Appendix I

Chiral Metamaterials exhibit Properties of Negative Refractive Index Metamaterials

Abstract

The focus of the current article is on the specifically designed materials that exhibit specific properties but do not exist in nature. These materials need to be fabricated artificially in labs and are termed as negative refractive index metamaterials (NIMs). These specific property exhibiting metamaterials (NIMs) were theoretically predicted by Veselago in 1968. J.B. Pendry effectively brought Veselago's theoretical prediction of negative refractive index metamaterials (NIMs) into reality. For a material to exhibit the properties of NIMs, crucial requirements are the presence of simultaneous negative permittivity (ε) and negative permeability (μ). Many natural materials exhibit negative permittivity, but achieving negative permeability is difficult since natural materials lack this characteristic property. To develop negative permeability, artificial structures need to be fabricated, and due to this, NIMs are completely artificially produced materials. NIMs has many applications in making perfect lens, invisibility cloaks, and antennas. In this appendix 1, we will discuss about a unique chiral route that does not require negative permittivity and negative permeability to produce NIMs. Along with the negative refractive index, these chiral NIM materials have the ability to exhibit optical rotation and circular dichroism.

9.1 Introduction

When light rays travel from one medium to another, they bend due to differences in optical densities. The bending of light is due to the difference in speed of the light in different media, and the parameter used to measure this difference is the refractive index (n). It is a unit less quantity and measured with Eq. 1. In nature, all materials that are found have a positive refractive index. When electromagnetic radiation travels through such materials, they bend light in one specific direction and follow Snell’s law, where incident angle (i) and refracted angle (r) related to each other. Refraction of light traveling through two different media is shown in Figure 9.1.

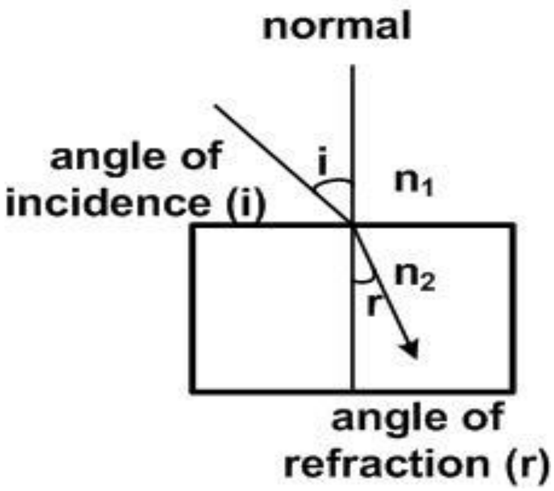


Figure 9.1: Refraction of light traveling through two different media.

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

If materials permittivity (ε) and permeability (μ) are known, the refractive index of the material can be calculated with Eq. 2.

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

The refractive index of the material is dependent upon the permittivity (ε) and permeability (μ) of the material. When electromagnetic radiation falls on the materials, these are the parameters that decide how the electric and magnetic fields will be affected. Hence, materials are bifurcated on the basis of permittivity (ε) and permeability (μ) values. Most materials found in nature have positive permittivity (ε), but some have negative permittivity as well. However, permeability (μ), is always positive, can only be produced negative artificially.(J. Pendry, 2001)

Materials that are found in nature with positive permittivity (ε) and positive permeability (μ) are termed as double-positive materials (DPM); these materials follow Snell's law and show normal positive refraction. The materials that have negative permittivity (ε) are termed as epsilon negative materials (εNG), and materials that have negative permeability are termed as Mu negative materials (μNG). The materials that have negative permittivity (ε) and negative permeability (μ) are termed as double- negative materials (DNMs). (Singh & Marwaha, 2015)

Is it possible to find double negative materials (DNMs) in nature that have both negative ε and μ or do they need to be fabricated artificially? Material classification chart on the basis of ε and μ values is shown in Table 9.1.

Table 9.1: Materials classified on the basis of ε and μ values.

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

The word "metamaterial" is a Greek word where "meta" signifies something that is beyond the real. DNMs are also termed as negative refractive index metamaterials (NIMs) and were first proposed theoretically by V.G. Veselago in 1968. According to Veselago et al., if DNMs exist, their electrodynamics will differ from DPMs.(V. G. Veselago, 1968) Pafomov et al. supported his idea and demonstrated mathematical calculations to observe effects if a material's permittivity (ε) and permeability (μ) are both negative. Through mathematical calculations, he found that for such systems, phase velocity and group velocity are antiparallel to each other, and it directly affects Snell's law. (Pafomov, 1959) According to Veselago et al., even though ε and μ are negative, it does not violate the mathematical expression for refractive index shown in Eq. 2 but changes the electrodynamics of the material completely. When ε and μ are positive, the refractive index (n) of such materials is a positive quantity, while if ε and μ are negative, the refractive index (n) is a negative quantity. (V. Veselago et al., 2006) Maxwell's curl equations shown in Eq. 3 and Eq. 4 demonstrated how electromagnetic waves behave when they travel through DNMs. Where $\vec{E}$ is electric field and $\vec{B}$ is magnetic field , and $\vec{D} = \varepsilon \vec{E}$ and $\vec{B} = \mu \vec{H}$.

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

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

Negative refractive index metamaterials (NIMs) are sometimes also termed left-handed materials. Figure 9.2 exhibits a blue colour refracted ray for ordinary refraction and purple refracted ray for negative refraction. The negative refracted ray direction is completely opposite (the mirror reflection) of the positive refracted ray.

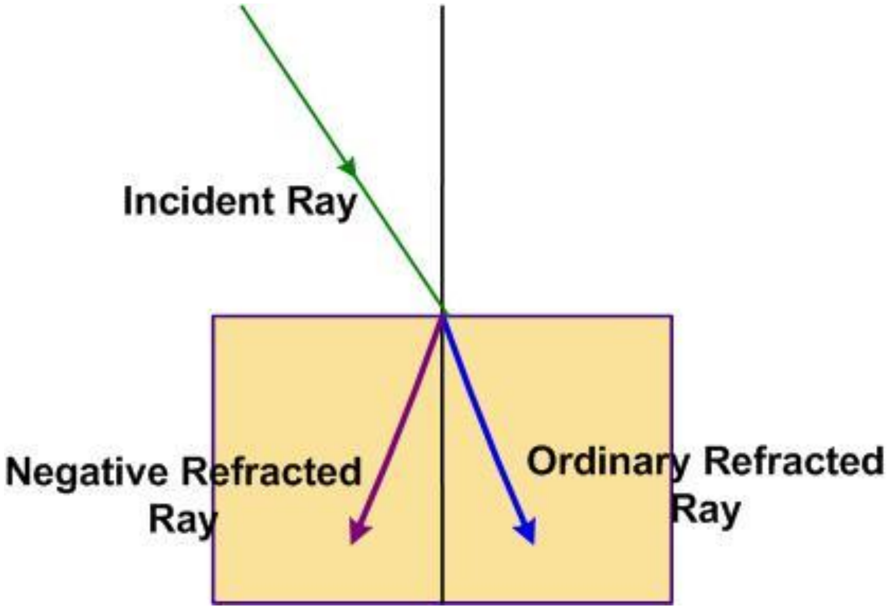


Figure 9.2: In a ray diagram, two different bending directions of light are represented. Blue refracted ray represents normal (positive) refraction through DPM, and the purple refracted ray represents refraction through NIM.

Although Veselago predicted NIMs in 1968, it took another three decades for such materials to be practically realized. To obtain negative permeability, it was quite challenging because NIMs properties are independent of the material of which they are made but depend upon their structures. (Shelby et al., 2001) To realize negative permeablity, structures need to be made very small compared to the incident wavelengths. (Singh & Marwaha, 2015)

If nanostructures are designed precisely for a certain frequency range, ε and μ can be obtained negative. Microstructures were initially designed to operate in the microwave region (GHz) only, but now microstructures are made that can operate in the near IR range (200 THz), mid IR range (100 THz), far IR range (1 THz), and also in the radio frequency region (MHz).

9.2 Major Advancements in Developments of NIMs

NIMs came into realization when Pendry et al. developed microstructured metallic wire systems in 1998 that could produce negative permittivity (ε). (J. B. Pendry, 1998) J. B. Pendry and his group in 1999, developed cylindrical structures that could produce low permeability (μ) values and provided the theoretical concept of split ring resonators (SRR) that can produce negative permeability for certain frequency range.(J B Pendry et al., 1999)

Smith et al. made a negative refractive index metamaterial in 2000 by combining an array of continuous wires and split ring resonators, as shown in Figure 9.3. Split ring resonators (SRRs) are a pair of concentric loops with splits on their opposite ends. If SRRs and periodically arranged continuous thin wires are paired in proper manner μ and ε can be made negative for a certain frequency range. In NIMs, wires present in the microstructure produce negative permittivity, while splits present at opposite ends of the SRR generate negative permeability. (Smith et al., 2000)

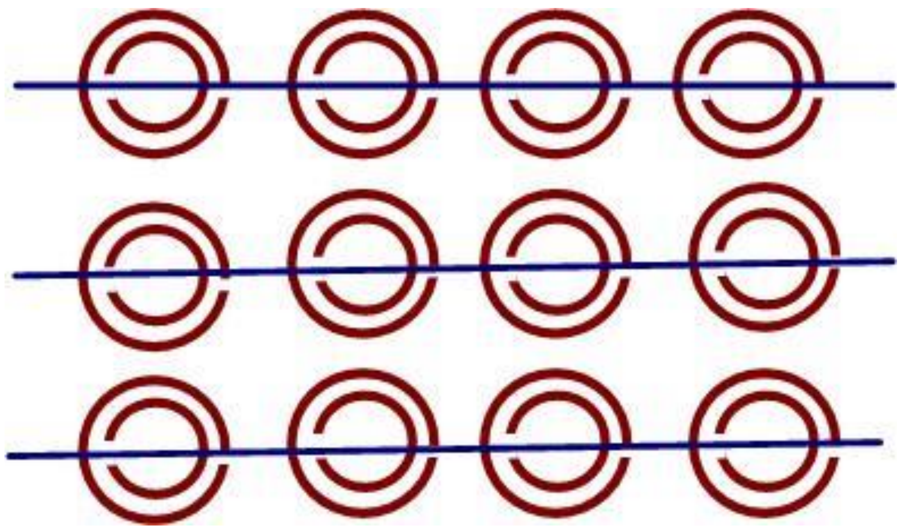


Figure 9.3: An array of continuous wires and split ring resonators.

These designed structures in the lab can act as a negative refractive index metamaterial for a particular frequency range. (Padilla, Willie J., Basov, Dimitri N., Smith, 2006) It entirely depends on the size, shape, and material chosen to fabricate such materials. Different structures of SRRs can be fabricated: circular, square, or U-shaped. Artificially fabricated structures are made up of repeated elements that resonate, and arise different properties from their combination that are entirely different from individual components. The operational role of

SRR is that of an LC oscillator. Thin continuous wires working entirely depends on plasma model, below plasma frequency, ε is negative.

9.2.1 Working of SRR as an LC Oscillator

The SRR present in NIMs functions as an LC oscillator. Let's understand the working of an LC oscillator. Schematic of LC oscillator is shown in Figure 9.4. In an LC circuit, electromagnetic oscillations occur between the electric field of the capacitor and magnetic field of the inductor, when both current and potential difference fluctuate sinusoidally.

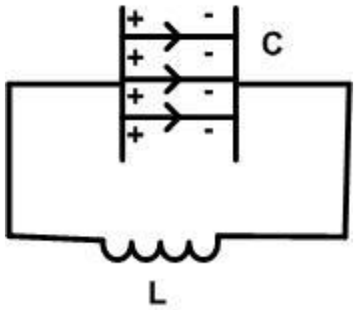


Figure 9.4: Schematic of an LC oscillator.

The amount of electric field energy stored in the capacitor is $E_E = \frac{q^2}{2C}$, where q is the electric charge present in the capacitor and C is the capacitance. In an inductor, energy is stored as magnetic field energy $E_B = \frac{Li^2}{2}$, where i is the current that passes through the inductor and L is the inductance. Before oscillations, electric field energy (E_E) stored in the capacitor is at its maximum (charge stored in the capacitor is maximum), and magnetic field E_B energy stored in the inductor is at its minimum (energy stored in the inductor is zero). Due to this difference in an LC circuit, no current is present in the circuit at the initial stage. When the LC circuit begins to oscillate, electric field energy starts converting to magnetic field energy and vice versa. During this exchange, follow the law of conservation.

The LC resonators resonate with maximum frequencies when electromagnetic radiation falls on them; this maximum frequency is termed the resonant frequency. A mathematical expression to calculate the resonant frequency is shown in Eq. 5.

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

Resonance is the state in which the system oscillates with a resonant frequency at its maximum amplitude. When, in an electrical circuit, the magnitudes of the inductive reactance and the capacitive reactance are equal, electrical resonance occurs. In the resonant circuit current is at its maximum and impedance is at its minimum. In Eq. 5, ω stands for the angular frequency of oscillations, C is for capacitance, and L is for inductance. (Walker et al., n.d.)

9.2.2 SRR Combined with Wires make Negative Refractive Index Metamaterials

Inductor and capacitor components are combined to form LC oscillators, and repeated patterns of LC oscillators form negative refractive index metamaterials. In electromagnetic radiation, electric and magnetic components vibrate in perpendicular planes. Two important microscopic parameters to control the electromagnetic radiation are: permittivity (ε) and permeability (μ) of the material. Permittivity (ε) of a material decides how it interacts with an electric component of an electromagnetic wave, and permeability (μ) decides how it interacts with a magnetic component of an electromagnetic wave. (Ramakrishna & Grzegorczyk, 2009) ε and μ both are frequency dependent parameters, as shown in Eq. 6 and Eq. 8. Both parameters are important as they influence the electromagnetic interaction with the material.

Eq. 2 signifies that these important parameters depend on the refractive index (n) of the material because it signifies the bending of the incident light. So, it's crucial to know the specific value (positive or negative) of the refractive index. Let's have a look at how metamaterials unique geometry and shape influence electromagnetic waves and provide desired properties to the material.(Shah & Ghalsasi, 2022)

9.2.2.1 SRR and Magnetic Response

In a split ring resonator (SRR), two concentric planar rings with a split in each ring are present. SRR are fabricated by lithographic technique and provide the necessary magnetic response when electromagnetic radiation falls on it. In SRR two rings are close to each other and operates as an LC oscillator. When electromagnetic radiation falls on the SRR, circulating current is induced in the SRR due to Faraday's law. As per the law, when a magnetic field of the electromagnetic wave is perpendicular to the SRR plane, it induces current. The induced circulating current in SRR is shown in Figure. 9.5.

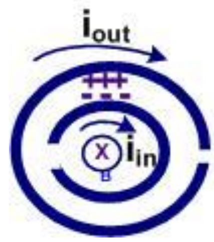


Figure 9.5: Schematic of SRR working as an LC oscillator.

In SRR, the current path acts as an inductor. The split gap of the SRR is induced with charge due to these circulating currents, and energy is stored as capacitance. Thus, the SRR resonator functions as an LC oscillator and resonates with a resonant frequency. To produce an effective magnetic response, an array of split ring resonators is arranged. Effective permeability (μ_{eff}) of the medium is shown in Eq. 6.

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\Gamma} \qquad (6)$$

The current that is induced in the rings of SRR produces magnetic field lines and can make the incident magnetic field either strong or weak. Let a split ring resonator acting as an LC resonant circuit, resonate with resonance frequency ω_0, let the frequency of incident radiation be ω, fractional area of the unit cell occupied by the split ring resonator is F; Γ is the dissipation factor; and μ_{eff} is the effective permeability of the medium. (Smith et al., 2000)

Positive (normal) refraction or negative refraction will take place entirely depends on the frequencies of the external magnetic field (ω). If incident frequencies of the external magnetic field(ω) are less than the resonant frequency (ω_0), a force is produced due to the externally changing magnetic field and current in the split ring resonator leads. The incident magnetic field is strengthened as electromagnetic interaction is in phase, the effective permeability (μ_{eff}) of the system increases, and positive (normal) refraction takes place. Opposite is the case when incident frequencies of the external magnetic field (ω) are greater than the resonant frequency (ω_0). The current in the split ring resonator is out of phase, and it lags. As electromagnetic interaction is out of phase due to the incident magnetic field being weakened, the effective permeability (μ_{eff}) of the system decreases and negative refraction is observed. The effective permeability (μ_{eff}) of the SRR can be tuned to the range of frequencies by adjusting and changing the dimensions of the split ring resonator.(Padilla, Willie J., Basov, Dimitri N., Smith, 2006)

9.2.2.2 Thin Wires and Electric Response

Periodic arrangements of metallic wires exhibit low-density plasma. Theoretical calculations, digital simulations, and experimental results indicate thin wires have the ability to attain negative permittivity for a specific frequency range. (J. B. Pendry, 1998) To understand thin wires electric response, first it is important to understand what Plasmons are. Plasmons are quasiparticles in which positive and negative charges are present in equal concentration. In solids, the positive charge is fixed in the core and is surrounded by free, negatively charged electrons and balance concentration of both charges as shown in Figure 9.6. When an electron is displaced from its equilibrium position, a force act on it, and moves it back to its equilibrium position. Due to this displacement, electrons start oscillating at plasma frequency (ω_p).

Plasma frequency is determined with Eq. 7, and the relationship reveals that it is directly proportional to e (charge of an electron), n (carrier density), and inversely proportional to m (effective mass of the electron).

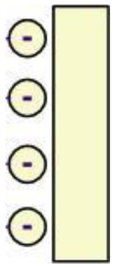


Figure 9.6: In solids, the positive charge is fixed in the core and is surrounded by free, negatively charged electrons.

$$\omega_p{}^2 = \frac{4\pi n e^2}{m} \tag{7}$$

$$\varepsilon = 1 - \frac{\omega_p{}^2}{\omega^2} \tag{8}$$

The permittivity (ε) of the medium can be calculated if the plasma frequency (ω_p) and frequency of external radiation (ω) are known. When precisely thin wires are placed as a mesh a few millimeters apart to fabricate NIMs, it reduces the effective density (n) of electrons. Thin wires present in NIMs enhance the inductance of wires, and any amount of current present in wires operates against inductance and makes electrons considerably heavier due to the increased effective mass of electrons.(J. Pendry, 2001)

It is evident from Eq. 7 that when the effective density (n) of electrons decreases and the effective mass of electrons increases, it reduces the plasma frequency (ω_p). Thin wires that resonate below their plasma frequency make their permittivity negative. Different negative values of permittivity (ε) can be generated for a wide range of frequencies because plasma frequency can be controlled by its geometry. At optical frequencies, different metals, such as thin silver, gold, and aluminium wires, are used to fabricate NIMs to achieve negative permittivity (ε).(Padilla, Willie J., Basov, Dimitri N., Smith, 2006; J. B. Pendry, 1998)

9.3 Details about NIMs Reported in the Literature

When SRRs are combined with thin wires, negative permittivity (ε) and negative permeability (μ) can be generated in the fabricated metamaterial. (John B Pendry & Smith, 2004) These combined structures are negative refractive index metamaterials and are also referred to as left-handed materials (LHM). Different structures of NIMs are reported in the literature that work in different frequency ranges, from radio frequency to the near IR range. (Padilla, Willie J., Basov, Dimitri N., Smith, 2006)

In 1998, the first artificial structure that could generate negative permittivity was proposed by Pendry et al. (J. B. Pendry, 1998) and in 1999, Pendry et al. proposed models that exhibited low and negative permeabilities. (J B Pendry et al., 1999) Different magnetic microstructures were proposed in 1999 to generate low and negative permeability. Models are named Model A, Model B, and Swiss Roll Structure (C). All of the artificial constructions presented were constructed from extremely light-weight nonmagnetic conducting sheets, and the size of the microstructures was made smaller than the wavelength of the incident radiation. Each structure is designed to resonate owing to internal capacitance and inductance.

Figure 9.7: Pendry et al. presented a model consisting of conducting metallic cylinders to achieve negative permeability. (J B Pendry et al., 1999)

Pendry et al. developed model A by arranging square arrays of conducting metallic cylinders as shown in Figure 9.7 and applying an external magnetic field parallel to the cylinders. Due to the external magnetic field, it allows current to flow around the cylinders. In this geometry, they obtained permeability (μ) between 0 and 1, but in this structure, it was still positive.

Model A was modified by Pendry et al. because of its limited range of permeability (μ). In modified Model B, sheets were divided into split ring structures that were separated by a distance d, as shown in Figure 9.8. The capacitance between the sheets and the inductance of the cylinders, induces a current in the split rings and makes it a resonant structure. In this model, permeability (μ) was less than unity when frequency was more than the resonant frequency, and the value of μ was observed to be higher when frequency was more than the resonant frequency.

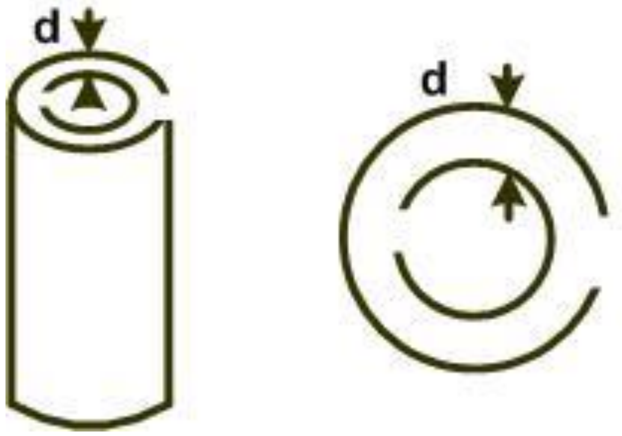


Figure 9.8: In Model B, conducting cylinders are made up of split ring structures separated by distance d.

Swiss roll (Model C) structure consist of metallic sheet wound around each cylinder in a coil, and gap between each coil was kept d as shown in Figure 9.9. Amount of current in coiled sheets reduces when magnetic field is applied parallel to the cylinder. The current flow is enabled by the capacitance between the first and last turns of the coils. In this modified version range of permeabilities can be obtained by fluctuating capacitive structure and resistivity of the material.

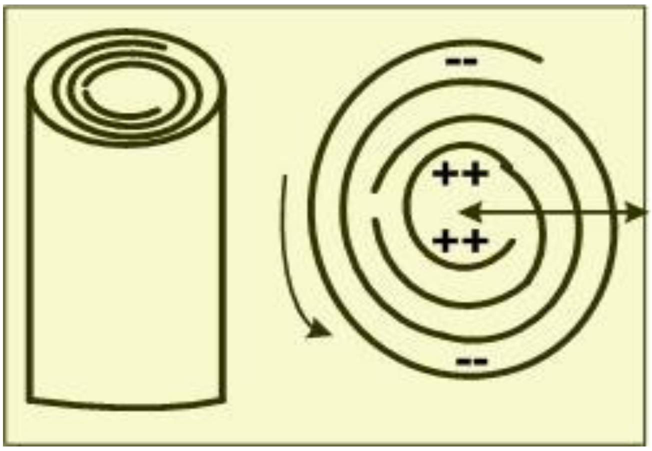


Figure 9.9: Model C, a magnetic field is applied parallel to an N-turn coil.

All of the structures outlined by Pendry performed well under microwave radiation, and by making modifications to the structure, different values of magnetic permeability were obtained. When the magnetic field is applied along the cylinder axis, all the structures change their magnetic properties, but no magnetic response is observed in other directions. The work of Pendry et al. (1999) was centred on achieving negative permeability through the use of cylindrical structures. Pendry's subsequent aim was to replace split ring cylinders with flat disc split rings to achieve negative permeability. (J B Pendry et al., 1999) In 2000, Smith et al. replaced the cylindrical structures present in Pendry's model with copper split ring resonators and combined them with continuous thin wires to fabricate the first NIMs. (Smith et al., 2000) A schematic of an array of continuous wires and split ring resonators is shown in Figure 9.3. Each unit cell consists of a pair of wire and SRR. The split ring resonator fabricated by Smith et al. parameters are shown in Figure 9.10**.** gap between two rings was g = 0.2 mm, the radius of the inner ring was r = 1.5mm, and the thickness of each ring was d = 0.8mm

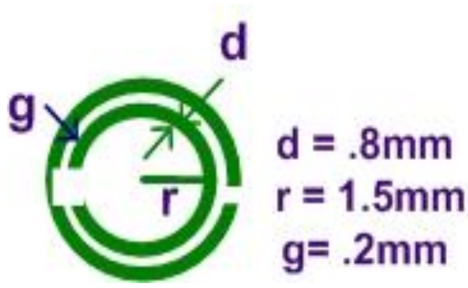


Figure 9.10: Split ring resonator parameters constructed by Smith et al.

9.4 Applications of Negative Refractive Index Metamaterials

The invention of negative refractive index metamaterials has opened the door to a plethora of unusual phenomena that were previously not observed using conventional resources. Their unique designs enable them to control (manipulate) optical wavelengths.(Litchinitser et al., 2008) In this section, I will discuss some of the uses of these amazing metamaterials.

9.4.1 Perfect Lens

Ordinary lenses are composed of glass that operate because of their unique shapes and are used to form images. Their capabilities are restricted since their optical resolution is limited to the wavelength of light. NIMs have been used to build perfect lenses since they work beyond the diffraction limit and improve resolution, resulting in perfect and sharp images.

When a wave propagates, it consists of two waves known as propagating waves and evanescent waves as shown in Figure 9.11. Oscillations present in propagating waves allow them to travel through normal lenses, while evanescent waves have an exponential wave function and decay exponentially in conventional (normal) lenses. Evanescent waves carry subwavelength information about an object but make no contribution to image formation in conventional lenses.

Figure 9.11: Propagating waves oscillate as Sine waves and evanescent waves decay exponentially.

Image formation in conventional lenses is only due to propagating waves, while in perfect lenses (NIMs), images are formed due to both propagating waves and evanescent waves. A further disadvantage of conventional lenses is that they diffract and produce blurry images due to their aperture. Image formation in conventional (normal) lenses is shown in Figure 9.12. A significant amount of information is lost due to these losses.

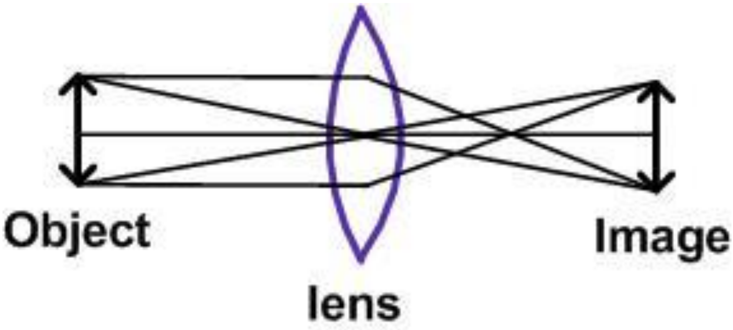
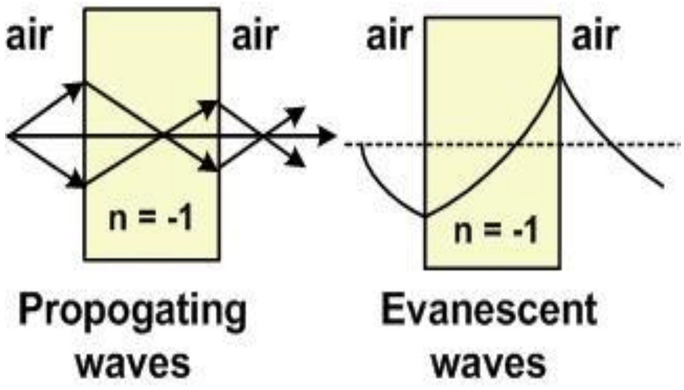


Figure 9.12: Image formation in normal lens.

If NIM lenses are placed close to an object, the near-field evanescent waves are enhanced across the lens. NIM-based lenses focus both propagating waves (Figure 9.13a) and enhanced evanescent waves (Figure 9.13b), and high resolution, perfect images are formed. NIM images are not limited to the diffraction limit; hence, images formed through them are very clear and ultra-sharp.



(a) (b)

Figure 9.13: (a) Negative refractive index metamaterial (NIM) lenses diverge propagating waves from a point source before converging to form images. (b) Evanescent waves are strengthened in negative refractive index metamaterials and contribute significantly to image formation.

When propagating waves travel through NIM lenses, waves first diverge propagating waves from a point source and then converge before image formation. Due to it, the phase of propagating waves and the amplitude of evanescent waves are restored. (J B Pendry, 2000; J B Pendry & Ramakrishna, 2003)

9.4.2 Invisibility Cloak

In 2006, John Pendry of Imperial College invented a device that can redirect microwave radiation around an object and has the ability to hide it and make it invisible. Cloaking implies concealing items from view. This special feature was created by the negative refractive index metamaterial's structural geometry. The electromagnetic field in these structures is controlled by the material's distinctive design, such that the displacement field, magnetic induction, and Poynting vector are all displaced in line. Electromagnetic radiation in these structures is manipulated by bending, absorbing, and amplifying it. A schematic of an invisibility cloak is shown in Figure 9.14. Metamaterials with special designs can control electromagnetic waves, and an invisibility cloak can work for a range of frequencies. (J B Pendry et al., 2006)

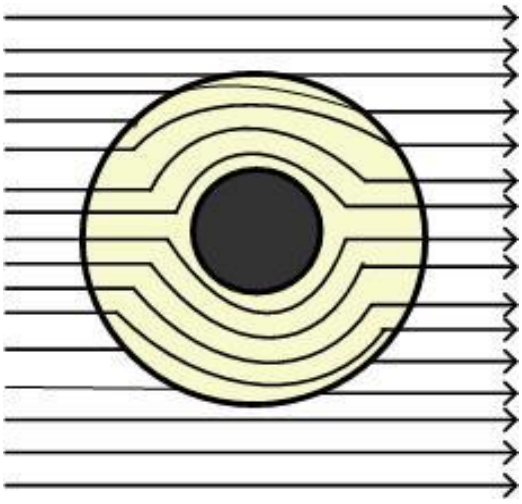
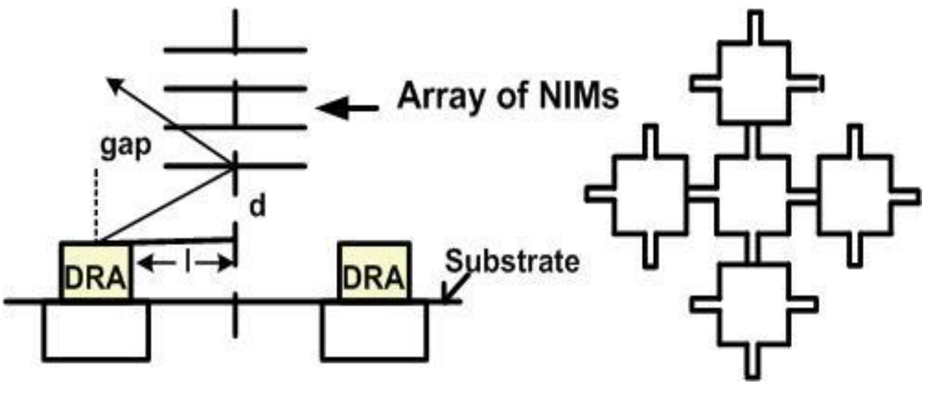


Figure 9.14: Schematic of an invisibility cloak that hides objects from view.

9.4.3 Antenna

Antennas are another prominent application of negative refractive index metamaterial. The beam tilting antenna, in which the NIM array is fixed between two dielectric resonator antennas (DRAs), is shown in Figure 9.15a. When an electromagnetic wave gets into the medium, its propagation direction changes by deflecting the beam because of its negative refractive index, which tilts the beam in the opposite direction and redirects the DRA beam. The beam tilting angle depends upon two important parameters, l and d (shown in Figure 9.15a), but it does not depend upon the number of NIM layers.

The number of NIM layers and the gap between them decides the gain of the antenna. An array of NIM unit cells kept above the DRA is shown in Figure 9.15b. Different experimental and simulation results indicate that by varying the parameters of the NIM structure, the beam tilting angle and the gain of the antenna can be modified. (Li et al., 2017)



(a) (b)

Figure 9.15: (a)A NIM beam tilting antenna installed between two dielectric resonator antennas. (b) Schematic of NIM unit cell.

NIMs are also employed in the fabrication of dynamic beam tilting terahertz antennas. The pattern structure is developed on a p-type Si substrate (dielectric constant 11.7) and coated with SiO2 (dielectric constant 4) to construct an antenna, as shown in Figure 9.16a. In a dynamic beam tilting terahertz antenna, the metallic resonant structure is embedded with graphene, as shown in Figure 9.16b. The chemical potential of graphene is changed by applying direct current (DC) to it. As graphene's chemical potential changes, so do the refractive index values of NIM. Graphene's surface conductivity may be tuned at THz frequencies.

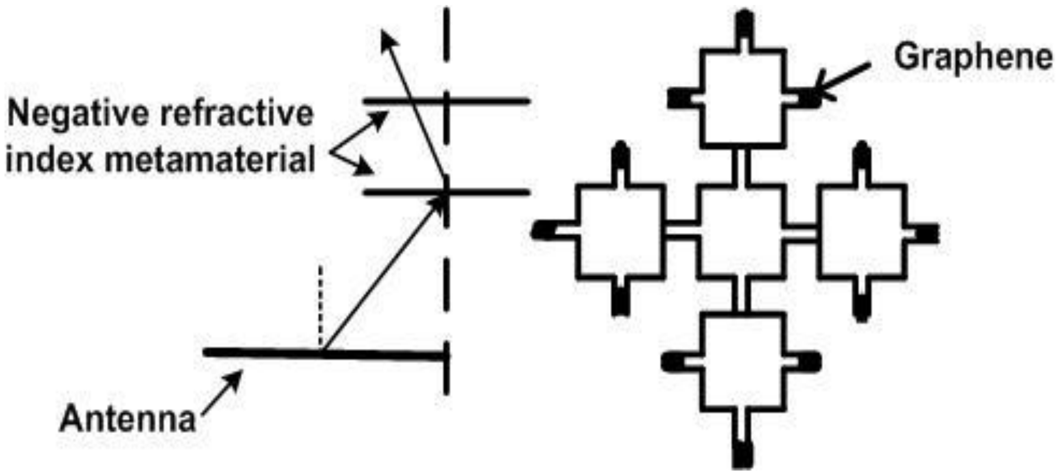


Figure 9.16: (a) Schematic of beam tilting terahertz antenna with NIM. (b) NIM embedded with graphene.

As the refractive index of the negative refractive index metamaterial fluctuates it changes the steering angle of the antenna. As a result, graphene may modify the negative refractive index, paving the way for the development of dynamic beam tilting antennas. (Luo et al., 2019)

9.5 Chiral Metamaterials (CMM), a Unique Technique for achieving Negative Refractive Index

From the above discussion, it can be summarized that a negative refractive index metamaterial must have negative permittivity and negative permeability. Some other methods, such as chiral metamaterials and photonic crystals, do not require these conditions to be completely fulfilled. Chiral metamaterials are artificially fabricated metamaterials that are made up of asymmetric unit cells and also lack mirror symmetry. Photonic crystals, on the other hand, are in order of wavelength and exhibit diffractive phenomena. The structures of CMM are asymmetric, and their phase velocity and group velocity are also in opposite directions, much similar to NIMs. (Smith et al., 2004)

Here, we introduce chiral metamaterials, which consist of asymmetric unit cells that lack an improper axis of symmetry. The optical activity of chiral metamaterials has been reported in the literature. A planar chiral metamaterial with a thickness of just hundreds of nanometers exhibits optical activity, which is a necessary condition for materials to be chiral. (Bai et al., 2007) Tretykov was the first to propose theoretically that chiral structures might exhibit negative refraction. He proposed that materials that have zero permittivity (ε=0) and zero permeability (μ=0) but a non-zero chiral parameter (κ) for a certain frequency range will be termed as chiral nihility materials and used Maxwell's equations to explain the behaviour of such materials. Maxwell's equations for chiral nihility media are shown in Eq. 9 and Eq. 10.

$$\nabla \times \vec{E} = k_0 \kappa \vec{E} \quad (9)$$

$$\nabla \times \vec{H} = k_0 \kappa \vec{H} \quad (10)$$

Where κ is chiral parameter and k_0 is wavevector in vacuum.

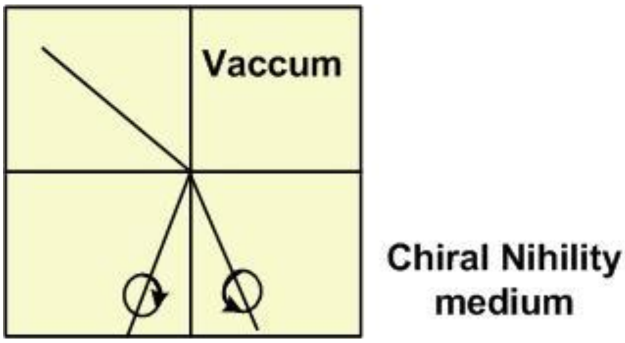


Figure 9.17: Double refraction occurs in chiral nihility material. Both refracted rays are circularly polarized (CP); one circularly polarized light is refracted positively, and the other is refracted negatively.

According to Tretykov et al., the chiral parameter present in chiral nihility material would lift the degeneracy and different refractive indices for different handed circularly polarized light. He proposed when linearly polarized waves travel through the chiral nihility materials double refraction will be observed. Both refracted rays are circularly polarized, one CP component is refracted positively and the other is refracted in negatively (backward refraction). Positive and negative refraction of circularly polarized light through chiral nihility material is shown in Figure 9.17. Chiral composites exhibiting negative refraction theoretical aspect was later explained in terms of the strong resonant interaction between chiral particles and dipoles. Due to these interactions a stop band rises that give rise to negative refraction. The propagation constants of two eigen waves in isotropic chiral mediums are calculated with $\beta = (n \pm \kappa)\, k_0,$ where κ is the chirality parameter, $n = \sqrt{\varepsilon\mu}$ is the refractive index, and k_0 is wavenumber. Around the resonance frequency of chiral particles, one of the eigenwaves show positive refraction and other show negative refraction. (Tretyakov et al., 2005) Experimental results indicate chiral metamaterials exhibit optical activity and circular dichroism. Also show properties of negative refractive index metamaterials without the need for negative permittivity and negative permeability.(Wang et al., 2009) When different handed circularly polarised light strikes chiral metamaterials, they exhibit high gyrotropy, and two distinct refractive indices are observed for different handed circularly polarized light. (Lin & Su, 2003) Density of the material (refractive index) is enhanced for one handed circular polarization and reduced for the other. As a result, one circular polarization is refracted in positive direction while other is refracted inopposite (negative) direction. (Monzon & Forester, 2005; Zhang et al., 2009) Hence, chiral metamaterials exhibit their own characteristic properties and can also be employed as negative refractive index metamaterials.

9.6 Artificially fabricated Chiral Metamaterials exhibiting Negative Refractive Index Properties.

Chiral metamaterial on a copper clad FR-4 board is reported in the literature. On both sides of the board, asymmetric bilayer cross wires were fabricated as shown in Figure 9.18. When an electromagnetic wave travels through chiral metamaterial, it splits into right circularly polarized light (RCP) and left circularly polarized light (LCP), and strong chirality is observed at resonant frequencies. Splitting of EM wave is much similar to natural chiral materials.

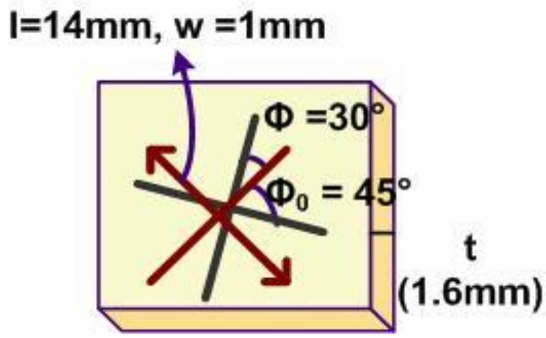


Figure 9.18: Asymmetric bilayer cross wires fabricated on a copper clad FR-4 board show strong chirality and act as chiral metamaterials.

This asymmetric structure exhibits chiral properties such as optical activity, circular dichroism, and strong chirality. Zhou et al. focused on how the chirality present in the metamaterial is sufficient to arise negative refractive index metamaterial properties in the material with no requirement of negative permittivity (ε) and negative permeability (μ). In this work, the refractive index formula was generalized in terms of the chiral parameter. The R.I formula for both handed circularly polarized light (RCP and LCP) is as shown in Eq. 11. Let κ be the chiral parameter, and n_+ and n_- are refractive indices when RCP and LCP strike with the proposed asymmetric structure.

$$n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa \qquad (11)$$

Experimental and simulation results indicate that for both RCP and LCP, chiral metamaterial was able to show a negative refractive index, but compared to LCP, RCP showed a more negative refractive index. The chiral parameter (κ) is a significant factor in Eq. 11. Simulation data recorded on achiral material shows no presence of a negative refractive index. (Zhou et al., 2009) A new design of chiral metamaterial, that exhibit negative refractive index metamaterial properties was proposed by J B Pendry. A continuous insulated metal tape was winded on a cylinder as shown in Figure 9.19. Inner and outer layers of the helix give rise to capacitance and coiled helix structure give rise to inductance. (J. B. Pendry, 2004)

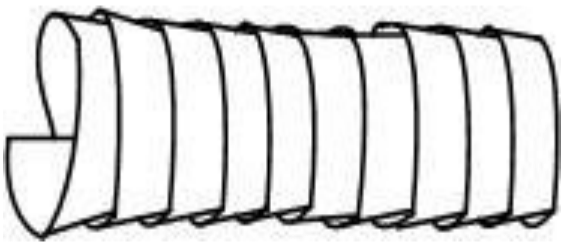


Figure 9.19: Schematic of chiral metamaterial made from an insulated strip of metal.

In the literature, several other structures that exhibit the properties of chiral metamaterials are reported. Zhang et al. fabricated the metamaterial with gold that exhibited chiral properties and worked as the NIM in the THz frequency range. Right circularly polarized light (RCP) and left circularly polarized light (LCP) have different refractive indices due to significant chirality.

Chiral metamaterial was kept between parallel and crossed polarizers, and transmission spectra for RCP and LCP were recorded. Experimental and simulation data revealed that RCP had less amplitude and phase modulation compared to LCP. Due to less modulation of RCP, R.I remains positive while R.I of LCP becomes negative. Here, only the chirality of the system is enough to exhibit NIM properties without the need for negative permittivity (ε) and negative permeability (μ). (Zhang et al., 2009)

9.7 Prospects for the Future

Recent research on negative refractive index metamaterials will undoubtedly aid in understanding negative refractive index metamaterials and their unique features. Their uniqueness enables them to do tasks that are entirely strange and exist only in human imaginations. In numerous ways, these realistically realized metamaterials have transformed the world. Chiral metamaterials maintain their characteristic properties and provide an alternate path to attain properties of negative refractive index metamaterial with no need of negative permittivity and negative permeability.