possess negative real parts, such double-negative (DNG) media can support wave propagation and exhibit the peculiar phenomenon of negative refraction, while media with a single-negative (SNG) parameter, such as plasmonic media (e.g., noble metals in the IR and visible regimes) support evanescent wave.

DNG and SNG metamaterials, formed by embedding arrays of metallic split-ring resonators (SRR) and wires in a host medium, have been successfully constructed in the microwave regime by several groups (see e.g., [1]), and some of their unusual properties (e.g., negative refraction) have been experimentally demonstrated [1]. One of the interesting research directions in DNG (or left-handed "LH") metamaterials is the development of such materials in the IR and visible regimes. In these frequency regimes, constructing DNG and MNG materials is challenging, in part due to the fact that in these frequency regimes the magnetic permeability due to the molecular currents in a material tends to approach to the free space permeability [2], and moreover, straightforward scaling of the metallic SRR in the optical wavelength may encounter other related issues. To address this challenge, several ideas have been put forward by various groups (see e.g. [3-7]).

To this purpose, we have suggested another idea for synthesizing negative magnetic response in the IR and visible regimes [8]. In particular, we propose a design for sub-wavelength inclusions that may show magnetic dipolar resonant response, and may therefore lead to the possibility of achieving negative effective magnetic dipole moment and negative effective permeability in the optical domain. Here, a circular array of plasmonic nanoparticles forms a single sub-wavelength "loop", in which a circulating "displacement" current due to the plasmonic resonance of the nanoparticles generates the magnetic dipole moment. Unlike the case of the conventional metallic loops or SRRs at the microwave frequencies, here in the case of loop of plasmonic nanoparticles the size of the loop does not directly influence the resonant frequency of the induced magnetic dipole moment. What matters here most is the plasmonic resonant frequency of the nano-particles. We have shown theoretically that by embedding many of these loops in a host medium one can obtain a bulk medium with negative effective permeability, and reasonably low losses, at certain bands of optical frequencies. Furthermore, we have also shown that the same inclusions may also provide resonant electric dipole response, and therefore having the two effects at the same frequencies can lead to double-negative materials in the IR and visible domains [8].

There are other ways to produce negative refraction at the optical frequencies. In our effort in understanding the concept of nanocircuit elements at the optical regime, we have shown how a nanoparticle, when exposed to optical signals, may be interpreted as a lumped "nano-capacitor" or "nano-inductor" operating at the optical frequencies, depending on whether its material has $\mathrm{Re}(\varepsilon) > 0$ (i.e., non-plasmonic) or has $\mathrm{Re}(\varepsilon) < 0$ (i.e., plasmonic), respectively [9]. Using this concept, we may form more complex circuits at optical frequencies when we arrange various plasmonic and non-plasmonic nanostructures near each other interacting in the near zone. The concept of optical nano-transmission line may be conceived by properly arranging two parallel linear chains of closely-spaced plasmonic nanoparticles (as series nano-inductors) with an array of non-plasmonic spheres (as shunt nano-capacitors) between the first two lines. By switching the roles of nano-inductors and nano-capacitors, we may obtain optical nano-transmission lines with negative phase velocity (effectively a left-handed (LH) transmission line in the optical domain), the optical analogue of what have been proposed in the microwave regimes using circuit lumped elements [10, 11].

This idea may offer interesting negative-index effects, as well as a road map for synthesizing negative-refraction (or left-handed) materials in the IR and visible regimes.

In this talk, we will give an overview of our research efforts in this area.

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