Metamaterials

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October 2021

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Introduction

Every kid has thought about having the ability to be invisible at least once in their life. Who doesn't want to be Harry Potter? What if I told you that the invisibility cloak is within reach? This is only one of the multiple applications of a new class of materials called Metamaterials. Although this sounds more related to the world of wizardry, the science behind using metamaterials to build an invisibility device is real. A metamaterial (from the Greek word meta, which means "beyond," and the Latin word materia, which means "matter" or "material") is any type of material that is engineered to have properties that cannot be found in naturally occurring materials. These materials derive their unique properties not from the materials themselves but from the arranged patterns of their structures at a scale smaller than the wavelength (i.e., the distance between identical points in the adjacent cycles of waveform signal propagated in space or along a wire) of the phenomena they influence.

Metamaterials' precise shape, geometry, size, orientation, and arrangements allow them to manipulate electromagnetic or mechanical waves, such as light or sound, by blocking, enhancing, and bending the waves. Their potential applications are multiples, including power transmission, energy harvesting, wireless charging, thermal management, and acoustic applications, Lidars, radars, superlenses for medical devices, AR displays. Electrical engineering, electromagnetics, classical optics, solid-state physics, microwave and antenna engineering, optoelectronics, material sciences, nanoscience, and semiconductor engineering are all involved in the metamaterial field's advancement.

Materials have two significant indexes that are the electrical permittivity ε (how the material reacts to an electric field) and the magnetic permeability v (how the material reacts to a magnetic field), which together control how a material responds to electromagnetic waves (EM). Electromagnetic waves are everywhere in our world: for example, radio waves, microwaves, visible lights, and also x rays. Natural materials, such as glass, diamond, metal, wood, have positive electrical permittivity and magnetic permeability. In metamaterials, both electrical permittivity and magnetic permeability are negative. Another important parameter used to characterize materials is the refractive index, which determines how much the path of light is bent or refracted when entering from a rarer material to a denser material. For example, consider the sun rays that pass from air to window glass. Sun rays are not completely reflected from the glass but can pass through the glass; this phenomenon also happens when the denser medium is water. Some light rays will be reflected off the surface of the water, but others will be refracted. The refractive index of metamaterials is negative, which means light "bends"' the wrong way when it enters the metamaterials, as depicted in Fig. 2. In traditional materials, light bends toward the normal direction to the interface when it enters from a rarer medium into a denser medium. Conversely, in metamaterials, light bends away from the normal.

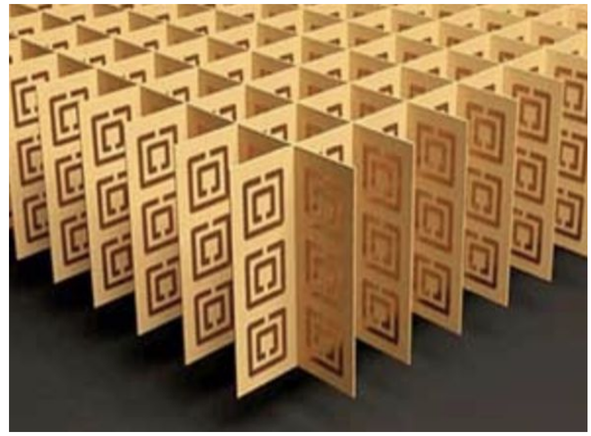


Figure 1. Metamaterial lattice is used to demonstrate negative refraction. The array of square split-ring resonators gives the material a negative magnetic permeability, whereas the array of straight wires gives it a negative permittivity. (Source: Houck, Andrew A.; Brock, Jeffrey B.; Chuang, Isaac L. "Experimental observations of a left-handed material that obeys Snell's law". Phys. Rev. Lett. American Physical Society.)

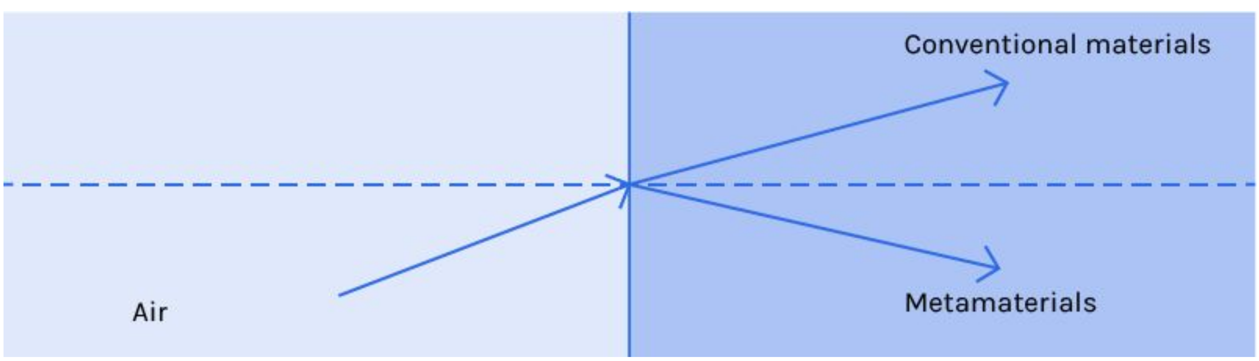


Figure 2. A comparison of refraction in conventional materials to that in metamaterials

This phenomenon could have implications for creating an invisibility cloak. Sight for humans and animals derives from the interaction between eyes, light, the physical world, and the brain. We can see because the light is reflected from the object and reaches our eyes. Invisibility could be accomplished by engineering metamaterials that will manipulate light paths and deflect them. Metamaterials cloaking is the process of shielding an object from view by controlling electromagnetic radiation. The object would be still there, but the light is guided around them. Several research groups and defense groups are working on this type of application. Scientists at Ben Gurion University of the Negev (BGU) have developed a new metasurface that, when put on an object, deflects light from it, rendering it invisible. The research group develops on-chip nanophotonic devices, which are a class of devices capable of controlling light on a chip to realize performance advantages over ordinary building blocks of integrated photonics. The most intriguing feature of their cloaking concept is that if an item covers 70 percent of the metasurface, it can be covered. The theory currently shows how cylindrical nanoparticles with a refractive index of 1.3 can be rendered invisible, according to the Light on a Chip group. Other objects, including metal and non-metal, can become invisible as well. The refractive index of water, human body fluids, and Teflon is approximately 1.3. The next step will be to build a physical prototype to prove the theory right. The cloaking chip could have immediate applications to improve existing technologies, such as radar-absorbing dark paint used on stealth aircraft, local optical camouflage technologies, and surface cooling technologies to minimize electromagnetic, infrared emissions.

Applications

Metamaterials are impacting several industries: Infrastructure (Thermal management, Acoustic management - vibration and noise control, Seismic metamaterials), Power and Energy (Energy harvesting, Power transmission, Wireless charging), Electronics and Sensors (Lidars, Super lenses for medical applications, Programmable metamaterials, AR displays), Telecommunications (MmWave antennas, 3D radar, Holographic beamforming).

1. Infrastructure applications

1.1. Thermal management and metamaterials

In electronics, thermal dissipation is always extremely important, and the current trend of electronics packaging with higher power, higher density, and 2.5D/3D structures making thermal management even more challenging. Conventional cooling solutions based on large thermal-conductivity materials as well as heat pipes and heat exchangers may dissipate the heat from a source to a sink in a uniform manner. Conversely, thermal metamaterials could help dissipate the heat in a deterministic manner and avoid thermal crosstalk and local hot spots.

Thermal management is becoming more difficult with the terrific development of nanoelectronics, 3D-integrated circuits (ICs), and flexible electronics. For example, in 2.5D packages, the logic power, as well as the number of high bandwidth memory (HBM) layers, is rapidly increasing. One fundamental challenge in 2.5D packages is thermal crosstalk because the logic chip and the HBM are located very close while they require different operating temperatures. Thus, thermal metamaterials can play a fundamental role in facilitating heat dissipation and protecting temperature-sensitive components. Ultimately, we can think about this problem as a way to have more powerful and compact computers (to enable gaming, processing, etc.) without lack in performance due to thermal heating.

Companies working on thermal metamaterials are US startups Radi-cool and Transaera.

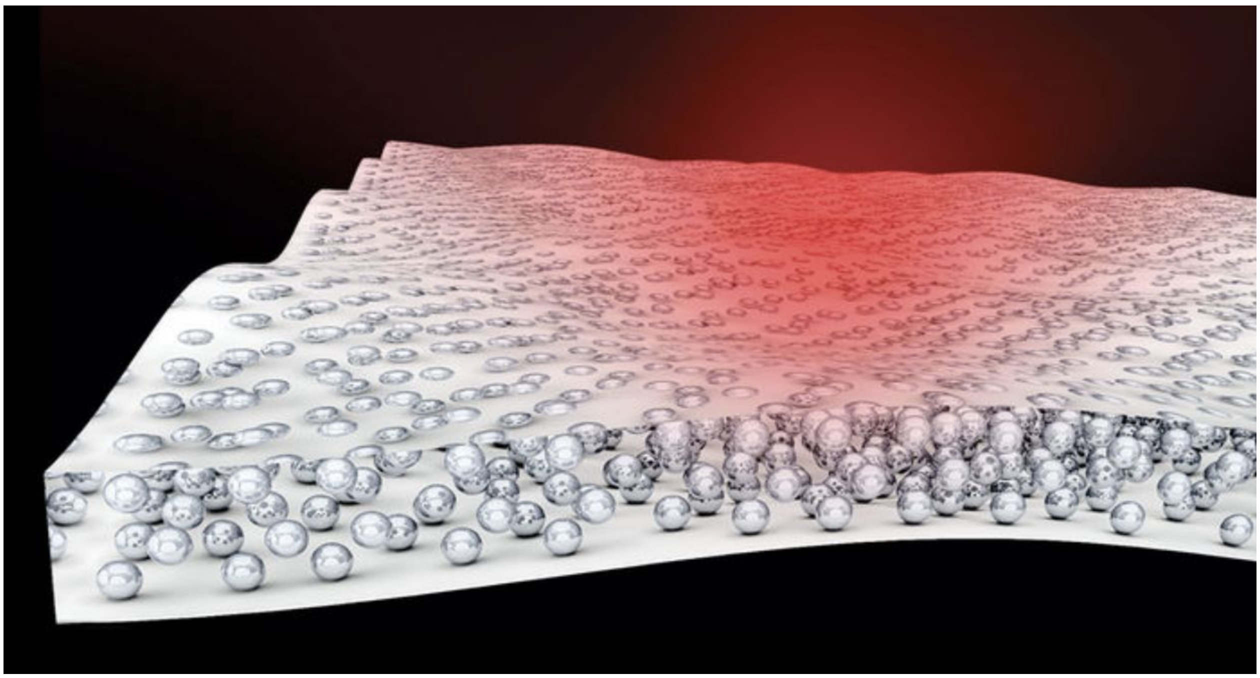


Figure 3. Radi-Cool technology uses ~10 µm in diameter glass spheres, embedded in a flexible polymer to create a thin-film cooling material. (Courtesy of Radi-cool)

Radi-cool develops metamaterials that can cool objects even under direct sunlight with zero energy and water consumption. The metamaterial film applied to a surface cools the object underneath by efficiently reflecting incoming solar energy into space while simultaneously allowing the surface to get rid of its heat in the form of infrared thermal radiation. Direct applications are in residential and commercial buildings, applied to rooftops, windows, skylights. Other applications are in transportation, used to shield cars or trucks, facilitating cooling and reducing power consumption.

Transaera developed a new class of highly porous materials, called the Metal-Organic Framework (MOF), to create air conditioners that can have one-fifth the impact on climate compared to traditional AC. The team can engineer a sponge-like material that grabs moisture from the atmosphere enabling the air conditioner to cool the air more efficiently. Moreover, the heat generated by the air conditioner is used to dry the material for the next cycle instead of going wasted.

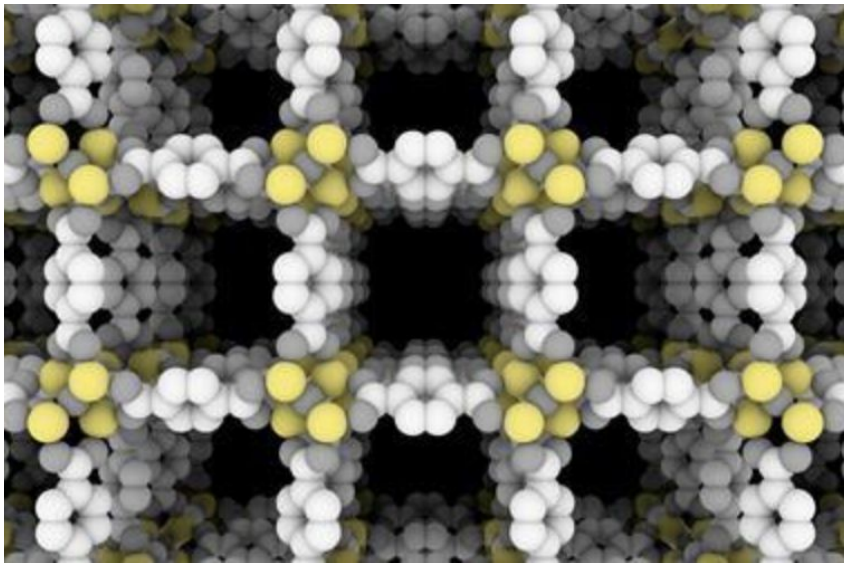


Figure 4. Metal-Organic Framework (MOF). Metal ions or clusters are held together by organic linkers to make highly ordered, crystalline 3D structures with ultra-high porosity. (Courtesy of beautifulchemistry.net/science photo library)

1.2. Vibration and noise isolation

Noise reduction barriers are one of the most recent and commercially effective applications of metamaterials, developed for potential use on highways and major roads. Noise barriers made of traditional materials struggle to block low-frequency sounds and degrade over time as moisture builds up inside them.

With so much new urban development and the continued expansion of transportation infrastructure, materials that minimize or eliminate the sound of roads and air traffic will inevitably become highly requested. Metamaterials-based technologies have the potential to be even more durable and long-lasting, opening up a lot of doors in this field of engineering. Also, at Prime Movers Lab, we recently invested in Boom Supersonic, a company developing a Mach 2.2 55-passenger supersonic jet, where noise isolation materials could be beneficial to make traveling even more comfortable.

Companies working on these applications are Italian startup Phononic Vibes and Hong Kong company Acoustic Metamaterials Group. Phononic Vibes uses metamaterials to create steel or concrete products, which can reduce vibrations issues caused by trains or trams. The company also engineers products such as acoustic panels made of recycled plastic for home or industrial settings and for noise control in appliances.

1.3. Seismic metamaterials

Scientists are also making important strides in fine-tuning the properties of materials to create radiation and seismic-resistant shields. Seismic waves will be absorbed or deflected by metamaterial barriers, eliminating the risks and effects of earthquakes. Since these new materials behave completely differently than conventional materials, it's likely that future buildings will be constructed with materials that are more resistant to earthquakes and other natural disasters than ever before. Research groups in France and China developed structured materials capable of dumping seismic waves' transmission. The material is made of a series of seismic metamaterial plates formed by horizontally arranging resonance elements on top of a soil substrate. Even if full-scale tests need to be built and manufacturing techniques have to be improved, this research is a promising approach to protect vulnerable buildings and cities with its simple design. A company working on seismic metamaterials is META Seismic.

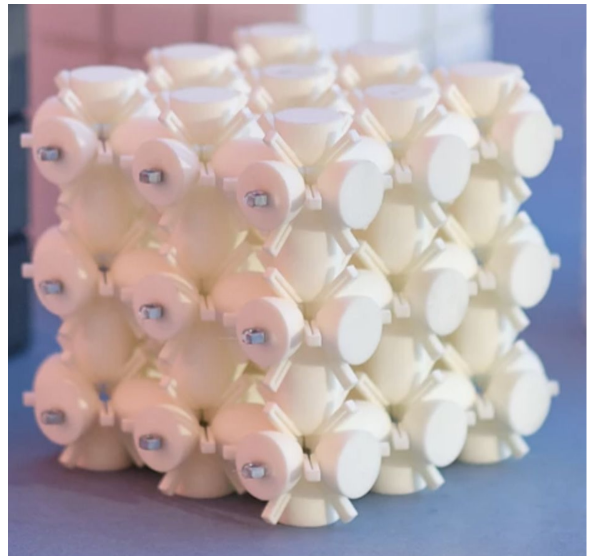


Figure 5. Periodic architected structures to damp out and absorb mechanical vibrations and noise Image source: Phononic Vibes

2. Electronics and Sensors

2.1. Optics - superlenses for cameras and VR headsets

Thanks to faster and more miniaturized chips, consumer electronics have made progress at an unstoppable pace in the past three decades, Moore's Law proved effective, and electronic devices became more sophisticated, faster, and more compact. However, one component of consumer electronic products that did not improve significantly (including its physics, design, and materials) is optical lenses. This fact created a bottleneck in developing next-generation optical devices, such as virtual reality headsets and augmented reality (AR) glasses which require lightweight, compact and inexpensive lenses. Optical metasurfaces might change this story. By using minuscule elements and patterns at the surface to manipulate light at will, metasurfaces overcome the performance of conventional lenses.

The Capasso Group at Harvard University developed a planar superlens (called metalens) that goes beyond the diffraction limit. The superlens can discriminate nanoscale features at distances smaller than the wavelength of light. This result is achieved with an engineered metasurface, where arrays of nano-waveguides bend and redirect light.

These nanostructures are made with titanium oxide and can be fabricated using a standard lithographic process (the one already used in traditional CMOS technology used in electronic chips). Compared to conventional lenses requiring polishing and other steps to be fabricated, the metalens can be manufactured in one single lithographic step, resulting in a wafer-thin chip (see Fig. 6).

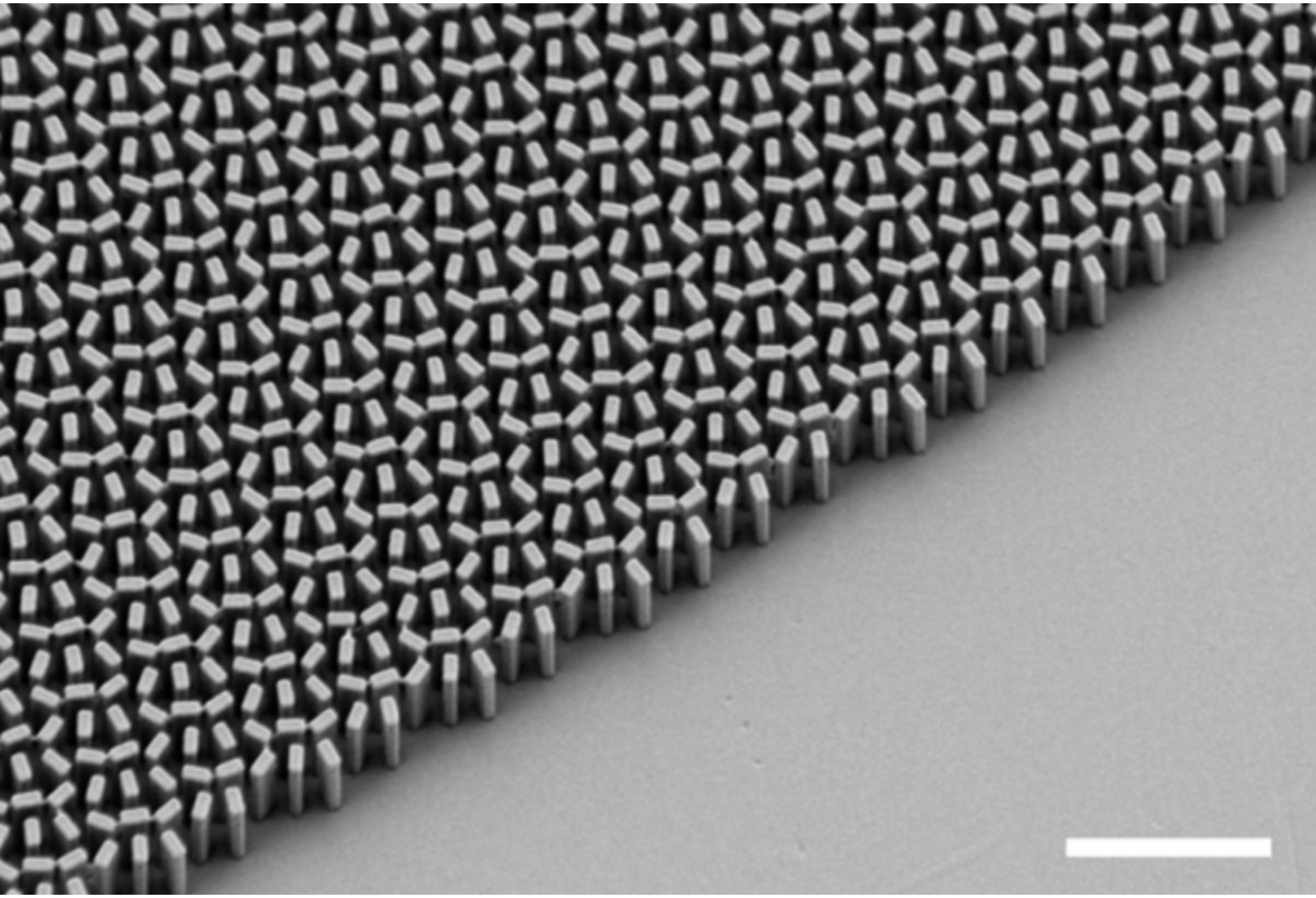


Figure 6. Scanning electron microscope micrograph of a metalens.
The lens is made of titanium dioxide nanofins on a glass substrate.
Scale bar: 2 microns.
Image courtesy of the Capasso Lab/Harvard SEAS.

A lens is usually made of plastic or glass and has a curved surface. It gets its name from the Latin word for "lentil." There are two types of lenses. A convex lens is also called a converging lens because it focuses the light rays to a specific point (called focal point) located beyond the lens. This type of lens is used in telescopes or binoculars to converge long-distance light rays and bring them to focus on the eyes. The other kind of lenses are called concave lenses, and they do the opposite. Concave lenses have an outer surface curving inward and make parallel light rays diverge. These lenses are used in TV projectors, for example, to create a larger image.

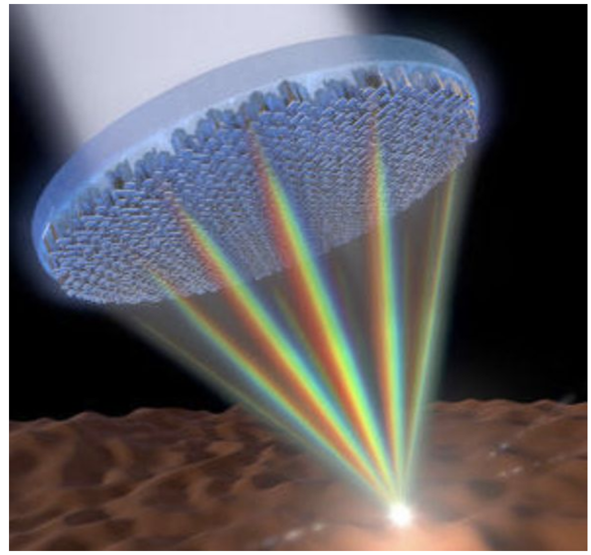


Figure 7. Flat metalens can focus the entire visible spectrum of light (including white light) in the same spot and in high resolution. This lens eliminates chromatic aberration. Image courtesy of Jared Sisler/Harvard SEAS.

Lenses slow down and bend light when light passes through the material. Different wavelengths of light move through materials at different speeds. For example, red wavelengths move through the lens's glass faster than blue, and the two colors will reach the same location at different times. This behavior creates what it's called chromatic aberrations. Existing cameras and other optical equipment use multiple curved lenses, different thicknesses, and materials to correct these aberrations, thus contributing to the bulkiness of the devices.

As discussed before, the Capasso group created metalenses that use arrays of titanium dioxide nanofins to equally focus wavelengths of light and eliminate chromatic aberration just as effectively. In previous research, the group was able to focus on different wavelengths of light but at different distances by optimizing the shape, width, distance, and height of the nanofins.

Recently, the researchers designed a new metalens surface where there are units of paired nanofins that control the speed of different wavelengths of light simultaneously. The paired nanofins control the refractive index on the metasurface and are engineered so that light passing through the fins has different time delays. For this reason, different wavelengths reach the focal spot at the same time, creating achromatic lenses that can perform high-quality imaging on white light (white light contains all the wavelengths of the visible spectrum at equal intensity). They have successfully produced lenses several millimeters in diameter, but the goal is to reach 1 cm in diameter, paving the way for their use in virtual reality headsets or cameras.

An interesting startup commercializing metalenses is Metalenz Inc. Exciting applications are in automotive where optical sensors are used inside a car to monitor the driver's state or for gestures control. One challenge for these optical systems is to operate across a broad range of temperatures. Traditional lenses are very susceptible to thermal changes because their optical properties vary. Metalenses have higher thermal stability compared to conventional lenses without requiring additional assemblies to compensate. Other applications are VR headsets which require compact form factor and low-weight optics.

2.2. Consumer electronics - displays

An attractive application of metalenses is in displays. Consumers want larger displays for movies, gaming, and work. Usually, immersive displays entail large displays such IMAX or VR/AR headsets that place minuscule lenses and screens close to the user’s eyes to emulate large displays and a broad optical view. One of the drawbacks of existing VR/AR headsets is the headset itself. Nobody really wants to wear a bulky headset on their head for many hours.

Metalenses again provide the solution, and another startup, Brelyon, is working to bring innovative display technology to market. A single 13x30 inch monitor will be perceived as a 122-inch screen and provide an immersive 101-degree field of view, 4K/8K resolution, and high frame rate. Imagine replacing six 32 inches displays with one single monitor.

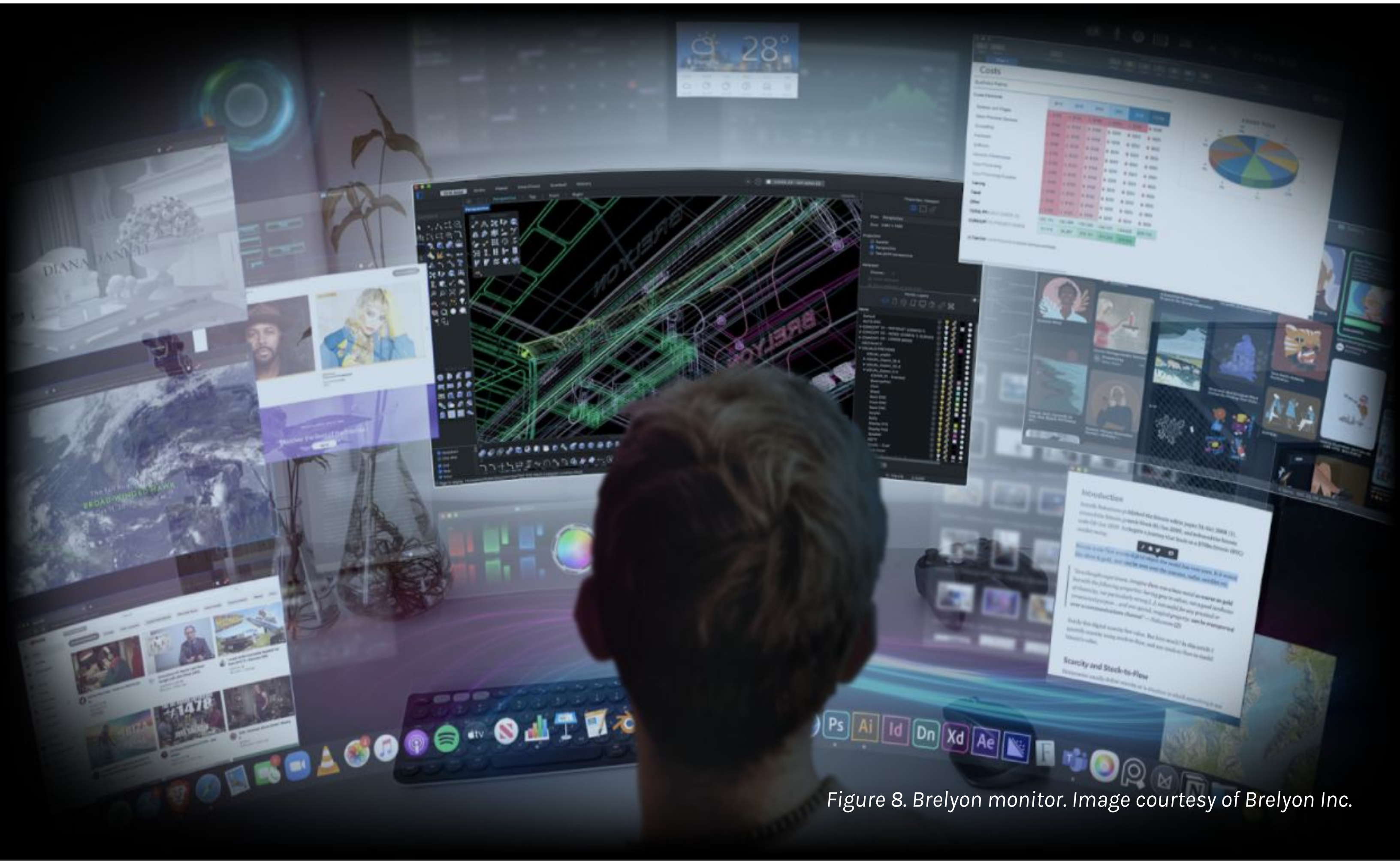


Figure 8. Brelyon monitor. Image courtesy of Brelyon Inc.

Brelyon places a metasurface in front of an LCD or OLED screen that manipulates the display's lights. The display is curved both horizontally and vertically. The emitted light overlaps in front of the display, making each pixel appear further than its actual distance from the user.

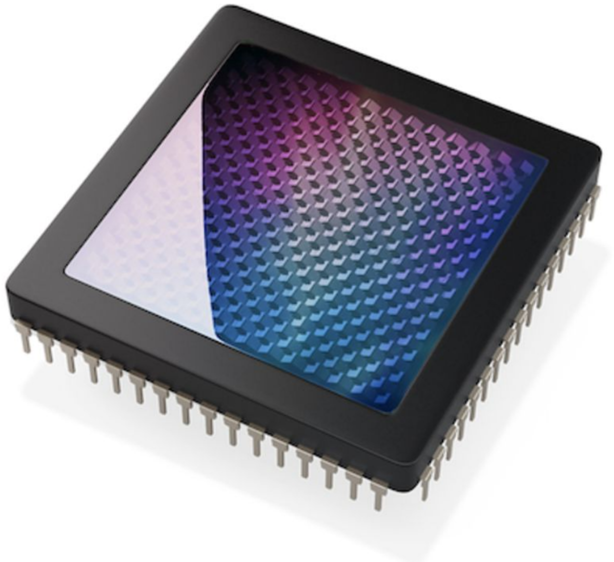
Supersonic light-field expansion technology (SLET) geometrically transforms and redistributes a uniform light-field into a concentric light-field distribution with great accuracy. The light rays from the generated light-field merge in front of the display so the user sees a larger image that appears further than the physical location and size of the monitor. One big difference with traditional stereoscopic displays is that Brelyon technology provides a monocular depth modulation which means that it creates a 3D image, eliminating the typical eye fatigue for the user.

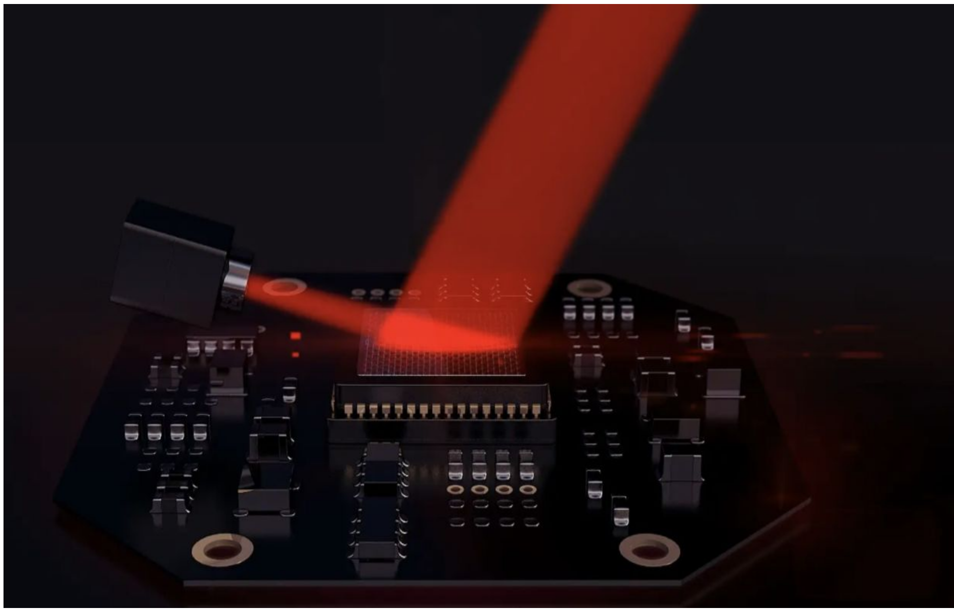
2.3. Sensors - Lidars

Among the sensors used for advanced driver assisted driving (ADAS) and autonomous vehicles, Lidars (which stands for light detection and ranging) are currently commonly used. Typical Lidars emit pulsed light waves. The pulses bounce back from the objects that obstruct their path and return to the sensors. The sensors measure the time that each pulse took to return to the sensor and calculate the distance traveled. Repeating this measurement a million times per second allows the sensor to reconstruct a 3D map of the surroundings. To get a 360 degrees scan of the surroundings, conventional Lidars use beam scanning, which requires moving a laser beam in 2D in a precise and reliable way. Traditional Lidars use a mechanical rotation to spin the sensor and cover a 360-degree area. Unfortunately, mechanical Lidars are not reliable; they are bulky and quite expensive.

One type of solid-state Lidar (i.e., no moving parts) deploys micro-electromechanical system (MEMS) technology where a MEMS-based mirror moves to "scan" the environment. Other types of solid-state Lidars are optical phased arrays, where the optical phase modulator controls the speed of light passing through the lens. The optical wavefront shape can be manipulated by carefully controlling the speed of light, effectively steering the laser beam to point in several directions. However, due to the small optical aperture of MEMS mirrors and the poor efficiency of phased arrays, both of these recent methods show limitations.

A new beam steering technology has been developed using liquid crystal metasurfaces (LCM), representing a completely solid-state Lidar with a higher resolution, range, and frame rate than existing mechanical Lidars. A startup named Lumotive developed this new solution. It combines a reflective optical metasurface with a liquid crystal layer. The silicon-based metasurface can be manufactured using CMOS standard technology. Lumotive claims that their high-performance Lidar with a large optical aperture can deliver long-range, 120-degree field of view, high angular resolution, and fast beam steering.





(Left) Figure 9. Liquid Crystal Metasurface (LCM) chip for beam steering used in Lidars.
(Right) Figure 10. Laser beam reflected at a certain angle from the liquid crystal metasurface.
Image courtesy of Lumotive.

A laser beam is incident on the reflective semiconductor chip and is reflected by the metamaterial surface elements in a certain direction, which is fully software programmable (see Fig. 10). The laser beam can be pointed in any direction. A metamaterial can be considered “a design approach” that can unleash new ways to control the flow of light and other wave excitations. In this case, thousands of optical resonant antennas can be formed as metal rails extending from the optically reflective surface. The optical reflective surface can be copper, and liquid crystal fills the gaps between the metal rails. The individual optical resonant antennas and the spacings between them may be less than one-half of a wavelength. A voltage controller can apply a voltage pattern to the metal rails to bias the associated liquid crystal to obtain a target reflection phase pattern. Each different voltage pattern across the metasurface corresponds to a different reflection phase pattern. Carefully controlling the local phase pattern allows the sensor to reach the target beam steering angle. This completely solid-state Lidar is promising thanks to a combination of factors, like performance, size, cost, and reliability.

3. Power and Energy

3.1. Power transmission

Wireless transmission has been a dream since the days of Nikola Tesla. Companies like Metapower in the United States and Emrod in New Zealand develop wireless power transfer transmitting systems.

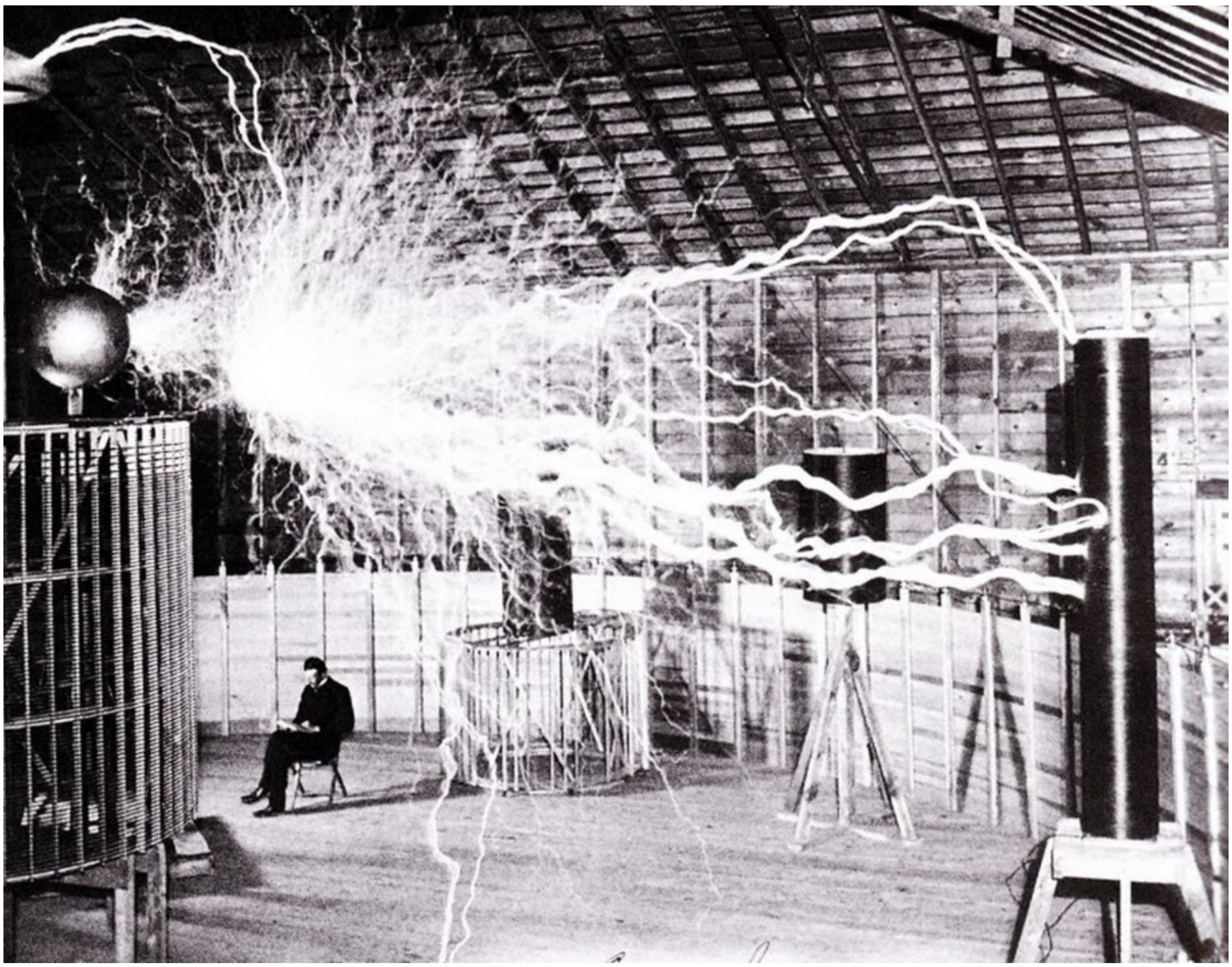


Figure 11. Serbian-American inventor Nikola Tesla in December 1899 sitting in his laboratory in Colorado Springs, CO next to his magnifying transmitter high voltage generator while the machine produced huge bolts of electricity. Image courtesy of Dickenson V. Alley, Wellcome Collection.

Metapower developed a power-beaming system that shoots microwaves at a metamaterials-based reflective array the size of a chalkboard, which focuses the waves on their intended target. The reflector can be shifted electronically to track a moving target and provide power across distances of several hundreds of feet through dust or fog.

Metapower's system operates within an unlicensed spectrum band, i.e., industrial, scientific, and medical (ISM), and requires little bandwidth so that wireless communication protocols like Wi-fi or Bluetooth can continue to operate in its presence. The advantage of using the metamaterials components is that the microwave can be focused and steered with high efficiency and no mechanical moving parts. The biggest challenge for this type of system is that it requires safety measures to limit human exposure to the microwave beam per federal safety guidelines. This could be achieved with a monitoring system that switches off the beam when a person comes close.

Figure 12. Metapower dynamic beam tracking system. Image courtesy Metapower Inc.

Emrod is a New Zealand company that has developed the first long-range, high-power wireless transmission system, eliminating the need for traditional copper wiring infrastructure to support the power grid. The company is doing a commercial pilot with PowerCo, the country's second-largest power distributor company.

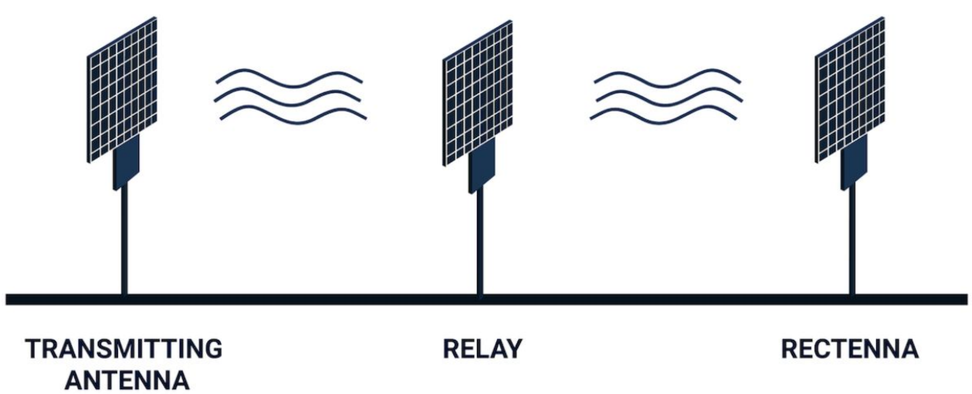


Figure 13. Wireless power system. Image courtesy of Emrod.

Emrod uses beam shaping and metamaterials technology to create columnated beams that safely transmit power over many kilometers with no radiation around the beam, as with high-voltage wire transmission.

The great advantage of this wireless technology compared to traditional wired one is reliability - it has fewer failure points, and is not affected by bad weather, lower infrastructure, and maintenance costs, "eco-friendly" status - replacing lines and underwater cables minimizes the human footprint on the environment.

In Fig. 13, you can see three components:

1. A transmitting antenna.
2. A relay that is essentially lossless, doesn't require any power, and acts as a lens refocusing the beam extending the travel range.
3. A rectenna that receives and rectifies the beam back to electricity. Metamaterials allow converting wireless energy back into electricity efficiently.

At the moment, a one-square-meter (10.7-sq-ft) transmitter could send about 10 kW for about 10 meters (33 ft), and a 40-square-meter (430.5-sq-ft) transmitter could provide about a 30-km (18.6-mi) range, which is enough for the vast majority of applications. The system's efficiency is around 70 percent, and the loss is primarily due to the transmitting side. Traditional copper wire transmission has an efficiency of 85-90 percent. Despite the lower efficiency, there is room for improvement, especially with the advancement of technologies related to communication, such as 5g. Also, there are already use cases where this application is already economically viable, for example, where there is difficult terrain, mountains, forests, or national reserves.

3.2. Wireless charging

An interesting application for metamaterials is wireless charging. Metamaterials can be cleverly used to improve the efficiency of low-power wireless charging systems. Wireless power transfer (WPT) technologies have attracted attention in the past years for a broad range of applications. For example, low-power consumer electronics implanted medical devices, industrial and electric vehicle applications. Magnetic coupling (also called inductive coupling) is used to charge your phones or electric toothbrushes, which are placed on a charging dock or pad without the need for any alignment or electrical contact.

Another name for wireless charging is inductive charging because the transfer of energy happens via inductive coupling. The mechanism is simple: an alternating current flows in an induction coil placed in a charging station or pad . The alternating current generates a magnetic field, which varies in strength over time. This changing magnetic field generates an alternating electric current in the device's induction coil (also known as receiving coil), which is then converted to a direct current by a rectifier. Finally, the direct current charges a battery or supplies power to a device. Very high efficiency of magnetic coupling can be achieved only at small distances between the transmitting coil and the receiving coil and usually distances less than a few centimeters. A way to increase the distance between the transmitting and receiving coils is to use resonant inductive coupling. A capacitor is added to each coil in order to create two inductor-capacitor (LC) circuits with a specific resonance frequency.

Figure 14. Wireless charging pad for mobile phones

Negative-index metamaterials (NIMs) can greatly improve the efficiency of wireless charging. A flat slab of NIM has negative refraction happening at both interfaces. When a transmitting object is in front of such a slab, the propagating wave components of the object can be focused inside the NIM slab and refocused on the other side of the slab. Moreover, evanescent wave components (the part of the electromagnetic wave formed when waves traveling in a medium undergo total internal reflection at its boundary) can be enhanced inside a NIM slab to levels similar to the levels adjacent to the original electrical conductor. Substantially, the NIM slab recovers both propagating and evanescent waves of an object and makes a “perfect magnetic lens” (Fig. 15).

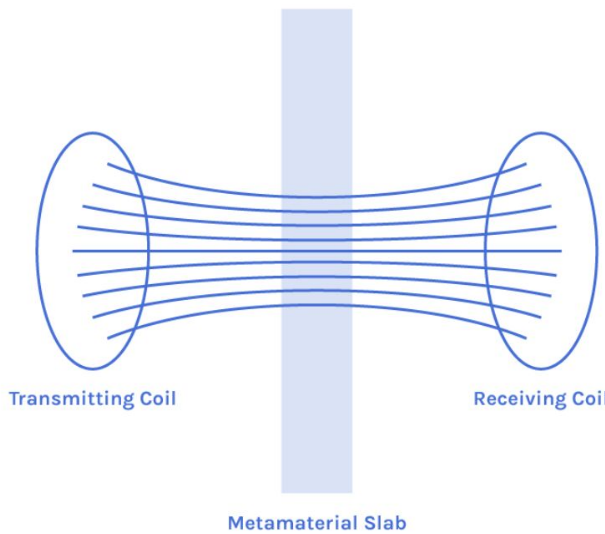


Figure 15. Wireless power transmission with metamaterial slab to focus the magnetic field.

A research group at Mitsubishi Electric Research Laboratories has fabricated the wireless power transfer system with a NIM lens. The [published results]() show that the wireless power transmission system with metamaterials has roughly double the efficiency of conventional without metamaterials (Fig. 16).

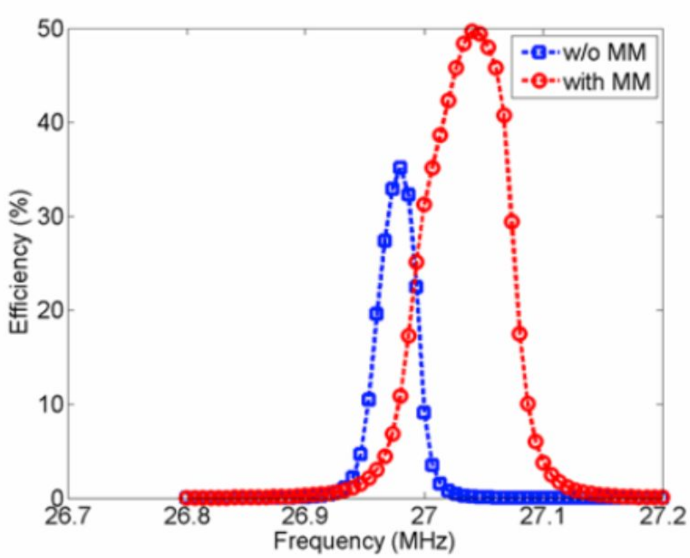


Figure 16. Efficiency comparison of a wireless power transmission system with metamaterials and without metamaterials. Source: [Wireless power transfer with metamaterials. Proceedings of the 5th European Conference on Antennas and Propagation, EUCAP 2011]()

Companies innovating in this space are Metaboards based in Oxford (UK) and Metamaterials Inc. (Meta) in Canada.

Metaboards is developing innovative and very flexible techniques to integrate wireless charging into surfaces so that several products can be charged simultaneously without the use of numerous power supplies or close alignment. Using a metamaterial layer that can be easily integrated into practically any surface (furniture, clothing, carpets, wallpaper, etc.), consumer devices (smartphones, tablets, laptops, cameras) can all be charged from the same surface.

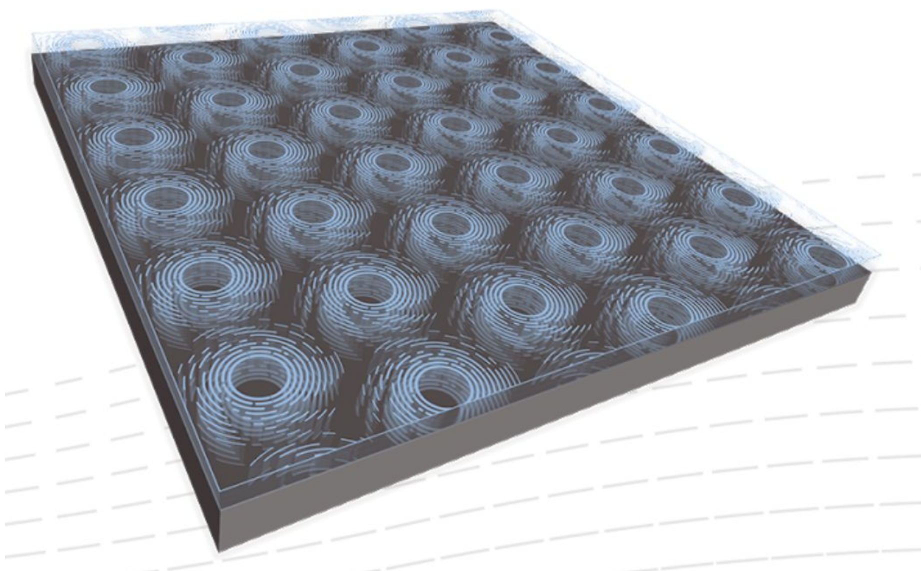


Figure 17. Wireless charging pad. Image courtesy of Metaboards.

3.3. Energy harvesting

The sun is a priceless source of life, providing energy to our planet in the form of light and heat. Global human population growth poses a serious threat in terms of energy scarcity, and this problem is becoming an important global challenge that humankind is trying to solve with technological solutions. One approach to solve energy scarcity is to harvest free and clean energy from the sun.

Solar energy harvesting can be done in three ways:

1. The photovoltaic approach converts photon energy into electricity.
2. The photochemical approach converts solar energy into storable chemical fuels, like hydrogen.
3. The photothermal approach converts photon energy into thermal energy by solar-thermal absorbers.

The third approach has the advantage that it exploits the broader bandwidth of the solar spectrum, enabling higher conversion efficiency and the smallest carbon footprint.

An Australian research group at the Swinburne University of Technology has investigated an interesting application of metamaterials: a solar-thermal absorber with an impressive solar-to-thermal conversion efficiency of 90.1 percent. An ideal solar absorber requires a selective and almost total absorption in the entire solar spectrum, minimized energy dissipation in the near and mid-infrared, and a tunable cut-off frequency. The group demonstrated a three-dimensional structured graphene metamaterial (SGM) that takes advantage of wavelength selectivity from metallic trench-like structures and broadband dispersionless nature, and excellent thermal conductivity from the ultrathin graphene metamaterial film. The results were published in Nature Communications.

The second approach mentioned above transforms photons, i.e., visible light, into energy. Thermovoltaic devices absorb wavelengths in the infrared spectrum instead of the visible spectrum, thus transforming heat into electricity. An expert group in metamaterials at Duke University used machine learning to optimize all-dielectric metasurfaces (ADMs), that absorb and emit specific frequencies of terahertz radiation. The ADM supercell consists of four cylindrical unit cells, as shown in fig. 18. The heights, diameter, and interspace of the cylinders affect the frequency of light the metamaterial interacts with. The team used ML to find the right parameters to produce a particular system's response (the frequency at which the system absorbs radiation).

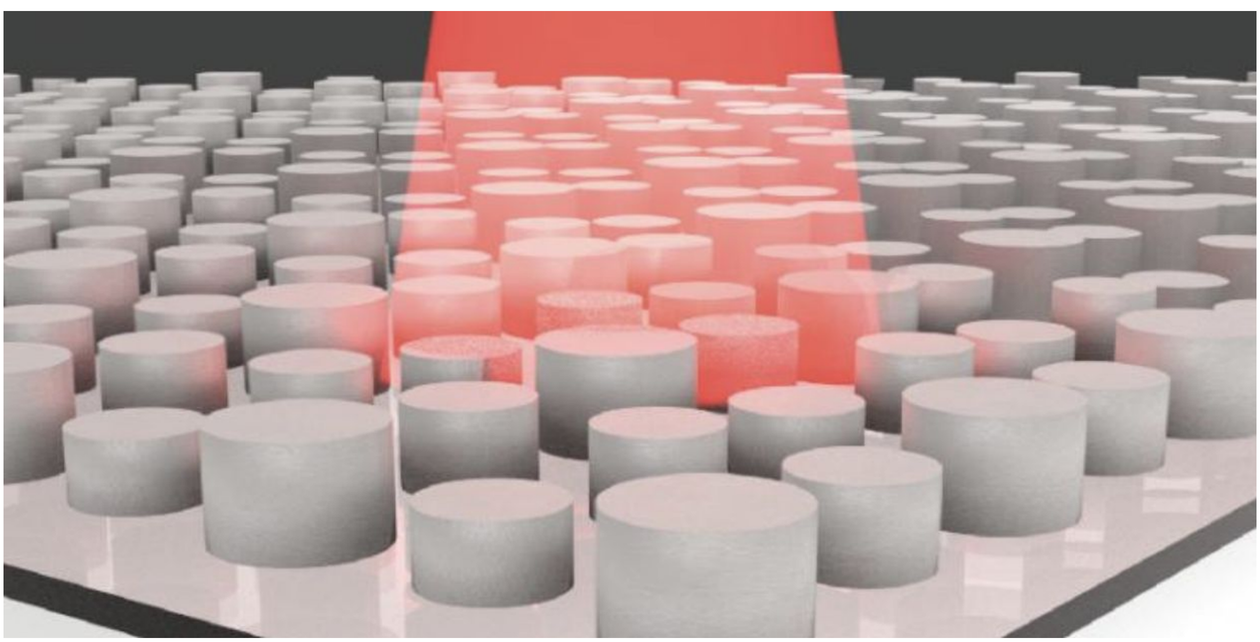


Figure 18. All-dielectric metamaterial with infrared light hitting the surface. Image courtesy of Duke University.

Face International Corporation in Norfolk, VA., patented a new coating that appears completely opaque when applied to a surface but allows 80 percent or more of the incoming light to pass through it. The coating technology, called Spectral, can be used like paint in virtually any color, pattern, or texture, making light-harvesting devices such as thin-film photovoltaic (PV) panels essentially invisible. Applications could be:

1. Solar-powered roof or other parts of the building which appear as the conventional counterpart (Fig. 19)
2. Electronic devices or cars being solar powered without any compromise to their aesthetics.
3. Military or surveillance devices that can be completely hidden.
4. Solar-powered commercial or private buildings can be energy efficient and blend with the surroundings.

Figure 19. A solar-powered roof shingle looks like a conventional shingle.
Image courtesy of Face International Corporation.

4. Telecommunication

applications Metamaterials are used in telecommunications applications, including mmWaves antennas and 3D radars. This space and its developments are extremely compelling because it affects wireless communication, GPS satellites, space communication, and automotive communication, which have always been strategically important sectors and are even more so now.

Let's start with the basics. An antenna is an electronic device that converts radiofrequency (RF) signals into alternating current or vice versa. Receiving and transmitting antennas are used to receive or transmit radio transmissions, respectively. Conventional antennas need to be half the size of the signal wavelength to operate efficiently. For example, at the 30MHz frequency, the antenna would need to be 1 meter long. Some use cases are less sensitive to size than others, but size and cost are key specifications for commercial products. An acronym SWaP-C, which stands for Size, Weight, Power, and Cost, was originally used in aerospace, defense, and government sectors, but now this term is used commercially. These parameters are extremely important and drive the design of new products.

Metamaterials can be used to improve antennas' performance and reduce their size. Experimental metamaterials antennas are as small as one-fiftieth of the wavelength.

4.1. MmWave antennas

An antenna radiates energy into free space so that users can watch TV, use a mobile phone or listen to their favorite radio station. New antennas can incorporate metamaterials, engineered materials with periodic structures that create physical properties not found in conventional materials. Antenna designs incorporating metamaterials can boast the radiated power of an antenna and radiate as much as 95 percent of the input radio signal.

Kymeta developed the first metamaterials-based flat panel antenna and made it commercially available for satellite communications in 2017. The use of metamaterials creates antennas that can steer a radio signal dynamically without any mechanical moving mechanisms. These metamaterials antennas use a software-control panel to track satellites across the sky without repositioning the antenna. The great feature of these antennas is that their power consumption is only a few watts compared to equivalent size phased-array antennas consuming more than one thousand watts. Also, metamaterials-based antennas deliver beam-steering of the radio wave without expensive and power-hungry shifting components used in the phased-array antennas. In a nutshell, think about these antennas as solid-state, simpler, and more compact. The reduction in size, cost, and power consumption opens up more possibilities for satellite antennas, including cars, aircraft, vessels, and portability devices.

Kymeta developed metamaterials-surface antenna technology (MSAT) where metamaterials are used to enhance the efficiency and directivity of microwave antennas. Metamaterials have periodic structures of scattering elements that are smaller than the wavelength of the electromagnetic waves they are interacting with. These structures made with metals or plastics have size, shape, orientation, and patterns designed to create precisely tuned resonances and other unconventional properties in certain frequency bands. Generally, metamaterials have 3D dimensional structures. But the same properties can be achieved if electrically subwavelength structures are fabricated on a thin surface. In this case, the metamaterial surface or metasurfaces are thinner, lighter, and less expensive because they can be printed using conventional lithographic processes (the same used in semiconductor chip manufacturing).

The Kymeta MSAT is based on diffractive metasurfaces rather than refractive, to define the beam holographically—a technique known as Holographic Beam Forming (HBF). The use of liquid crystals, which are compatible with traditional liquid crystal display (LCD) fabrication processes, allows to tune each radiating element and steer the beam electronically.

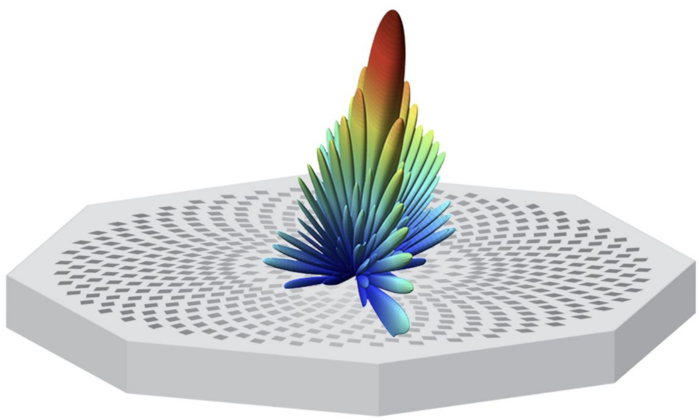


Figure 20. Metamaterial surface antenna technology for satellites and 5G using liquid crystals. Image courtesy of Kimeta Inc.

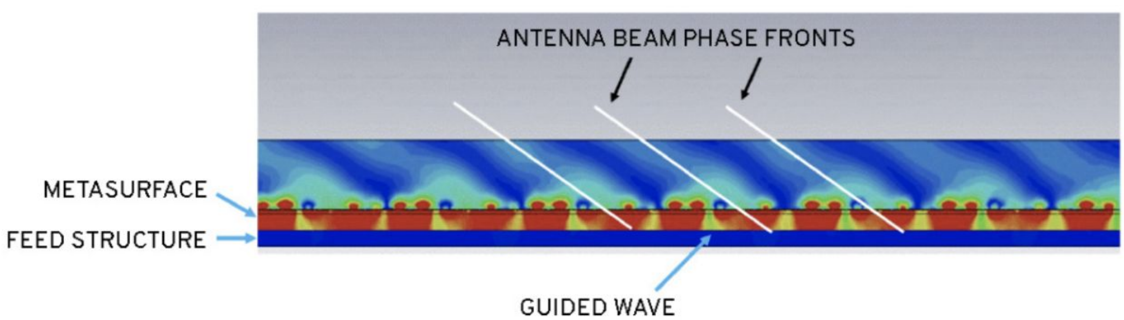


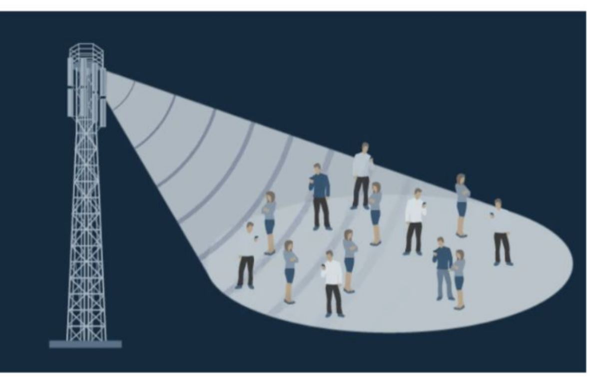
Figure 21. Cross-section of the antenna. Image courtesy of Kimeta Inc.

The metasurface is printed with hundreds or thousands of elements periodically repeated and is placed on top of a rectangular waveguide feed structure that couples the elements to a radio frequency wave generated by a single transmitter (see Fig. 21). Each element is electronically tuned to resonate at a particular frequency and radiate the waveguide.

This is obtainable by controlling the liquid crystals. A simple explanation is that by applying a low-frequency voltage to the liquid crystals in correspondence of each element, the capacitance of the element changes, thus changing its resonance frequency (Metamaterial Surface Antenna Technology whitepaper provides details). The elements are physically spaced to radiate waves in phases at the desired scan angle of the antenna beam. They are tuned to scatter (radiate) while the elements out of phase cancel each other out so that they won't radiate. The total energy is the sum of the waves radiated by each element. It's a similar phenomenon that happens when vibration waves produced, for example, by wind, increase in amplitude due to resonance and destroy a bridge. This type of antenna is slim, light, does not have moving parts, and has a high throughput (up to 10MBps). Also, this antenna can transmit and receive with a single aperture, and this is obtained by interleaving receiving and transmitting elements on the same substrate and controlling them independently.

Pivotal Commware is another HBF antenna company. They focus on broadband wireless networks and air-to-ground transmission.

Holographic beamforming enables wireless service providers to reuse the same band of the spectrum, at the same time, in a given spatial region. Unlike traditional cellular systems, which use 60-90 degree sector beams, narrow beamforming permits more focused communication between the users and the base station. The result is better spectral hygiene (i.e., less interference) and the possibility to have multiple concurrent transmissions in the same frequency with higher intensity.



(Left) Figure 22. Traditional cellular network. (Right) Figure 23. Antenna with beamforming. Images courtesy of Pivotal Commware.

The beamforming technique is not new. Phased arrays have been used in the defense industry for decades. Multiple-Input Multiple-Output (MIMO)antennas can be used for digital beamforming. However, both phased arrays and MIMO are quite expensive for commercial use. The phased-array antennas require array elements (phase shifters and power amplifiers) that drive the cost up, while MIMO requires a digital signal processor (DSP) for any element. In general, both approaches are costly, have high power consumption, and are bulky.

Contrary to both approaches, the HBF only requires a single and cheap control component such as a varactor (which is a variable capacitance) or a transistor. The HBF transforms a radio frequency signal into a steerable beam by manipulating the bias state of the control components. In the case of the Kimeta antenna, the variable component was the capacitance of each scattering element that could be changed by applying a voltage to the liquid crystal. In the case of Pivotal, the antenna consists of a printed circuit board (PCB) covered in metal cells smaller than the wavelength of the radio waves they manipulate (Fig. 24). Via software, the antennas' elements can be activated to create beams of radio waves. Changing the voltage applied to the elements, they can switch within microseconds. Thanks to holographic beamforming, signals have much higher gain. This can be helpful, for example, to prevent millimeter waves (the ones used in 5g networks) from being blocked by buildings or losing intensity after a few miles. This type of antenna can be designed to span from 1 GHz to 70 GHz spectrum.

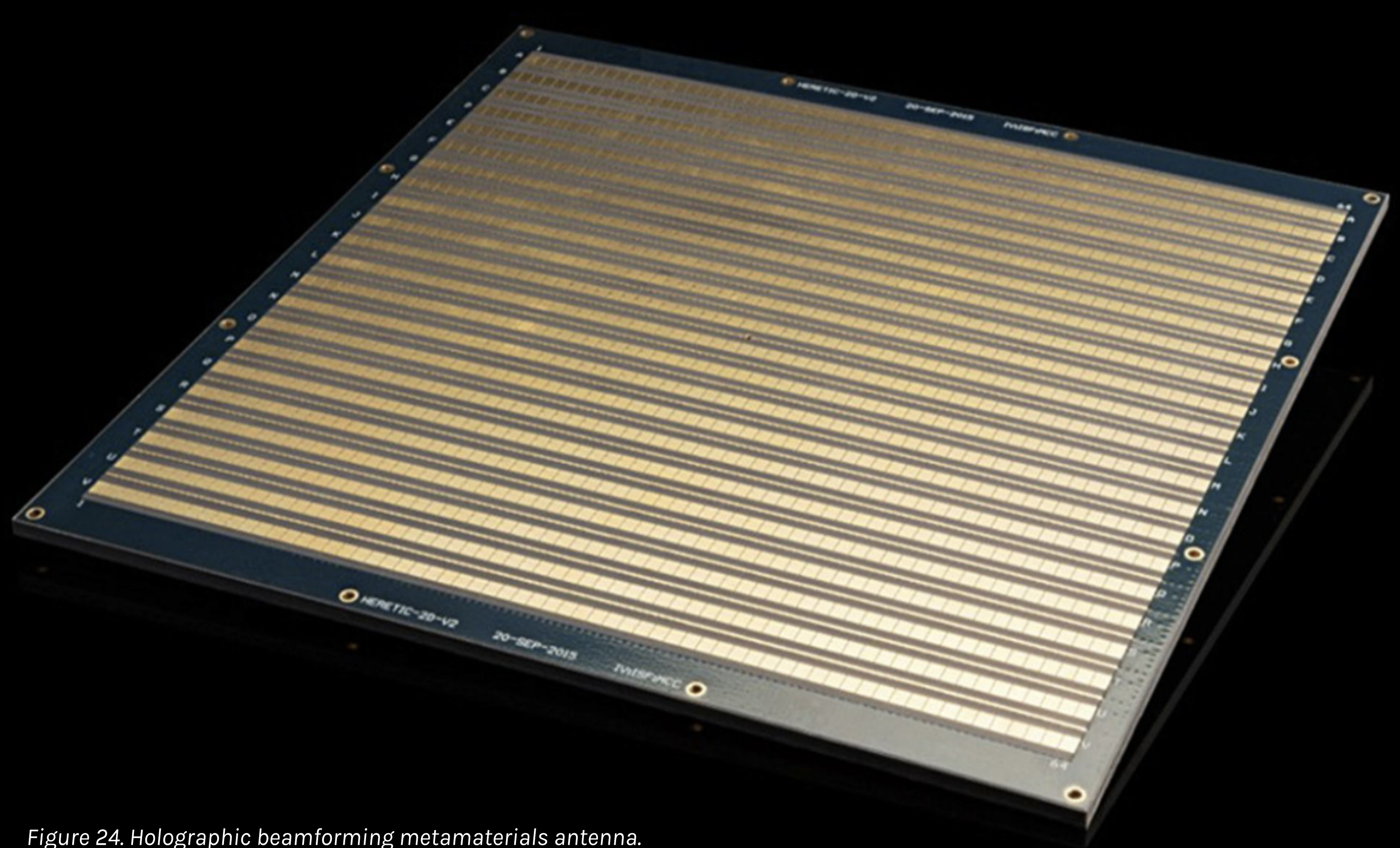


Figure 24. Holographic beamforming metamaterials antenna.
Image courtesy of Pivotal Commware.

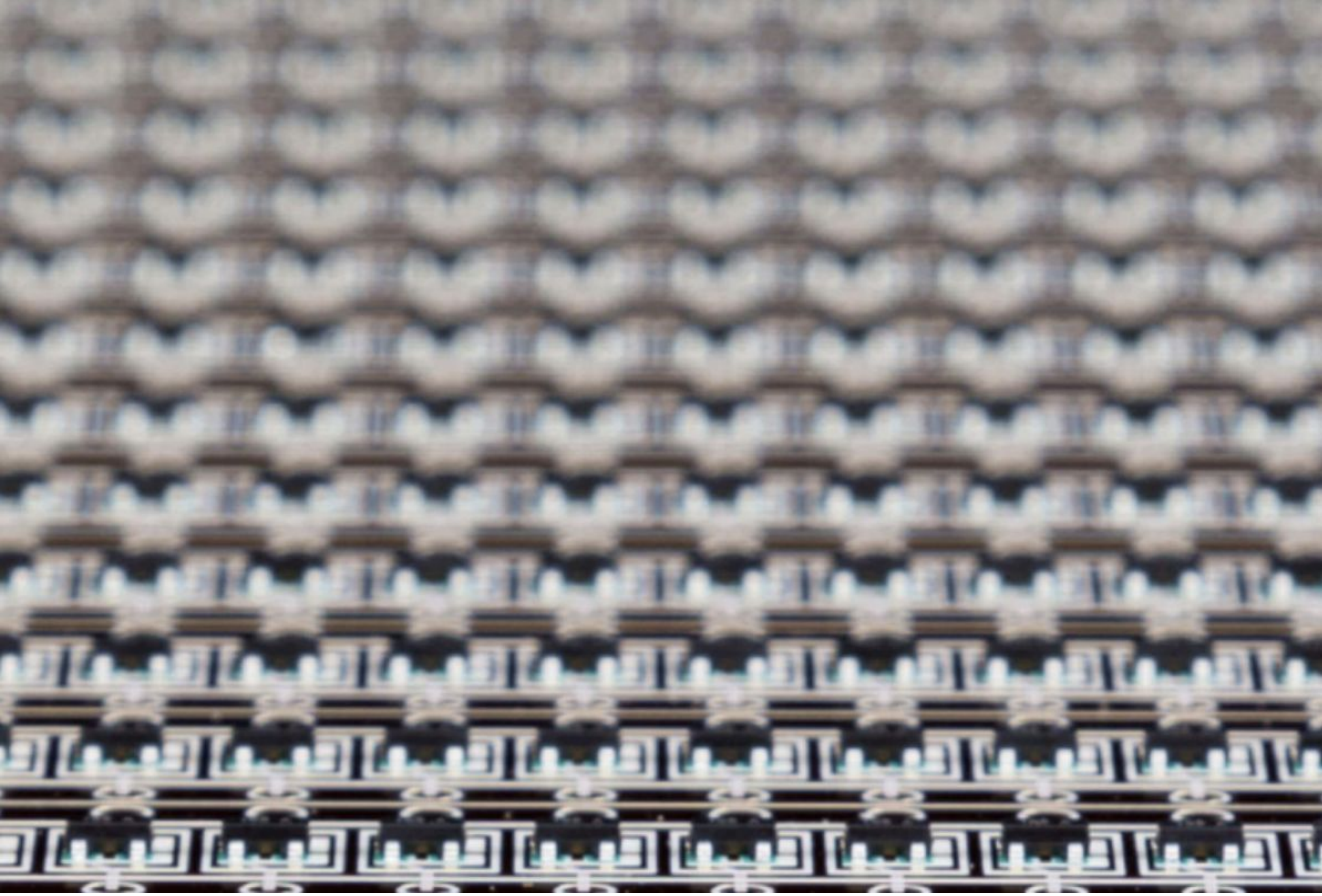


Figure 25. Metamaterial electronically scanned array (MESA) radars.
Image courtesy of Echodyne Inc.

4.2. 3D radars

An interesting application of metamaterials is radars, where metamaterials electronically scanned (MESA) radars can be compacted to be as small as an iPad. The metamaterials can be fabricated using standard PCB fabrication and assembly processes. The MESA radar uses a metamaterial antenna to steer its beam, as we have seen for other types of antennas for wireless communications. MESA radars have the advantages of size, weight, power, and cost over conventional ESA radars. In commercial applications, such as infrastructure monitoring, unmanned aircraft, autonomous vehicles, using conventional phased-array radars could not be possible because they are expensive and bulky. These radars rely on a grid of phase shifters that together steer the radio beam. Controlling and manufacturing all these shifters can be complex. Metamaterials antennas replace all these components with a metamaterial array, dramatically cutting cost, size, and complexity. One interesting player in this space is Echodyne Inc., based in Seattle, WA.

The applications discussed earlier are nonexhaustive. The industries that will be impacted by metamaterials solutions and other applications are depicted in Fig. 26.

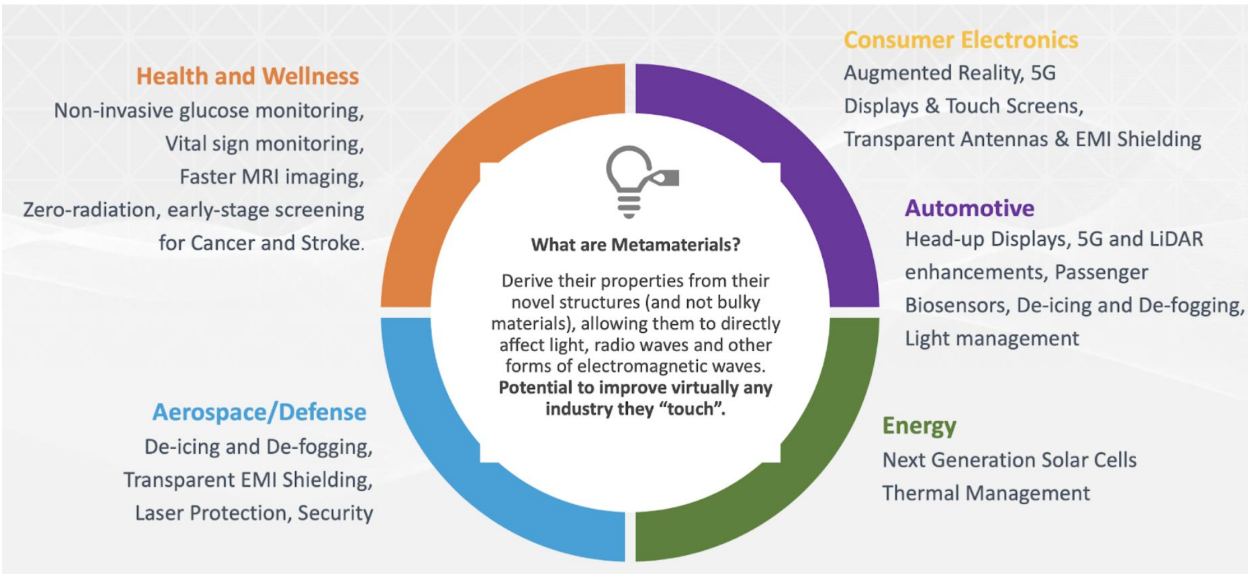


Figure 26. Main sectors and applications for metamaterials. Source: Meta Investor presentation

Metamaterials bring to a simplification of the complexity of products, which usually have multiple components, multiple materials requiring further steps in their integration such as mechanical and thermal simulations. The complexity in metamaterials products is in the digital design, i.e., the design of the patterns to achieve what the designer is planning. For example, in the case of optical metamaterials, the engineered metamaterials layer carefully controls the path of light to achieve the desired effect. This design process is done via software and allows startups to rely on manufacturing partners while keeping their core design expertise in-house.

As a rule of thumb, metamaterials-based products have the following features:

- Lightweight and thin: combining multiple functionalities in a single layer of metamaterials can have fewer components. For example, lenses for phones which require multiple components for zoom will be dramatically simplified. Similarly, AR/VR displays can integrate a single metamaterial optical layer to accurately control light patterns.
- Digital design: the complex patterns are designed via software. Complexity is shifted to the knowledge on how to design these patterns and not in the integration of multiple components. This means a faster design time compared to conventional components.
- Device design freedom - metamaterials control lights or other wavelengths with angles, trajectories, or ways that are impossible with traditional materials or conventional components. This allows manufacturers to have greater freedom of design.

Market Forecast

While the first metamaterial devices, wireless communication antennas, were introduced to the market in 2009, the difficulty of developing metamaterial structures and the high cost of producing them rendered their usage in most applications impractical. Due to advancements in modeling and simulation software, additive manufacturing, and lithography in recent years, design and production processes have developed, making near-term at-scale metamaterial adoption conceivable in numerous significant applications. Electromagnetic and acoustic metamaterials have likely the most immediate and medium-term impact.

Metamaterials are also a major economic opportunity. According to a Lux Research report, the metamaterial market will reach $10.7 billion by 2030. The research focused on the potential addressable markets and the likelihood of adopting metamaterials solutions, based on multiple factors, such as cost, maturity, and performance. The main market applications for metamaterials components are communications, sensing, and acoustic applications. Other minor applications are included in the subcategory "Other." By 2025, communications will represent a large portion, with a $4 billion market value, but by 2030, sensing applications will represent the largest market segment reaching $5.5 billion.

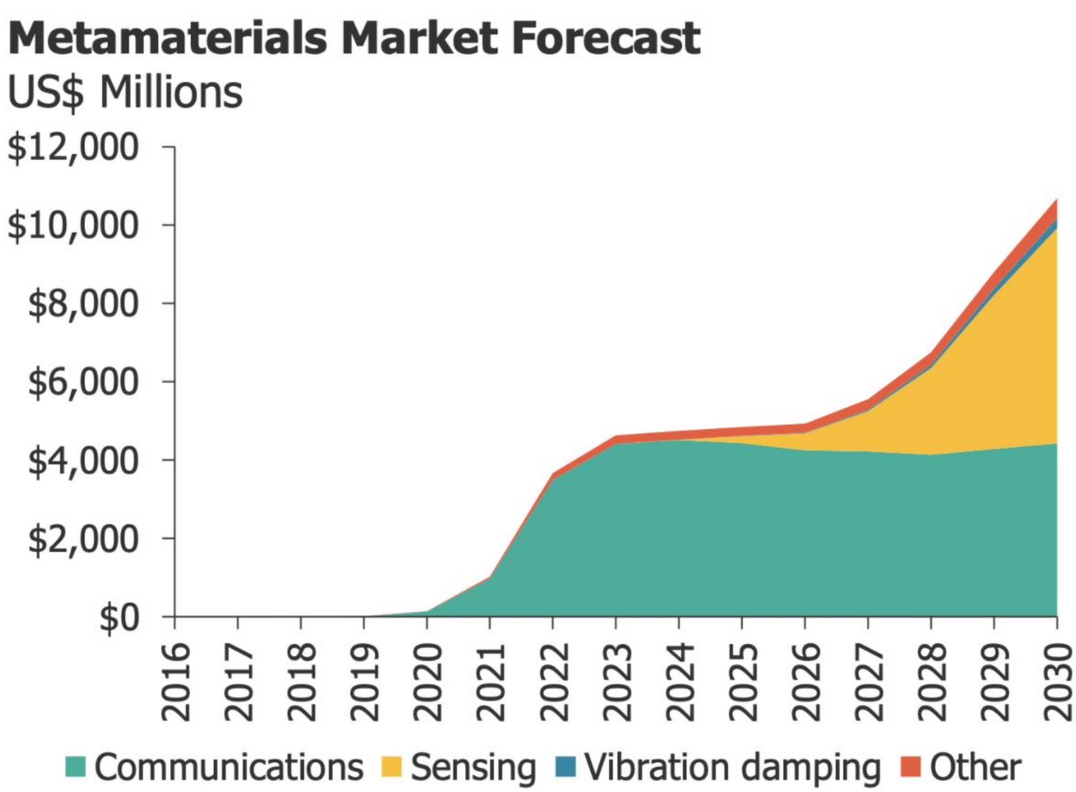


Figure 27. Market forecast for metamaterial-based products. Source: [Lux Research]

Landscape and investment recommendations

After I joined Prime Movers Lab, I started researching metamaterials as I believe they are at the inflection point to disrupt lucrative market applications. A landscape of companies deploying metamaterials is reported below. We had the opportunity to meet with some of these firms, and we are now in discussions with others.

The time appears to be ripe to invest in this sort of innovation, as evidenced by the establishment, in June 2021, of new venture capital firms, such as MetaVc Partners (supported by Bill Gates), with a purpose to invest in metamaterials companies.

Metamaterials
Went public via merge with Torchlight Energy in June 2021
Amount Raised/Valuation: $250M merge (CNQ:MAX)
Sector: Energy, Transportation, Manufacturing
Technology: Metamaterials technologies designed for multiple applications
Market Targeted: De-icing, de-fogging for aerospace; solar films for solar cells; transparent antenna; holographic HUD, de-fogging coating for automotive

Metavision
Out of business in 2019
Amount Raised/Valuation: $82.7M/$300M post-money
Sector: Human Augmentation/AR
Technology: AR glasses

Brelyon
Amount Raised/Valuation: $3.6M/$18M post-money
Sector: Manufacturing/ Displays/Lenses
Technology: Ultra reality monitor for immersive experience, better performance than existing monitor, 3d experience, 122" virtual monitor at 8k resolution in a 32" monitor
Market Targeted: Defense, industrial, medical, simulation at first. Then prosumer via Dell, HP co-branding deals.

Radi-cool
Amount Raised/Valuation: $3M non dilutive funding
Sector: Infrastructure/Manufacturing
Technology: Optical Metamaterials that Cool Objects Underneath
Market Targeted: Building envelope and cars/trucks

[Metalenz]
Amount Raised/Valuation: $17.36M/$44M post-money
Sector: Manufacturing/Lenses
Technology: Meta lenses act as waveguides to manipulate light and provide a degree of control not possible with traditional refractive lenses. A single thin meta-optic can outperform a stack of refractive lenses and provide significant system-level performance and cost advantages. Meta-optics are fabricated using standard semiconductor processes and are made in the same foundries that produce microelectronics and CMOS image sensors.
Market Targeted: Lenses for mobile phones, automotives

[Transaera]
Amount Raised/Valuation: $2M in non-dilutive funding
Sector: Energy
Technology: Highly porous materials called metal-organic frameworks, or MOFs
Market Targeted: HVAC building

[Metaseismic]
They will fundraise in October 2021) a $3M seed round. The servers and data center racks are a very lucrative market.
Amount Raised/Valuation: $1M in non dilutive funding.
Sector: Infrastructure/Buildings
Technology: METAseismic develops cost-effective metamaterials to protect buildings and valuable objects from earthquakes. The anti-vibration is important also in non-seismic areas, because big companies such as Google, FB are using huge data centers.
Market Targeted: They are going after the data-center racks market.

[Lumotive]
Amount Raised/Valuation: $31.50M/ NA
Sector: Transportation/Lidar
Technology: Solid-state Lidar technology that leverages unique beam-steering technology based on patented Light Control Metasurface chips to deliver an unprecedented combination of high performance and readiness for mass adoption as measured by cost, reliability and small form factor.
Market Targeted: Solid-state Lidar developer

[Kymeta]
Amount Raised/Valuation: $442.54M/ $374.96M
Sector: Infrastructure/Telecomm/Space
Technology: Kimeta develops the first electronically scanning, flat-panel satellite terminal for fixed and mobile platforms. Kimeta's antenna is flatter, consumes less power and has better performance than traditional phased-array antennas. The company also offers connectivity services using its satellites and terminals.
Market Targeted: First company to successfully commercialize metamaterials based product

[Echodyne](#)
Amount Raised/Valuation: $64M/$140M
Sector: Transportation/ Radar
Technology: Developer of metamaterials-based radar technology designed to operate autonomous machines safely at any time and in any weather.
Market Targeted: Defense, transportation.

[Metawave](#)
Amount Raised/Valuation: $107.99M/$225M
Sector: Infrastructure/Telecomm
Technology: The core technology is based on combining the best of analog front-end beamforming and steering Antenna in Package (AiP) modules, hybrid virtual MIMO arrays architectures, and simplified back-end digital signal processing
Market Targeted: Advanced ADAS for automotive (5d radar - range, velocity, angular accuracy or resolution in both horizontal and vertical axis, real-time object classification); 5G mm-wave Repeaters and Reflectors for Economical Deployment.

[Pivotal Commware](#)
Amount Raised/Valuation: $91.75M/$318M
Sector: Infrastructure/Telecom
Technology: The core technology is Holographic Beam Forming. Holographic Beam Forming (HBF) enables wireless service providers to continuously reuse the same band of spectrum, at the same time, within a given spatial region. Like several narrow, high-intensity spotlights illuminating discrete objects in a theater, beamforming antennas can focus their radiated energy on separate targets without illuminating adjacent users.
Market Targeted: Telecommunication market with a network repeater for cost-effectively extending and shaping gNB mmWave signals outdoors.

[Teraview](#)
Amount Raised/Valuation: $46.88M/$24.32M
Sector: Manufacturing
Technology: Developer of a terahertz imaging platform designed to provide spectroscopic information and 3D image maps with a unique spectroscopic signature. The realization of high-performance tunable absorbers for terahertz frequencies is crucial for advancing applications such as single-pixel imaging and spectroscopy.
Market Targeted: Semiconductor, pharmaceutical

[Sonobex](#)
Amount Raised/Valuation: Acquired by Merford in 2017 (undisclosed amount)
Sector: Infrastructure/Buildings
Technology: Acoustic panel technology, using acoustic metamaterials.

[Imagia]
Amount Raised/Valuation: $2M/$9M post-money
Sector: Manufacturing/Lenses
Technology: Optical metamaterials for lenses
Market Targeted: AR glasses

[Phononic Vibe]
Amount Raised/Valuation: $3.28M/ NA
Sector: Infrastructure/Buildings/Manufacturing
Technology: New patented technology for the vibration and noise control and isolation.
Market Targeted: Buildings and home appliances

[Anywaves]
Amount Raised/Valuation: NA
Sector: Infrastructure/Telecomm
Technology: European company developing miniaturized antennas for satellite constellations.
Market Targeted: Satellites

[Evolv Technology]
Amount Raised/Valuation: SPAC 07-19-2021 at $1.8B (NASDAQ: EVLV)
Sector: Defense
Technology: Developer of new metamaterials-based imaging and detection technology for use in airports and other high-risk facilities. 'The Evolv Express system delivers up to a 70% reduction in cost and is up to ten times faster than traditional metal detectors.

[Fractal Antenna]
Amount Raised/Valuation: NA
Sector: Infrastructure/Telecomm
Technology: Antenna developer
Market Targeted: Defense, commercial such as stadium and public venues

[Emrod]
Amount Raised/Valuation: $1.68M / NA
Sector: Infrastructure/wireless power
Technology: Developer of tele-energy technology designed to enable long-range wireless energy transmission. The company's technology includes truck-mounted outage response units, network delivery, wireless distribution network, and backup installation, enabling utilities, line companies, and engineering firms to transmit energy where traditional wire-based connections are not economically viable. They use a proprietary technology, including beam shaping, metamaterials and rectenna.
Market Targeted: Energy marketing targeting utilities companies

Based on our experience, the most interesting companies at a very advanced stage of development, or ready for commercialization, will have the opportunity to immediately disrupt current products or create new markets. These include consumer (displays, VR lenses, camera lenses), automotive (Lidars, radars), defense (imaging detectors), telecommunications (5g repeaters and satellite antennas), infrastructure (anti-vibration, anti-seismic, acoustic applications).

When metamaterial choices become available on the market, traditional offers in these sectors are likely to become uncompetitive.

Metamaterial adoption does not necessitate a large capital outlay because devices may continue to employ traditional materials and techniques with metamaterial designs. However, developers will need time to become fluent in metamaterials as a design language, and organizations that do not start this process immediately risk falling behind. Manufacturing is extremely important to bring this technology from a prototype-lab scale to a mass-production scale. Reaching enhanced performance at extremely small wavelengths requires manufacturing ultra-small unit cells, which is a non-trivial process. When moving from 2D metasurfaces to 3D structures, the manufacturing complexity goes up substantially. In general, good manufacturing processes should be fast, affordable, and applicable to large areas. There are a lot of research efforts to bring new manufacturing processes to a large scale. For example, promising processes include nanoimprint lithography, pattern transfer, additive manufacturing, and self-assembly methodologies. Focused research in those areas is needed to improve or develop these enabling technologies into mass production manufacturing useful for metamaterials.

Because metamaterials rely on conventional materials and methods, well-protected design IP is likely to be important. Metamaterials startups are coming out of strong research hubs, such as MIT and Duke University, and show the unique technical knowledge required to design metamaterials applications. This core expertise is their strongest wedge that is hard to replicate in traditional materials, components, or consumer companies.

Conclusion

Since the first metamaterials product went to market in 2009, relatively few products became commercially available because the difficulty in designing metamaterials structures and their high manufacturing cost made them prohibitive for commercial applications. In the last few years, improvements in the software for design and simulation in additive manufacturing made the near-term scale adoption of metamaterials-based products possible. Sectors like automotive, telecommunication, and consumer electronics are ripe for disruption. Once metamaterials options reach the market, the conventional products will suffer and likely become obsolete. The metamaterials products don’t require high CapEx because they rely on conventional materials and manufacturing processes with innovative design. When considering a new investment opportunity or starting a company, keep in mind that companies such as Intellectual Ventures have aggressively acquired strategic patents and launched several spin-offs, including Kymeta, Pivotal Commware, and Echodyne. Intellectual property in this field is strategic for the survival of incumbents. Early patents are expected to expire between 2024-2028, and more companies will likely pop up in analogy to what happened in the 3D printing industry in 2005. Exciting times lie ahead to transform many industries with metamaterials products.

Selected References

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The Global Market for Metamaterials and Metasurfaces to 2031

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Lux Research Forecasts $10.7 Billion Market Opportunity in Metamaterial Devices

Wireless Energy for Drones? Intellectual Ventures Beams Power With Metamaterials