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LEFT HANDED MATERIALS: A NEW PARADIGM IN STRUCTURED ELECTROMAGNETICS

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Abstract

A new paradigm has emerged exhibiting reverse electromagnetic properties. Novel composite and micro-structured materials (metamaterials) have been designed to control electromagnetic radiation. Such substances have been called as Left Handed Material (LHM) with simultaneous negative permittivity and negative permeability and negative refractive index as well. Left handed materials are of importance because of their ability to influence the behavior of electromagnetic radiation and to display properties beyond those available in naturally occurring materials. Typically these are sub–wavelength artificial structures where the dimensions are very small compared to the working wavelength. These dimensions are normally of the order of $\lambda/10$ where λ is the wavelength of electromagnetic wave propagating in the material. Emergence of this new paradigm leads to some very interesting consequences, such as, to create lenses that are not diffraction limited, cloaking, sensors (chemical, biological and individual molecule), optical and radio communication. This new development in structured electromagnetic materials has had a dramatic impact on the physics, optics and engineering communities.

Introduction

The former century has been the age of artificial materials. One material that stands out in this regard is the semiconductor. Revolution in the electronics industry in the last century was made possible by the ability of semiconductors to microscopically manipulate the flow of electrons. Further advancement in the field prompted scientists to suggest that the new millennium will be the age of photonics in which artificial materials will be synthesized to microscopically manipulate the flow of electromagnetic waves. One of these will be Left Handed (LHM) materials. Such new man-made materials often referred to as Negative Index Media (NIM), Backward Wave Media (BWM), negative (DNG) metamaterial [1] in which research has attracted tremendous attention in the past few years because of their electromagnetic properties and ability to guide evanescent field, are significantly different from those of Right Handed Materials (RHMs). They exhibit simultaneous negative values for permittivity, ε, and permeability, μ, in an overlapping frequency region, since the values are derived from the effects of the composite medium system as a whole; these are defined as effective permittivity ε_{eff} and effective permeability μ_{eff}. Real values are then derived to denote the value of negative index of refraction and wave vectors. This means that in practice losses will occur for a given medium used to transmit electromagnetic radiation such as microwave or infrared frequencies, or visible light for example real values describe either the amplitude or the intensity of a transmitted wave relative to an incident wave, while ignoring the negligible loss values [2,3]. Further, the European Virtual Institute for Artificial Electromagnetic Materials and Metamaterials defines the metamaterials as 'an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties'. If certain electromagnetic properties of materials (usually measured in terms of its permittivity and permeability) are needed for an application in a certain range of wavelengths of electromagnetic radiation, this material should appear homogeneous at the scale of wavelength. This means that the size of its molecules, as well as the distance between molecules, should be much smaller than the wavelength. If the application is for instance in the microwave frequency range, where the wavelength is of the order of centimeters, the size of a single 'molecule' can be of the order of millimeter, and it can be engineered and manufactured from ordinary material consisting of usual, negligibly small at this wavelength, scale molecules. This is one of the origins of the term 'left handed materials or metamaterials'. It is an artificial material with unusual properties made of usual materials with usual properties [4,5,6]. Most recently Cui et al. defined a metamaterial as a macroscopic composite of periodic or non periodic structure, whose function is due to both the cellular architecture and chemical composition [7].

LHMs or metamaterials can be distinguished [8] from other structured photonic materials, i.e., photonic crystals or photonic band gap materials [9-17]. In the photonic crystals or photonic band-gap materials the stop bands or band–gaps arise as a result of multiple Bragg scattering in a periodic array of dielectric scatters. In fact, the periodicity of the structure here is of the order of the wavelength, and hence homogenization in this sense cannot be carried out. In left handed materials the periodicity is by comparison far less important and all the properties mainly depend on the single scattered resonances. As a result NIMs and photonic crystals with negative refraction often show very different behavior particularly regarding image formation. In a nutshell the idea is to briefly discuss recent advances which have brought LHMs and their fascinating properties from theoretical origins into the domain of experimental physics and device engineering.

Overview of the left handed material

The overview will not be complete without discussing some early relevant work on effective media. It was Bose [18] in 1898, who used man-made twisted fibers (jute) to rotate the polarization of electromagnetic waves produced by liquid like sugar solution. Horace Lamb [19] in 1904 and Henry Pocklington [20] in 1905 pointed out that mechanical systems, such as certain loaded chains, can have the phase and group velocities in the opposite direction. Lindman [21] in 1914 studied artificially chiral media formed by an ensemble of small wire helices. Arthur Schuster [22] showed that this behavior could also be related in optical systems. In 1948 Winston E. Kock [23] of the Bell Telephone Laboratories introduced the concept of the artificial dielectric in order to realize light weight lenses at microwave frequencies. The inverted Doppler Effect, Cerenkov Effect in isotropic medium and negative refractive index were examined as early as 1959 by Pafomov [24]. These hypothetical media were systematically studied by Victor Veselago [25] in the 1968. Due to lack of experimental verification, research in LHMs was dormant for about three decades. In 1996, Pendry et al. [26] discovered the artificial electric plasma using the wire medium whose permittivity is negative. This work was followed by the discovery of artificial magnetic plasma having negative permeability in 1999 [27]. In 2000 Smith, Schultz and co-workers [2] demonstrated that it is possible to fabricate an artificial material with electrodynamic characteristics that can be described by a negative index of refraction i.e. Negative Index Material or Left Handed Materials [28]. Shelby et al. [29] constructed a prism shaped section from such a metamaterial and their sample consists of square copper split ring resonators and copper wire strips on fiber glass circuit board material. The rings and wires are on opposite sides of the boards, and the boards have been cut and assembled into an interlocking lattice. They have been able to observe the negative refraction, as illustrated in Figures 1A and 1B.

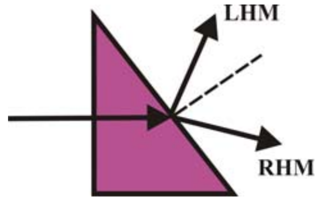

Figure 1A: Negative vs Positive refraction [30].

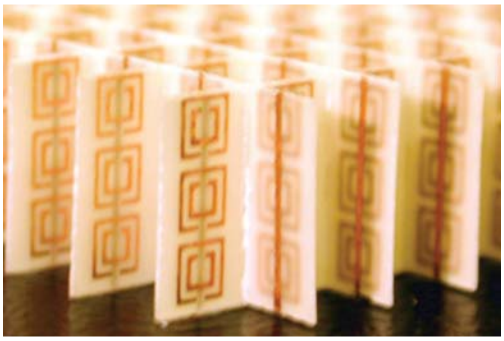

Figure 1B: Photograph of the left handed metamaterial sample [29].

Negative refraction by a slab of materials bends a ray of light back toward the axis and thus has a focusing effect at the point where the refracted rays meet the axis (Fig. 2A) [31]. In 2000 when Sir Pendry [32] at Imperial College London (UK) published a remarkable paper analyzing that a negative index lens exhibits an entirely new type of focusing phenomenon, bringing together not just the propagating rays but also the finer details of the electromagnetic near fields that are evanescent and do not propagate (Fig. 2B) [31].

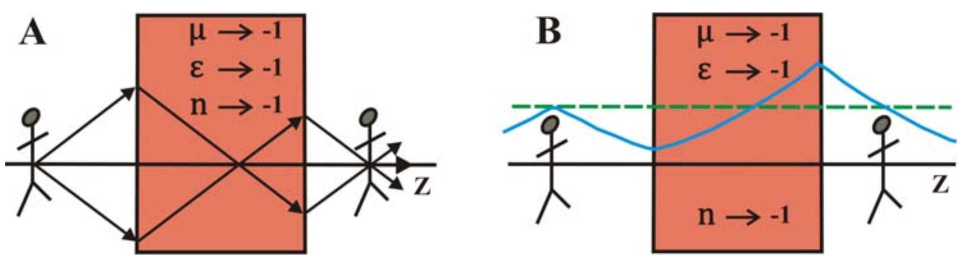

Figure 2: Perfect lensing in action: (A) the far field and (B) the near field using a slab of left handed material.

For a planar slab of negative index material under idealized conditions an image plane that contains a perfect copy of an object placed on the opposite side of the slab exists. Although realizable materials will never meet the idealized conditions, nevertheless, these new negative index concepts show that wavelengths imaging is achievable. In 2004 Smith et al. [33] realized the gradient reflection index medium to bend electromagnetic waves. In the following year Pendry and his co-workers [34] proposed optical transformation to make invisible cloaks to control the propagation of electromagnetic waves using left handed materials in the microwave regime. Since then the field has become a hot topic of scientific research and debate. A large number of publications are coming every year and it is not possible to cite all of them. We concentrate only on the pioneer developments which had a great impact on the physics, optics and engineering communities.

Physics of the left handed material [35]

In a slab of conventional material, with an ordinary refractive index- a Right Handed Material- the wave front is transmitted away from the source. In a LHM the wave front travels towards the source. Although the magnitude and the direction of the flow of energy essentially remains the same in both materials, the impedance of these two materials matches. Hence the sign of the intrinsic impedance is still positive in a LHM [36,37]. Light incident on a LHM will bend to the same side as the incident beam and for Snell's law to hold, the refraction angle should be negative. In a passive metamaterial medium this determines a negative real and imaginary part of the refractive index [1].

The LHMs display a different property of matter compared to ordinary matter in terms of the way in which electromagnetic waves propagate or travel through them. In naturally occurring material, the energy flows in the same direction as the phase motion of the wave. Energy flow of an electromagnetic wave can be represented by a vector, known as Poynting vector **P** and the phase front by another vector **k**. At any given point **P•k** > 0, where the dot indicates the scalar product of two vectors. LHMs do not produce positive dot products between the power (i.e. energy flow /sec) and phase vectors. Rather they have **P•k** < 0, in seeming contradiction to the normal behavior. But according to Maxwell's equations, the dot product, which is the multiplication of the two vectors, must always be positive. Since **P = E x H** where **E** is the electric field and **H** is the magnetic field, in normal matter **E**, **H**, and **k** form a right-handed system (Fig. 3A). If **k** points oppositely to **P**, the **E**, **H**, and **k** must form a left-handed system (Fig. 3B). And this is why the origin of the term left handed materials occurred.

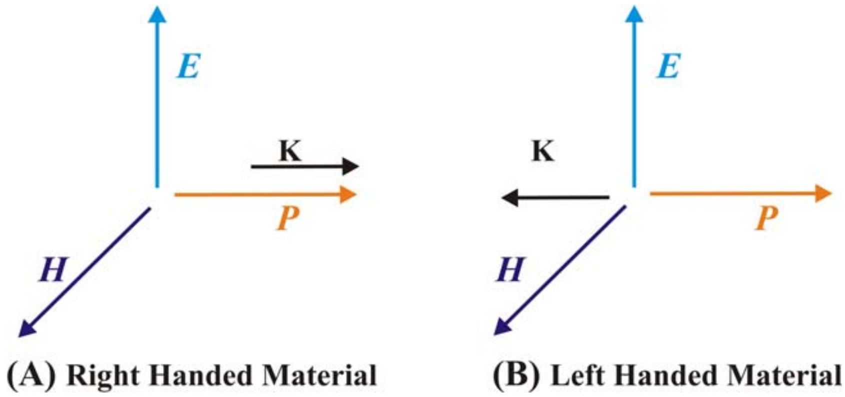

Figure 3: Orientation of the electric E, magnetic H, power P, and phase K vectors.

The response of a material to external field is determined only by the parameters ε and μ, an electromagnetic parameter space can be used to classify materials based on these two values [38], as illustrated in Figure 4. The first quadrant (ε>0 and μ>0) represents right handed materials which support the forward propagating wave. Further, Maxwell equation states that electric field E, the magnetic field H and the wave vector K form a right handed system. While in the third quadrant (ε<0 and μ<0) represents the backward propagating waves as proposed by Veselago [25] in the left handed material. Whereas in the second (ε<0 and μ>0) and fourth (ε>0 and μ<0) quadrant representing electric and magnetic plasma respectively supports propagation of evanescent waves.

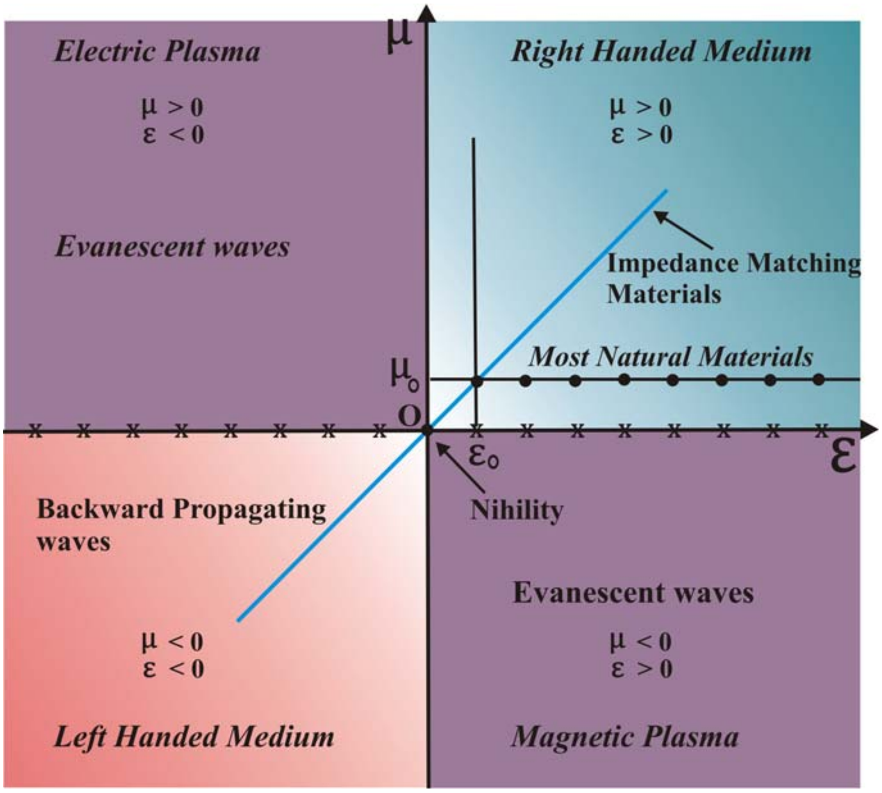

Figure 4: All possible properties of isotropic materials in ε - μ domain.

Applications

The idea of a LHMs since its experimental verification finds several applications [39-46] such as in the near field technologies, photonic crystals and plasmonics combined with innovation on high dielectric antennas, wireless systems and photonic circuits open the prospect of integrated circuits, sensors (chemical, biological and individual molecule), medical scanners, display and images which have the potential to outperform conventional technology and create many commercial opportunities. Some of the limitations that metallic lenses have, such as imperfect matching with the free space, can be overcome by these materials. The backward wave propagation in LHM with opposite direction of the group and phase velocities provides new applications including delay time filter and phase shifters from microwave to optical frequencies.

The fabrication of LHMs with magnetic response at THz and optical frequencies can be used for such applications as compact cavities, tunable mirrors, security imaging, bio-molecular finger printing and remote sensing. Further, unlike electrical networks and filters which primarily control voltage and current quantities in the frequency domain, transmission line metamaterials should also control the electromagnetic field distribution in the spatial domain (e.g. for deranging lenses, cloaks etc.).

Challenges and targets

To the best of our knowledge, up to date, these materials have only been demonstrated at frequencies below the visible spectrum. In addition NIM are fabricated from opaque materials, and are usually made of non-magnetic constituents. However, as an illustration, if these materials could be demonstrated at visible frequencies, and a flashlight is shined on a NIM slab, the material should focus the light at a point on the other side. This is not possible with a sheet of ordinary opaque material [21,29,47]. Metamaterials structures include not only dielectrics but also metals. Their extension to the optical domain also participates to the strong revival of plasmonics with the help of truly subwavelength photonics.

If the desired application is at very high frequencies, such as in the visible range, the size of these artificial molecules should be of the order of tens of nanometers or even smaller [48], placing nanoscale meta atoms into an uniform 3D arrangement of the desired topology [49,50], along with reduction of the size of the structure, pushing the frequency range towards optical frequencies, widening the frequency band and reducing the loss and fabrication cost. The design and characterization of new types of left handed materials suitable for imaging applications in the Microwave and Infrared domains, and the development of truly three dimensional metamaterials can be thought of as a purely technological challenge for engineers and scientists and advance research should be focussed to achieve this target with accuracy and in a wider frequency spectrum.

Conclusion

The present study provides a technical overview of the rapidly emerging LHM technology. The article discusses the theory and principles of LHM and practical applications of possible devices. These artificial structures with electromagnetic response are tailored to a particular objective, such as the magnetic mirror [51] or an electromagnetic cloaking device [34]. Their development may well enclose the area of LHM. Emphasis is placed on key developing technologies that will enable to replace several conventional devices. The quest for optical NIM and the superlens has already initiated a whole new field of left handed materials. The technology has potential applications, especially in optics, medicine, and telecommunication. This article briefly presents all experimental and theoretical aspects of rapidly developing fields ranging from basic science to applications and products.

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