Bending Back Light

The Science of Negative Index Materials

Costas M. Soukoulis

Using the right type of man-made materials, light can be made to bend, or refract, backwards. After years of painstakingly developing and testing the necessary materials, scientists are notw looking to translate negative refraction into positive applications such as sub-wavelength, high resolution imaging across the electromagnetic spectrum.

When light enters specially engineered materials called metamaterials, it takes a sharp turn to the left— a negative turn—bending in the opposite direction of light going through natural materials. Scientists frequently refer to these unique synthetic materials as left-handed materials (LHMs) or negative index materials (NIMs).

Since the first demonstration of an artificial negative refractive index material in 2000, metamaterials have drawn considerable attention from scientists because of their broad range of potential applications. For example, they may one day lead to the development of a flat superlens that operates in the visible spectrum, which would offer superior resolution over conventional technology and provide images much smaller than one wavelength of light.

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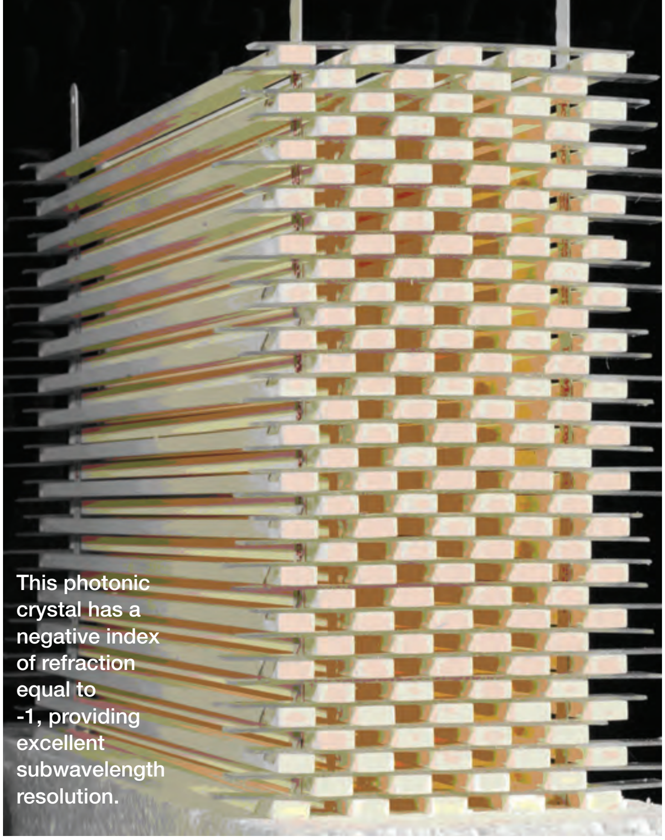
Costas Soukoulis examines one of the photonic crystals that was constructed to observe negative refraction and superlensing in the microwave region of the electromagnetic spectrum.

They also have many promising applications for defense and security. Because NIMs can match the impedance, or the properties of free space (air without matter), they result in zero reflectance for all the incident angles. Thus, coating a stealth plane with a metamaterial could enable it to evade detection. Several research groups have used the metamaterial approach to fabricate and demonstrate an NIM at microwave frequencies.

NIMs were first conceptualized nearly 40 years ago. Victor Veselago speculated that materials could exist for which both $\epsilon < 0$ and $\mu < 0$. The idea was met with some skepticism, however. The realization of such NIMs seemed improbable due to the inherent difficulty associated with finding conventional materials that had overlapping electric and magnetic resonances. The fundamental processes that give rise to electric and magnetic responses in materials naturally occur over different frequency ranges, making their overlap unlikely.

However, by making use of artificially structured metamaterials, in which macroscopic inclusions replace the atoms and molecules of a conventional material, scientists can circumvent this limitation. Metamaterials can be designed to exhibit both electric and magnetic resonances that can be separately tuned to occur in frequency bands from the low RF to the visible.

Subsequent theoretical and experimental confirmations indicated that negative refraction was indeed possible. In fact, the development of NIMs at microwave frequencies has progressed to the point where scientists and engineers are now vigorously pursuing microwave applications. In contrast, research on NIMs that operate at higher frequencies is at an



This photonic crystal has a negative index of refraction equal to -1, providing excellent subwavelength resolution.

A negative index lens can not only focus the propagating rays, but also the finer details of the EM near fields that are evanescent and do not propagate.

early stage, with issues of material fabrication and characterization still being sorted out.

Recent History of LHMs

In 1996 and 1998, Sir John Pendry suggested that a periodic structure composed of thin infinite wires arranged in a simple cubic lattice mimics the response of a metal to EM radiation. In a typical example, the wires might be a few tens of microns in diameter and spaced several millimeters apart, giving a plasma frequency in GHz. In 1999, Pendry proposed an artificial material consisting of the so-called split ring resonators (SRRs), which exhibit a band of negative μ values in spite of being made of non-magnetic materials.

In 2000, Smith and colleagues demonstrated the first NIM, which consisted of an array of SRRs and thin wires in alternating layers. That same year, Pendry introduced the idea of the perfect flat lens for a metamaterial that possesses an index of refraction $n = -1$. He calculated that a negative index medium could be used to make a perfect lens that would focus an image with resolutions that were not restricted by the wavelength of light.

A negative index lens can not only focus the propagating rays, but also the finer details of the EM near fields that are evanescent and do not propagate. Although many researchers initially refuted the plausibility of "perfect lenses," Pendry and Smith addressed their concerns by clarifying the concept and its limitations using numerical simulations and experiments.

In 2001, Smith and his colleagues demonstrated experimentally that a wedge-shaped metamaterial gives negative refraction. Further experiments and simulations have been performed by other groups (at Boeing, MIT, Northeastern, Ames and Bilkent), confirming the existence of negative refraction.

In 2002, Smith and I, along with our collaborators, developed a retrieval procedure to obtain the effective ϵ and μ of metamaterials by introducing a homogeneous effective medium (HEM). We found that the recovered frequency-dependent ϵ and μ is entirely consistent with analytic expressions predicted by effective medium arguments. Of particular relevance, we discovered that a wire medium exhibits a frequency region in which the real part of ϵ is negative, and the SRRs produce a frequency region in which the real part of μ is negative.

In the combination structure, at frequencies where both the recovered real parts of ϵ and μ are simultaneously negative, the real part of the index of refraction is also found to be unambiguously negative. This technique is readily applicable to the experimental characterization of metamaterial samples whenever the scattering parameters are known.

In 2003, I collaborated with Foteinopoulou and Economou to perform computer simulations on a properly designed negative index photonic crystal. This work showed that causality and the speed of light are not violated by negative refraction. Also in 2003, researchers from Ames Laboratory, Bilkent University in Turkey and the Institute of Electronic Structure and Lasers (IESL) at FORTH laboratory in Crete, Greece, demonstrated negative refraction in a photonic crystal in the microwave regime and a sub-wavelength resolution of $\lambda/3$. The following year, these groups fabricated an NIM with the highest NIM transmission peak of only -0.3dB/cm at 4 GHz.

Ames and Crete researchers also established that SRRs have a resonant electric response in addition to their magnetic response. The electric response is cut wire-like and can be demonstrated by closing the gaps of the SRRs, thereby destroying the magnetic response. In addition, the studies of the electric response of NIMs introduced a very simple criterion to identify if an experimental transmission peak is left- or right-handed. This criterion was used experimentally by Bilkent investigators and other groups, and it confirmed the Ames and Crete predictions.

Ames, Crete and Bilkent scientists did further theoretical and experimental work in 2004 to study the transmission properties of a lattice of SRRs for different EM field polarizations. Not only could the external magnetic field couple to the magnetic SRR resonance, it could also do so to the external electric field, E. This happens when the incident E is parallel to the gap-bearing sides of the SRR and is manifested by a dip in the transmission spectrum. The origin of the transmission dip is a resonant ϵ, arising from the non-zero average polarization introduced by the resonant circular currents excited by E.

In 2005, researchers from Ames, Crete, as well as Smith's group, introduced a periodic effective medium theory, which is a significant improvement over the HEM approach. This theory explains and resolves the problems associated with HEM, such as the negative product of Imϵ Imμ, all of which originate from strong resonances. The wavelength inside the NIM is, in some cases, comparable to the periodicity, and thus a homogeneous effective medium fails to describe these cases accurately.

The negative promise of photonic crystals

The use of photonic crystals (PCs) represents a different approach to achieving a negative index of refraction. The PCs can be made only from dielectrics and can, in principle, result in fewer losses than the metallic NIMs, especially at high frequencies, and even at the optical range. The success of constructing metamaterials for microwave frequencies has been accompanied by a desire to create a technology-altering superlens. This has driven physicists' interest in developing a negative refractive index material for visible light.

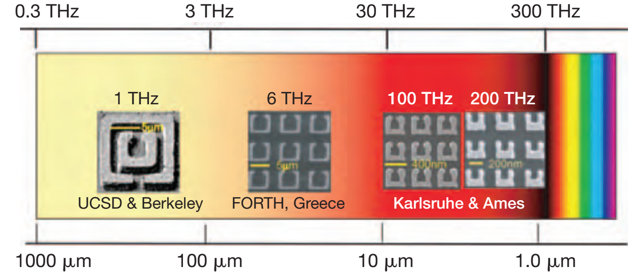
Working toward that goal, the Soukoulis and Ozbay research teams have been investigating photonic bandgap crystals—man-made materials that can transmit wavelengths of light up and down the electromagnetic spectrum and therefore have alternating regions of different refractive indices. One must be very careful in distinguishing the LH behavior from Bragg scattering effects, which might also give negative refraction.

I and my colleagues at Ames Laboratory and the FORTH laboratory in have calculated and developed the first computer simulations that show negative refraction in a two-dimensional, left-handed PC.

The PC metamaterial that Ozbay and I designed and tested consists of a square array of alumina rods. We aimed a beam of microwaves at the rods to demonstrate negative refraction and superlensing in the microwave region of the electromagnetic spectrum. In addition to showing that the incoming beam is negatively refracted, the simulations revealed another significant piece of information: Refraction does not occur immediately. The incoming electromagnetic wave is temporarily delayed and trapped at the boundary between the air and the negative refractive index photonic crystal before it eventually moves in a negative direction.

We maintain that the outer rays in the delayed beam give the impression of traveling faster than the speed of light because of

[The progress of scaling metamaterials]



Advances in scaling metamaterials with artificial magnetic response for high-frequency structures has been rapid. The 1, 6 and 100 THz models were fabricated in 2004, and the 200 THz in 2005.

this trapping mechanism. These calculations and simulations are an important confirmation that the speed of light is not violated by negative refraction. While most of the experiments in PCs were performed at microwave frequencies, the same structures scaled at optical frequencies must experience much less loss than the NIMs, which are based on metallic elements. Nevertheless, to date, very few researchers have made experimental demonstrations of negative refraction in PCs in the near-IR frequency region.

Moving toward optical frequencies

Researchers are just beginning to explore applications for negative refraction at microwave frequencies—and there are many. But even as this work gets underway, some physicists are focusing their attention on visible light. I and my collaborators at the University of Karlsruhe in Germany are leaders in this effort.

The NIM community succeeded in fabricating and demonstrating the magnetic response of SRR structures operating at 2 THz, 6 THz (Ames and Crete collaboration) and 100 and 200 THz (Ames and colleagues at the University of Karlsruhe). In most of the THz experiments, only one layer of SRRs were fabricated on a substrate and the transmission T was measured only for propagation perpendicular to the plane of the SRRs, exploiting the coupling of the electric field to the magnetic resonance of the SRR via asymmetry. With this approach, it is not possible to drive the magnetic permeability negative.

Metamaterials structures such as those shown in these split-ring resonators (SRRs) are amenable to manufacture by common planar lithography. The structure to the left has a magnetic response perpendicular to the plane, which is difficult to detect by direct incidence measurements. Those shown in the center and to the right make use of multilayer processing and have been used to fabricate metamaterials that give both negative ϵ and μ, as well as n for perpendicular propagation.

Lei Zhang adjusts a photonic crystal for angle and transmission measurements.

A Look at Negative Index Materials—the Experiments

Now that scientists have simulated the expected behavior of negative index materials, researchers are constructing metamaterials and photonic crystals to observe negative refraction. Lei Zhang, an Ames Laboratory graduate assistant, carries out many of these experiments under the supervision of Gary Tuttle, an Ames associate working at Iowa State University's Microelectronics Research Center.

Zhang has conducted a series of experiments with metallic structures that were built to conform to the author's simulations. Her work supports his theoretical calculations for the microwave region of the electromagnetic spectrum. The metamaterials exhibit properties associated with negative refraction— negative electric permittivity, negative permeability and negative index of refraction—the combination of which can exist only in synthetic devices.

Zhang's experiments with photonic crystals confirm what the theorists predicted: Negative refraction and superlensing can be observed in photonic crystals in the microwave region. The next step will be to adapt the technology to other regions of the electromagnetic spectrum, with the ultimate goal of reaching the visual region. However, achieving that feat will require researchers to fabricate the photonic structures at extremely small length scales. Zhang considers that an achievable but somewhat distant prospect. For now, she would be thrilled to create a successful negative index material closer to the infrared region of the electromagnetic spectrum.

Recent theoretical work towards achieving a magnetic response from metallic elements has shown that pairs of finite-length (short) wires would not only be able to replace the SRRs, but could also lead to a negative refractive index directly, without the need for additional metallic wires.

Also, no negative *n* has yet been observed at the THz region. One reason is that it is very difficult to measure both the transmission, *T*, and reflection, *R*, along the direction parallel to the plane of the SRRs with the existing topology of SRRs and continuous wires. Thus, there is a need for improved and simplified designs that can be easily fabricated and experimentally characterized, especially in the infrared and optical regions of the spectrum. Such a design is offered by design extensions of pairs of finite-length wires.

Recent theoretical work towards achieving a magnetic response from metallic elements has shown that pairs of finite-length (short) wires would not only be able to replace the SRRs, but could also lead to a negative refractive index directly, without the need for additional metallic wires. Recent experiments have shown evidence of negative *n* at THz frequencies, using finite wires.

The observed negative *n*, though, was most probably due to the significant imaginary parts of ϵ and μ, which lead also to a dominant imaginary part of *n* and, thus, to a rapid attenuation of electromagnetic (EM) waves, which makes such types of metamaterials inapplicable.

Very recent work at Ames introduced new designs of short-wire-pair-based metallic structures to obtain a negative index of refraction in the microwave and in the THz regime. The basic structures of single unit cells of these NIMs were built from different-shaped wires and are shown in the left column of the figure on the facing page.

A pair of short parallel "wires," which provide both negative magnetic and negative electric response, replace the conventional SRR. The short wire pair consists of a pair of metal patches separated by a dielectric spacer of thickness t_s. For an electromagnetic wave incident with a wave vector and field polarization, the short wire pair will acquire not only a magnetic resonance resulting in a negative μ but also an electric resonance with a negative ϵ simultaneously.

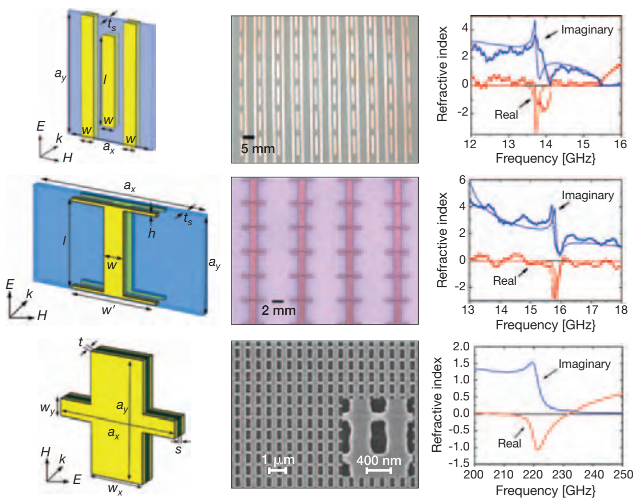
The magnetic resonance originates from the anti-parallel current in the wire pair with opposite sign charge accumulating at the corresponding ends; the electric resonance is due to the excitation of parallel current in the wire pair with the same sign charge accumulating at the ends of both wires. In the transmission measurements, the EM waves were incident normal to the sample surface. This set-up is much simpler than that for conventional SRRs and wires, where the incident EM waves have to propagate parallel to the sample surface. With the conventional orientation of the SRRs, it is almost impossible to do these types of measurements in the THz region, since only single-layer samples are usually fabricated. Using the transmission and reflection results from a single layer, we can extract the effective refractive index that would result if a periodic multi-layer sample were built using the single-layer structure as a building block.

These results show clearly the viability of using short wire pairs to build NIMs. Also, wire-pair arrangements with significantly different geometries may lead to negative-index materials. The relative ease of fabricating wire-pair structures may hasten the development of NIMs working at optical wavelengths. In recent unpublished work, Karlsruhe and Ames researchers have fabricated a negative index metamaterial at 1.4 µm, with Re(n)=−1.0 and Im(n)=0.30. This is the highest frequency negative n material with the smallest imaginary part.

A positive future

Research efforts over the past several years, including ours, have been instrumental in proving that negative index metamaterials can be designed, fabricated and characterized. Negative refraction has now been demonstrated many times in steady state experiments. Researchers have also shown image resolution beyond the diffraction limit via a negative index slab. Thus, the work of several groups in the last four years has placed negative refractive index on solid ground. We are now looking to further develop the technology and methods that will translate these novel materials into useful applications.

[Fabricated Wire-Pair Structures.]



(Left) Schematic representation of one unit cell of three wire-pair structures. (Center) Photograph of fabricated wire-pair samples. (Right) The measured (thick line) and calculated (thin line) real and imaginary parts of index of refraction.

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