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META-MATERIALS

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ABSTRACT

Meta-material is a word made of two parts; ‘meta’ meaning *beyond* and ‘materials’. They are materials engineered to exhibit properties which are not found in nature. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. The structural elements of these materials are arranged in repeating as well as non-repeating patterns. Meta-materials derive their properties from the base metal i.e., chemical composition as well as from their newly designed structures. Their precise shape, geometry, size, arrangement and orientation give them their smart properties capable of manipulating, absorbing, enhancing as well as bending waves ranging from acoustics to electromagnetic waves to achieve benefits that go beyond what is possible with conventional materials.

Metamaterial research is an interdisciplinary field and involves various engineering domains such as electrical engineering, mechanical engineering, material science, solid state physics and more. Potential applications of metamaterials are diverse and include optical fibres, medical equipment, sensors as well as military operations and aerospace applications.

INTRODUCTION

Material science is one of the most fascinating and challenging areas of science and technology. It is both an old and a new science. It ranges from the Bronze Age to the Quantum Computing Age. It is a discipline that lies between multidisciplinary science and a real basic science. Materials are present in all physical devices and all physical forms in our day-to-day life. In certain application, there are various requirements from a material. In construction of a building, a material’s strength and its ability to sustain high load without disintegrating are important. While, to make a wire, we need ductility and low electrical resistance from a material.

But, with time our needs become more complex, we cannot work now with iron or aluminium alone. Certain engineering applications now ask for use of alloys as they provide benefits that outweigh their costs. They are light in weight and provide comparatively same amount of strength. In the wake of 20th century, scientists developed a way to use polymer chain in form of Bakelite (in 1909 by Leo Baekeland). Since then, various natural metals used in engineering applications have been replaced by synthetic polymers.

There have been increasing interests in metamaterials in the past 10 years in the scientific communities. The term metamaterial was first synthesized by Rodger M. Walser, University of Texas at Austin in 1999. According to him, “*a metamaterial is a macroscopic composite of periodic or non-periodic structure, whose function is due to both the cellular architecture and the chemical composition.*” Although, metamaterials were first described to exhibit reversed physical properties was theoretically proved by Victor Veselago in 1967.

Metamaterials were first known as LHM (Left-Handed Materials) or NIM (Negative-Index Materials). The earliest publication on negative refractive index was in lecture notes of Prof. Mandelstam from Moscow University.

HISTORY OF META-MATERIALS

The history of meta-materials begins with artificial dielectrics in Microwave Engineering developed just after the World War II. As the science of metamaterials progressed, photonic materials were developed that use photons of light as the fundamental carrier of information, which also served as the base for quantum computing technology. This was followed by the first proof of principle for metamaterial cloaking. In 1967, Victor Veselago produced a seminal work on a theoretical material that could produce extraordinary effects that are difficult or impossible to produce in the nature.

Based on his research, many scientists started experimenting with various atomic lattices to make an NIM (Negative Index Material). These materials can be used to refract any electromagnetic radiation in opposite direction to conventional materials. They are now used in building telescopes as they provide an image which has high resolution even below the diffraction limit due to sub-wavelength imaging.

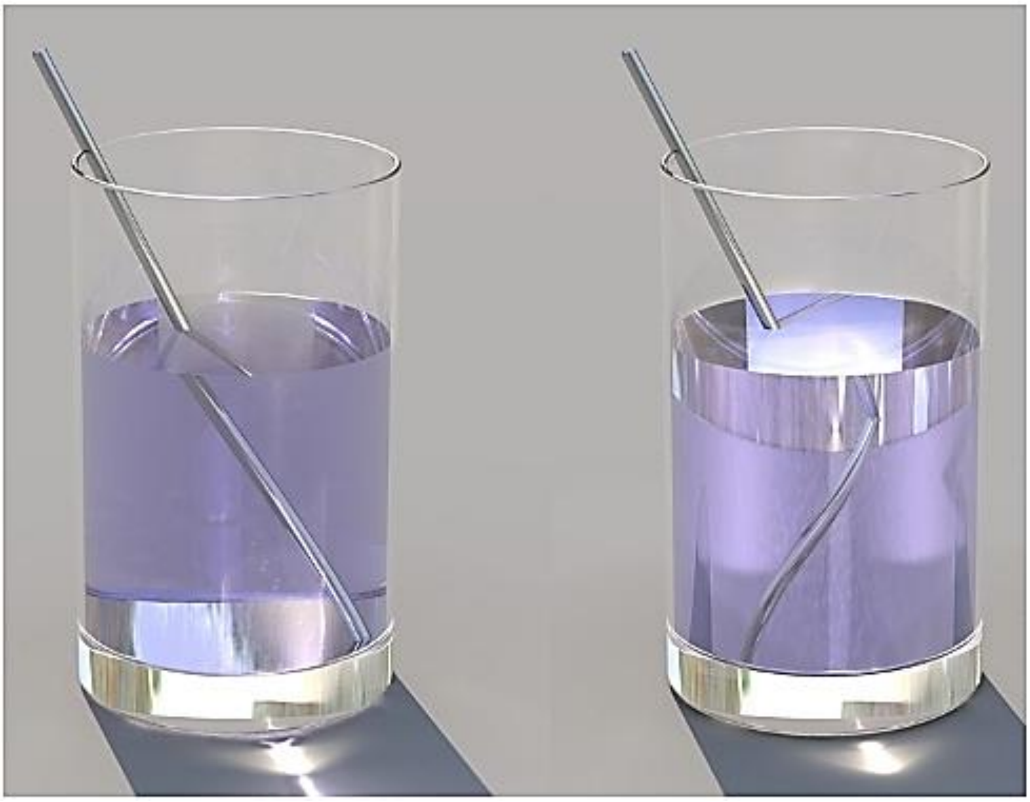


Figure 1: *Normal liquid (left) with positive refractive index. Meta-material liquid (right) with negative refractive index.*

NIM are also used to manufacture flat lenses. As we know, conventional lenses need to be curved in order to focus light rays or deflect light rays. But, by using an NIM lens we can perform the same set of functions while using a flat surface lens, which can be helpful in making compact telescopes and other optical instruments.

Also, in recent years, material scientists have found that combination of these materials can be designed to have desired effects that are not found in nature. In 2000, a team of scientists led by David Smith at University of California, constructed a copper split ring meta-materials that was able to demonstrate negative refractive index with electromagnetic radiation.

Initially, till 2005, metamaterials were thought to be useful only with electromagnetic waves, but today the field is rapidly expanding beyond electromagnetics. It also provided a breakthrough in cloaking devices. In 2009, British military experimented with what is known as active cloaking. It uses video cameras to record landscapes and project it on screens to provide camouflage. But, in 2008, scientists at University of California, Berkeley developed meta-materials with extraordinary capabilities to bend electromagnetic waves in such way that they can be used for cloaking.

Since then, there have been numerous researches to develop meta-materials that exhibit a range of desired properties like acoustic metamaterials, seismic metamaterials, etc. It also encouraged development of self-healing materials that can repair damages by themselves without external interference.

THEORY OF META-MATERIALS

The prefix *meta* indicates that the characteristics of the material are beyond what we see in nature. Metamaterials are artificially crafted composite materials that derive their properties from internal microstructure, as well as from chemical composition found in natural materials.

The core concept of metamaterial is to craft materials using artificially designed and fabricated structural units to achieve the desired properties and functionalities. These structural units – the constituent artificial ‘atoms’ and ‘molecules’ of the metamaterials – can be tailored in shape and size, the lattice constant and interatomic interaction can be artificially tuned, and ‘defects’ can be designed and placed at desired locations.

By engineering, the arrangement of these nanoscale units into a desired architecture or geometry, one can tune the refractive index of metamaterials to positive, near-zero or negative values. For example, a naturally available gold nugget will be yellow in colour, but by re-arranging the atoms on the surface of Gold, we would be able to reflect any desired light like green or blue while still retaining the chemical composition of Gold i.e., Au.

Structurally, metamaterials are very similar to nano-materials but, metamaterials are developed by re-arranging same element’s atoms and molecules, while in nano-material, the structures are limited to the use of carbon atoms only.

Metamaterials can be defined by their two chief properties: Electric permittivity and Magnetic Permeability.

Permittivity is a measure of resistance offered by a material in the formation of an electric field in the medium. It is defined as the ratio of electric displacement to the electric field intensity and is denoted by ε. Its SI unit is Farad/Meter.

$$\varepsilon = \frac{Dielectric\ displacement\ field}{Electric\ field\ intensity} \tag{1}$$

The vacuum characterizes the least value of permittivity. This is commonly referred to as the Permittivity of Free Space or electric constant and is denoted as ε_0. And, its value is 8.85×10^{-12} Farad/meter. Also, for materials relative permittivity (ε_r) is measured as a ratio of the absolute permittivity of materials and electric constant.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{2}$$

This quantity represents the number of charges (electrons) required to generate unit amount of electric flux in the given medium. Higher value of permittivity means, that the material polarizes more in response to an applied electric field than a material with low permittivity.

In materials with negative permittivity, the dipoles in the material will arrange themselves against the applied electric field causing unusual behaviours in the material.

Permeability is the measure of the ability of the material to allow the formation of magnetic lines of force in the presence of a magnetic field. A material with higher magnetic permeability will be easily magnetized in the direction of external magnetic field. It is denoted by μ and is defined as the ratio of Magnitude of magnetic induction to the intensity of magnetic field. Its SI unit is H/m.

$$\mu = \frac{Magnitude\ of\ magnetic\ induction\ (B)}{Intensity\ of\ magnetic\ field\ (H)} \tag{3}$$

The permeability of free space is known as Permeability constant (μ_0)and has the value of $4\pi \times 10^{-7}$ H/m. Magnetic permeability is a scalar quantity in an isotropic medium while it is a second rank tensor quantity in an anisotropic medium. A material with permeability less than μ_0 are known as diamagnetic materials.

As we know that light is an electro-magnetic radiation, both permittivity and permeability of a given medium affect its propagation through that medium. The speed of light in any given medium is square root of the product of inverse of permittivity and permeability.

$$c = \frac{1}{\sqrt{\mu \times \varepsilon}} \tag{4}$$

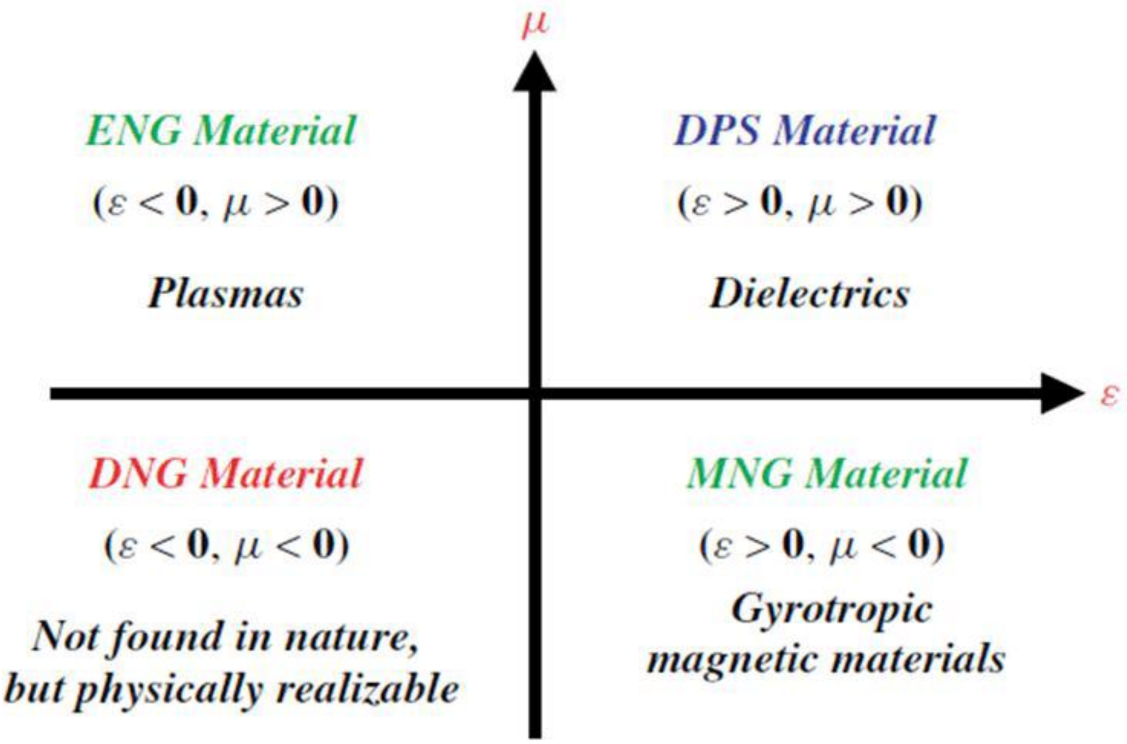


Figure 2

DPS – Double Positive Materials are the most commonly found materials in nature, like iron, glass, etc.

ENG – Epsilon Negative Materials – these materials change the direction propagation of electric fields but do allow magnetic waves to propagate through them.

DNG – Double Negative Material – these are metamaterials and are not found naturally in any form. They alter both aspects of an electromagnetic wave.

MNS – Mu Negative Material – these materials allow propagation of electric fields but produce opposing magnetic fields when exposed to an external magnetic field.

DEVELOPING METMATERIALS

Metamaterials are artificial structures that manipulate electromagnetic waves at will. They are periodic lattices that give engineers and researchers a larger about of degrees of freedom of control over EM radiation and can be used to create exciting and novel structures such as invisibility cloaks, super-lenses and devices with super hard structures. But, the geometrical design of these structures is a large challenge in creating them. Their size which is in the range of nano-meters pose a difficult in developing these materials. But there have been two processes developed by scientists to make these materials.

Researchers at ETH Zurich in Switzerland along with a team from Caltech have developed a method to create and design metamaterials. This method relies on quantum mechanics, and could be the key for making metamaterials a mainstream tool. The team designed a topological insulator, which conducts electricity across its surface while simultaneously acting as an insulator. After achieving this prototype, they also developed a macro-scale material that was capable of insulating against vibrations produced in its environment.

According to Chiara Daraio, professor of mechanical engineering and applied physics at Caltech,

“*Before our work, there was no single, systematic way to design metamaterials that control mechanical waves for different applications. Instead, people often optimized a design to fulfil a specific purpose, or tried out new designs based on something they saw in nature and then studied what properties would arise from repeated patterns.*”

Metamaterials are typically built from an array of geometric structures. These structures are connected in repeating patterns; this is an important factor that allowed the scientists to design various types of different metamaterials. The group was also able to make metamaterials as varied as vibration insulators, acoustic lenses and waveguides.

In 2014, a team led by George M. Whitesides and Alex Nemiroski at Harvard University used a technique known as shadow-sphere lithography (SSL) to rapidly produce complex nanoscale patterns on materials. Initially, these materials were made using slow and expensive processes like ion-beam lithography, but by using this new technique, they can make metamaterials relatively faster and at lower costs. In this new process, a simple stencil, sometimes made of packed nanospheres is used, which blocks deposition of atoms in a physical vapour deposition (PVD) chamber. Many complex patterns can be made by changing the position of the atom source many times during deposition.

SSL enables the efficient design and fabrication of two-dimensional array of complex, high-density, multimaterial structures by harnessing the parallelism of bottom-up self-assembly, the rationality of software-aided design and the precision of top-down physical vapor deposition. This process has several advantages that make it feasible to use for producing meta surfaces.

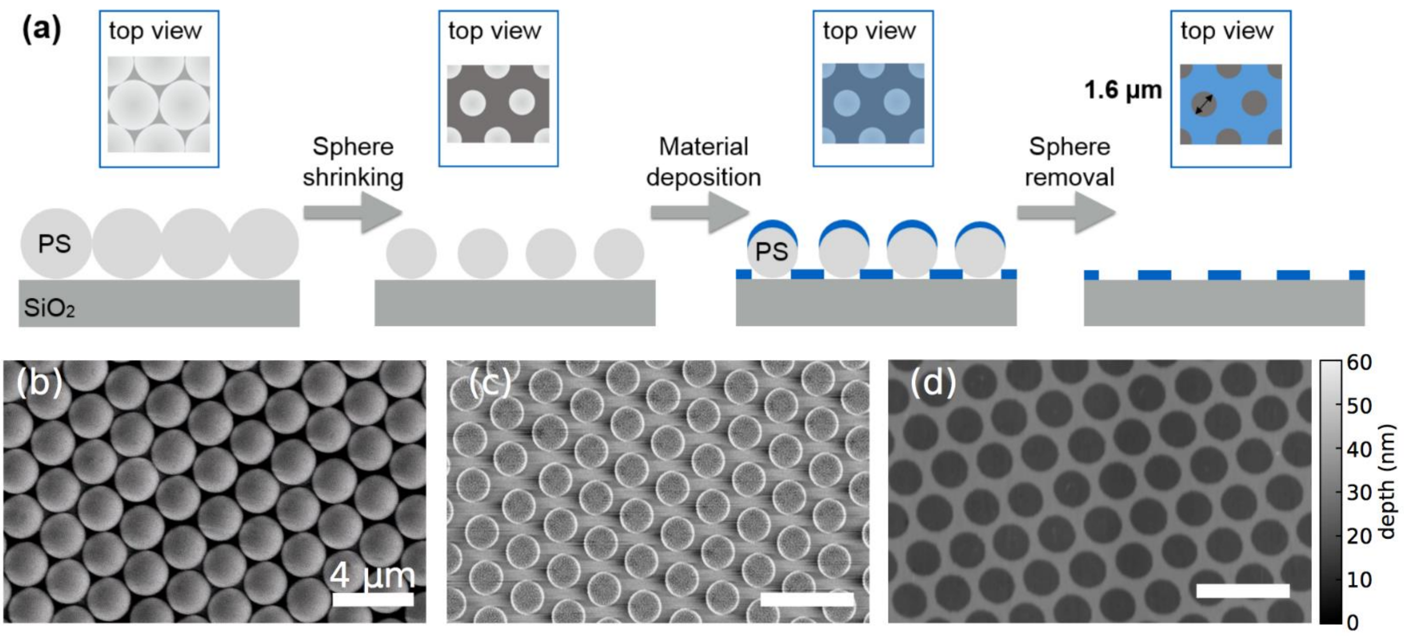


Figure 3

In the above figure we can see that initially spherical nanostructures are arranged on the SiO2 surface, then to make certain amount of gap between the spheres they are subjected to external forces, either thermal or electrical (a). After that, the surface is bombarded with required material, here represented by blue colour (b), it leaves its imprints through the gaps formed between spheres. In the last step, the spheres are removed, leaving the surface with nanostructures.

As shown above, the method can be used to make multi-material surfaces too. In figure 4, it can be seen that the surface is engraved with multiple materials (here shown by three different colours *violet*, *yellow* and *cyan*). Such surfaces, can show multiple properties according to its constituent materials.

This is one of the strengths of SSL, i.e., the simplicity with which multiple materials can be incorporated into meta surface without removing the sample from PVD chamber. Any material that can be deposited using PVD chamber can be used in SSL.

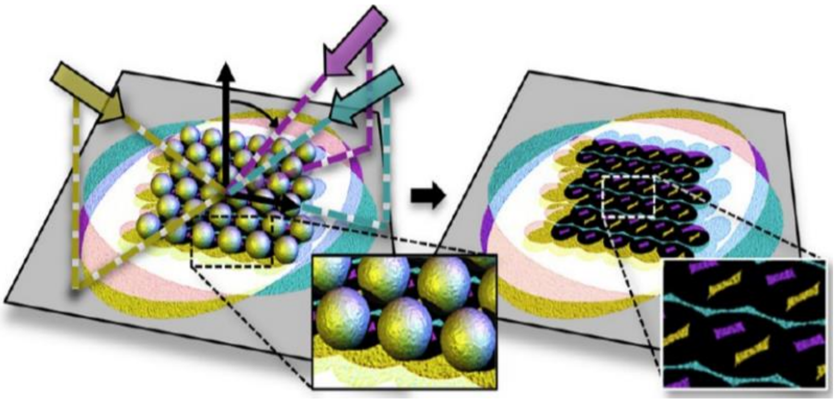


Figure 4

Recently, in 2018, the survey conducted by MForesight stated that the global metamaterials market size was around $300 million and is expected to growth at 36% compounded annual growth rate. This is possible due to the fact that many companies are now trying to make metamaterials at mass production scales. Many US Federal Agencies like US Air Force, US National Science Foundation and NASA are developing their own metamaterials.

Researchers in Taiwan and the US have developed a technique that could also lead to the large-scale production of optical metamaterials. Their method works on the same principle as SSL but it can produce metamaterials on very large scales. Yi-Jun Jen of Taipei University of Technology, Taiwan and his colleagues, have turned their attention to a more established production technique known as Oblique-Angle Deposition (OAD), which is widely used in the photonics industry to deposit thin films. Jen and his colleagues first vaporized a block of silver by firing electrons into it and then directed the vapor at a two-inch substrate of silica. These deposits tend to accumulate in patches on the substrate at certain angles to form nanorods that can grow preferentially towards the incoming vapor. It was the first macro-scale NIM made in just hours. They also found that this material was able to refract all visible light in opposite direction.

SELF HEALING MATERIALS

Self-healing materials are artificially or synthetically created substances that have the built-in ability to automatically repair damages to themselves without any external diagnosis of the problem or human intervention. Generally, materials will degrade over time due to fatigue, environmental conditions or damages occurred while operation. Cracks and other microscopic defects have shown to alter thermal, acoustic as well as structural properties of the material. Cracks are usually hard to detect and require periodic human inspection. In contrast, self-healing materials counter degradation through the initiation of a repair mechanism that responds to micro-damage. Although most common type of self-healing materials are polymers, new developments in this field has led to development of self-healing materials made from metals, glass and ceramics.

The ancient romans used a form of lime mortar with a mixture of Pozzolanic Rossa, that has been found to have self-healing properties. Self-healing materials only emerged as a widely recognized field of study only in the 21st century. The first international conference on self-healing materials was held in 2007.

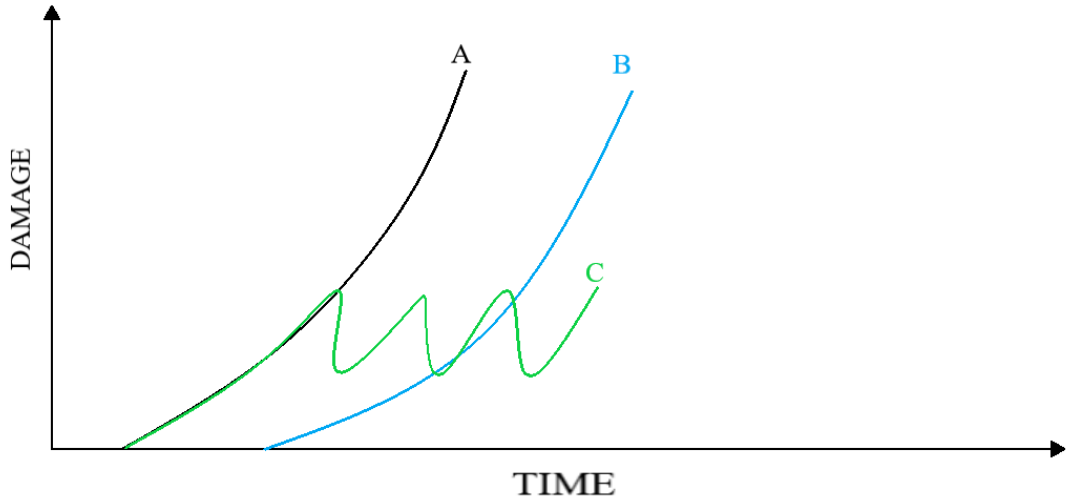


FIGURE 5

In this graph above, X axis represent the time for which a material is under operation and Y axis represents the damage incurred to the material. Line A represents a naturally occurring material. Line B is an improved grade of same material, while C is the self-healing version of that material. An ideal self-healing material will exhibit the same graph as Line C but for infinite time periods.

There are two main approaches to autonomic self-repairing:

1. Hollow Tube Approach
   In this method a mesh of carbon nanotubes is incorporated in the structure itself. In this method, the tubes are able to store functional agents for self-repair, like the base materials and catalysts for quick hardening as well as they act as a reinforcement. A bespoke Hollow Glass Fibre (HGF) making facility can produce HGF with diameter ranging between 30-100 µm with a hollowness of around 50%. These tubes are then embedded in Glass Fibre-Reinforced Plastic (GFRP) and infused with uncured resin to impart a self-healing functionality.

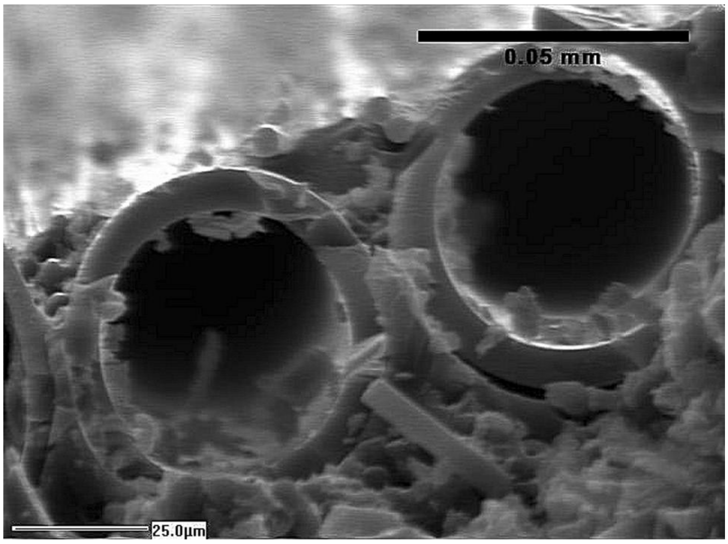


Figure 6

In the Figure 6, HGF tubes can be seen. These tubes have a diameter of 30 µm and hollowness of 50%.

These tubes will be fractured when subjected to severe impact in their laminar structure. On breaking, the uncured resin and hardening catalysts will leak out from the fractured tubes and mix with each other at the site of damage. This process will be completed in few seconds without any external influences like UV light or heat.

2. Hollow sphere approach.

   In this method hollow spheres are used to encapsule base materials and hardening catalysts. Figure 7 shows a broken capsule embedded in a material. The working principle of hollow spheres is same as that of hollow tubes. They are also made of Glass Fibre (GF) or Carbon Fibres (CF).

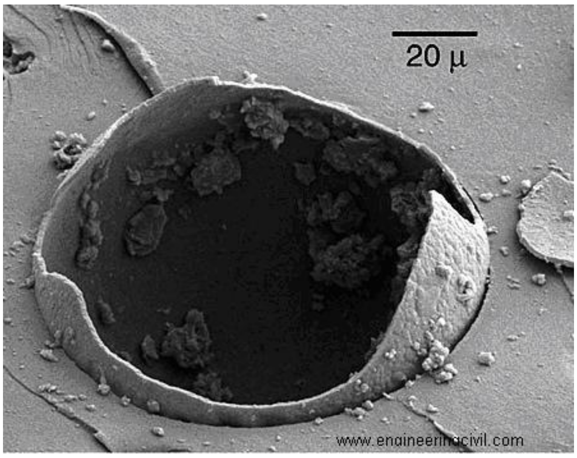


Figure 7

These self-healing techniques are applied in polymer coating, which are widely applied on the off-shore rigs. Generally, metals are coated with paints to prevent oxidation of surface which might result into corrosion. If there are any cracks on the surface of this coating, the metal beneath is exposed to humidity in atmosphere and starts to corrode. A paint with self-healing properties can repair itself quickly and avoid such exposure to air and eventually help in preventing corrosion. Researchers at University of California, Berkeley are currently working on using these practices with metals, which will enable metals to last longer than usual. This can also be applied to concrete as well to prevent damages to concrete structure.

CLOAKING MATERIALS

Interest in metamaterials and special materials has grown in recent year and there have been various application of them. One set of novel and exciting applications deals with making any given object nearly 'invisible' to impinging electromagnetic waves. This application of metamaterials has immediately attracted the attention of general public, associating it with term "Cloaking".

Figure 8

In Figure 8, a man is seen standing. The parting line is the edge of cloaking sheath. It can be clearly seen that he is visible on left, but he is not visible when he is covered by cloaking sheath.

This sheet has lenticular lenses on one of its sides and the other side is completely flat. This allows, light to enter the sheet at any angle but exit at a pre-determined angle only. Due to this phenomenon, we can have an invisibility cloaking device.

Apart from this, cloaking devices made from metamaterials can effectively hide an object from all types of electromagnetic waves, ranging from microwave radiation to Gamma rays.

In 2006, a group of scientists led by Dr. David R. Smith at Duke University demonstrated a simplified cloaking device. This cloaking device was made from a group of concentric circles (Figure 9) with open space at the centre, where the object to be hidden is kept. These concentric circles were fitted with SRR (Split Ring Resonators) (Figure 10). Their key purpose is to alter the path of EM waves. When they directed microwave lights at the device, the waves split into two, flowing around the device and re-joining on the other side.

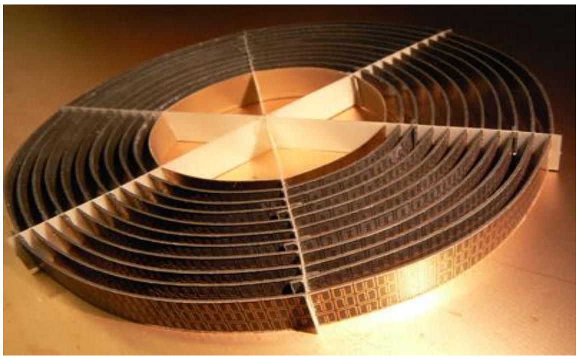


Figure 9

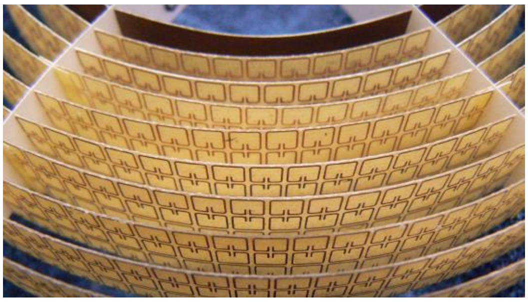


Figure 10
Concentric circles with SRRs.

According to Dave Schurig, a researcher on Dr. Smith’s team, the effect is analogous to “*a river flowing around a smooth rock”* Metamaterials are very useful in making surfaces with atoms arranged in a way that works similar to a SRR, so no need to add SRR externally. The researchers made a mosaic-like constructions out of fibreglass sheets stamped with loops of wire, somewhat similar to a circuit board. The arrangement of copper wires determines the way device interacts with EM waves.

The principle used here is the principle of refraction. Generally, materials have a constant value for refractive index, so the light only bends once it passes the boundary of material. But, with metamaterials, we can have variable refractive indices, so that light can bend multiple times inside the material without interacting with its borders. The Duke University team made the concentric circle coils which had varying refractive index to microwave light. The outer-most ring had a refractive index of 1, then it decreases gradually, so that the inner-most ring has a refractive index of 0.

Due to the varying refractive index, the light subtly bends around the object and is able to reform on the other side. This is also known as coordinate transformation cloaking scheme. Figure 11(A) shows a 2-dimensional schematic diagram of the principle on which coordinate transformation cloaking schemes work. Figure 11(B) shows the same principle in 3-dimensional. The electromagnetic rays are bent to pass through the cloak without entering the cloaked region, making the object inside the region, effectively invisible.

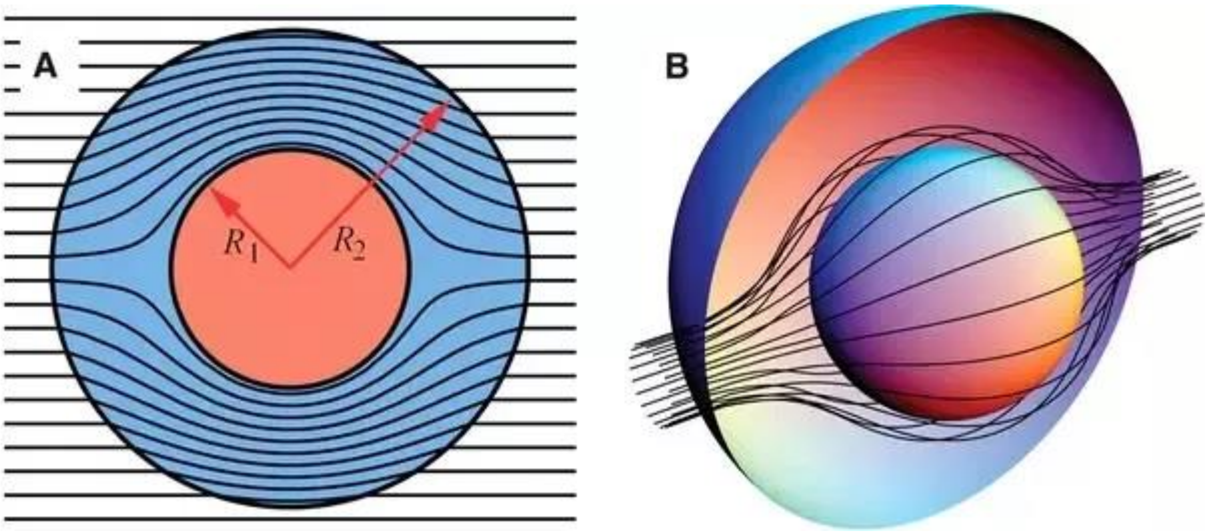


Figure 11

This device can be used in military operations as well as in other professions as well. A group of scientists at University of Rochester developed a cloaking device using a set of normal lenses, which works on the same principle of refracting light multiple times. They claim that their device can be used by doctors to perform operations without their own hand blocking the vision. It can also be used in car dashboards, enabling driver to have clear vision of things ahead of him.

VOXELS

Researchers at MIT’s Center for Bits and Atoms (CBA) have created tiny building blocks that exhibit a variety of unique mechanical properties, such as the ability to produce twisting motion when squeezed and also negative Poisson’s Ratio. This study was led by Dr. Benjamin Jennet who is a MIT doctoral graduate. These subunits can be assembled in a variety of forms to build macro-structures with varied properties. Researcher created four types of voxels; each one exhibits special properties not found in typical natural materials.

These are also known as mechanical metamaterials as they exhibit properties that are not available in naturally occurring materials. They offer exotic properties based on local control over cell geometry and their global configuration into structures and mechanisms.

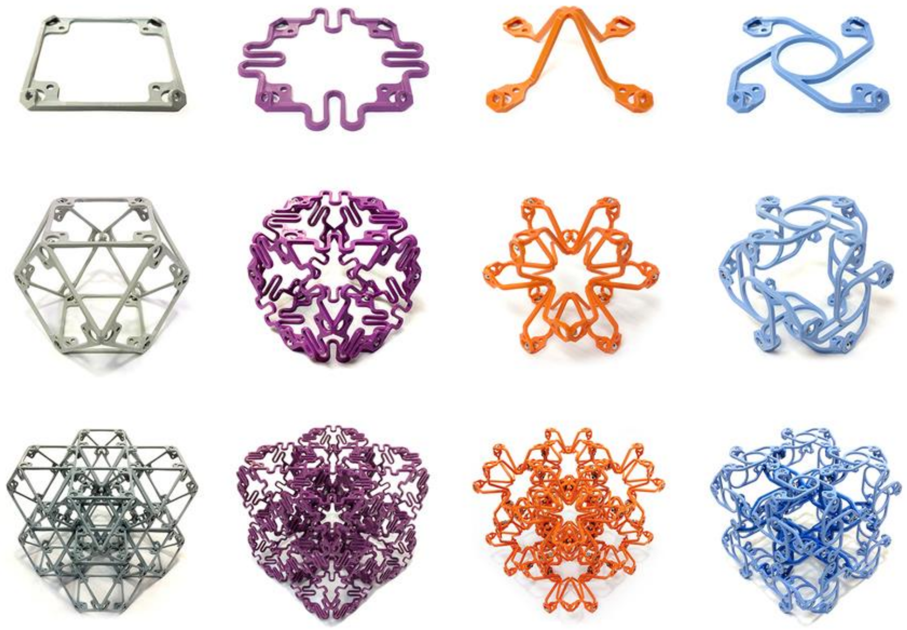


Figure 12

In Figure 12, the grey ones exhibit high rigidity than usual materials. Purple has lesser weight to strength ratio. Orange is an auxetic material i.e., with negative Poisson’s Ratio and Blue is a chiral material.

According Dr. Benjamin Jennet “These parts are low-cost, easily produced and very fast to assemble, and you get his range of properties all in one system. They are compatible with each other, so there’s all these different types of exotic properties, but they all play well with each other in the same scalable, inexpensive system. We were able to demonstrate that the joints effectively disappear when you assemble the parts together. It behaves as a continuum, monolithic material.”

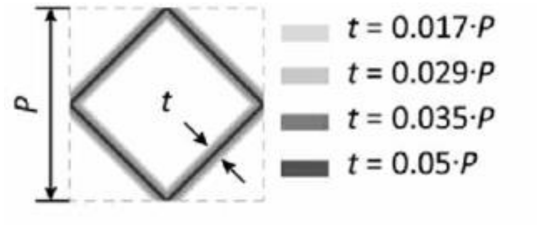
The voxels are assembled from flat frame pieces of injection-moulded polymers, then combined into three-dimensional shapes that can be joined into larger functional structure. They are mostly open space and thus provide an extremely lightweight but rigid framework when assembled.

There are four types of voxels created by MIT team:

a. RIGID VOXEL UNITS

These materials offer a high stiffness to weight ratio, even at low densities. This is achieved by lattice connectivity and internal architecture's triangulation.

Figure 12 shows a voxel unit under loading conditions. The image shows loading of a 1x1, 2x2, 3x3 and a 4x4 voxel units. Also, it can be seen that as the amount of voxel units increase there is an increase in structural rigidity. A key parameter that helps in determining the rigidity of a voxel unit is the beam thickness(t) to lattice pitch (P).



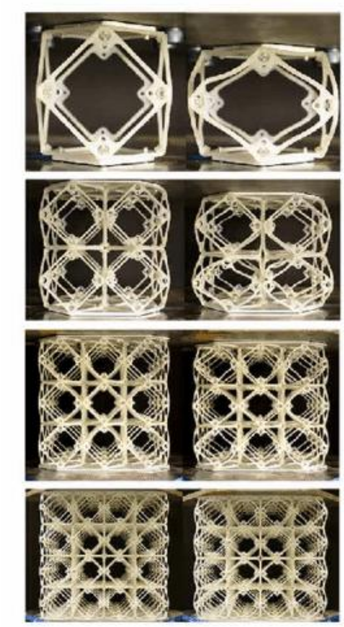


Figure 13

Figure 14, shows the graph showing the relationship between the Elastic modulus of a voxel unit and the number of subunits in it.

It can be clearly seen that, by increasing the number of voxel units, the effective modulus increases gradually. Also, by increasing the beam thickness (t) to Lattice pitch (P) ratio, we can increase the effective modulus. The effect of ratio is very minimal for a single unit, but its effect increases with increase in the number of units.

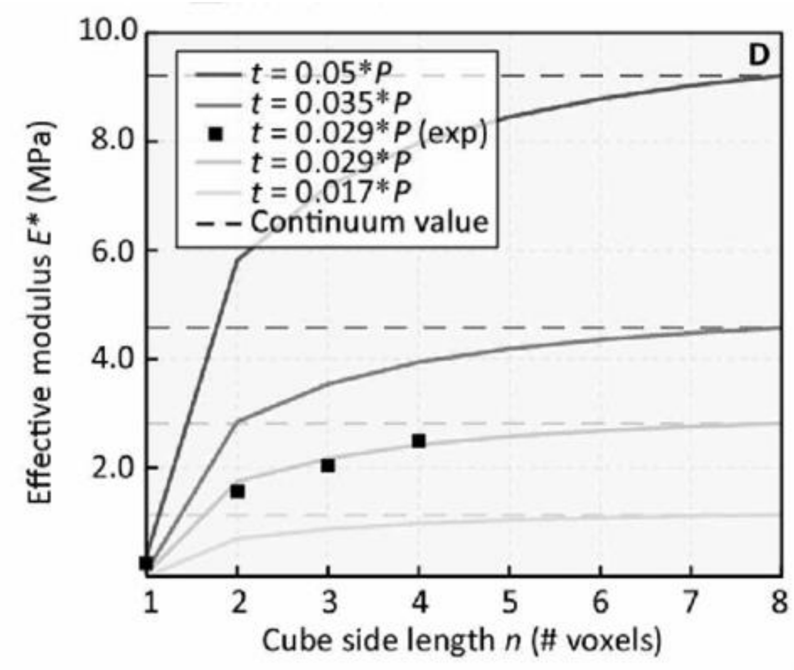
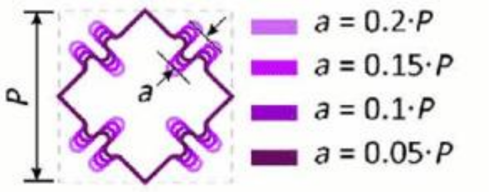


Figure 14

b. COMPLIANT VOXEL UNITS

These structures replace stiff beams with planar spring elements. They allow significant elastic strain and deformation without plastic failure. These units also exhibit continuous effective stiffness from single to multi-voxel assemblies.
Figure 15 shows compliant voxel structures under loading conditions. Here, left-side column shows unloaded conditions for 1x1, 2x2, 3x3 and 4x4 voxel units, while the right-side column shows loaded conditions for respective lattice structures.

The compliant voxel structure is defined by its two key geometrical parameters: Lattice Pitch (P) and Spring-beam amplitude (a).



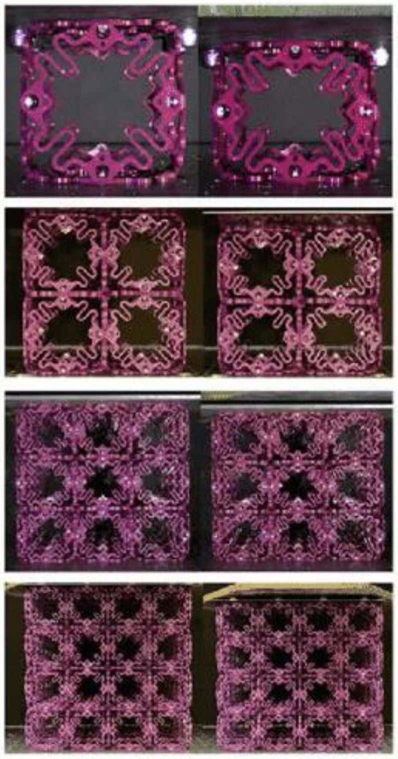


Figure 15

Figure 16, shows a graph that demonstrates the relationship between the effective modulus and the number of voxel units. Here, it can be seen that effective modulus changes largely because of the geometric parameters of the voxel unit. It the ratio of spring-beam amplitude (a) to lattice pitch (P) is lower than changing the number of voxel units will not affect the effective modulus. But on increasing the ratio, we can increase the effective modulus by increasing the number of voxel units.

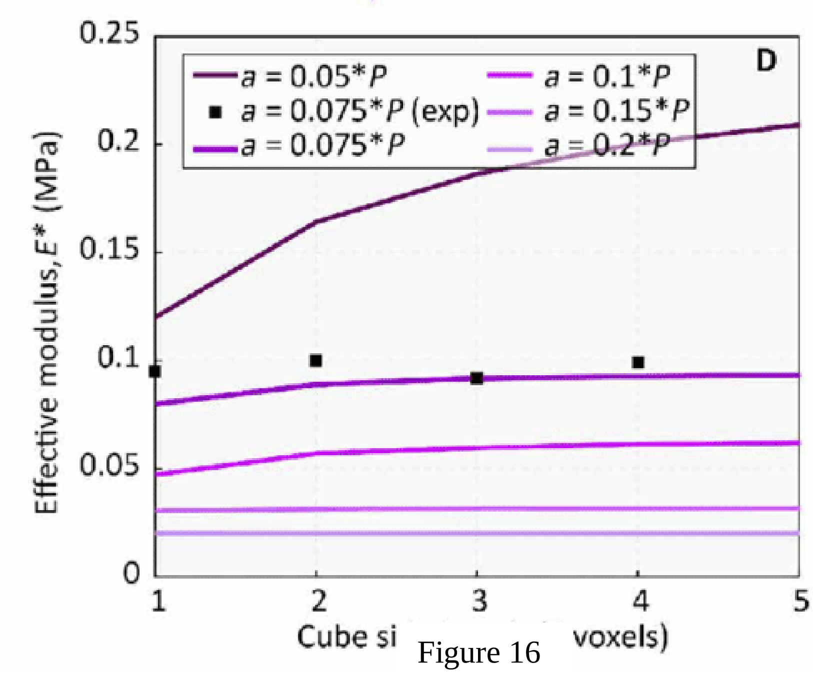


Figure 16

c. CHIRAL VOXEL UNITS

These materials respond to in-plane extension with out of plane twisting. This is achieved with clockwise or counter-clockwise part designs. They react to axial compression or tension with a twisting motion. This is an uncommon property, but custom-made metamaterials can allow macro-structures to use this property.
Figure 17, shows how by axial loads, the unit produces a twisting motion. In conventional mechanics to perform such action, we need to use threads.

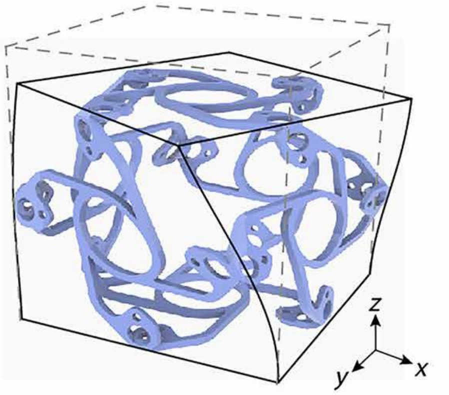


Figure 17

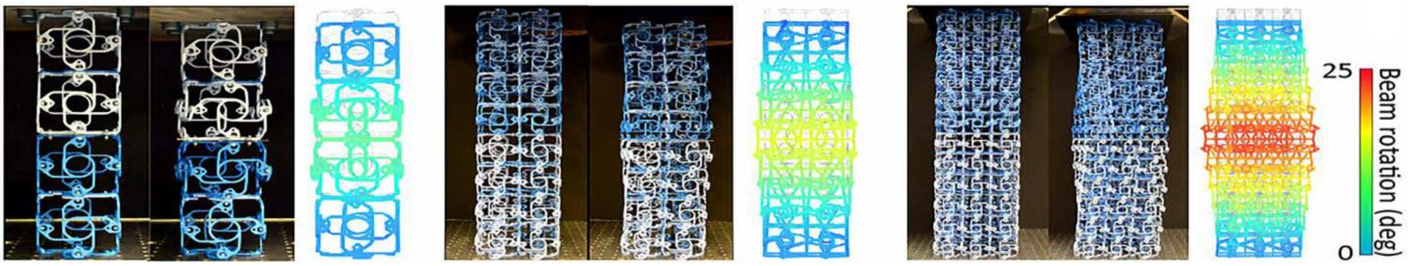
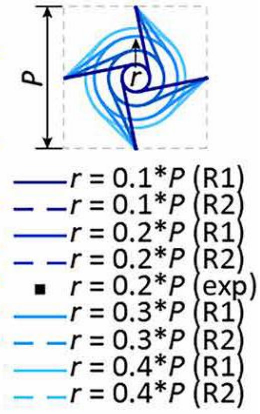


Figure 18

In Figure 18 a structure made of chiral units is kept under unloaded (left) and loaded conditions (right). Along with the loading cc [illegible] eam rotation diagram is also shown alongside each structure. It can be se[illegible] diagram that with increasing number of voxel units, the rotation also increases.

A chiral voxel unit is defined by two geometric parameters; radius of face part (r) and lattice pitch (P). Here, R1 and R2 represent the face radius for two different design rules. Design rule 1 applies to structures with odd number of columns while Design rule 2 applies to structures with even number of columns.

Figure 19 demonstrates the relationship between the cross-sectional number of voxel units and the amount of twist produces i.e., the ratio of degrees of twist to the %strain generated in structure under load. Here the results show that a 1x1 cross-sectional voxel structure will produce more twist than a 2x2 cross-sectional voxel structure. This can be attributed to the internal architecture, which also causes a scalable twist in more cross-sectional voxel columns.



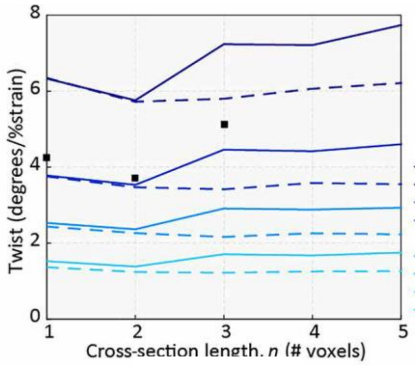


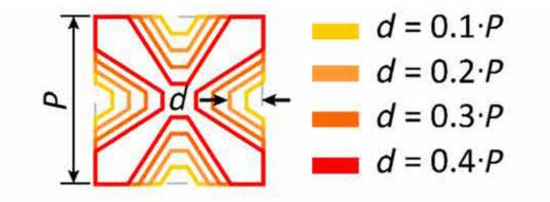
Figure 19

d. AUXETIC VOXEL UNITS

These structures have a controllable negative Poisson’s Ratio. They expand laterally in response to an axial tension (pull), which is completely opposite to behaviour of a conventional materials. This is achieved by a 3D re-entrant mechanism that makes up the cell faces.

In figure 20 (B), a structure made of auxetic voxels is demonstrated under un-loaded conditions(left) and loaded condition(right). In Figure 20(C) simulation results are shown with Poisson’s ratio. It can be seen here that by using a larger number of auxetic units larger negative Poisson’s ratio can be achieved.

An auxetic structure is defined by two geometrical parameters: lattice pitch (P) and re-entrant distance (d).



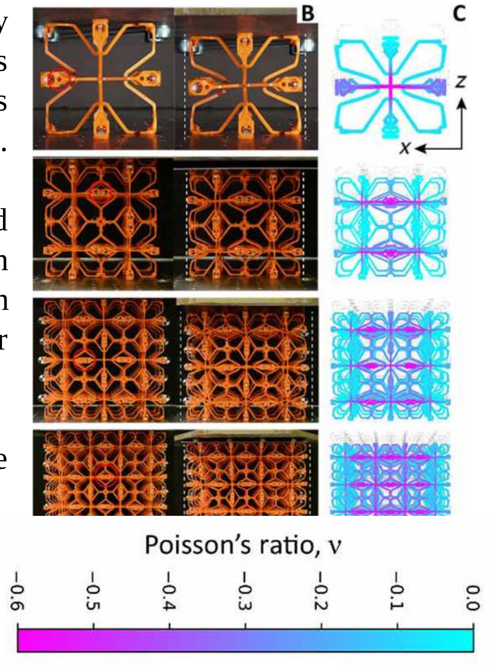


Figure 20

In Figure 21, the graph shows relationship between Poisson’s ratio and the number of voxel units in the structure. Here, it is clearly visible that by having larger re-entrant distance we can have more negative Poisson’s ratio. For structures with lower re-entrant distance the Poisson’s ratio initially increases from -0.4 to -0.2 by increasing voxel units from 1 to 2. But all variation of re-entrant distance has same Poisson’s ratio for two voxel units. This characteristic can be attributed to the increase in internal mechanisms relative to boundary conditions. Boundary conditions increase as a function of n2, while internal mechanisms increase as a function of n3.

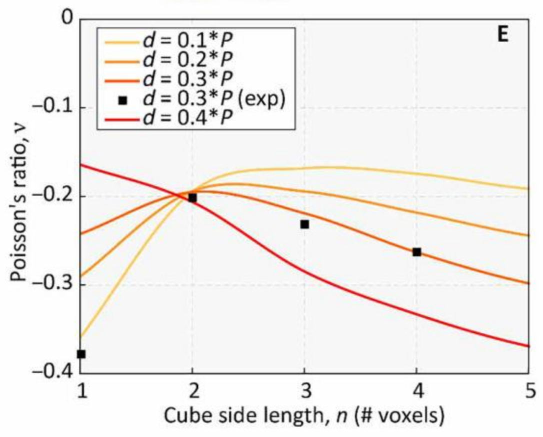


Figure 21

Also, the effective Poisson’s ratio decreases as the value of d is increased for voxel specimens with n>1. This can be understood considering the continuous beams of the re-entrant faces as a pseudo-rigid body model, where continuous flexural mechanisms are discretized as effectively rigid links connected by planar joints with torsional stiffness.

COMMERCIALIZATION

For more than a decade, metamaterial science has captured the imaginations of researchers around the globe. What has been so compelling about metamaterials is the ability to exert unprecedented control over the properties of a material. The discovery of metamaterials has unleashed an enormous burst of creativity from the research community, leading to demonstrations of invisibility cloaks, negative refractive index materials and many other exotic materials like MIT's voxels.

Yet, compelling science does not always translate into usable technology, at least not without a great deal of work. While metamaterials have brought us new perspectives and new directions for design, it would be difficult to implement this direction if not available for use. To address these problems currently, many small and large companies are at work developing metamaterial-based products and answering to common needs along with Invention Science Fund (ISF)

Starting in 2004, the Invention Science Fund (ISF) began building a metamaterials portfolio that included metamaterial related inventions. At that time, metamaterials were extremely controversial in the scientific community, generating nearly as much scepticism as they did enthusiasm. But, despite the criticism, Nathan Myhrvold, CEO of Intellectual Ventures and Casey Tegreene, Executive Vice-President and Chief Patent Officer at ISF were convinced that metamaterials held potential for commercialization and decided to invest in this nascent but incredibly active field.

In 2010, with an expanded business development team and more serious marketing effort, a concerted effort was made at ISF to identify the best commercial opportunities and develop specific metamaterial paradigms that could become metamaterial products. ISF leveraged the substantial laboratory resources of Intellectual Ventures, forming a metamaterial study group led by Nathan Kundtz, that would ultimately design and demonstrate product prototypes. Later, ISF made a new department of Metamaterials Commercialization Center (MCC), whose first director was Dr. Kundtz.

Since its establishment, MCC has spun off many companies that leverage metamaterials to create innovative hardware.

1. KYMETA CORPORATION
   In 2012, Kymeta Corporation was established in Redmond, Washington to commercialize the metamaterial antenna for satellite communications
   .
2. EVOLVE TECHNOLOGY
   In 2013, Evolv technology was formed with the intent to develop novel metamaterial-based apertures for next-generation microwave and millimetre wave security imaging systems. Evolv is led by CEO Anil Chitkara.
3. Carillon Technology
   This company was founded in 2017 by Dr. John Evans, and it specializes in radio communications for US military and other security organizations around the world.

4. Imagia Technologies
   This company was established in 2019 by Gregory Kress and it specializes in research with optical metamaterials.

5. HyperStealth Corporation
   This company has developed “Invisibility Cloak” initially designed only for military purpose, but as it changed its status to ‘For Profit Organization’ it has decided to make its products available to free market.

Metamaterials applications will represent a multi-billion-dollar market within the next decade with product advances in radar and LiDAR for autonomous vehicles, telecommunications antenna, 5G networks, coatings, vibration damping, wireless charging, noise prevention and more. Initially, R&D in metamaterials was focused on cloaking and light manipulation, but in the last few years, it has seen applications development in:

- Telecommunications
- Acoustics
- Sensors
- Radar and LiDAR imaging
- Optics
- Coatings
- Medical Imaging

There are currently over 25 metamaterial product developers worldwide, who have received more than $300 million in recent investment rounds worldwide as the metamaterials market is picking up pace.

To facilitate fast-paced research to match the increasing demands of modern world a group of universities have established MURI (Multidisciplinary University Research Initiative) that encompasses dozens of universities like UC Berkeley, UC Los Angeles, UC San Diego, MIT and Imperial College of London.

IN coming decades, we can see huge developments in currently used technology as companies embrace the vast field of metamaterials and by the help of institutions like ISF and MURI.

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