Manipulating Light with Optical Left-Handed Metamaterials

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Left-handed metamaterials (LHMs), i.e. artificial composite structures with simultaneously negative electrical permittivity and magnetic permeability, giving rise to negative index of refraction, have attracted great attention in the last decade. This is due to the novel and unique properties of those materials, such like backwards propagation (i.e. opposite phase and energy velocity), negative refraction, reversed Doppler effect and Cerenkov radiation, etc. These novel properties empower the left-handed materials with unique capabilities in the manipulation of electromagnetic waves and give the possibility to create novel electromagnetic components and devices, like sensors, anternnas, waveguides, transmission lines etc. Among the main capabilities of LHMs an important one is their superlensing capability, i.e. the ability to give subwavelength resolution imaging. This ability, which was proposed first in 2000, can lead to revolutionary solutions in imaging, lithography and data storage devices.

To be able to exploit the superlensing capability of LHMs in the optical part of the electromagnetic spectrum, many efforts have been devoted recently to push the operation regime of LHMs from microwaves (where the first and most of todays metamaterials have been demonstrated) to the optical regime. Most of those efforts are based on a scaling approach, i.e. they attempt to scale down successful microwaves LHM designs. This is not a straightforwatd approach though, since the unique properties of todays LHMs are based on a large degree on the perfect conductor properties of the metallic components of those materials; in the optical regime metal does not behave as an almost perfect conductor like in microwaves, and the response of the electrons at the interior of the metallic structures can alter the metamaterial properties, while losses are extremely pronounced and can very easily kill the desired metamaterial response. Moreover, since the experimental demonstration of optimized optical metamaterials requires the fabrication of complicated nanoscale patterns, something difficult with the current fabrication capabilities, the optimization of advanced nanofabrication techniques or the employment of new techniques is an essential step for the achievement of optimized optical metamaterials.

Despite the above mentioned complications, there have been already demonstrated LH metamaterials operating in 100 THz, 200 THz and recently in the lower visible range [1]. These metamaterials though are in their majority monolayer structures, suffering from high losses, and thus they are not very much appropriate for imaging applications.

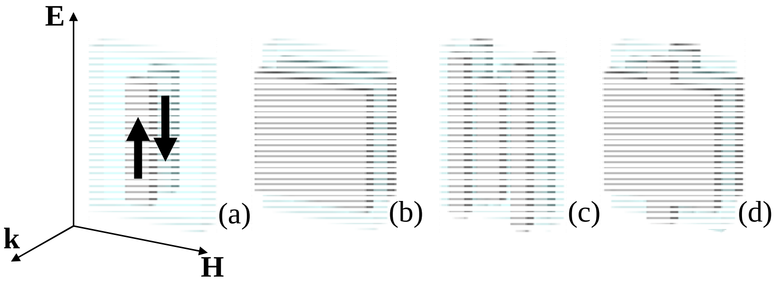

Fig. 1: The unit cell of four designs studied here. (a): Slab-pair system, which provides a resonant permeability response, owned to the resonant antiparallel current mode at the two slabs of the pair (see arrows); (b) wide-slab-pair system; (c) slabs&wires system, which provides both negative permittivity and permeability response; (d) fishnet design.

In this work, with aim to achieve optimized optical LHMs, we study the behaviour of basic metamaterial structures as they are scaled down from mm to nm scale, and we try to understand the wave propagation in those structures. The majority of the structures studied are structures of combining negative permittivity and permeability, such as the ones shown in Fig. 1(c) and 1(d), or structures of only negative permeability (Fig. 1(a) and 1(b)) (the negative permeability component of LHMs is the most difficult to be achieved component in the optical regime, as negative permittivity can be easily obtained using metals). These structures are based on pairs of short slabs, combined or not with continuous wires. The pair of slabs has been found to exhibit a resonant current mode with antiparallel currents at the two slabs of the pair, providing a resonant magnetic moment and thus resonant permeability with negative permeability values. The continuous wires provide a plasma like response, with a reduced plasma frequency determined by the geometrical characteristics of the wire-lattice. The combination of both leads to negative refractive index behaviour. The specific combination shown in Fig. 1(d), known as fishnet structure, where the slabs are wide along the **H** direction and are physically connected with the wires, has been proven the most successful up to now structure for the achievement of optical LHMs.

The advantage of the structures of Fig. 1, apart from their fabrication simplicity, is that they show LH response for incidence normal to the plane of the structure, allowing thus experimental demonstration of this response using only one or very few structure layers.

Detailed study of the structures of Fig, 1, and attempts of their optimization, led to two main conclusions:

(a) The magnetic resonance frequency of the structures, while in the mm length-scale it scales inversely proportional to the structure size, going to the sub-micron scale it saturates to a constant value (see Fig. 2). This value depends on the geometrical characteristics of the structure and can go up to the plasma frequency of the bulk metal.

(b) The resonant permeability response of the structures, going to smaller scales, becomes more and more weak, and ultimately ceases to reach negative values [2]. Thus, in nm scale the resonant permability response of the structures dies out.

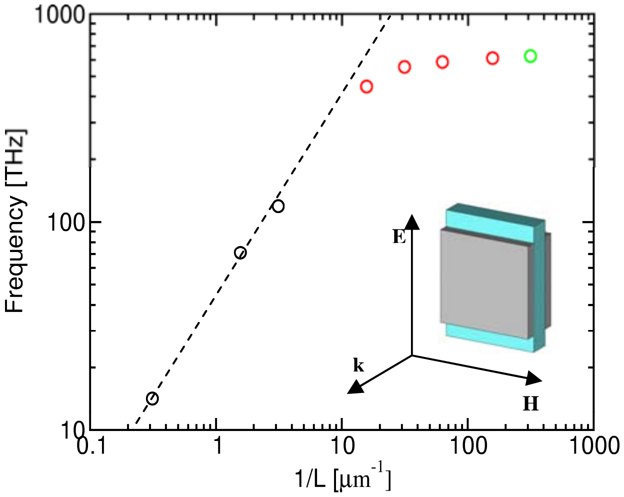

Fig. 2: Scaling and saturation of the magnetic resonance frequency of the wide short-slab pair structure (shown in inset) with the inverse of the unit cell size, *L*. The black circles indicate that the magnetic resonance form is affected by periodicity, the red circles indicate that the structure is subwavelength in scale, while the green circle indicates that the resonance is too weak to reach negative values for the permeability.

Detailed examination and analysis of the wave propagation in the structures of Fig. 1 showed that both the above mentioned results can be understood taking into account the dispersive properties of the metal, which lead to an inductive contribution in the metal resistance (electrons' inductance). This inductive component scales inversely proportional to the structure length scale (in contrast to the magnetic field inductance which scales proportional to the length scale) and in the submicron scales dominates the wave propagation, weakening any magnetic response of the structures. Detailed calculations, treating our structures as resonant inductor-capacitor circuits, showed that the consideration of the electron's inductance can explain both the saturation of the magnetic resonance frequency and the weakening of the permeability resonance. Moreover, these calculations led to basic design rules for achievement of optimized negative permeability and/or negative refractive index structures in the optical regime [3].

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