MUKESH PATEL SCHOOL OF TECHNOLOGY MANAGEMENT AND ENGINEERING

(Affiliated to NMIMS Deemed to be University, Mumbai)

Theory Project
on
"Metamaterials"

Reneeka Nadkarni	**C034**
Amishi Desai	**C044**
Chahel Gupta	**C049**
Aneri Patel	**C056**

B. Tech Integrated Program

Department of Computer Science Engineering

MPSTME, Mumbai

INDEX

Introduction

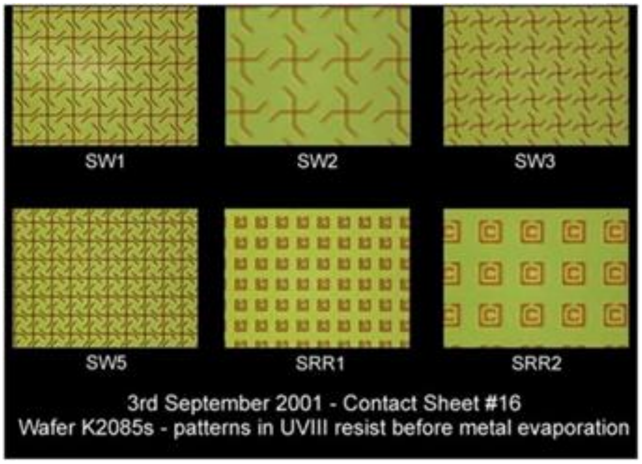
- A metamaterial is defined as an artificial composite that gains its electrical properties from its structure rather than inheriting them directly from the materials it is composed of. This term is particularly used when the resulting material has properties not found in naturally formed substances.
- Metamaterials, which in general can be made in microwave through optical wavelengths, are a subset of a larger group of heterogeneous structures consisting of a base solid material added with elements of a different material. It is an artificially structured material that exhibits extraordinary electromagnetic properties not available or not easily obtainable in nature.
- They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. The materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence.
- The distinction of metamaterials is that they have special, sometimes anomalous, properties over a limited frequency band.
- The properties of metamaterials are tailored by manipulating their internal physical structure. This makes them remarkably different from natural materials, whose properties are mainly determined by their chemical constituents and bonds.
- Since the early 2000s, metamaterials have emerged as a rapidly growing interdisciplinary area, involving physics, electrical engineering, materials science, optics, and nanoscience
- The primary reason for the intensive interest in metamaterials is their unusual effect on light propagating through them.

- Some examples of available metamaterials are negative index metamaterials, chiral metamaterials, plasmonic metamaterials, photonic metamaterials, etc.

History

- The history of metamaterials begins with artificial dielectrics in microwave engineering as it developed just after World War II.
- Yet, there are seminal explorations of artificial materials for manipulating electromagnetic waves at the end of the 19th century.
- Hence, the history of metamaterials is essentially a history of developing certain types of manufactured materials, which interact at radio frequency, microwave, and later optical frequencies.
- As the science of materials has advanced, photonic materials have been developed which use the photon of light as the fundamental carrier of information.
- This has led to photonic crystals, and at the beginning of the new millennium, the proof of principle for functioning metamaterials with a negative index of refraction in the microwave- (at 10.5 Gigahertz) and optical range.
- The theoretical properties of metamaterials were first described in the 1960s by Victor Veselago, who focused on the purely theoretical concept of negative index materials.
- This was followed by the first proof of principle for metamaterial cloaking (shielding an object from view), also in the microwave range, about six years later.
- However, a cloak that can conceal objects across the entire electromagnetic spectrum is still decades away.

- Many physics and engineering problems need to be solved for that.
- Nevertheless, negative refractive materials have led to the development of metamaterial antennas and metamaterial microwave lenses for miniature wireless system antennas which are more efficient than their conventional counterparts.
- Also, metamaterial antennas are now commercially available. Meanwhile, subwavelength focusing with the superlens is also a part of present-day metamaterials research.



Contact sheets of the first photonic metamaterial samples developed at Southampton University

What is a Metamaterial?

- We are familiar with the tools that we use to control light waves. A great example is a magnifying lens or else the lens of an eyeglass. Now, when we think in terms of ray paths, i.e., the direction in which the light travels, it is bent by the shape of the glass so that on the other side light converges and creates a focus or an image, at the spot.

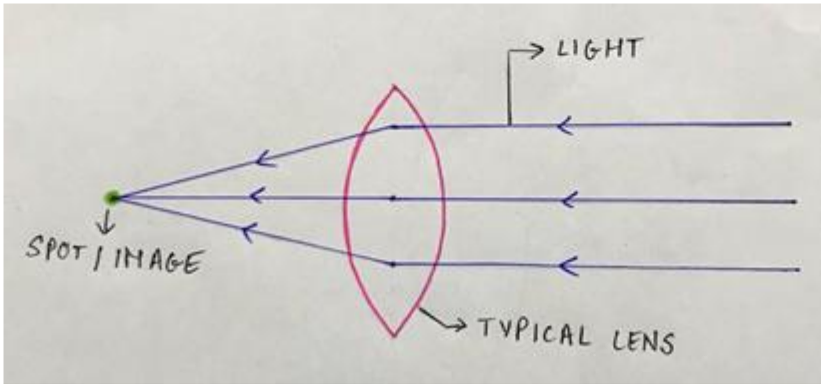


Fig. 1

- From the perspective on how the waves travel, there is an alternative way regarding the functioning of lens. Now in fig 2 there are individual peaks and valleys of the wave fronts of the light waves travelling toward the lens and what happens is in the middle of the lens the light is slowed down while on the edges where the lens is thinner, the light is slowed down less. And so, what happens is the shape of the wavefront as it emerges from the lens is now curved or slowed down, which thus creates a converging wavefront and we get a spot or image similar to what that we had got earlier.

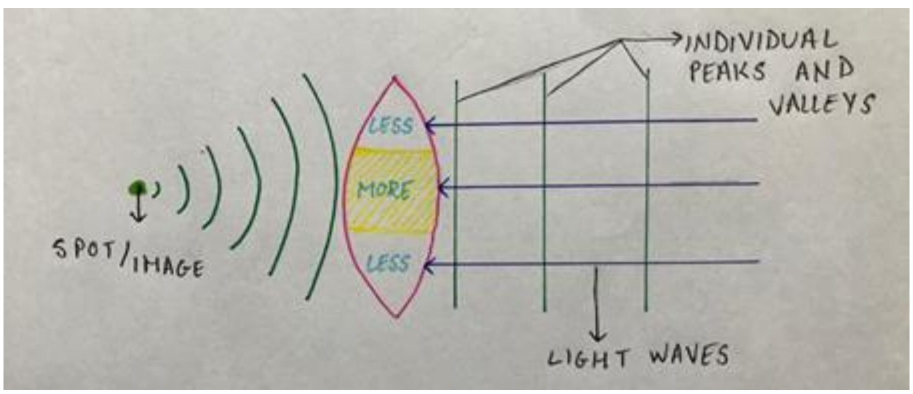


Fig. 2

- We all know that the conventional eyeglass lens specifically work because of this shape. This shape of lens is the core reason which makes them expensive and complicated because we are stuck with the material properties of glass.
- But what if we are no longer struck with the materials properties like glass that are fixed? If we had more flexibility in the material properties, then we could imagine creating a lens that has much similar shape, and we simply need a different material property in the middle of the lens, in order to slow down the light waves there and allow light waves to travel

faster at the edges which would hence require a different material.. And if we had the ability to do that, we could create a lens that does the exact same thing i.e., creates a converging wavefront and an image over here which is as much similar as that we got in a conventional lens.

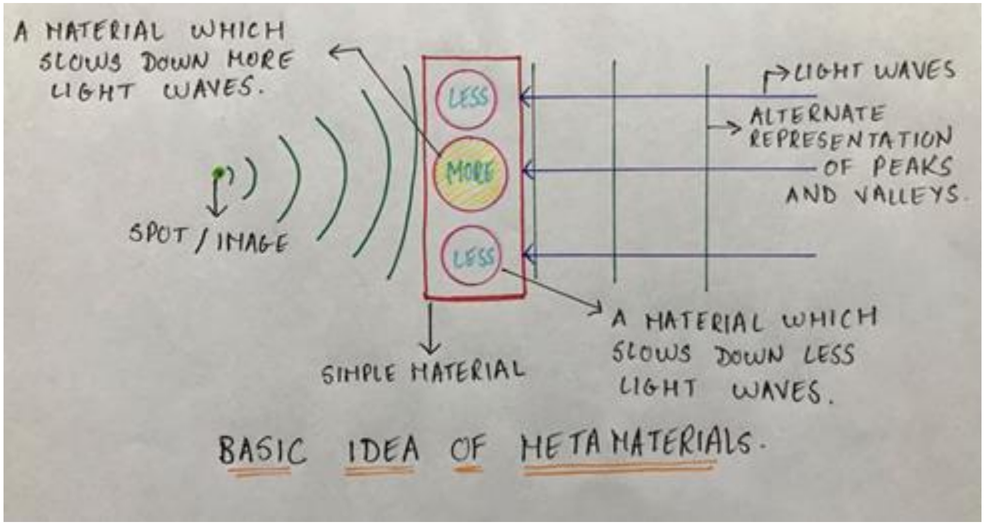


Fig. 3

- The basic idea of how we can control those light waves controlling material properties and that's the basic idea of metamaterials. The most important feature of metamaterials is the wavelength which is the distance between two consecutive crests or troughs. So, while designing a metamaterial, we should consider the wavelength we need to control.

- Engineered microstructure metamaterials demonstrate many intriguing properties for the propagation of electromagnetic waves including negative refraction and negative refractive index. Such materials have been studied extensively during recent years. Typically, the metamaterials are fabricated as composite structures created by many identical resonant scattering elements with the size much smaller than the wavelength of the propagating electromagnetic waves. Such microstructure materials can be described in terms of macroscopic quantities–electric permittivity ε and magnetic permeability $\boldsymbol{\mu}$. By designing the individual unit cells of metamaterials, one may construct composites with effective properties not occurring in nature.

Types of metamaterials

1. *Electromagnetic Metamaterials*

- Electromagnetic metamaterials are man-made materials comprised of structures whose electromagnetic properties are deliberately engineered to offer a range of response difficult or impossible to achieve in naturally occurring materials or composites.
- Metamaterials have become a new sub discipline within physics and electromagnetism (especially optics and photonics).
- They are used for optical and microwave applications such as new types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna radomes.

- **Types of electromagnetic metamaterials:**

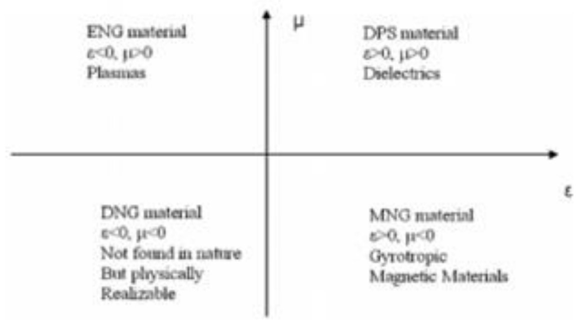
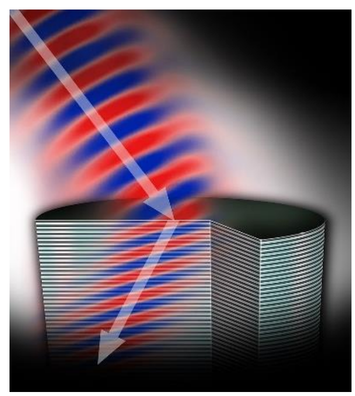


Fig. 1.1: Metamaterial Classification

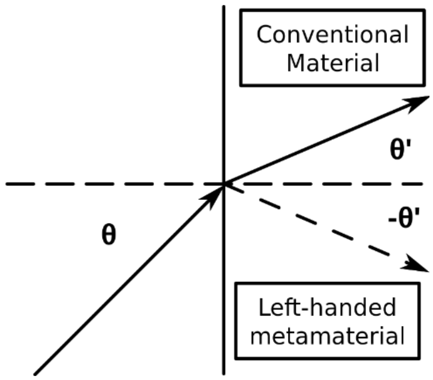
a) *Negative Refractive Index*

- It is the greatest potential of metamaterials to create a structure with a negative refractive index,
- Almost all materials encountered in optics, such as glass or water, have positive values for both permittivity ε and permeability μ.
- However, many metals (such as silver and gold) have negative ε at visible wavelengths.
- A material having either (but not both) ε or μ negative is opaque to electromagnetic radiation.



A negative-index metamaterial causes light to refract, or bend, differently than in more common positive-index materials such as glass lens.

- Although the optical properties of a transparent material are fully specified by the parameters ε and μ, refractive index n is used in practice.
- The above figure shows the refraction in left-handed metamaterial & conventional material.



A comparison of refraction in a left-handed metamaterial to that in a normal material

- All known non-metamaterial transparent materials possess positive ε and μ.
- By convention the positive square root is used for n.
- However, some engineered metamaterials have ε < 0 and μ < 0. Because the product εμ is positive, n is real.
- Under such circumstances, it is necessary to take the negative square root for n.
- Physicist Victor Veselago proved that such substances can transmit light.
- They are being developed to manipulate electromagnetic radiation in new ways.

b) *Double negative metamaterials*

- The third quadrant represents metamaterial, a medium with both permittivity & permeability less than zero (ε < 0, μ < 0) also called double negative material(DNG). Due to the negative μ and negative ε, the refractive index of the medium is calculated to be negative. This class of materials has only been demonstrated with artificial constructs.
- In double negative metamaterials (DNG), both permittivity and permeability are negative resulting in a negative index of refraction.
- DNGs are also referred to as negative index metamaterials (NIM).
- Other names for DNGs are “left handed media”, “media with a negative refractive index”, and “backward-wave media”.
- They are used in the field of sensor and energy transmission technologies.

c) *Single negative metamaterials*

- In single negative (SNG) metamaterials either permittivity or permeability are negative, but not both.

- Interesting experiments have been conducted by combining two SNG layers into one metamaterial.
- These effectively create another form of DNG metamaterial.
- A slab of ENG material and slab of MNG material have been joined to conduct wave reflection experiments.

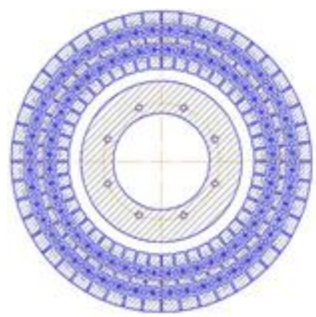
  (The second quadrant represents a medium with permittivity less than zero & permeability greater than zero ($\varepsilon < 0$, $\mu > 0$), electric plasmas supporting evanescent waves and are also called as Epsilon negative (ENG) medium. In certain frequency regimes many plasmas exhibit this characteristics.

  The fourth quadrant represents a medium with both permittivity greater than zero & permeability less than zero ($\varepsilon > 0$, $\mu < 0$) are called as μ negative (MNG) medium. In certain frequency regimes some gyrotropic material exhibits this characteristic.)

- This resulted in the exhibition of properties such as resonances, anomalous tunnelling, transparency, and zero reflection.
- Like DNG metamaterials, SNGs are innately dispersive, so their permittivity å, permeability μ, and refraction index n, will alter with changes in frequency.

d) *<u>Electromagnetic bandgap metamaterials</u>*

- Electromagnetic bandgap metamaterials control the propagation of light.
- They are structures that create a stopband to block electromagnetic waves of certain frequency bands by forming a fine, periodic pattern of small metal patches on dielectric substrates.
- This is accomplished with either a class of metamaterial known as photonic crystals (PC), or another class known as left-handed materials (LHM).



- Both are a novel class of artificially engineered structure, and both control and manipulate the propagation of electromagnetic waves (light).

e) *<u>Double positive medium</u>*.

- The first quadrant represents a medium with both permittivity & permeability greater than zero ($\varepsilon > 0$, $\mu > 0$) are called as double positive (DPS) medium. Most occurring media (e.g. dielectrics) fall under this designation. The forward propagation of wave takes place in the first quadrant. it is commonly used material and follows the right hand thumb rule for the direction of propagation of waves.

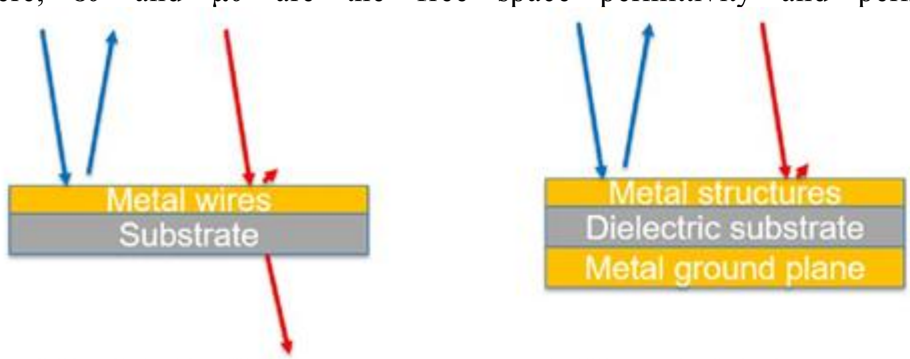
- Double positive mediums (DPS) do occur in nature such as naturally occurring dielectrics.

- Permittivity and magnetic permeability are both positive and wave propagation is in the forward direction.

2. ***Metamaterial Absorber***

- Metamaterial absorbers have received significant attention owing to their ability of achieving complete absorption of the electromagnetic waves with deeply subwavelength profiles.
- A metamaterial absorber is a type of metamateral intended to efficiently absorb electromagnetic radiation such as light.
- Furthermore, metamaterials are an advance in materials science.
- Hence, those metamaterials that are designed to be absorbers offer benefits over conventional absorbers such as further miniaturization, wider adaptability, and increased effectiveness.
- There are two general theories that explain the origin and underlying physics for achieving perfect absorbtion in metamaterials.
- The first one is: Impedance matching theory and the other is Interference Theory

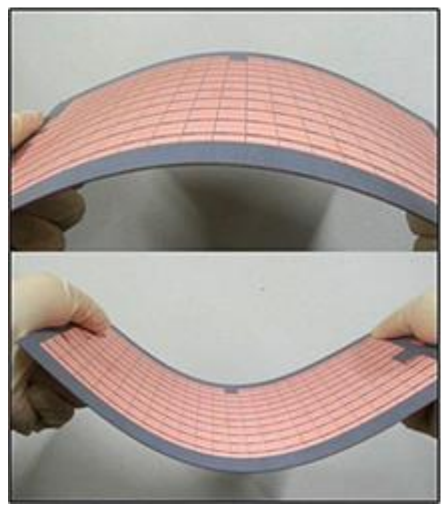
- *Impendence Matching Theory*:
  - ➢ The first theory is by designing both electric and magnetic resonances in a metamaterial, so that the effective permittivity and permeability of the metamaterial can be tailored for achieving impedance matching with free space.
  - ➢ In such a case, no reflection occurs at the interface and the entire incident energy has a chance to be absorbed inside the metamaterial absorber.
  - ➢ A metamaterial absorber is typically a sandwiched structure, consisting of an array of certain metallic patterns on one side of a substrate and backed with a highly conductive metallic ground plane.
  - ➢ The electric permittivity and magnetic permeability of the metamaterial are $\varepsilon=\varepsilon 0\varepsilon r(\omega)$ and $\varepsilon=\varepsilon 0\varepsilon r\omega$ and $\mu=\mu 0\mu r(\omega)$ and $\mu=\mu 0\mu r\omega$, respectively.
  - ➢ Here, $\varepsilon 0$ and $\mu 0$ are the free space permittivity and permeability.



Wire grating film

Metamaterial absorber

- *Interference Theory:*
  - This is the second theory which is based on the destructive interference of multiple-order reflections due to the multiple inner reflections inside the dielectric substrate.
  - A metamaterial absorber can be regarded as a coupled system and, particularly, its magnetic resonance is induced due to the anti-parallel currents between the front and back metallic layers.
  - However, we may also independently consider the functionalities of the front meta-layer and the ground plane on the other side.
  - The front layer with certain metallic patterns functions as a partial reflection surface, which can be utilized to modify the complex reflection and transmission coefficients.
  - On the other hand, the highly conductive ground plane works as a perfect reflector, offering a phase delay of 180° to the electromagnetic wave reflecting on it.
  - Metamaterial absorbers can be used to improve the performance of photodetectors.
  - Skin depth engineering can be used in metamaterial absorbers in photovoltaic applications as well as other optoelectronic devices, where optimizing the device performance demands minimizing resistive losses and power consumption, such as photodetectors, laser diodes, and light emitting diodes.
  - They can be broadly classified into 4 subtypes namely: Narrowband metamaterial absorber, Broadband metamaterial absorber, Frequency tunable metamaterial absorber, Coherent metamaterial absorber.
  - Intended applications for the metamaterial absorber include emitters, photodetectors, sensors, spatial light modulators, infrared camouflage, wireless communication, and use in solar photovoltaics and thermophotovoltaics.



Properties of Metamaterials

The response of a system to the presence of an Electromagnetic field is determined by the properties of the materials involved. These properties are described by defining the macroscopic parameters permittivity ε and permeability μ of these materials.

The properties of metamaterials can be discussed based on the type of metamaterial:

- Mechanical or elastic metamaterials:

  Mechanical or elastic metamaterials are the artificial composite metamaterial consisting of different types of mechanical properties, these types of Metamaterials have Negative Poisson’s ratio, Negative Elastic Modulus, Frictional properties and zero Shear Modulus. These metamaterials use different parameters to achieve a negative index of refraction in materials that are not electromagnetic. These are made up of material with a controlled pored structure or inclusion of secondary materials.

- Acoustic or phononic metamaterials:

  Acoustic or phononic metamaterials can exhibit acoustic properties not found in nature, such as negative effective bulk modulus, negative effective mass density, or double negativity. They find use in (mostly still purely scientific) applications like acoustic subwavelength imaging, superlensing, negative refraction or transformation acoustics. For acoustic metamaterials, both bulk modulus and density are component parameters, which define their refractive index. In certain frequency bands, the effective mass density and bulk modulus may become negative. This results in a negative refractive index.

- Metamaterials with negative longitudinal and volume compressibility transitions:

  In a closed thermodynamic system in equilibrium, both the longitudinal and volumetric compressibility are necessarily non-negative because of stability constraints. For this reason, when tensioned, ordinary materials expand along the direction of the applied force. It has been shown, however, that metamaterials can be designed to exhibit negative compressibility transitions, during which the material undergoes contraction when tensioned (or expansion when pressured). When subjected to isotropic stresses, these metamaterials also exhibit negative volumetric compressibility transitions. In this class of metamaterials, the negative response is along the direction of the applied force, which distinguishes these materials from those that exhibit negative transversal response (such as in the study of negative Poisson's ratio).

- Thermal metamaterials:

Thermal metamaterials have amazing properties in heat transfer beyond naturally occurring materials owing to their well-designed artificial structures. The idea of thermal metamaterial has completely subverted the design of thermal functional devices and makes it possible to manipulate heat flow at will. It is the basis of transformation theory which is used for thermal cloaking, i.e, cloaking by using controlled heat flow. The above two pioneering works started up the study of manipulating heat flow by using artificial structures. But they are confined to steady states, namely, the temperature distribution of the whole system is independent of time.

Other properties exhibited by Metamaterials

Victor Veselago's Concept

- Russian physicist Victor Veselago first investigated left-handed metamaterials in the late 1960s. In 1968, Veselago published a paper that theoretically described the electromagnetic properties of a hypothetical material with simultaneously negative values for the electric permittivity and the magnetic permeability.
- Veselago concluded that a material such as this would have a negative index of refraction.
- This conclusion carried enormous implications for almost all electromagnetic phenomena.
- A negative index of refraction would reverse the Snell effect at the interface between a left-handed material and a normal material. For example, light that enters a left-handed material from a normal material will undergo a refraction that is opposite to what usually occurs.

Negative Refractive Index

- Snell's law states that the relationship between angle of incidence and refraction for a wave impinging on an interface between two media with different incidences of angle is always constant, The law follows from the boundary condition that a wave be continuous across a boundary, which requires that the phase of the wave be constant on any given plane.
- The greatest potential of the Metamaterial is to create a structure having the negative refractive index, negative permittivity, and negative permeability that is not found in the non-synthetic materials.
- Refractive index in the third quadrant is negative in the Snell law. In metamaterials or left-handed materials light is refracted in a contrary way as compared to the normal refractive materials.
- N. Engheta (2006) described that an incident wave faces negative refraction at the interface Ray bends in inside direction after refracting into the medium which is contrary to positive index medium as shown in figure:

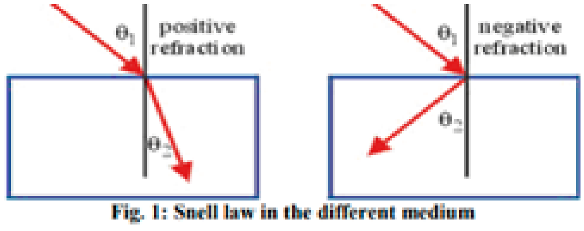


Fig. 1: Snell law in the different medium

Inverse Doppler Effect

- The Doppler effect refers to the change in frequency of a wave source as a consequence of the relative motion between the source and an observer.
- Veselago theoretically predicted that materials with negative refractions can induce inverse Doppler effects. With the development of metamaterials, inverse Doppler effects have been extensively investigated.
- However, the ideal material parameters prescribed by these metamaterial design approaches are complex and also challenging to obtain experimentally.
- These omni-directional, double-negative, acoustic metamaterials are constructed with ‘flute-like’ acoustic meta-cluster sets with seven double meta-molecules; these metamaterials also overcome the limitations of broadband negative bulk modulus and mass density to provide a region of negative refraction and inverse Doppler effects.

Synthesis

A. Synthesis using Genetic Algorithm (GA)

- Metamaterials are artificially synthesized periodic structures with lattice constant that is much smaller than the wavelength of the incident electromagnetic wave, thus considered as homogeneous media.
- The idea of the GA came from Charles Darwin's theory of evolution, natural selection or survival of the fittest. In the GA, the structure of the metamaterial is encoded using a binary string filled with "1's" and "0's" representing metal and free space, respectively. (like in Darwin's theory instead of using two sets of chromosomes, we are using 1's and 0's)
- Generating structures by computer shows the typical FSP (Filling Square Pixel) method. How genetic algorithm is used:
  1. The metamaterial is formed by the elementary metallic patches printed on one side (x-z plane) of the dielectric substrate, which is a 1.5-mm-thick FR4 with relative permittivity εr = 4.4.
  2. Since our interest frequency is in the range of 4~10 GHz, the artificial lattice constant is ax = ay = az = 7.5 mm, which assures to be 1/4 ~ 1/10 the wavelength of the electromagnetic wave.
  3. Then discretize the unit cell into many elements (square-pixels or beehive-cells); each element can be filled by metal or in free space (ε0 = 1). Here we define Ns and Nc as the number of elementary patches at each side for the FSP and FBC method, respectively.

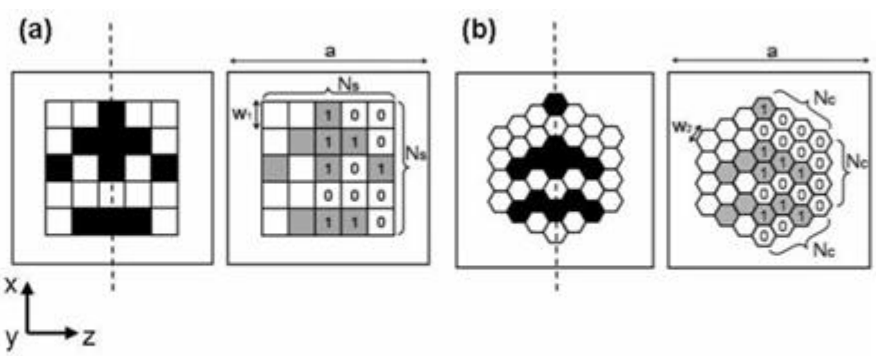


Fig. 1. Illustration of (a) filling square-pixel (FSP) and (b) filling beehive-cell (FBC) method for the structural design of a metamaterial unit cell. The lattice constant $a_x = a_y = a_z = a$ is set to 7.5mm. The dimensions of the metallic patches are $w_1 = 0.8$ mm, $w_2 = 0.55$ mm for $N_s = N_c = 7$, and $w_1 = 0.5$ mm, $w_2 = 0.35$ mm for $N_s = N_c = 11$.The thickness of the substrate (FR4 with ε_r = 4.4) and the metallic patches are 1.5 mm and 0.035 mm, respectively.

- The structure is forced to be mirrored to ensure the 1D-symmetry of the metamaterial. Although this CAD approach seems to be ideal as a variety of structures can be discovered, the problem is that the total number of possible structures are too many. The For the FSP method, the total number of possible structures are 2.6×10^8 and more. Therefore, the full search method is not practical.
- For problems involving such a large search space, it is also impossible to land the result in the global optimum by the gradient-based local search method. As a result, the GA technique should be introduced to automatically generate the optimal structure.

- The GA is a very powerful and attractive optimization tool, and has been applied to several electromagnetic problems, such as the microwave antennas, photonic crystals, ion-optics, and some other metamaterial designs like in the synthesis of metamaterials by FSP method.

B. Bio enabled synthesis

- In metamaterials, artificially structured mesoscopic inclusions usually replace the atoms and molecules of conventional materials.
- Elastic metamaterials can exhibit a negative effective Young modulus, i.e., an increasing volume under a compressive triaxial stress. The electromagnetic counterpart of elastic metamaterials is represented by optical metamaterials with a negative index of refraction.
- Composite architectures have been proposed that exhibit magnetic properties despite the nonmagnetic character of their constituents. As a result of its technological promise for optical super-resolution and other imaging applications, the field of optical metamaterials is currently experiencing growth.
- As with conventional materials, properties of metamaterials can be described by a small set of effective material constants, provided the operating wavelength, be it elastic or electromagnetic, is much larger than the spatial period characterizing the particular arrangement of mesoscopic subunits.
- The presence of defects in the periodic arrangement changes these properties and interferes with the wave propagation. Fabrication methods are required to achieve three-dimensional (3D) lattices with accuracies in the placement of the building blocks that are better than a fraction of the wavelength.
- For negative index of refraction metamaterials, the building blocks have to exhibit an optical resonance at wavelength, which can be achieved by using metal inclusions that support surface plasmon resonances. Plasmons are collective oscillations of the valence electrons that have close to X-ray wavelengths at optical frequencies. Therefore, with a wavelength that is significantly shorter than the vacuum wavelength of light, the requirement for accurate positioning of a plasmonic lattice element becomes even more stringent.

Applications

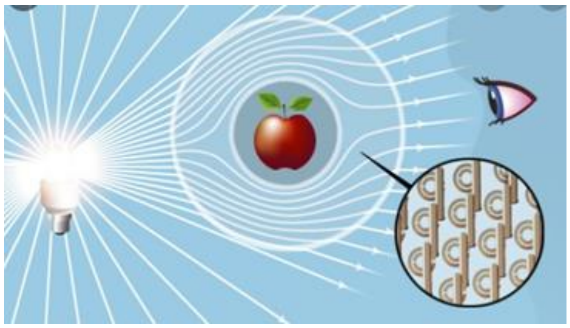
1. ***Broadband ground-plane cloak/ Metamaterial Cloaking***

What is Cloaking/Invisibility?

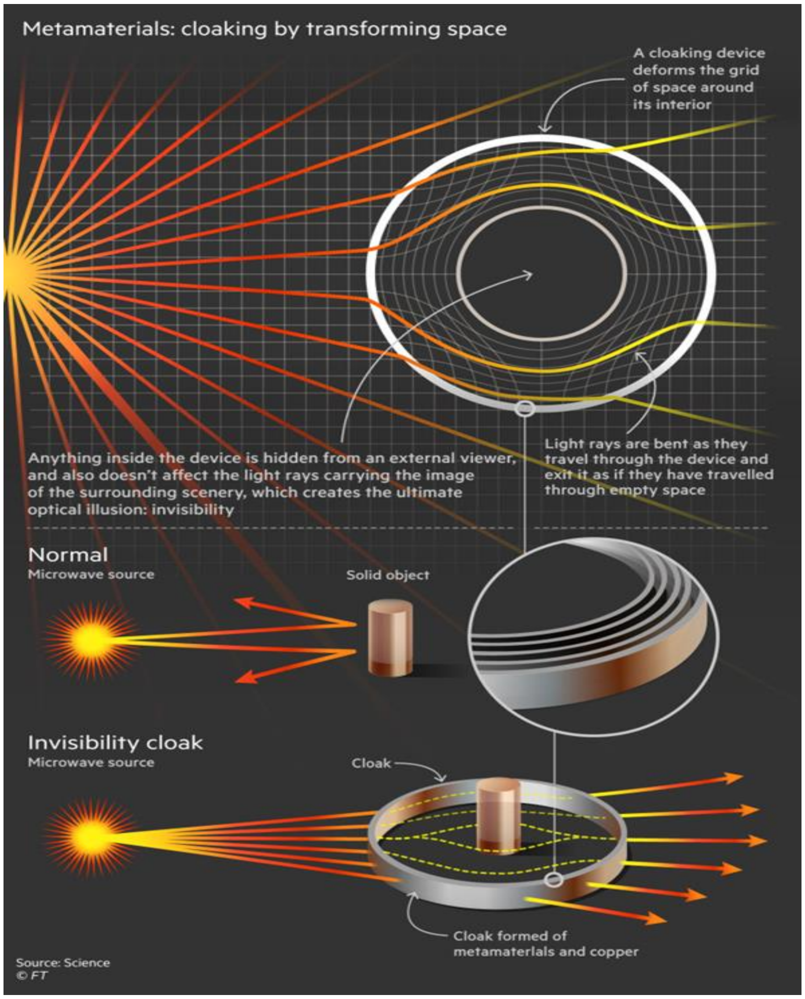
- An object is invisible if it does not reflect waves back to the source and if it does not scatter waves in other directions, thus it does not create any shadow.
- In other words, the object does not absorb any power and should not disturb the fields existing outside the object.
- In terms of the theory of scattering of electromagnetic waves (including light), to "cloak" an object means to reduce its total scattering cross section, to almost zero. The cloak decreases scattering from the hidden object while at the same time reducing its shadow, so that the cloak and object combined begin to resemble empty space.

A Cloaking Device:

- The first functioning cloak made objects invisible to microwaves rather than to visible light. Since metamaterials can control electromagnetic waves, they were used to improve the performance of satellite antennas and sensors instead.
- However, engineer José Azaña reported that they had developed an invisibility cloak technology in the form of a cloaking device that could make objects invisible in daylight. The optical filter manipulates the various frequencies of visible light, like the wavelengths of red, blue and green. The filter works by shifting one frequency of light to another as the light passes through a particular object, for instance, the filter would shift the red wavelength of light passing over an apple to another frequency, making the apple seem invisible.



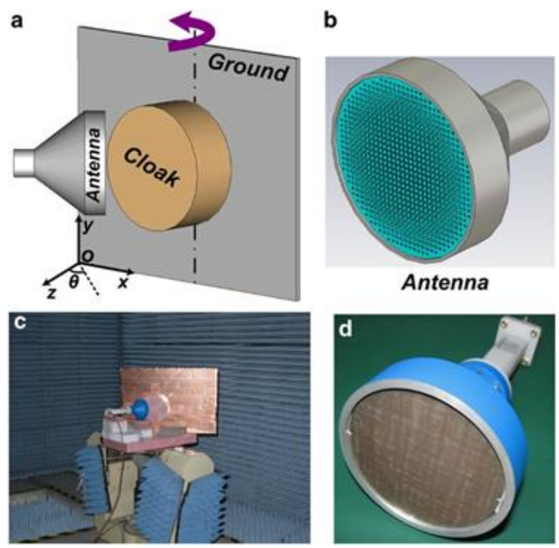
- This filter can be used to cloak military operations or be used in telecommunications to improve radio signals.

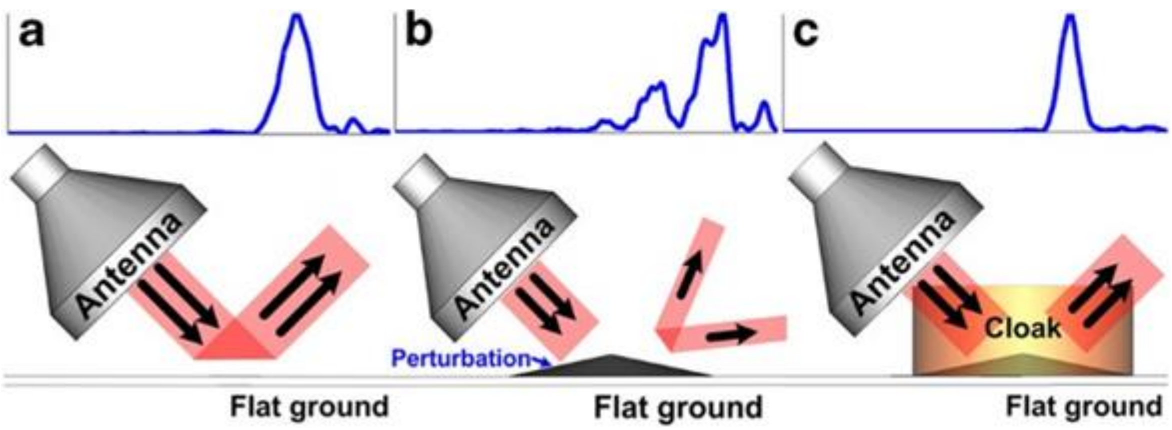


Three-dimensional broadband ground-plane cloak made of metamaterials:

- The first practical implementation of a 3D broadband and low-loss ground-plane cloak at microwave frequencies was realized by drilling inhomogeneous holes in multi-layered dielectric plates, it can conceal a 3D object located under a curved conducting plane from all viewing angles. It is based on optical transformation theory which has provided complicated electromagnetic and optical devices by controlling the paths of wave propagation.
- When the incoming electromagnetic waves are guided to propagate around a metamaterial shell region and return to their original propagation paths without interacting with the object inside, the metamaterial shell is called a free-space invisibility cloak. This cloak is used to compress the object into a point.

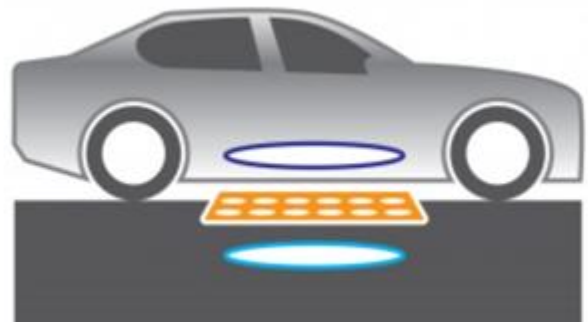
- Unlike free space cloaks, the ground-plane cloak crushes the hidden object to a conducting sheet instead of a point. So, the hidden object appears as a flat conducting sheet.
- Experimental demonstration of the ground-plane cloak used the microwave frequencies. I-shaped non-resonant metamaterial structures were used to construct the cloak, as it has good cloaking properties of broadband and low loss.
- Unfortunately in the experiments the cloaking devices were 2-D and were performed on a 2D planar waveguide.
- The 3D ground-plane cloak has important potential applications in the microwave frequencies, such as to hide aircrafts on the airport and automobiles on the road from radar detection.





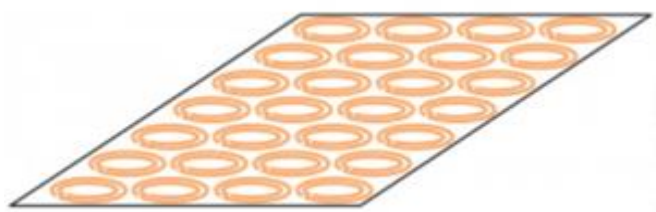
2. ***Wireless Power Transfer (WPT)***

- Wireless power transfer (WPT) technologies have attracted a lot of attention in recent years. The applications of WPT technologies include: low-power consumer electronics , implanted medical devices, high-power industrial and electric vehicle applications.
- WPT was first pursued by Tesla over 100 years ago. However, safety, efficiency, and other issues have prevented WPT from real applications in our daily life.
- Metamaterials can be used as a means of "channeling" the energy from the transmitter to the receiver.

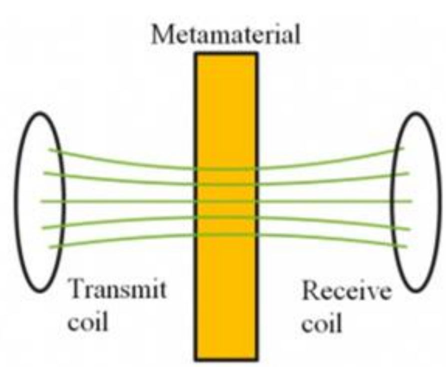


Wirelessly charging the electric vehicle

- Electric permittivity (ε) and magnetic permeability (μ) are important factors in WPT.
- A common type of metamaterial is inductors arranged on a plane in a regularized manner.
- Inductors have self-resonance properties at a certain frequency.



- This arrangement of inductors can be equivalent to a slab of metamaterial having certain values of permittivity and permeability. Thus, depending on the frequency, the values of permittivity and permeability can be below zero.
- When illuminated by an incident electromagnetic wave, metamaterials refract the wave and change the direction of propagation (like when light moves from one region of lower density to a region of higher density). Here, with permittivity and permeability below zero, the bending occurs in a "negative" direction.



The slab of metamaterial is placed in the centre

- At the frequency of the transfer the magnetic permeability is less than zero, then the slab of metamaterial acts as a magnetic lens, changing the direction of the magnetic field and focusing it toward the receiver coil.

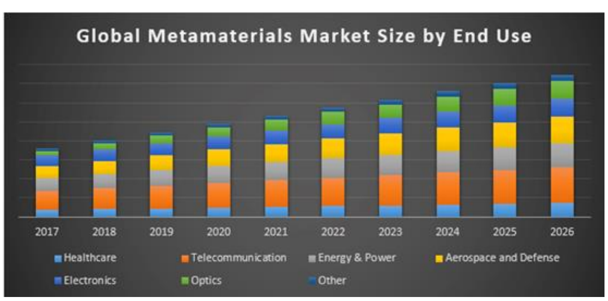
- Therefore, a slab of metamaterial can be placed between transmit and receive coils in order to enhance the efficiency of the power transfer.

3. Increase in Usage of Antennas for Communication

- Recently, there has been an increased interest in microwave applications across the telecommunication sector. Metamaterials can be engineered to produce exotic electromagnetic signals. These materials exhibit various refractive properties, such as negative refractive index (NRI) and left-handed material (LHM). For this reason, such materials are indispensable in the manufacture of microwave components, and in the design and manufacture of high-functioning antennas.
- A negatively permeable metamaterial shell is utilized to enclose loop antennas in magnetic induction (MI) communication systems. It has been theoretically proved that a communication range of around 20m can be achieved with acceptable data rates, by using metamaterial-enhanced MI communication systems and pocket-sized loop antenna. Thus, the usage of these materials in remote environments can have significant impact on connectivity.
- The usage of metamaterial antennas have been increasing over the past few years. The demand for such antennas is due to their use in vessels, radar, and special smartphones.
- Using metamaterials in antennas enables an individual to focus six times beyond the diffraction limit at 0.38 µm. These metamaterials are used in cell phones to provide antennas, which are five times smaller and have a bandwidth range of 700 MHz - 2.7 GHz.
- Currently, scientists are engaging in the research of wide angle impedance matching (WAIM) technology. It has been proven that metamaterials can be used to achieve superior wide angle impedance for phased array antennas.
- The aforementioned factors are expected to increase the demand for metamaterials, during the forecast period.

Future uses of metamaterials

- Scientists are also making significant progress into honing the properties of materials to create protective shields against radiation and seismic activity.
- Barriers made of metamaterials would absorb or deflect seismic waves, thus reducing the risks and impact posed by earthquakes. This works very differently from traditional materials so it is entirely possible that future cities could be built using materials that offer more robust protection against earthquakes and other natural disasters than ever before.
- Apart from shielding and absorbing waves, metamaterials can also help us tap off some of the energy these waves carry.
- Metamaterials can be designed to trap, convert and recycle this energy. With prospective application in advanced solar batteries and residual radio-noise harvesting, metamaterials are in the spotlight of breakthrough greener technologies .
- With the ability to control the propagation of waves, metamaterials are also enabling scientists to take power and data transfer to the next level. Specific types of waves, such as magneto-inductive waves, existing in the metamaterial, can carry power in a controlled manner.
- This phenomenon has paved the way for scientists to significantly expand wireless charging for mobile phones and other electronic devices.
- For an individual, a metamaterials-based charger will mean hassle-free charging on large surfaces – one can just drop a device onto the charging surface without the need to worry about alignment.
- This is a huge step towards making wireless power as ubiquitous and convenient as modern data connectivity.
- Including many aspects of physics and engineering, metamaterials offer new possibilities for developing technologies for smart cities, houses and transport and could help reduce costs, increase security and safety and lessen environmental impact all in one go.
- In addition, the design of future medical and health technologies could employ metamaterials to help enhance product features, particularly where personal data security is paramount or where very high-quality imaging is needed.
- Metamaterials have opened up a new treasure chest of possibilities for safer, greener and more effective and efficient technologies.
- If metamaterials technologies keep up the pace, metamaterials will be used extensively yet unobtrusively in our daily lives.
- Undoubtedly, these are exciting times for metamaterials and the next decade will carve out their place in the world of technology and engineering.

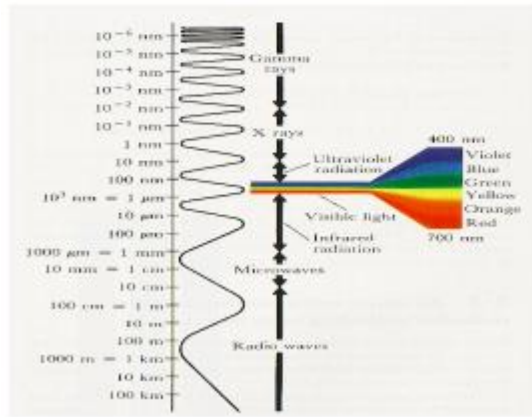


Advantages

- The advantages of metamaterials are that their effective medium properties can be controlled by designing the macro units to constitute special materials that do not exist in nature.
- Metamaterial is a research area with importantly theoretical significance and challenges, which has achieved significant breakthroughs in theory. Metamaterials can save lives and prevent catastrophes when you are able to protect and redirect seismic waves away from complexes and other important setups.
- The Army is exploring metamaterials to develop biological and substance detectors. These metallic nanostructures react electromagnetically to incoming molecules detecting single molecules that could be of great use for passenger or cargo verification.
- Using metamaterials in antenna design may lead to size reduction, gain or bandwidth enhancement. It seems that antenna miniaturization is the most promising advantage and there are some commercial miniaturized antennas that use metamaterials.

Limitations

- Although the theoretical applications of metamaterials are broadening, the intrinsic limitations of the material become more prevalent.
- For smaller wavelengths, a smaller unit is required to design. As discussed before, the material must be considered a uniform mass and loses effective qualities if this assumption is not met. That is, if the wavelength being manipulated is very small, it becomes very difficult to manufacture units that are small enough to be considered uniform.



- Researchers have successfully developed metamaterials that can redirect microwaves and infrared radiation that have relatively large wavelengths. Visible light, however, ranges from 400nm to 700nm wavelength. Only the largest of these wavelengths (red light) has successfully been cloaked against in the laboratory.
- Different wavelengths require a meta-atom of different dimensions.

- Another intrinsic limitation of metamaterials is that each metamaterial is designed and tuned to operate with a specific wavelength. That is, only when encountering this specified wavelength can the material redirect and manipulate the waves.

- This leads to obvious difficulties in cloaking the entire visible light spectrum. (For example, an object that is being cloaked in red light will still be visible in violet light. In response to this limitation, researchers have developed a new branch of metamaterials called frequency selective surfaces (FSS). FSS, also called tunable metamaterials, are designed so that they can handle a range of wavelengths. This does not mean that these materials can handle more than one wavelength at a time; rather, they can be tuned to a specific known wavelength within its range of capability.)
- The designing and execution process is very expensive.

- Although we have thorough knowledge of theoretical concepts of invisibility but we do not have enough practical implementation of these concepts.

- Metamaterials still need more consideration and a lot has remained undiscovered and needs thorough study.

Conclusion

Metamaterials are artificial structures composed of periodic or nonperiodic subwavelength macro cells and they exhibit extraordinary electromagnetic properties not available or not easily obtainable in nature. The materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence. While designing a metamaterial, we should consider the wavelength we need to control. Since the early 2000s, metamaterials have emerged as a rapidly growing interdisciplinary area, involving physics, electrical engineering, materials science, optics, and nanoscience. They can be described in terms of macroscopic quantities–electric permittivity ε and magnetic permeability μ. Negative refractive materials have led to the development of metamaterial antennas and metamaterial microwave lenses for miniature wireless system antennas which are more efficient than their conventional counterparts. The metamaterials can be applied to improve bandwidth, power gain, or to create compact, multifrequency-band antennas. Effectiveness of improving the parameters of the antenna depends on the structure, size, quantity, and method of use of the unit cell of the metamaterials. While designing a metamaterial, we should consider the wavelength we need to control. Although we have thorough knowledge of theoretical concepts of invisibility but we have not enough practical implementation of these concepts. Metamaterials still need more consideration and a lot has remained undiscovered and needs thorough study.

References

- http://csjournals.com/IJITKM/PDF%204-1/17.Shridhar%20E.%20Mendhe1%20&%20Yogeshwar%20Prasad%20Kosta2.pdf
- https://en.wikipedia.org/wiki/Metamaterial#History
- https://www.ijariit.com/manuscripts/v4i3/V4I3-2011.pdf
- https://www.sciencedirect.com/topics/materials-science/metamaterials#:~:text=A%20metamaterial%20is%20defined%20as,naturally%20formed%20substances%20%5B51%5D.
- https://www.slideshare.net/NishargoNigar/metamaterial-69680131
- https://www.britannica.com/topic/metamaterial
- https://www.slideshare.net/SaktiPrasannaMuduli/metamaterials-a-great-achievement-of-material-science
- https://metamaterial.com/technologies/metamaterials-and-functional-surfaces/
- https://www.slideshare.net/MTarunkumarreddy/metamaterialsppt
- https://link.springer.com/chapter/10.1007/978-3-319-48933-9_56
- https://www.researchgate.net/publication/323156879_An_Overview_of_Metamaterials_and_Their_Achievements_in_Wireless_Power_Transfer
- https://www.waves.utoronto.ca/prof/gelefth/PIEEE_Oct_2011.pdf
- https://www.researchgate.net/publication/262320155_Metamaterials_Definitions_properties_applications_and_FDTD-based_modeling_and_simulation_Invited_paper
- https://www.ijert.org/research/metamaterial-materials-with-exceptional-properties-IJERTCONV2IS03058.pdf
- https://www.nature.com/articles/srep32388#:~:text=An%20inverse%20Doppler%20shift%20in,obtain%20the%20inverse%20Doppler%20effect.
- https://link.springer.com/content/pdf/10.1007%2F978-1-4419-8825-6_16.pdf
- https://www.sciencedirect.com/science/article/pii/S2589004220308294
- https://en.wikipedia.org/wiki/Mechanical_metamaterial#:~:text=Pentamode%20metamaterials%20or%20meta%2Dfluids,-SEM%20image%20of&text=Thus%2C%20it%20has%20a%20finite,five%20(penta)%20vanishing%20eigenvalues.
- https://www.youtube.com/watch?v=s0UZ6-oeiIE
- https://content.metamaterial.com/blog/what-are-metamaterials#:~:text=Metamaterials%20are%20artificial%20materials%20that,of%20refraction%20or%20electromagnetic%20cloaking.
- http://infrared.ucsd.edu/electromagnetic.html#:~:text=Electromagnetic%20metamaterials%20are%20man%2Dmade,naturally%20occurring%20materials%20or%20composites.
- https://www.slideshare.net/NishargoNigar/metamaterial-69680131
- https://www.intechopen.com/books/electromagnetic-fields-and-waves/electromagnetic-field-interaction-with-metamaterials
- https://www.researchgate.net/publication/262320155_Metamaterials_Definitions_properties_applications_and_FDTD-based_modeling_and_simulation_Invited_paper
- https://www.youtube.com/watch?v=gOehU7bYOAs
- https://link.springer.com/book/10.1007/978-981-13-8649-7

- https://news.gatech.edu/2015/06/15/theory-turns-reality-nonlinear-optical-metamaterials
- https://iopscience.iop.org/article/10.1088/2043-6262/5/1/013001
- https://link.springer.com/chapter/10.1007/978-3-319-66044-8_9
- https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-16-25-20266&id=175004
- https://iopscience.iop.org/article/10.1088/1367-2630/12/9/093010/meta
- https://iopscience.iop.org/journal/2040-8986/page/Special-issue-on-the-history-of-metamaterials
- https://www.intechopen.com/books/metamaterials-and-metasurfaces/electromagnetic-metamaterial-absorbers-from-narrowband-to-broadband
- https://onlinelibrary.wiley.com/doi/abs/10.1002/adom.201800995
- https://arxiv.org/abs/1112.5168#:~:text=Here%20we%20present%20a%20different,field%20interactions%20or%20magnetic%20resonances.
- https://www.mwrf.com/technologies/components/article/21846341/metamaterials-provide-technology-for-the-future
- https://www.ijariit.com/manuscripts/v4i3/V4I3-2011.pdf
- https://studybayhelp.co.uk/blog/advantages-of-metamaterials/
- https://www.mordorintelligence.com/industry-reports/metamaterials-market
- https://www.intechopen.com/books/metamaterials-and-metasurfaces/metamaterials-in-application-to-improve-antenna-parameters
- https://www.sciencedirect.com/science/article/pii/S1369702109700720#bib1
- https://www.ft.com/content/c6864c76-de7d-11e7-a0d4-0944c5f49e46
- https://now.northropgrumman.com/engineered-metamaterials-make-invisibility-cloaks-and-more/
- https://science.sciencemag.org/content/314/5801/977
- https://www.nature.com/articles/ncomms2219
- https://www.nature.com/articles/ncomms1023
- https://www.cambridgeconsultants.com/insights/wireless-power-transfer-with-metamaterials
- https://www.merl.com/publications/docs/TR2011-052.pdf
- https://pubmed.ncbi.nlm.nih.gov/20055682/
- https://dragnea.lab.indiana.edu/publications/annurev.physchem%2061%20323%20(2010).pdf
- https://ir.nctu.edu.tw/bitstream/11536/8459/1/000259268700042.pdf