Negative Refractive Index Metamaterials- Introduction and Methods to produce Achiral and Chiral Metamaterials

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Abstract

J.K. Rowling's fantasy series book "Harry Potter" talks about an invisibility cloak. It's not just the author's imagination; it can be practically realized in the real world. Anyone who learns about this magical world in real life will undoubtedly want to read about it. The present article focuses on such materials that don't exist in nature and need to be prepared artificially, termed negative refractive index metamaterials. Negative refractive index metamaterials (NIMs) theoretically predicted by Veselago in 1968 came into practical realization by J.B. Pendry. NIMs essential requirements in the material are to have simultaneous negative permittivity(ε) and negative permeability (μ). Negative permittivity occurs in many natural materials, and it is easy to achieve. On the other hand, it is a tedious task to achieve negative permeability, as natural materials do not possess this property, and such materials need to be fabricated artificially. Hence, NIMs are completely artificially generated materials. An invisibility cloak is just one application of NIMs. It has many more applications. In this paper, we will discuss an alternate chiral path to achieve NIMs with no requirement of negative permittivity and negative permeability. These chiral NIM materials are capable of showing optical rotation and circular dichroism along with the negative refractive index.

Keywords

Permittivity, Permeability, Negative refractive index metamaterials (NIMs), Chirality.

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Introduction

When electromagnetic radiation travels from one medium to another, it bends rays due to the variation in optical densities. In different media, the speed of light is different, and this difference is measured in terms of refractive index (n), a dimensionless quantity referred to as Eq. (1). All naturally occurring materials have a positive refractive index, and thus they bend light in one particular direction and thus follow Snell's law.

$$n = \frac{n_2}{n_1} \tag{1}$$

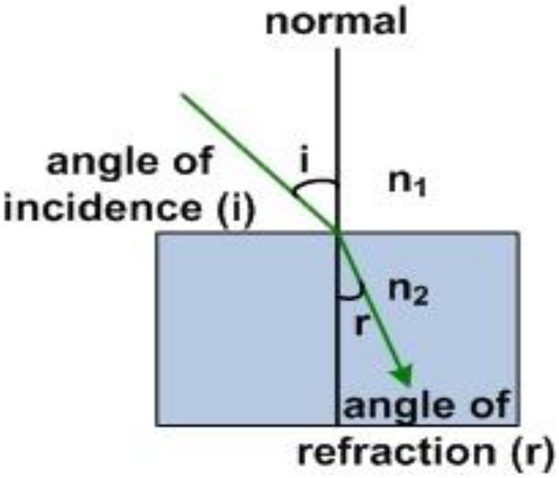

Figure 1: Ray traveling through two different media, showing refraction

Snell's law shows how incident angle (i) and refracted angle (r) relate to each other, as shown in Figure 1 The refractive index of the material can be calculated with the formula in terms of permittivity (ε) and permeability (μ), refer to Eq. (2)

$$n = \pm\sqrt{\varepsilon\mu} \tag{2}$$

Permittivity (ε) and permeability (μ) of the material are important parameters as they directly affect the refractive index of the material and decide how the electric and magnetic fields will respond when electromagnetic radiation falls on it. As a result, materials are classified on the basis of ε and μ values. In nature, the permittivity (ε) of most materials is positive, but for some materials, it is negative as well, but permeability (μ) is always positive and has to be achieved negatively artificially.[1]

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The materials that have positive permittivity (ε) and positive permeability (μ) are known as double-positive materials (DPM), and follow Snell's law. In addition, DPMs show normal positive refraction. The materials with negative permittivity (ε) are epsilon negative materials (εNG), and materials with negative permeability are Mu negative materials (μNG).[2]. The question arises whether double negative materials (DNMs) with both negative ε and μ exist in nature? If **yes**, how are they different from DPMs? If not, how can such materials be fabricated artificially?

The term "metamaterial" is a Greek word in which "meta" means something that is beyond the real'. Theoretically, DNMs, also known as negative index metamaterials (NIMs), were first anticipated by V.G. Veselago in 1968. Veselago et al. proposed that if such materials exist, their electrodynamics will be completely different from DPMs.[3] With mathematical calculations, Pafomov et al. showed that if ε and μ both negative, then the phase velocity and group velocity will be antiparallel to each other,[4] directly affecting Snell's law, as shown in Figure 2. The bifurcation of materials based on ε and μ values is shown in Table 1.

ϵ	μ	Material
+	+	Double positive materials (DPM)
-	+	Epsilon negative materials (εNG)
+	-	Mu negative materials (μNG)
-	-	Negative refractive index metamaterial (NIMs)

Table 1: Materials classification chart having different ε and μ values

According to Veselago et al., negative permeability and permittivity do not result in a mathematical conflict with the expression for the refractive index (Eq. 2). The electrodynamics of materials when both microscopic parameters (ε, μ) are negative, is completely different from the materials that have both microscopic parameters positive (Refer to equations 3 and 4).He proved the behaviour of an electromagnetic wave when it travels through a medium that has permittivity (ε) and permeability (μ) simultaneously negative, through Maxwell's curl equations, Eq. (3) and Eq. (4).

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \tag{3}$$

$$\nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} \tag{4}$$

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s lies in the direction of phase velocity and a Poynting vector lies in the direction of group velocity. The phase velocity and group velocity are antiparallel when permittivity (ε) and permeability (μ) are simultaneously negative.[5] DNM (-ε,-μ) will refract light in the mirror reflection direction as in case of DPM (+ε,+μ). As a result, the material's permittivity and permeability influence its refractive index, refer Eq. (2). When ε and μ are positive, n is the positive quantity, and when they are negative, n is the negative quantity.[5]

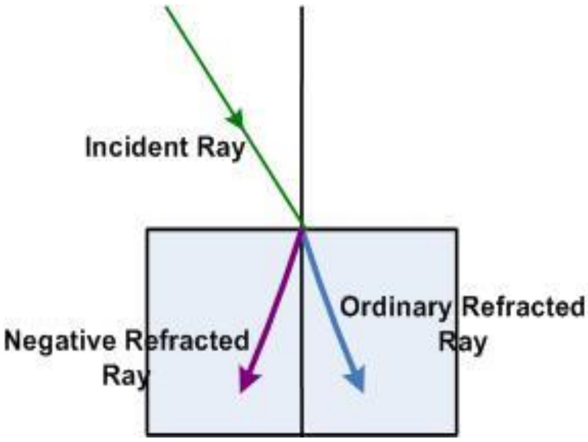

Figure 2: A ray diagram represents two different bending directions of light. Blue refracted ray is for refraction through DPM and purple is for NIM.

Major Advancements

Although the prediction of NIMs was made by Veselago in 1968, no such materials were practically realized until three decades. As achieving negative permeability was really difficult.[1]Theproperties of NIMs are independent of the material from which they are made, but their properties are solely dependent on their structures,[6] which must be very small in comparison to the incident wavelengths.[2] By designing microstructures appropriately, specific features (-ε, -μ) can be achieved for a certain frequency range. In the initial years, microstructures were designed only to work in the microwave region (GHz), but now microstructures are prepared that can work in the radio frequency region (MHz), far IR range (1 THz), mid IR range (100THz), and even the near IR range (200THz).

In 1998, Pendry et al. prepared thin structures of metallic wires that were able to produce negative ε[7] and in 1999 proposed different cylindrical structures that were able to produce different low μ values and gave the theoretical idea of split ring resonators that can generate negative μ when certain frequency range electromagnetic radiation falls on them.[8]

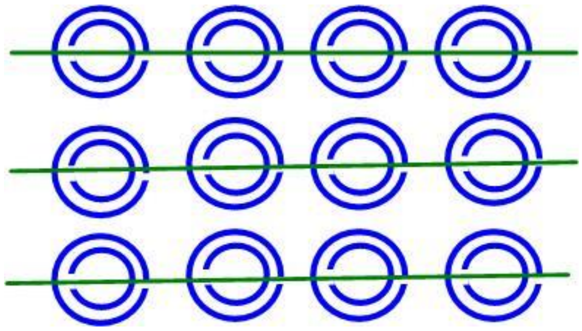

Figure 3: An array of Split ring resonators (SRRs) and continuous wires. SRR has splits in opposite ends and produces negative permeability and wires produce negative permittivity in negative refractive index metamaterial.[14]

Re-drawn from "Aydin, K., Guven, K., Kafesaki, M., Zhang, L., Soukoulis, C.M. & Ozbay, E. (2004). Experimental observation of true left-handed transmission peaks in metamaterials. *Opt. Lett., 29*(22), 2623–2625."

In 2000, Smith et al. practically realized such a metamaterial. It consists of an array of split ring resonators (a pair of concentric loops) (Figure 3) on a substrate with splits at opposite ends and arrays of continuous thin wires. Proper combination of SRR and periodically arranged continuous thin wires make μ and ε negative for a certain frequency range to form NIMs.[9] SRRs act as an LC oscillator. They can be circular, square, or U-shaped. Such artificial structures work on resonance formed by repeated elements, and their properties are completely different from those of individual components. These engineered structures have the potential to function as negative refractive index metamaterials for a specific frequency range.[10]The working of continuous thin wires depends upon plasma model with a frequency limit below which ϵ is negative.

Before going deeper into the negative refractive index metamaterial world, let's understand the workings of the LC oscillator. Electromagnetic oscillations in an LC circuit take place between the capacitor's electric field and the inductor's magnetic field and charge where, current and potential difference vary sinusoidally. The schematic of an LC oscillator is shown in Figure 4 Electric field energy stored in the capacitor is $E_E = \frac{q^2}{2C}$, where C is the capacitance and q is the

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electric charge in the capacitor. The magnetic field energy stored in the inductor is $E_B=\frac{Li^2}{2}$, where L is the inductance and i is the current through the inductor. At the initial stage, charge stored in the capacitor is maximum (electric field E_E is maximum) and energy stored in the inductor is zero (magnetic field E_B energy is minimum) and no current is present in the circuit. When the LC circuit oscillates, energy starts alternating from electric field energy to magnetic field energy and vice versa by following the law of conservation.

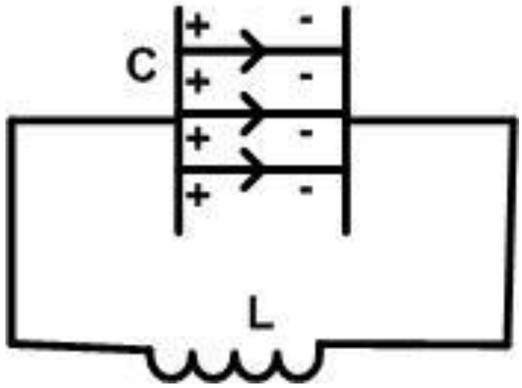

Figure 4: The schematic of an LC oscillator. Electromagnetic oscillations in LC circuit take place between capacitor's electric field and inductor's magnetic field

Negative refractive index metamaterials are made up of repeated combinations of inductor and capacitor elements, forming LC oscillators. When electromagnetic radiation falls on these LC oscillators, they resonate at a maximum frequency, termed the resonant frequency. At the resonant frequency, Eq. (5), the system oscillates with maximum amplitude, and this condition is termed resonance. Electrical resonance occurs when the inductive reactance and the capacitive reactance are equal in magnitude in an electrical circuit.

$$\omega = \frac{1}{\sqrt{LC}} \tag{5}$$

ω is angular frequency of oscillations, L is inductance and C is the capacitance. At the resonance circuit, impedance is minimum and current is maximum.[11]

How does the combination of SRR and wires generate negative refractive index?

Electromagnetic radiation consists of electric and magnetic components vibrating in perpendicular planes. When electromagnetic radiation falls on the material, it is controlled by two microscopic parameters: first, the permittivity (ε) and second, the permeability (μ) of the

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material. Permittivity (ε) describes the response of a material to the electric component of an electromagnetic wave, and permeability (μ) describes the response of a material to the magnetic component of an electromagnetic wave.[12] Both are crucial microscopic frequency dependent parameters (Refer Eq. (7) and Eq. (9) that affect the interaction of electromagnetic radiation with the material. These microscopic parameters depend up on the refractive index (n) of the material, which is referred in Eq. (2). It is significant to know refractive index specific value, as it signifies in which direction the incident light will bend. Artificially engineered metamaterials' electrodynamics is completely different from initial materials. Let's review how unique metamaterial shape and geometry manipulate electromagnetic waves to provide them with desired properties.

a) *Magnetic response:*

The split ring resonator (SRR) consists of two concentric rings with a split on each ring. It is planer and fabricated by lithographic technique to give a desired response to the magnetic component of the electromagnetic field. Two rings of a split ring resonator are near to one another and acts as an LC oscillator. When electromagnetic radiation falls on the SRR, a magnetic field that is polarized perpendicular to the SRR plane induces circulating current due to Faraday's law. These circulating currents induce charge across the split gap of SRR and energy is stored as capacitance as shown in Figure 5. The current path of SRR acts as an inductor. Hence, the SRR resonator acts as a simple LC resonator, oscillating with a resonance frequency refer to Eq. (6).

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

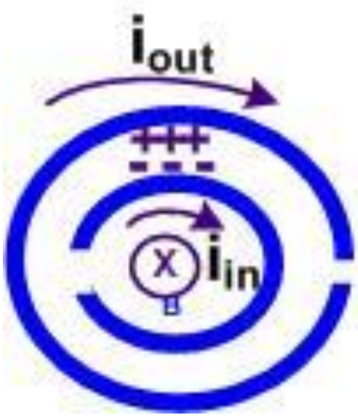

Figure 5: Split ring resonator acting as LC resonator. Circulating currents induce charge across the split gap of SRR and energy is stored as a capacitance and current path of SRR acts as an inductor.[8]

Re-drawn from "Pendry, J. B., Holden, A. J., Robbins, D. J. & Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on Microwave Theory and Techniques*, *47*(11), 2075–2084."

The current in the rings produces magnetic field lines. Current flows through SRR, which can either strengthen or weaken the incident magnetic field. A split ring resonator behaving as an LC circuit resonates with a resonance frequency (ω_0). When magnetic field is incident on the resonator effective permeability (μ_{eff}) exists in the medium and its value can be varied by making the constituting unit resonate. Refer to Eq. (7).

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\Gamma} \qquad (7)$$

Where effective permeability (μ_{eff}) depends upon incident frequency(ω), resonant frequency of the resonator (ω_0), fractional area of the unit cell (F) occupied by the split ring and dissipation factor (Γ).[9]

When frequencies of the external magnetic field(ω) are less than the resonant frequency(ω_0), current in the split ring resonator leads due to force produced by the external varying magnetic field, EM interaction is in phase and it strengthens he incident magnetic field, effective permeability (μ_{eff}) is enhanced and normal (positive) refraction takes place. If the external magnetic field's frequencies (ω) are more than resonant frequency (ω_0), the split ring resonator's current lags and is out of phase, and it weakens the incident magnetic field. Its effective permeability (μ_{eff}) is reduced, and negative refraction occurs.[10]Every split ring resonator has its own tuned frequency. Its negative permeability can be adjusted to the range of frequencies by changing the split ring resonator's dimensions. An array of split ring resonators is arranged to get an efficient magnetic response. Different modifications and changes in metamaterial designs were able to operate over a wide range of frequencies, from the radio frequency range to near IR. [10]

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b) Electric response:

Metallic wires arranged periodically behave as low-density plasma. Analytical theory, computer simulation, and experiments prove that the thin wires are able to achieve negative permittivity for a certain frequency range.[7]

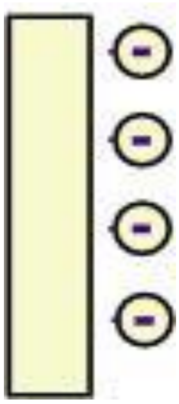

Figure 6: In solids positive charge is fixed in core and free negatively charged electrons are present around it

Plasmons are quasiparticles with an equal concentration of positive and negative charges. In solids, positive charge is fixed in the core and free negatively charged electrons are present around it (Figure 6), balancing the equal concentration of positive and negative charges. As electrons are displaced, a force acts on them and brings them back to equilibrium. As a reaction to this displacement, electrons start to oscillate with (ω_p)plasma frequency.

$$\omega_p{}^2 = \frac{4\pi n e^2}{m} \tag{8}$$

Where plasma frequency (ω_p) is directly proportional to n (carrier density), e (charge of an electron), and inversely proportional to m (effective mass of the electron) refer to Eq.(8). The dielectric function permittivity (ε) is related to the plasma frequency with the following relation. Refer to Eq.(9).

$$\varepsilon = 1 - \frac{\omega_p{}^2}{\omega^2} \tag{9}$$

By making sufficiently thin wires, effective density (n) is reduced and effective mass of electrons is increased. As a mesh of thin wires is spaced a few millimeters apart, these spaced structures reduce the density of electrons but increase the concentration of electrons. Sufficiently thin wires (less radius) increase the inductance of thin wires, and any current that

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is present in wires works against inductance and makes electrons much heavier than they are. Hence, effective mass is increased. [1] Due to the variation in these parameters, the plasma frequency (ω_p) is reduced. Hence, such thin wires, when resonated below their plasma frequency, achieve negative permittivity values. As plasma frequency can be tuned by geometry, different negative values of permittivity (ε) can be obtained for a wide frequency range. Thin silver, gold and aluminum wires can be fabricated on the substrate to get negative permittivity (ε) at optical frequencies.[7,10]Combinations of these structures can provide negative permittivity and negative permeability and are used to make NIMs.[13]Refer Eq. (2)

Details of NIMs reported in Literature

The combination of structures that are capable of generating negative values of permittivity (ε) and permeability (μ) for a certain frequency range, called NIMs, are also termed as left-handed materials (LHM). Padilla et al. have shown different metamaterials working from radio frequency to the near IR range.[10]Pendry et al. (1998)[7]proposed the first feasible structure that exhibited negative permittivity, and Pendry et al. (1999)[8]proposed models that exhibited negative permeability. They proposed magnetic microstructures and named them models A, B, and Swiss roll structure (C) to achieve different imaginary magnetic permeabilities. Each magnetic microstructure discussed was made with a size less than the wavelength of the incident radiation. All structures discussed were made from nonmagnetic conducting sheets of very low density and are extremely light-weighted. Each structure is fabricated in a way that resonates due to internal capacitance and inductance.

In model A, Pendry et al. arranged square arrays of conducting metallic cylinders, and an external magnetic field was applied parallel to the cylinders as in Figure 7. It induces currents that flow around the cylinders and produce a magnetic field. In this model, they achieved a permeability (μ) more than 0 and less than 1. Although the artificially achieved μ value was very low, it was still positive ,hence model A was further modified.

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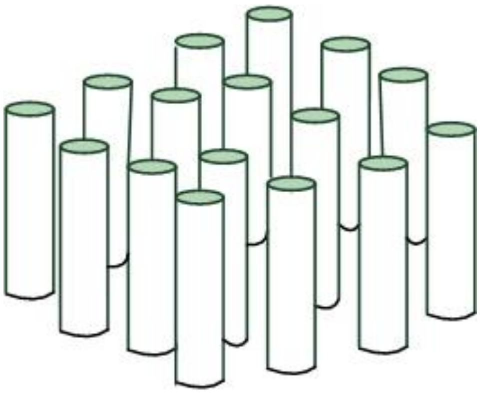

Figure 7: Model proposed to produce negative permeability by Pendry et al.[8] made up of conducting metallic cylinders

Re-drawn from "Pendry, J. B., Holden, A. J., Robbins, D. J. & Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on Microwave Theory and Techniques*, *47*(11), 2075–2084."

Pendry et al. modified model A due to its limited range. In model B, sheets were divided into split ring structures (Figure 8), separated by a certain distance, and a magnetic field was applied parallel to the cylinders. It induces a current in the split rings and makes it a resonant structure due to the capacitance between the sheets and the inductance of the cylinders. When the frequency was kept lower than the resonant frequency, the value of μ was calculated more, but when the frequency was more than the resonant frequency, μ was calculated less than unity. Thus, around the resonant frequency μ was found to be negative.

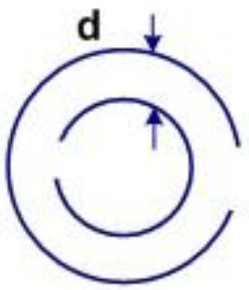

Figure 8: In model B conducting cylinders consists of split ring structures separated by distance d to produce negative permeability. (Top view).[8]

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Re-drawn from "Pendry, J. B., Holden, A. J., Robbins, D. J. & Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on Microwave Theory and Techniques*, *47*(11), 2075–2084."

To achieve more capacitance, Pendry et al. modified model B and named it the Swiss roll structure (model C). In model C, metallic sheet was wound around each cylinder in a coil and each coil spacing was kept d from the earlier sheet (Figure 9). When a magnetic field is applied parallel to the cylinder, it reduces current in coiled sheets, and capacitance between the first and last turns of the coils enables the current flow. In it, the resistivity of the material and capacitive structures variates the µ. These capacitive structures were capable of adjusting magnetic permeabilities.

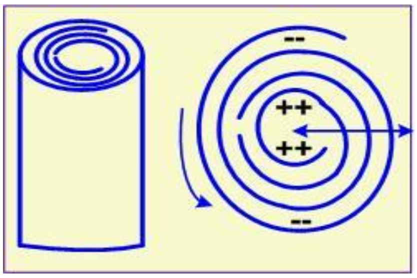

Figure 9: In model C magnetic field is applied parallel to the coil having N turns. Current is reduced in coiled sheets and capacitance is developed between first and last turns of the coil, due to its current flows in the circuit.[8]

Re-drawn from "Pendry, J. B., Holden, A. J., Robbins, D. J. & Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on Microwave Theory and Techniques*, *47*(11), 2075–2084."

All the structures discussed by Pendry worked well in microwave radiation, and by changing the structure's design, different values of magnetic permeability were achieved. All the structures discussed above vary their magnetic properties when the magnetic field is applied along the cylinder axes, but zero magnetic response is observed in other directions. To overcome this insufficiency, Pendry's further plan was to replace split ring cylinders with flat disk split rings to achieve negative permeability.[8]Pendry et al. (1999) work was focused on achieving negative permeability by using cylindrical structures. Smith and Padilla (2000)[9]fabricated the first NIMs by replacing cylindrical structures with split ring resonators.

They combined continuous wires (negative permittivity) with copper split ring resonators (SRRs) (negative permeability) on board to construct negative refractive index metamaterials.

A unit cell consists of a wire paired with SRR. Thin continuous wires provide negative permittivity. SRR are two split rings facing opposite to each other. Smith et al. fabricated a split ring resonator with the following dimensions: the thickness of each ring was kept at d = 0.8mm, with a gap of g = 0.2mm, and the radius of the inner ring was r = 1.5mm, as shown in Figure 10 The gap between the rings acts as a capacitor, and the rings act as an inductor. Due to the presence of splits in rings, SRR can resonate.

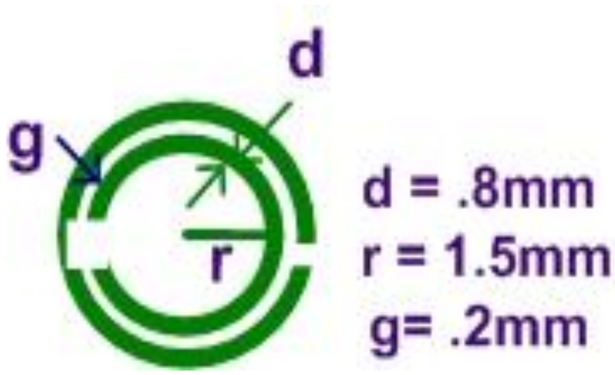

Figure 10: Parameters of Split ring resonator prepared by Smith et.al.[9]

Re-drawn from "Smith, D. R., Padilla, W. J., Vier, D. C. & Schultz, S. (2000). Composite medium with simultaneously negative permeability and permittivity. *Phys. Rev. Lett., 84*(18), 4184–4187."

Aydin et al. prepared a negative refractive index metamaterial on FR4 circuit board with a copper layer deposited of 30μm thickness. They prepared two structures, one combining SRRs with wires and other combining closed SRRs (CSRRs) with wires. On one side, SRRs were arranged and wires on the other side of dielectric board as shown in Figure 11. SRR details: d = t = .2mm, w = .9mm, r = 1.6mm. 5, 15 and 18 SRRs unit cells were arranged periodically along the x, y, and z directions. Wire details: The thickness, length and width of wire 30μm, 13.5cm and 0.9mm. With the same parameters, CSRRs were fabricated on one side of board and wires on the other side of the dielectric board. Through experiment, they showed transmission band that coincides with the region where both μ & ε are negative. The plasma frequency of this combination is less than the plasma frequency of wire. Combining SRRs and CSRRs with wires exhibits negative refractive index properties.[14]

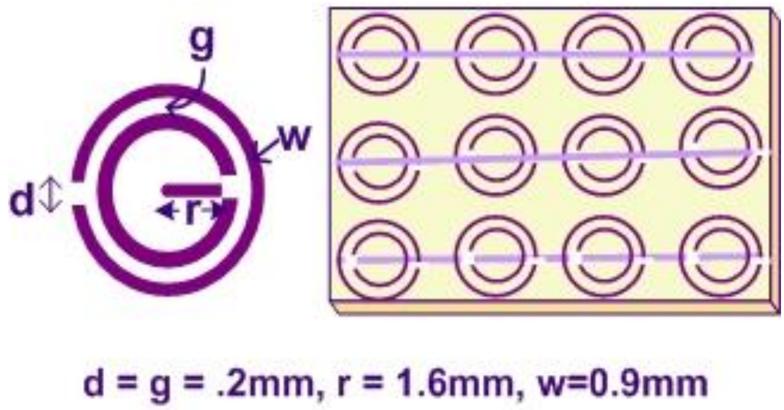

Figure 11: Parameters of metamaterial prepared by Aydin et al. Transmission curves of these structures show Negative refractive index region where both permittivity and permeability is negative.[14]

Re-drawn from "Aydin, K., Guven, K., Kafesaki, M., Zhang, L., Soukoulis, C.M. & Ozbay, E. (2004). Experimental observation of true left-handed transmission peaks in metamaterials. *Opt. Lett.*, *29*(22), 2623–2625."

Ozbay et al. observed a negative refractive index by different techniques. By combining a split ring resonator with wire patterns fabricated on an FR4 circuit board. The length of continuous thin wire was 19cm and width 0.9mm. They were able to observe negative refraction through three different methods, beam shift method, the phase shift method and the wedge shaped method.[15]

The split ring resonators built by[15] consist of two concentric metal rings on a dielectric printed circuit board (thickness 1.6mm and permittivity (ε) 3.85 of the board). The width of the metal is kept .9mm and the gap between the inner and outer rings is .2mm. This SRR structure helps to attain magnetic resonance in the microwave frequency region. The copper of a thickness of 30 μm is deposited to make SRR. They arranged an array of these SRR's to achieve negative permeability (μ). The array consists of a number of unit cells along the x, y and z axis 10, 15 and 25, respectively, with lattice spacings of $a_x = a_y = 8.8$mm and $a_z = 6.5$mm. Through experiments, they found the resonance frequency of such SRR is in the GHz range.

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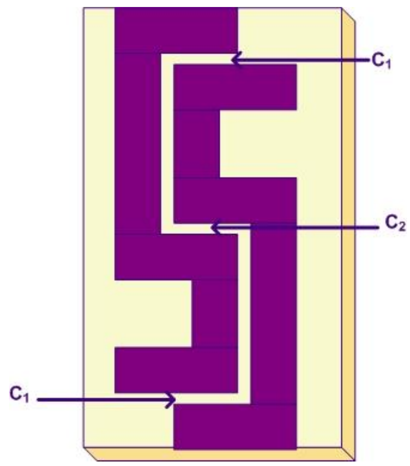

Figure 12: S shaped metamaterial prepared by printing only on one side on F4 board.[16]

Re-drawn from "Wang, D., Ran, L., Chen, H., Mu, M., Kong, J. A. & Mu, B. I. (2007). Experimental validation of negative refraction of metamaterial composed of single side paired S-ring resonators. *Appl. Phys. Lett. 90*(25), 254103(1–3)."

Wang et al. introduced a unique and easy technique to fabricate controllable negative refractive index metamaterials. They printed a one-dimensional S-shaped metallic strip on one side of the dielectric board that was easy to fabricate, as shown in Figure 12. Inductance is introduced by the two metallic strips, and the capacitances is introduced by the gaps between the strips. Numerical simulations and experimental results show negative permittivity and negative permeability can be achieved simultaneously by this basic structure that is printed only on one side of the 1 mm thick F4 board.[16]

Later, much simpler negative refractive index structures were fabricated[17]**.** Short wires were paired with continuous wires separated with dielectric spacers to form negative refractive index metamaterials through microfabrication as shown in Figure 13(b). Unit cell of wire pair structure is shown in Figure 13(a). The short wire shows inductive behavior along the wire and capacitive behavior between adjacent ends of short wires. Simulations and microwave experiments for transmission and reflectance show that fabricated material shows negative refractive index properties. The calculated frequency (f_m) of magnetic resonance.

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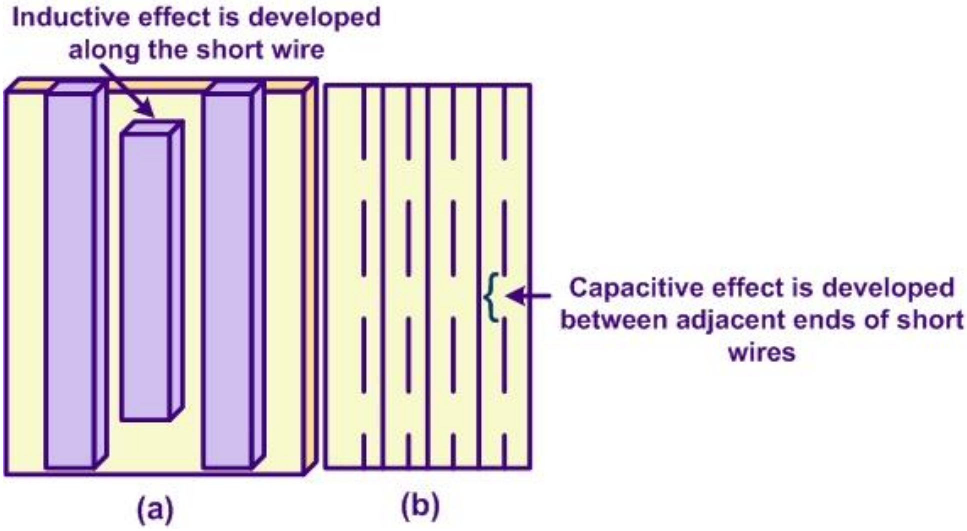


Figure 13: a) Unit cell of wire pair structure. b) Wire pair structure fabricated on FR4 Board.[17]

Re-drawn from "Zhou, J., Zhang, L., Tuttle, G., Koschny, T. & Soukoulis, C. M. (2006). Negative index materials using simple short wire pairs. *Physics review B. 73*(4), 041101(1-4)."

$$f_m = \frac{c}{\pi l \sqrt{\varepsilon_r}} \tag{10}$$

where c is the speed of light in a vacuum, *l* is the length of the short wire, and ε_r is the relative dielectric constant between the wires. The magnetic resonance frequency is inversely proportional to *l* refer to Eq.(10). The unit cell dimensions of metamaterial are kept much smaller than the wavelength of incident radiation.

Applications of Negative refractive index metamaterials:

The development of negative refractive index metamaterials has opened the world to multiple unusual phenomena that were never observed in past with conventional resources. Their specific designs help them manipulate optical frequencies.[18] Here I am going to discuss some of the applications of these (NIM) wonder metamaterials.

a) Perfect lens:

Ordinary lenses are made up of glass and are used for image formation. They work because of their specific shapes, but their work has certain limitations as their optical resolution is limited to the wavelength of light. So today, NIMs are used to make perfect lenses as they go beyond the diffraction limit and enhance resolution to form sharp and perfect images.

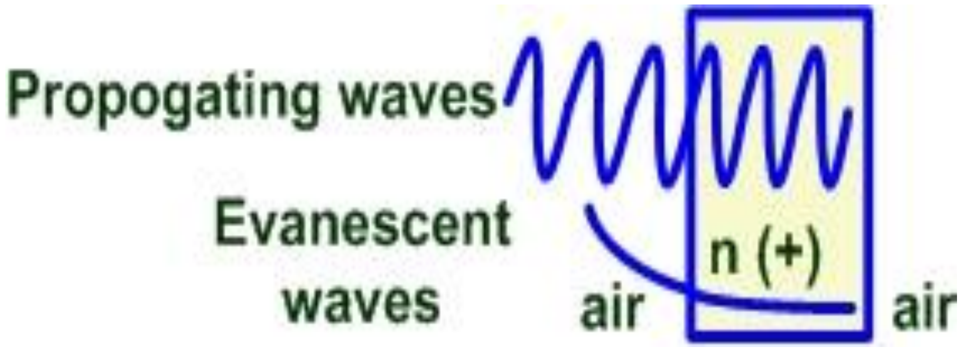


Figure 14: Propagating and evanescent waves travelling through the normal lens. Evanescent waves decay exponentially in normal lenses and make less or no Contribution to form images.[19]

Re-drawn from "Goudus, S. K., (2017*). Microwave Systems and Applications (edition).* InTechOpen. https://doi.org/10.5772/62931"

As the field coming out of an object is a superposition of plane waves that consists of propagating waves and evanescent waves, as shown in Figure 14.[19] In normal lenses, an image is formed due to propagating waves as evanescent waves carry subwavelength information about an object and decay exponentially in normal lenses (positive refractive index). One more limitation of normal lenses is that, due to their aperture, they diffract and form blurred images (Figure 15(a). A lot of information is lost due to these losses. If lenses are made up of NIMs and placed close to the object, the near-field evanescent waves are enhanced across the lens. Lenses made up of NIMs focus both propagating waves (Figure 15(b)) as well as enhanced evanescent waves (Figure 15(c)) in phase and amplitude to form high resolution perfect images. Images formed with NIMs are ultra-sharp as they do not have to go through the diffraction limit.

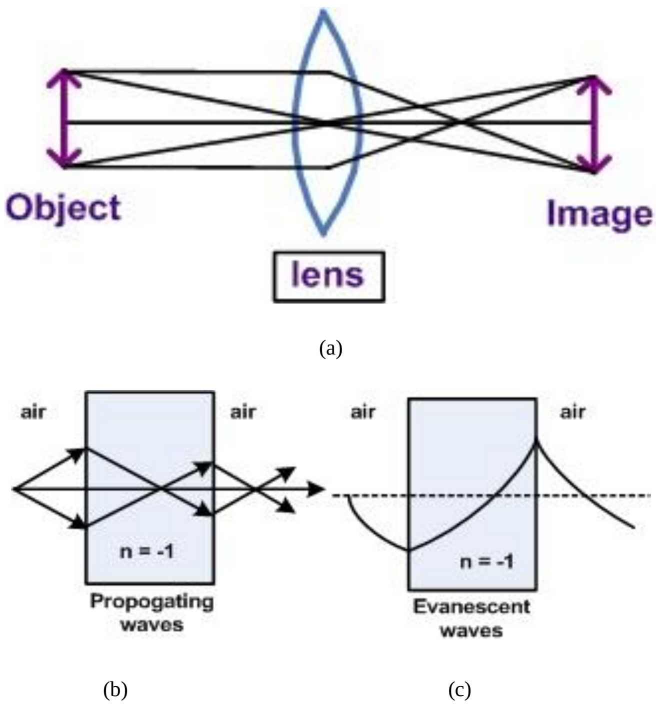


Figure 15: (a) Image formed through normal lens. Its aperture diffracts light and limit it to make sharp images
(b) Lenses made up of negative refractive index metamaterial (NIMs) first diverge propagating waves from point source and then converge to form images.
(c) Evanescent waves are enhanced in negative refractive index metamaterial and give good contribution to form images. Images formed through NIMs are not limited to diffraction limit and images from through it are very sharp.[(20,21)]

Re-drawn from "Pendry, J. B. (2000). Negative refraction makes a perfect lens. *Phys. Review Letters, 85*(18), 3966–3969." & "Pendry, J. B. & Ramakrishna, S. A. (2003). Refining the perfect lens. *Phys. B., 338*(1-4), 329–332."

NIMs bend light to a negative angle with the normal, first diverge, and then converge to form images by restoring the phase of propagating waves and amplitude of evanescent waves.[20] Today, perfect lenses are also made by combining a series of thin slices of the negative refractive index metamaterial, as this combination enhances absorption and resolution to form low loss images (Figure 16).[21]

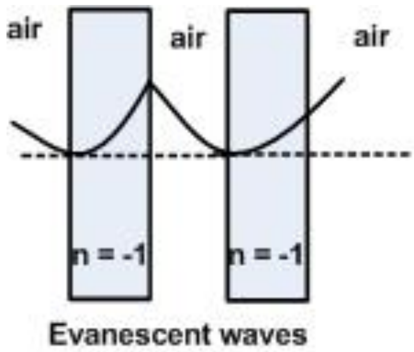


Figure 16: A perfect lens made up of combining slices of NIMs to get lossless image due to good absorption and enhanced resolution.[21]

Re-drawn from "Pendry, J. B. & Ramakrishna, S. A. (2003). Refining the perfect lens. *Phys. B., 338*(1-4), 329–332."

b) Invisibility Cloak:

John Pendry of Imperial College in 2006 created a small device that can redirect microwave radiation around an object and can hide the object, making it invisible. Cloaking means hiding objects from view. This property was derived from the structural geometry of the metamaterial. In these structures, the electromagnetic field is controlled by the material's specific design so that the displacement field, magnetic induction and Poynting vector are displaced in line. Variation in these values affects electromagnetic waves and this distortion in the field is represented by coordinate transformations. These structures are capable of manipulating electromagnetic radiation by either amplifying, bending or absorbing it (Figure 17). Especially designed metamaterials can redirect electromagnetic waves and adjust it to the desired configuration for a particular frequency. [22]

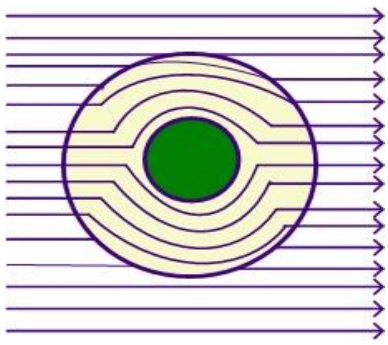


Figure 17: Invisibility cloak, to hide objects from the view.[22]

Re-drawn from "Pendry, J. B., Schurig, D. & Smith, D. R. (2006). Controlling electromagnetic fields. *Science, 312*(5781), 1780–1782."

Schruing et al. prepared an invisibility cloak with a NIM for a narrow band of microwave frequencies. The cloak that is formed around an object decreases the scattering of the hidden object and parallelly reduces its shadow. The metamaterial structure prepared by Schruing et al. consists of equally spaced 10 concentric cylinders, and the height of each cylinder was 3unit cells tall (Figure 18). In each successive cylinder, the number of unit cells is increased.[23]

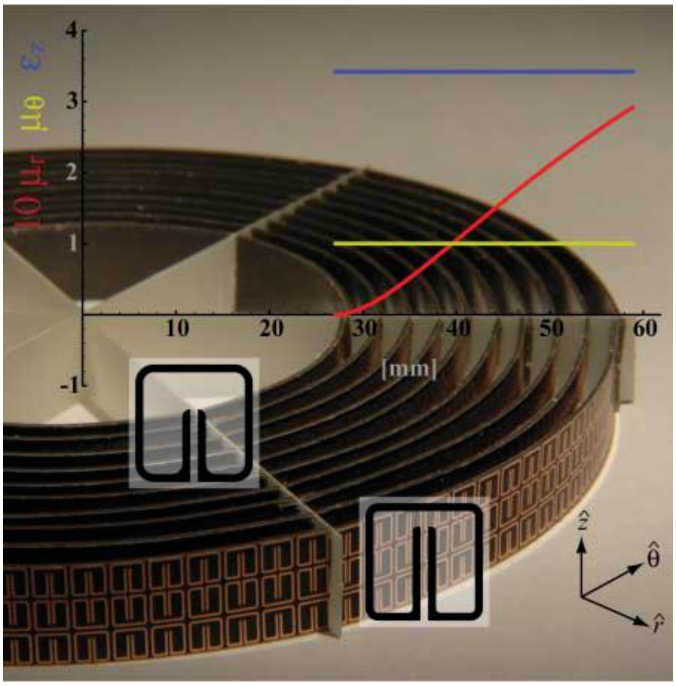


Figure 18: Schruing et al.[23] consists of equally spaced 10 concentric cylinders and height of each cylinder was 3-unit cells tall.

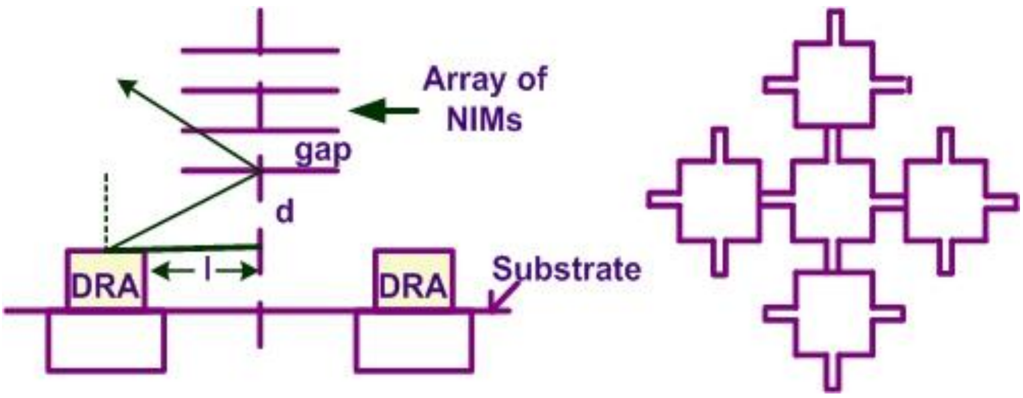
Adapted with permission from permission from "[Schurig, D., Mock, J. J., Justice, B. J., Cummer, S. A., Pendry, J. B., Starr, A. F. & Smith , D. R. (2006). Metamaterial electromagnetic cloak at microwave frequencies. *Science, 314* (5801), 977–980.] Copyright 2006, The American Association for the Advancement of Science"

c) Nonlinear Optics:

J. Pendry and coworkers predicted nonlinear optical properties could be achieved from metamaterials. Klein et al. observed second harmonic generation from metamaterial that was made up of split ring resonators.[24, 25]

d) Antenna:

Another important application of negative refractive index metamaterial is to make antennas. One of the examples is the beam tilting antenna, where the NIM array is fixed between two dielectric resonator antennas (DRAs). When an electromagnetic wave enters the medium, the direction of propagation changes by deflecting the direction of the beam. The beam tilting angle depends upon l and d (parameters shown in Figure19a and is independent of the number of NIM layers while the gain of the antenna is dependent on the number of NIM layers, and gap between them. The NIM unit cell (Figure 19b) array is kept above the DRA, tilts the beam in the opposite direction due to its negative refractive index property, and redirects the DRA beam. Experimental and simulation data show that by variating d, l and gap parameters of the structure, beam tilting direction and antenna gain can be changed.[26]



(a) (b)

Figure 19: (a) A beam tilting antenna made up of NIM, fixed between two dielectrics resonator antennas. (b) NIM unit cell.[26]

Re-drawn from "Li, J., Zeng, Q., Liu, R. &Denidni, T. A. (2017). Beam-tilting antenna with negative refractive index metamaterial loading. *IEEE Antennas Wirel. Propag. Lett. 16,* 2030–2033."

NIMs are also used to make dynamic beam tilting terahertz antennas. In this type of antenna, the pattern structure is designed on a p-type Si substrate (dielectric constant 11.7) and covered with SiO_2 (dielectric constant 4) to make an antenna. The dynamic beam tilt antenna consists of the antenna (above mentioned) and the NIM (Figure 20a).

Graphene is embedded in a metallic resonant structure to variate the refractive index of NIM (Figure 20b). By varying the chemical potential of graphene values of negative refractive index values can be varied. Graphene can tune its surface conductivity at a THz frequency range. If direct current (DC) is applied to graphene, it changes its chemical potential and variate refractive index of the NIM. The variation in refractive index of the negative refractive index

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metamaterial variate the steering angle of the antenna. Hence, graphene is able to control the negative refractive index and opens the path to fabricating dynamic beam tilting antennas.[27]

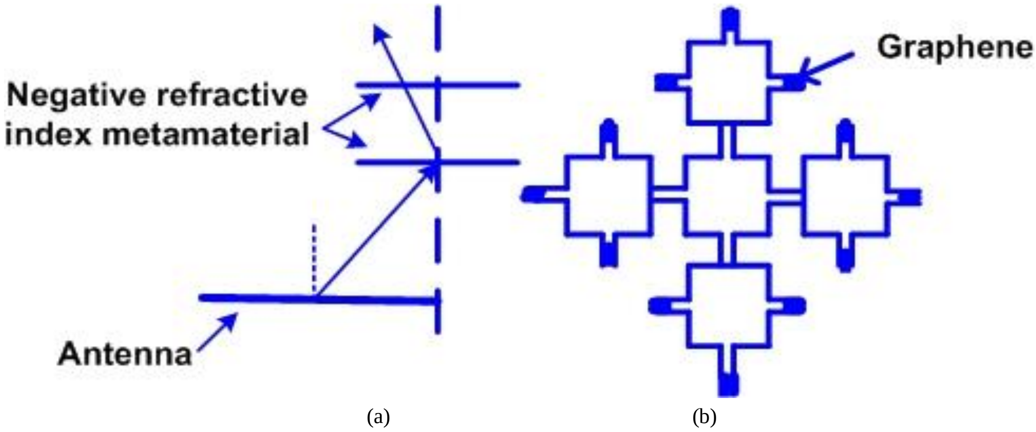

Figure 20: (a) Antenna with NIM. (b) Graphene embedded in NIM, by modulating chemical potential of graphene negative refractive index values is changed and an effective way to make beam tilting antenna.[27]

Re-drawn from "Luo, Y., Zeng, Q., Yan, X., Jiang, T., Yang, R., Wang, J.,Wu, Y., Lu, Q. & Zhang. X. (2019). A graphene-based tunable negative refractive index metamaterial and its application in dynamic beam-tilting terahertz antenna. *Microw. Opt. Technol. Lett.*, *61*(12), 2766–2772."

Chiral metamaterials, a unique way to achieve negative refractive index:

The above discussion summarizes two essential conditions for negative refractive index metamaterials: first negative permittivity and second negative permeability. Some alternate paths do not need these conditions to be completely filled, and such alternatives are chiral metamaterials and photonic crystals. Chiral metamaterials are asymmetric unit cells that lack mirror symmetry, while photonic crystals are order of wavelength and show diffractive phenomena. Their phase velocity and group velocity are in opposite directions, which are very similar characteristics to NIMs.[28]

Here, our primary focus is on chiral metamaterials that are artificially fabricated in labs and consist of unit cells that are asymmetric, lack mirror symmetry, inversion symmetry, and improper axis of symmetry. Benfeng et al. studied optical activity in planar chiral metamaterials (manufactured artificially) made up of dielectric and metal. Through numerical analysis, they proved a thickness of only hundreds of nanometers of chiral metamaterial can achieve optical activity, an essential condition of chiral materials.[29]

The idea that chiral structures can exhibit negative refraction was first theoretically proposed by Tretykov[30]. In his work he talked about chiral nihility materials (ε=0, μ=0) and (κ) chiral parameter is non-zero for a certain frequency and explained the properties of such materials through Maxwell's equations.

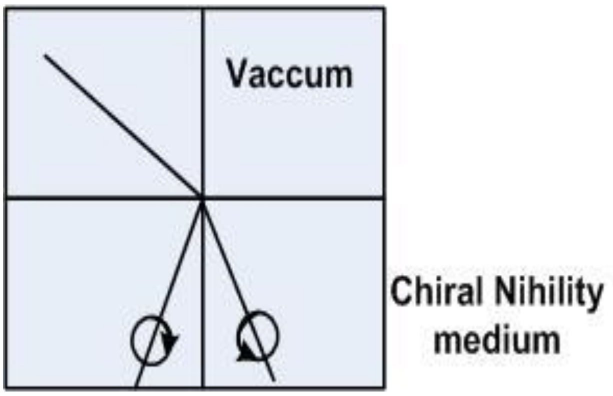

Figure 21: Double refraction taking place through chiral nihility material (ε=0, μ=0). Both refracted rays are circularly polarized (CP), one CP refracted ray is refracted positively and other is refracted negatively (opposite to incident ray).[30]

Re-drawn from "Tretyakov, S., Nefedov, I., Sihvola, A. , Maslovski, S. &Simovski, C. (2003). Waves and energy in chiral nihility. *J. Electromagn. Waves Appl. 17*(5), 695–706."

Maxwell's equations for chiral nihility media. Refer to Eq. (11) and Eq. (12)

$$\nabla \times \vec{E} = k_0\,\kappa\vec{E} \tag{11}$$

$$\nabla \times \vec{H} = k_0\,\kappa\,\vec{H} \tag{12}$$

Where k_0 is wavevector in vacuum and κ is chiral parameter. Chiral parameter lifts the degeneracy and show different refractive indices for different handed circularly polarized lights. Solutions of Maxwell's equations of chiral nihility media are the eigenvectors of the curl operator and represent circularly polarized waves with helicity parameter $k_0\,\kappa$. Cantarella et al. discuss the complete derivation of helicity[31] where the helicity parameter can either be positive or negative.

Tretykov et al. did mathematical calculations and proved that when linearly polarized waves travel through chiral nihility materials, double refraction takes place and one of the two eigen waves with a positive group velocity has a negative phase velocity, so that one of the waves is backward wave and shows negative refraction. Both refracted rays are circularly polarized with

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one ray refracting positively (normal refraction) and the other refracting negatively (negative refraction) as shown in Figure 21. These materials were not realized practically then. Later researchers put this theoretical aspect into practical realization.

Tretyakov et al. studied chiral composites to observe negative refraction and discussed it in terms of the strong resonant interaction between chiral particles and dipoles, giving rise to a stop band where negative refraction is observed. Propagation constants of two eigen waves in isotropic chiral media is $\beta = (n \pm \kappa)\, k_0$, where $n = \sqrt{\varepsilon\mu}$ is the refractive index, κ is the chirality parameter and k_0 is wavenumber. Near the resonant frequency of chiral particles, n (refractive index) becomes less than (κ) chirality parameter so that negative refraction takes place and one of the eigenwaves shows negative refraction while the other is positively refracted.[32]

Wang et al. did experiments and numerical calculations for chiral metamaterials and were able to show optical activity and circular dichroism exhibited by the metamaterial and were able to discover one more complimentary property of the chiral metamaterial-negative refractive index[33] with no requirement for negative permittivity and negative permeability. When different handed circularly polarized light falls on the chiral metamaterials, they derive strong gyrotropy and different handed circularly polarized light shows two different values of refractive indices.[34]The refractive index is increased corresponding to one circular polarization and reduced for the other. Due to it one circular polarization being positive and other negative,[35-36] work as well theoretically supports the idea that chiral materials can work as NIMs. Hence, it supports how chirality in the system is sufficient to introduce negative refractive index.

Artificially fabricated chiral metamaterials that exhibit negative refractive index properties as well.

a) Zhou et al. fabricated a unique chiral metamaterial on a copper clad FR-4 board. Asymmetric bilayer cross wires were fabricated on both sides of the board. (Figure22) Due to its asymmetrical structure, light propagated through such a metamaterial is split into right circularly polarized light (RCP) and left circularly polarized light (LCP) and shows strong chirality at resonant frequencies. This asymmetric structure shows optical activity, circular dichroism, and strong chirality.

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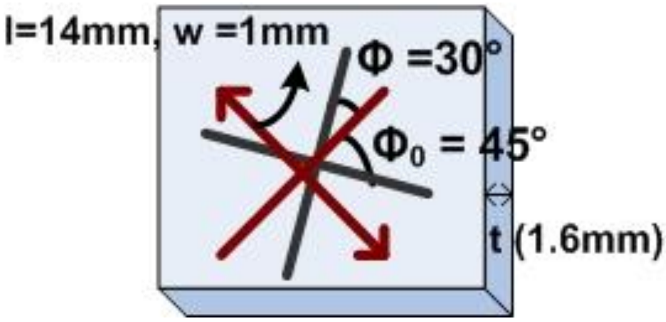


Figure 22: Schematic of chiral metamaterial prepared by Zhou et al. Asymmetric pattern is fabricated on both sides od FR-4 board.[37]

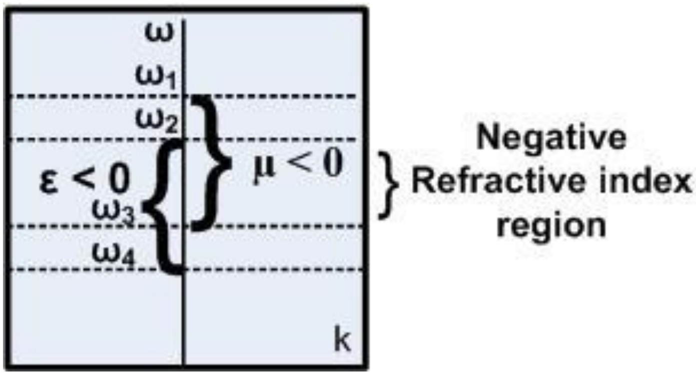
Re-drawn from "Zhou, J., Dong, J., Wang, B., Koschny, T., Kafesaki, M. & Soukovlis, C.M. (2009). Negative refractive index due to chirality. *Phys. Rev. B, 79*(12), 121104(1–5)."

The paper focuses on how strong chirality in the system is sufficient to make metamaterial negative refractive index too and how chiral parameter plays an important role to achieve it with no requirement of negative permittivity (ε) and permeability (μ). The refractive index for RCP (+) and LCP (-) are n_+ and n_- respectively and κ is the chiral parameter refer to Eq.(13).

$$n_\pm = \sqrt{\varepsilon\mu} \pm \kappa \tag{13}$$

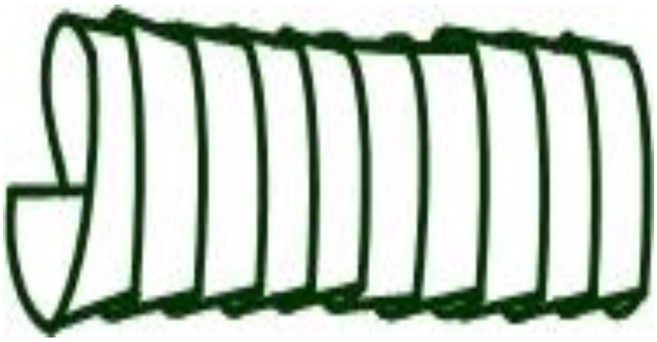
For RCP (+) refractive index value was observed to be -2.5 at 6.8 GHz and for LCP, -1 at 7.8 GHz. In the system, both circularly polarized light were able to show a negative refractive index but RCP shows more negative refractive index value compared to LCP. Hence negative refractive index for RCP and LCP in the system had developed due to the chiral parameter (κ). Same simulation performed on achiral material shows no different graphs for RCP, LCP, and for n (conventional refractive index). The system had no chirality; hence no negative refractive index was observed.[37]

J B Pendry manufactured simple chiral design, a chiral structure by winding a continuous insulated metal tape onto a cylinder [38]. The coiled helix structure give inductance, inner and outer layers of the helix give capacitance (Figure23(b)). Chiral materials are able to achieve single gap because their intersecting bands do not hybridize (Figure23(a)). This single gap eliminates the problem of two resonances and gives a smooth path to achieve a negative refractive index. Hence, the chiral structure with a single band gap makes the material have a negative refractive index too.



$\mu<0$	**$\omega_1 > \omega > \omega_3$**
$\varepsilon<0$	**$\omega_2 > \omega > \omega_4$**

Figure 23: (a) Stop bands showing negative refractive index region



(b) A chiral metamaterial prepared with insulated strip of metal wound in a form of overlapping helix.[38]

Re-drawn from "Pendry, J. B. (2004). A chiral route to negative refraction. *Science, 306*(5700), (1353-1355)."

b) Zhang et al.[35] proposed metamaterial made up of gold that show chiral nature and at terahertz frequency range work as NIM. Due to strong chirality, right circularly polarized light (RCP) and left circularly polarized light (LCP) show different refractive indices. The system acts as a chiral resonator with the inductor formed by the loop and capacitor formed between two metal strips (Figure 24). When an electromagnetic wave falls on this chiral metamaterial, cross coupling takes place between the electric and magnetic dipoles in the same direction. It breaks degeneracy between two circularly polarized waves and refractive index is increased for one circular polarization and decreased for the other.

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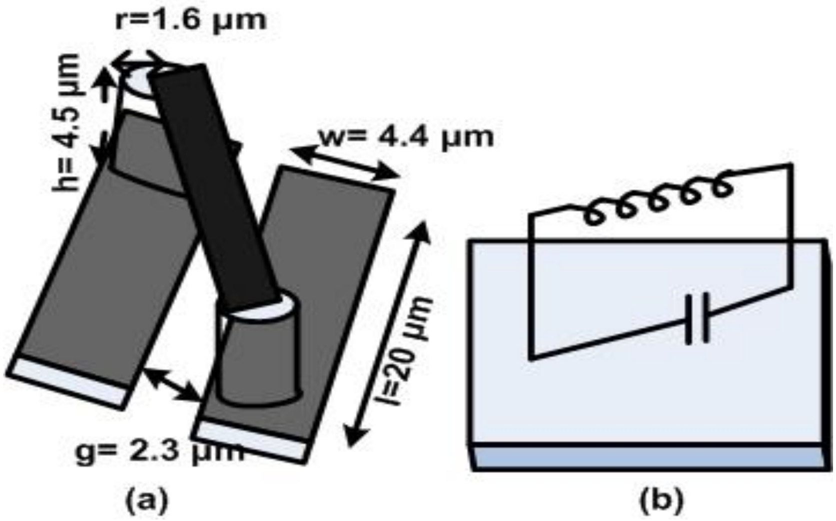

Figure 24: Schematic of chiral metamaterial prepared by Zhang. Two vertical metallic Cylinders of height 4.5μm and radius 1.6μm on two 4.4μm bottom strips of thickness. 6 μm that are spaced at 2.3μm. One strip of thickness. 3μm is bridged on top of the vertical cylinders. The bottom strip makes an angle of 29.25°with the top strip.[35]

Re-drawn from " Zhang, S., Park, Y. S., Li, J.,Lu, X., Zhang, W. & Zhang, X. (2009). Negative refractive index in chiral metamaterials., *Phys. Review Letters, 102*(2),023901(1–4)."

The material is characterized by terahertz time domain spectroscopy and time domain simulation software. Chiral metamaterial is placed between two polarizers kept either parallel or perpendicular to each other and transmission spectra for RCP and LCP are recorded. Both measured and simulation data showed that LCP had strong amplitude and phase modulation while RCP showed less modulation. Large modulation helps LCP to achieve (-5) negative refractive index and less modulation for RCP and it remains positive for the entire frequency range. Here, chirality is enough to make it NIM with no requirement of negative permittivity (ε) and negative permeability (μ).

Future Directions

Present work will definitely help to understand Negative refractive index metamaterials and their specific properties and one can understand how they are different, compared to positive refractive index materials. Their difference makes them eligible to do tasks that are completely strange and lie in human imaginations. These practically realized metamaterials have changed the world in several aspects. Chiral metamaterials sustaining their own properties give an alternate route to achieve negative refractive index with no requirement of negative permittivity and negative permeability.

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Glossary

Refractive Index-It is a parameter that indicates light bending ability of the medium.

Metamaterials-Meta means beyond. Materials that are artificially made in labs to manipulate light.

Negative refractive index metamaterial-A metamaterial whose refractive index is made negative artificially for a certain frequency range. It bends light in opposite direction in comparison to conventional materials.

Chiral metamaterial- Artificially structured materials that rotate the plane polarized light and lack mirror symmetry. Lack of mirror symmetry means the object and image are not exactly the same.

Polarizability- The term polarizability is defined as how easily the electron cloud of an atom or molecule is distorted to form an induced dipole.

Permittivity-It is a measure of an electric polarizability and ability of the material to transverse electric fields. When electric field is applied on an atom electrons are displaced from the nucleus. Due to this displacement, an electric dipole is produced within the atom. This dipole moment is directly proportional to electric field strength (E). Hence electric polarizability of an atom is the ratio of dipole moment to the electric field strength.

Permeability-It is a measure of magnetic polarizability and ability of the material to transverse magnetic lines. When magnetic field acts on an atom, the magnetic dipole moment is directly proportional to the magnetic field strength. Hence, magnetic polarizability is the ratio of magnetic dipole moment and magnetic field strength.

Polarized light – Light is an electromagnetic wave; whose electric field vectors vibrate in all planes perpendicular to the propagation direction. If electric field vector is confined to a single plane, it is termed as polarized light.

Optical rotation-The ability to rotate plane polarized light with certain angle. Rotation of plane polarized light can either be clockwise or anticlockwise

Circular Dichroism-The difference in absorption of left and right circularly polarized light. Also known as CD.

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Plasma frequency-Plasmons have an equal concentration of positive and negative charges. In solids, positive charge is fixed in the core and free negatively charged electrons are present around it, balancing the equal concentration of positive and negative charges. When electromagnetic radiation falls on the material, electrons are displaced due to the photoelectric effect Once electrons are displaced, positive charges at the core exert an electrostatic attraction on the electrons and brings them back to equilibrium. As a reaction to this displacement, electrons start to oscillate with (ω_p)plasma frequency.

Evanescent waves-Evanescent waves carry subwavelength information of an object and decay exponentially in normal lenses.

Chiral nihility-Chiral nihility materials permittivity and permeability is zero and (κ) chiral parameter is non-zero for certain frequency range.

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