Photonics Metamaterials: Challenging and Opportunities

Costas M. Soukoulis,[1,2]

[1]*Institute of Electronic Structure and Laser, FORTH, Heraklion, Crete, Greece*
[2]*Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[*]*Email:Soukoulis@ameslab.gov*

Abstract

In the last decade, a new area of photonics research has emerged, that has given the ability to produce materials with entirely novel electromagnetic properties. Known as metamaterials for their ability to take beyond conventional materials. Clearly, the field of metamaterials can develop mould-breaking technologies for a plethora of applications, where control over light (or more generally electromagnetic radiation) is a prominent ingredient—among them telecommunications, solar energy harvesting, biological and THz imaging and sensing, optical isolators and polarizers. In this talk, I give an introduction into this emerging field, review recent progress, and highlight remaining challenges and opportunities.

1. Introduction

One of the most exciting and promising developments in basic physics, applied physics and engineering is the endowment of photons with revolutionary propagation and spectral properties, through their interaction with novel artificial materials, called metamaterials [1-3]. This development, which actually started about a decade ago, has been intensified over the last five years, and it is expected to grow in the years to come. Metamaterials represent a broad class of micro- or nanostructures composed of tailored building blocks that are ideally much smaller than the wavelength of light, enabling dense packing into an effective material. Resonances of the building blocks are the key for opening the door to a new world of possibilities. In particular, magnetic-dipole resonances can be achieved by “simply” shrinking the size of usual metallic electromagnets such that their resonances go optical. The split-ring resonator (SRR) is a paradigm example [4]. The incident light field can induce a circulating and oscillating electric current in the ring. These magnetic-dipole resonances and the numerous variations thereof have reminded the optics community that light is an electromagnetic wave. If one aims at obtaining complete control over an electromagnetic light wave inside of a material, one needs to be able to independently control both the electric and the magnetic field [2]. Thus, the newly achieved magnetic control has opened one half-space of optics that is still considered irrelevant in many optics textbooks. Yet, it shouldn’t. The other half of optics allows for impedance matching, hence zero reflection at a material’s interface – for any refractive index. The refractive index can also become negative or assume exceptionally large positive values. For many of these far-reaching ideas one eventually needs three-dimensional structures [5].

In Figure 1, we present the development of the operation frequency of metamaterials with negative permeability, *m*, and/or a negative refractive index, *n*, over the last ten years. In the early years (2000-2003) the design of choice for obtaining negative *m*, was the split-ring resonator (SRR). In 2004, a negative *m* at 1, 6, and 100 THz frequency was obtained by scaling down the SRR structure. The scaling down of the SRRs has given negative values of *m* up to 200 THz. At microwave frequencies, where the SRRs have sizes on the order of 1 cm, the SRR can be combined with wires providing an effective negative electric permittivity to achieve a negative index of refraction. It is also relatively easy to form multi-stacks and to propagate along the plane of the SRRs (so as to have the magnetic field perpendicular to the plane of the SRRs and the electric field parallel to the wires, and thus to be able to obtain negative *n* response). However, this configuration cannot easily be translated to optical frequencies. Thus, there was a need to find alternative designs providing negative *m* and negative *n* at infrared and visible frequencies. This led to cut-wire pairs and double fishnet structures for $\mu<0$ and $n<0$, respectively. Clearly, these structures are uniaxial, providing the requested properties only for propagation of light normal to the substrate surface. Cut-wire pairs were independently experimentally realized and published by three groups in 2005. They can be viewed as strongly compressed SRRs

ISBN 978-952-67611-0-7

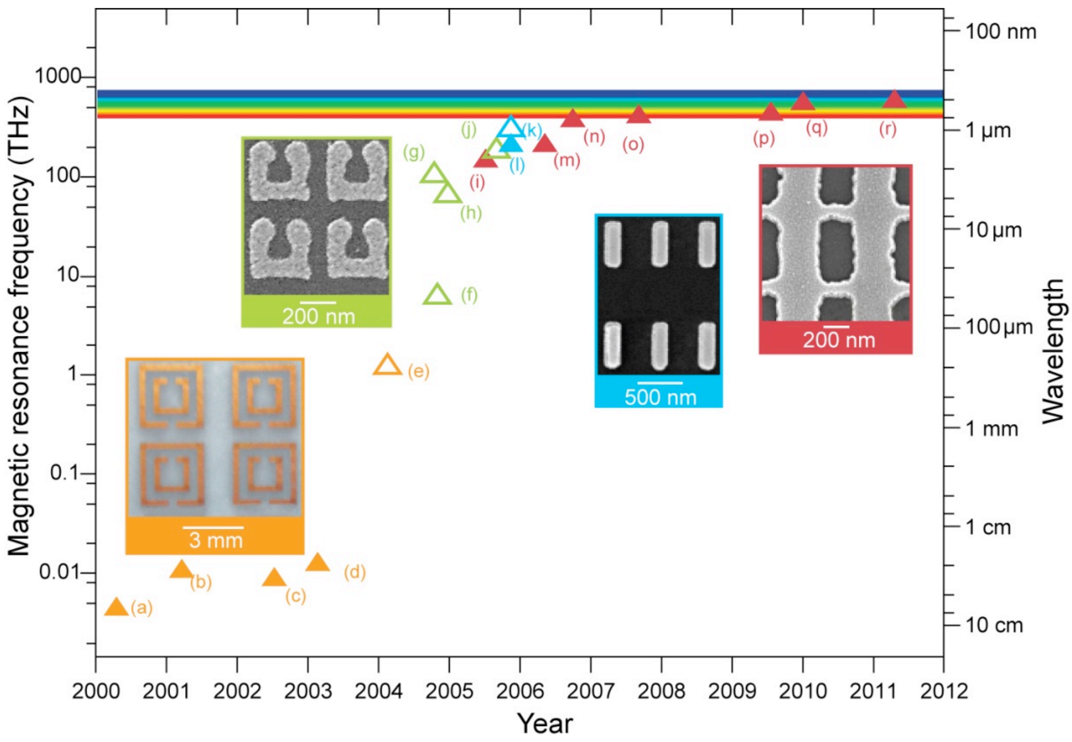

Figure 1. The progress in the negative permeability, m, and the negative index, n, materials development in the last 10 years. The solid symbols denote n<0; the open symbols m<0. Orange: data from structures based on double SRR; green: data from U-shaped SRR; blue: data from metallic cut-wire pairs; red: data from fishnet structure. The four insets give pictures of fabricated structures in different frequency region. This figure reproduced with permission from ref. 5.

with two slits. The dielectric material between the resulting two parallel wire pieces merely serves as a spacer. The double fishnet essentially adds long metal wires to this arrangement for additionally providing a negative electric permittivity ε in the same frequency range where the cut wires lead to $\mu<0$. The resulting so-called "double-fishnet" structure was introduced at infrared frequencies in 2005 and made it into the visible in 2007. However, most of the fishnet metamaterials shown in Figure 1 are really only 2D planar structures, which are sometimes also referred to as meta-films, meta-surfaces, or frequency selective surfaces. As mentioned above, most metamaterial experiments have been limited to 2D structures, whereas any normal person would expect structures extended in all three spatial dimensions on the scale of at least several wavelengths when speaking about a "material". However, the fabrication of such 3D bulk metamaterials still poses a formidable challenge for nanotechnology [5].

2. Metamaterials towards 3D

Most metamaterials that exhibit artificial magnetism and/or a negative refractive index at (far-) infrared frequencies consist of only a single functional layer [2] (or "monolayer"). Pioneering experimental work [6-13] on several functional layers (i.e., several lattice constants) is summarized in Table 1. All of these structures except for Ref. [12], are significantly thinner than the operation wavelength (also see Fig. 2). All are layered and work only for one particular propagation direction. How many layers are sufficient to qualify for being called " 3D bulk", i.e., for convergence when starting from 2D? Nobody would seriously question that the optical properties of a monolayer SiO_2 film are significantly different from those of ten atomic layers—despite the fact that the total thickness is much smaller than an optical wavelength in both cases. Yet, in metamaterials, the situation can be more complex, because the building blocks ("photonic atoms") can interact strongly. Thus, one must study how the optical properties (ε, μ, and n) change as the number of layers increases.

Table 1: Summary of fabricated (far-) infrared double-fishnet negative-index metamaterials composed of an integer, *N*, of functional layers (or lattice constants), in which case the number of actual layers is *M*=2*N*+1.

# Functional Layers	Ref.	Year	Type	Operation Frequency
N=5	[6]	2006	Magnetic	6 THz
N=3	[7]	2007	Negative index	214 THz
N=4	[8]	2008	Magnetic	70 THz
N=10	[9]	2008	Negative index	166 THz
N=5	[10]	2008	Negative index	210 THz
N=4	[11]	2008	Negative index	1 THz
N=100	[12]	2010	Magnetic	0.35 THz
N=3	[13]	2011	Negative index	439 THz

There is no unique answer to the above question. In some cases, one layer may already be sufficient, in other cases a few layers suffice. The answer strongly depends on the coupling between adjacent layers, hence on their spacing. If the distance between adjacent functional layers is small, we have

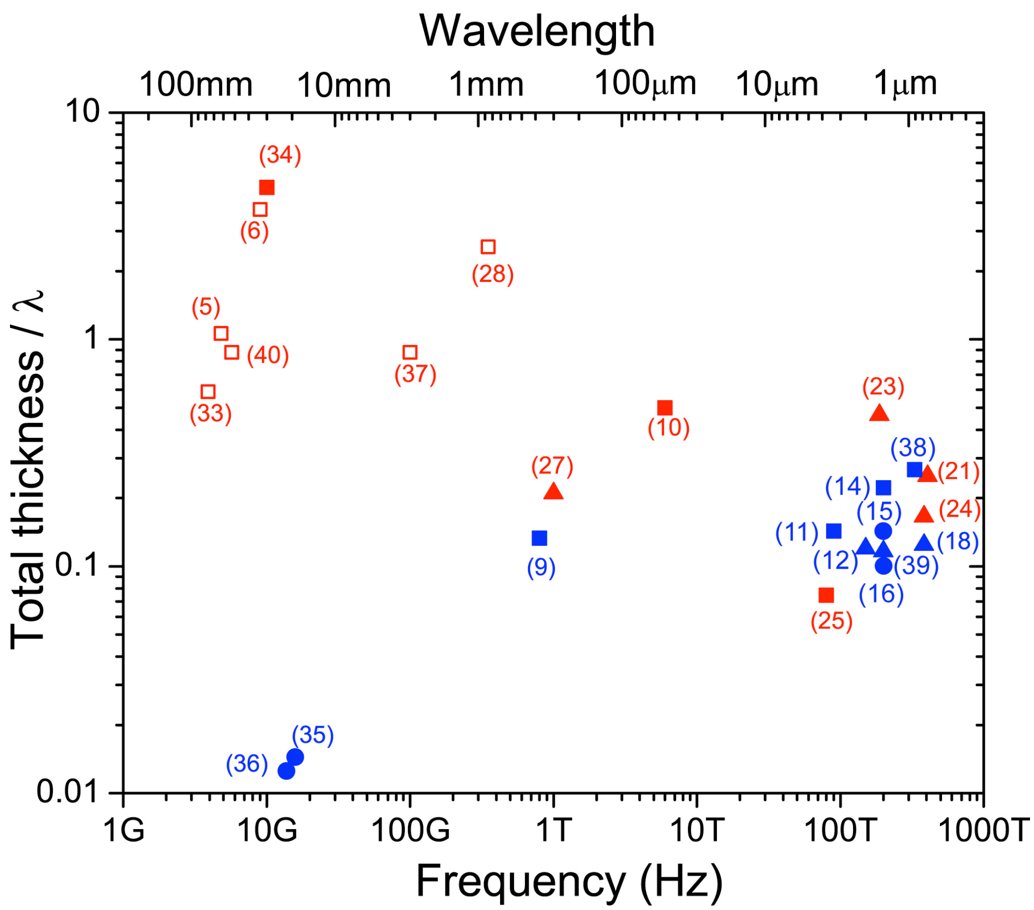

Figure 2. The total thickness over wavelength for different metamaterials. Red: Multiple layers; Blue: single layers; Hollow: Parallel incident; Solid: Normal incident; Square: SRRs; Triangle: Fishnet; Circle: cut-wires. This figure reproduced and updated with permission from ref. 15.

ISBN 978-952-67611-0-7

strong coupling, and the convergence of the optical properties is slow (one needs at least four functional layers) [14]. Importantly, the behavior does not converge to that of the monolayer case. In contrast, for larger distances, the coupling is weak and the retrieved optical parameters for several functional layers are very close to the monolayer case [14].

Figure 2 summarizes a large variety of metamaterial experiments. Here, the total metamaterials thickness, *t*, normalized to the free-space operation wavelength, *l*, is plotted versus operation frequency. At microwave frequencies, the metamaterial thickness is up to four to five times larger than the wavelength. At infrared to visible frequencies, this ratio decreases, reaching values well below unity in most cases. Increasing this ratio remains to be a challenge. However, there is more to three-dimensional metamaterials than just making them ever thicker. Flexibility in tailoring the metamaterial's unit cell interior is another crucial factor. In this regard, the various existing fabrication approaches exhibit substantial differences with particular strengths and weaknesses for each case. One can use electron-beam and focused-ion-beam-lithography to fabricate many layers of metamaterials [7-9, 13], no isotropic metamaterials. SRRs oriented in all three dimensions, fabricated using membrane projection lithography [16], and direct laser writing can fabricate 3D isotropic metamaterials [17].

3. Conclusion

Throughout the last decade, electromagnetic metamaterials have come a long way from microwave frequencies to the visible. More recently, they have also become truly three-dimensional "materials" at optical frequencies. Much of this research has been inspired by the fascinating and far-reaching vision of the perfect lens, as introduced by John Pendry based on the dream of lossless isotropic negative-index metamaterials. While this dream may never come into reach, it has fueled an entire field. Meanwhile, some researchers have also identified more short-term applications that get away with essentially two-dimensional metamaterial structures. For example, even meta-surfaces can approach perfect absorbers, i.e., structures that neither transmit nor reflect light in a certain frequency regime and for a broad range of angles. Such compact perfect absorbers might prove useful for detectors or energy converters. Other researchers have explored field-enhancement effects for improving the performance of solar cells. Yet others employ the (sharp) metamaterial resonances for sensing applications *via* their dependence on environment or investigate nonlinear frequency conversion. The magnetic response is also a prerequisite for huge chiral optical effects in three-dimensional metamaterials, e.g., enabling compact broadband circular polarizers.

References

[1] For recent reviews see: (a) D.R. Smith, J.B. Pendry & M. Wiltshire, "Metamaterials and Negative Refractive Index," *Science* **305**, 788 (2004); (b) C. M. Soukoulis, et al., "Negative index materials: New frontiers in optics," *Adv. Mat.* **18**, 1941 (2006); and (c) A. Boltasseva and V. M. Shalaev, "Fabrication of optical negative-index metamaterials," *Metamaterials* **2**, 1 (2008).

[2] For recent reviews on optical metamaterials see: (a) V. M. Shalaev, "Optical negative-index materials," *Nature Photonics* **1**, 41 (2007); and (b) C. M. Soukoulis, S. Linden & M. Wegener, "Negative index metamaterials at optical wavelengths," *Science* **315**, 47 (2007).

[3] For recent perspectives on metamaterials see: (a) N. I. Zheludev, "The road ahead for Metamaterials," *Science* **328**, 582 (2010); (b) C. M. Soukoulis and M. Wegener, "Photonic Metamaterials: More bulky and less lossy," *Science* **330**, 1633 (2010); and (c) A. Boltasseva and H. Atwater, "Low-Loss Plasmonic Metamaterials," *Science* **331**, 290 (2011).

[4] J. B. Pendry et al., "Magnetism from Conductors and Enhanced Non-linear Phenomena", *IEEE Trans. MIT* **47**, 2075 (1999).

[5] C. M. Soukoulis and M. Wegener, "Past Achievements and Future Challenges in the development of 3D photonic metamaterials," *Nat. Phot.* **5**, 523 (2011).

[6] N. Katsarakis, et al., "Magnetic response of split-ring resonators in the far infrared frequency regime", *Opt. Lett.* **30**, 1348 (2005).

[7] G. Dolling, M. Wegener & S. Linden, "Realization of a three-functional-layer negative-index photonic metamaterial," *Opt. Lett.* **32**, 551 (2007).
[8] N. Liu, et al., "Three-dimensional photonic metamaterials at optical frequencies," *Nature Mater.* **7**, 31 (2008).
[9] J. Valentine et al., "Three-dimensional optical metamaterial with a negative refractive index," *Nature* **455**, 376 (2008).
[10] N. Liu, et al., "Planar Building Blocks for Magnetic Molecules in Three-Dimensional Optical Metamaterials," *Adv. Mater.* **20**, 3859 (2008).
[11] O. Paul et al., "Negative index bulk metamaterials at THz frequencies," *Opt. Express* 16, 6736 (2008).
[12] F. Miyamaru et al., "Three-dimensional bulk metamaterials operating in the THz range," *Appl. Phys. Lett.* **96**, 081105 (2010).
[13] C. Garcia-Meca et al., "Low-loss multilayered metamaterial exhibiting a negative index of visible of refraction at visible wavelengths," *Phys. Rev. Lett.* **106**, 067402 (2011).
[14] J. Zhou, Th. Koschny M. Kafesaki and C. M. Soukoulis, "Negative refractive index response of weakly and strongly coupled optical metamaterials," *Phys. Rev. B* **80**, 035109 (2009).
[15] C. M. Soukoulis, J. Zhou, Th. Koschny, M. Kafesaki and E. N. Economou, "The Science of Negative Index Materials," *J. Phys.: Condens. Matter* **20**, 304217 (2008).
[16] D. B. Bruckel et al., "Fabrication of 3D metamaterials using self-aligned membrance projection lithography," *Adv. Mat.* **22**, 3171 (2010).
[17] M. Deubel et al., "Direct laser writing of 3D photonic crystal templates for photonic bandgaps at 1.5 micrometers," *Nature Mater.* **3**, 444 (2004).