Course Name: Introduction to Microwave and Optical Metamaterials
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Institute Name: Indian Institute of Technology, Guwahati
Week-1
Lecture-4

Lec 4: Classifications of Metamaterials-II

Hello students, welcome to online lecture 4 of the course Introduction to Microwave and Optical Metamaterials.

Lecture Outline

- Metamaterials – Classification based on functionalities
  - Electromagnetic Metamaterials
    - Intelligent Metamaterials
    - Quantum Metamaterials
  - Acoustic metamaterials
    - Acoustic cloaking metamaterials
    - Acoustic cloaking carpets
  - Thermal metamaterials
  - Mechanical Metamaterials

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So, today's lecture will be a continuation of the classification of metamaterials that we discussed in the previous lecture. So, here is a brief outline of the lecture. So, we will continue with the classification of metamaterials based on functionalities. We will go into the details of electromagnetic metamaterials and focus on intelligent metamaterials and quantum metamaterials. We will also have a better understanding of acoustic metamaterials, how they can be used for acoustic cloaking, and acoustic cloaking carpets.

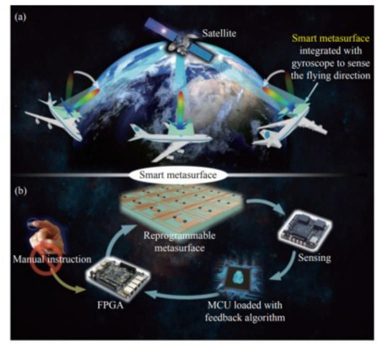
We will also see how thermal metamaterials work. And what are the mechanical metamaterials? All those things are important for you to get a better picture of the capabilities of metamaterials and to help you understand that this particular domain is not only related to or limited to microwave and optical; rather, the metamaterial concept is applied in other areas. Engineering disciplines, as you can see in the acoustic area and the thermal in mechanical, and so on.

Electromagnetic Metamaterials

Intelligent metamaterials:

For smart sensing:

- In the past decades, several information metamaterials have been proposed, which still require human beings to give instructions or produce pre-designs to perform specific functions.
- Smart metamaterials, which can sense the surrounding information in real time and actively make adjustments themselves, have become the main target of modern-day research.
- Smart metamaterials can sense changes in the external environment through sensing elements and realize autonomous judgment and active adaptation via a feedback loop.



(a) Illustration of the smart metamaterial with the function of self-adaption without manual instruction

(b) Feedback loop system of the intelligent metamaterial, which is composed of a digital coding metamaterial, an FPGA (Field Programmable Gate Array), a sensor, and a microcontroller unit loaded with the feedback algorithm.

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Source: You, J. *et al.*, 2023, Electromagnetic Science, 1(1), pp.1-33.

Okay, so let us go into the details of electromagnetic metamaterials and look into how intelligent metamaterials work.

They are basically used for smart sensing. So we have seen in the last decades or so that several information metamaterials have been proposed, which still require human beings to give instructions and produce pre-designs to perform some specific functions. So smart metamaterials that can sense the surrounding environment and the information in real time, and can actively make adjustments themselves, have become the main target of modern-day research. So you can understand that these materials are dynamically responsive to the surrounding information in real time, right? So smart metamaterials can sense changes in the external environment through sensing elements and realize autonomous judgment and active adaptation via a feedback loop. So, here you can see from the figure that it shows a smart metamaterial with the function of self-adaptation without manual instruction.

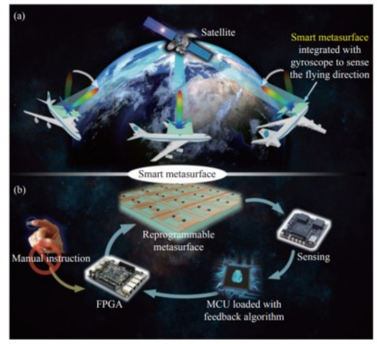
So, what is shown here is the satellite, and there is an aircraft, which has some smart metasurface integrated with its gyroscope to sense the flying direction, right? So, what is happening here, as shown in figure B, is that you have basically got a feedback loop of this intelligent metamaterial, which is composed of a digital coding metamaterial, and then you have got an FPGA. So, an FPGA is basically a digital IC that can be programmed to perform specific operations after manufacturing. So, it allows for customization and reprogrammability. Okay, reconfigurability is important, so FPGA stands for Field Programmable Gate Array. Then you have a sensor and a microcontroller-based unit (MCU) that is loaded with a feedback algorithm.

Electromagnetic Metamaterials

Intelligent metamaterials:

For smart sensing:

- A scenario in which an aircraft equipped with the smart metamaterial communicates with a satellite is illustrated in Figure (a).
- In this example, when the integrated sensor, a gyroscope sensor, detects changes in the flight status of the aircraft, which is represented by the rotation angle of the metamaterial, it instantly transmits the information to the microcontroller.
- Then, the microcontroller (MCU) instructs the FPGA to automatically calculate the digital coding pattern according to the preloaded feedback algorithm.
- Ensuring the radiation beam always focuses on the target object in real time.



Source: You, J. *et al.*, 2023, Electromagnetic Science, 1(1), pp.1-33.

So this is how the loop works: you have got a sensor, which is a gyroscopic sensor, okay, and then it goes to the feedback algorithm; then you basically readjust your metasurface, and that is how it works. So, this is a situation that I just described; it is a situation where an aircraft equipped with this kind of smart metamaterials can communicate with a satellite that is shown here. So, here in this particular example, the integrated sensor is a gyroscope sensor that detects the changes in the flight direction or flight status of the aircraft. Which is represented by the rotation angle of the metamaterial, and it can instantaneously transmit that information to the microcontroller. And then what happens is the microcontroller basically instructs the FPGA to calculate the digital coding pattern that is required on your metasurface, according to a preloaded feedback algorithm, and that will ensure that the radiation beam keeps focusing.

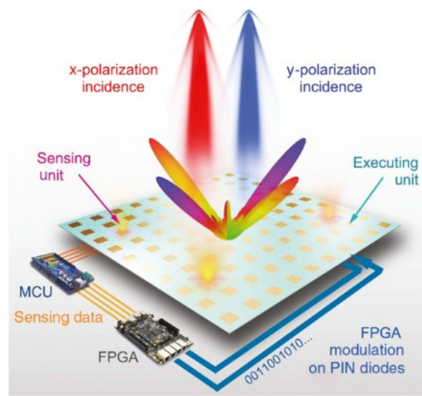
To the real target object in real time, here you can see that when the aircraft is this way, the beam is focused towards the satellite. When it comes here, the beam gets adjusted and again realigns with the satellite. This is how it also happens here. A reconfigurable intelligent metamaterial works. So, what is the fun? So we are basically working with smart metamaterials.

Electromagnetic Metamaterials

Intelligent metamaterials:

Working of the smart metamaterial:

- Schematic of the smart metasurface, which is composed of the sensing units (S-units) and executing units (E-units).
- Under the incidences of different polarizations, the sensing units are able to recognize the incident power levels and transmit the data to the microcontroller unit for digitizing.
- After collecting the data, the FPGA is able to determine the coding patterns independently on the specific polarization and drive the executing units to realize the desired scattering fields.



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Source: You, J. *et al.*, 2023, Electromagnetic Science, 1(1), pp.1-33.

OK, so the good thing here is that you can make things work and change in real time, and that is the fun part in these particular intelligent metamaterials, right? So, here you see the schematic of a smart metasurface, which is basically composed of the sensing units, which are S units, and there are also some executing units, or E units. So, what happens under the incident of different polarizations? So, the red one shows X polarization, and the blue one shows Y polarization. The sensing units are able to recognize the incident power levels and transmit the data to the microcontroller unit for digitization. So that is what the sensing unit is doing. And after collecting the data, the FPGA is able to determine the coding sequence independently of the specific polarization and drive the executing units to realize the desired scattering pattern.

And that is how it works. So you've got the sensing unit that is given to the microcontroller. They are getting the sensing data, which is transferred to the FPGA for calculation. And then it is basically giving you the coding pattern that is required to program the metasurface to behave in a particular polarization. So, here the FPGA modulation can also be achieved by using PIN diodes. So, you are basically integrating the PIN that is also called a pin diode. So, I stand for intrinsic. So, here you have a wide, undoped intrinsic region between your P-type and N-type regions. So, that is how you make these PIN diodes. So, when you integrate pin diodes in orthogonal directions, both E units and S units can modulate the phases independently. So, that is a good thing here. So, you can modulate the phase response independently, which guarantees excellent capabilities to control the scattering fields. So, according to the power levels from the sensing data, your metasurface can generate various scattering fields based on the pre-designed algorithms. Another type of electromagnetic metamaterial that is also booming is quantum metamaterials. So here we have understood that electromagnetic metamaterials have shown very high degrees of freedom in controlling classical electromagnetic waves.

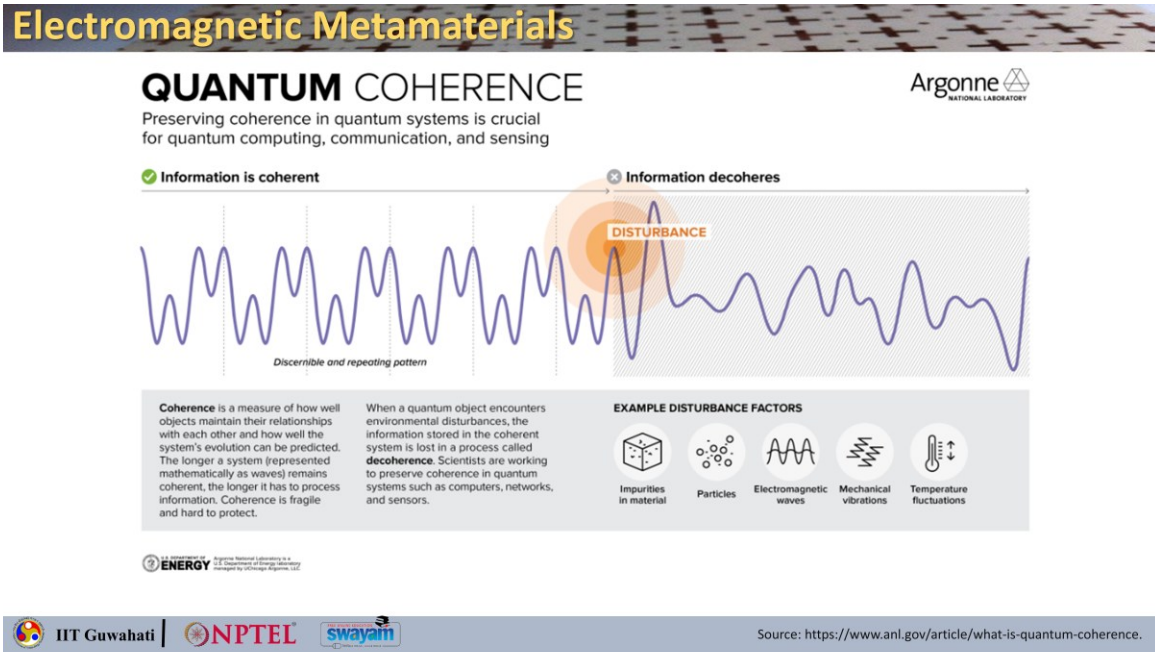
Electromagnetic Metamaterials

Quantum Metamaterials

- Electromagnetic metamaterials have shown very high degrees of freedom to control classical electromagnetic (EM) waves.
- Such a flexible and powerful manipulation capacity can also be used to significantly promote the development of fundamental science and engineering technology in the nonclassical EM regime, especially in the field of quantum information science.
- In recent years, quantum information science has been rapidly developed, and its superiorities in information communication, measurement, sensing, computing, and other aspects are expected to revolutionize current science and technology.
- These innovative quantum technologies can be further advanced by using EM metamaterials, leading to the emergence of quantum metamaterials.
- To date, quantum metamaterials have become a revolutionary extension of the classical EM metamaterial concept and have provided an important physical platform for the generation, manipulation, and detection of quantum information.
- Quantum metamaterials are a new concept bridging traditional metamaterials and quantum technologies, and they are also a new type of artificial atom.

Source: You, J. *et al.*, 2023, Electromagnetic Science, 1(1), pp.1-33.

Such a flexible and powerful manipulation capability can be further used to significantly promote the development of fundamental science and engineering technology, also in the non-classical electromagnetism regime, which is where we are stepping into the field of quantum information science. So in recent years, quantum information science has also developed very rapidly and its superiorities have been established in information communication, measurement, sensing, computing, and other different aspects, which are expected to revolutionize current science and technology. So that is why a lot of researchers are kindly working on these quantum technologies. So, these innovative quantum technologies can be further advanced by using electromagnetic metamaterials or EM metamaterials, which has led to this new field of quantum metamaterials. So, until now, quantum metamaterials have become a revolutionary extension of the classical electromagnetic metamaterial concept, and they have provided an important physical platform for the generation, manipulation, and detection of quantum information.



Just like you know, the classical electromagnetic metamaterial allows for the manipulation of electromagnetic waves or information in the quantum domain; you are also getting similar kinds of effects. So, quantum metamaterials are a very new concept bridging traditional metamaterials and quantum technologies, and they are also a new type of artificial atom, or you can say, meta-atoms. So, here this particular picture shows the concept of quantum coherence. So, it basically allows preserving coherence in quantum systems because it is very crucial for quantum computing, communication, and sensing. So, here you can see that the information is coherent, but because of some disturbance, the information decoheres here.

So, this is basically a repeating pattern. So, coherence, when we talk about coherence, is basically a measure of how well the objects maintain their relationships with each other and how well the system's evaluation evolution can be predicted. The longer a system remains coherent, the longer it has to process the information. So, coherence is fragile, and it is hard to protect because, as you can see here, a little disturbance can break the coherence, right? So, when a quantum object encounters environmental disturbances, the information stored in the coherent system is basically lost in the process called decoherence. Scientists are basically working towards preserving coherence in quantum systems such as computers, networks, and sensors. So, what are the examples of this disturbance factor? It can come from impurities in material, particles, external electromagnetic waves, mechanical vibrations, and also temperature fluctuations. So, you see, the coherence is basically a very, very sensitive thing, okay?

Electromagnetic Metamaterials

Quantum Metamaterials

- Their coded units (i.e., qubits) have typical physical properties of quantum states, such as quantum coherence, and the quantum states of these units can be externally controlled.
- Meanwhile, the system of these artificial atoms can maintain quantum coherence on the time scale of the EM pulse propagation across it.
- In general, quantum metamaterials include superconductor quantum metamaterials, nonlinear quantum metamaterials, space-time quantum metamaterials, and so on.
- Due to their low loss, compact structure, and strong nonlinear properties, superconductors have become one of the most widely used platforms for quantum metamaterials.
- At present, superconductor quantum metamaterials have broad application prospects in the fields of single microwave photon detection, quantum birefringence, and phase transition of quantum superradiance.

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Source: https://www.anl.gov/article/what-is-quantum-coherence.

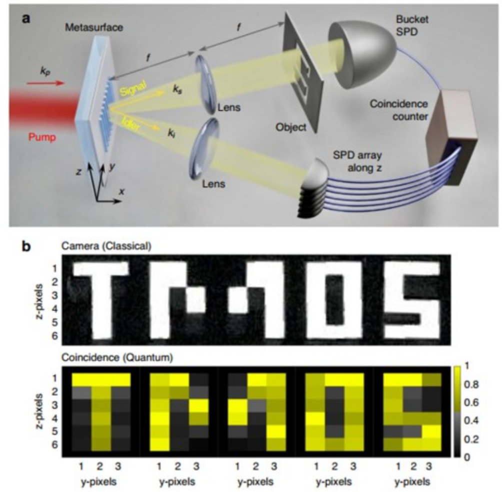
So, with that understanding, we can see that quantum metamaterials and their coded units, which are basically qubits, have typical physical properties of quantum states, such as quantum coherence, and the quantum states of these units can be externally controlled. Meanwhile, the system of these artificial atoms can maintain minimum quantum coherence on the time scale of the electromagnetic pulse propagation across it. So, in general, you can say that quantum metamaterials basically include superconducting quantum metamaterials, non-linear quantum metamaterials, spacetime quantum metamaterials, and so on. So many new concepts are coming in.

So, we will not go into so much detail about all these concepts in this course, but yes, if you want to study further or research further in this particular domain, which is very new and upcoming, you are very welcome. Due to their low loss, compact structure, and strong non-linear properties, semiconductors have become one of the most widely used platforms for quantum metamaterials. Currently, you know semiconductor quantum metamaterials have broad application prospects in the fields of single microwave photon detection, quantum birefringence, and phase transition of quantum superradiance. So, let us take some examples of these quantum metamaterials in the field of quantum imaging.

Quantum Metamaterials

For quantum imaging:

- Quantum imaging systems utilizing spatially entangled photon pairs demonstrate the potential to achieve high resolution and high sensitivity, surpassing traditional classical optical methods.
- A team led by Prof. Andrey A. Sukhorukov presented research findings on quantum imaging of two-dimensional objects using spatially entangled photon pairs generated from a nonlocal nonlinear metasurface composed of a one dimensional grating structure.
- This study represents the first demonstration of utilizing nonlinear metasurface ebased quantum photonic sources for quantum imaging.
- In this research, the team employed a lithium niobate metasurface with a subwavelength-scale silica metagrating to achieve enhanced SPDC for the generation of spatially entangled photon pairs.



So, quantum imaging systems basically utilize specially entangled photon pairs that demonstrate the potential to achieve high resolution and high sensitivity surpassing what you can get from classical optical methods.

So, quantum entanglement is basically considered one of the most powerful resources of quantum information. In this respect, pairs of photons are the simplest systems showing genuine quantum entanglement in all their degrees of freedom. Such as spatial, spectral, and polarization. A team led by Professor Andrey Sukhukov presented research findings on quantum imaging of two-dimensional objects using spatially entangled photon pairs, which are generated from a non-local, nonlinear metasurface composed of a one-dimensional gridding structure that is shown here. So, what happens in this particular case, I will explain.

So, this study basically presents the first demonstration of utilizing a non-linear mirror surface based on quantum photonic structures for quantum imaging. There are a couple of new terms here that we need to understand. So, we will go one by one. So, here you need to understand that the first team employed a lithium niobate metasurface with a sub-wavelength scale silica matter grating on it. To achieve enhanced SPDC, which is nothing but spontaneous parametric down conversion for the generation of spatially entangled photon pairs.

So, what is SPDC? It is basically a popular technique for producing spatially entangled photon pairs. So, in its conventional form, a coherent Gaussian beam is okay for light. Considered to be the pump beam, as you can see here, it illuminates a non-linear crystal that has, say, chi-square non-linearity, which produces pairs of photons in accordance with energy and momentum conversion. If you see this particular figure okay, you can see the optical setup.

Shown here for quantum imaging. So, in this particular figure, you see the optical setup for quantum imaging with spatially entangled photon pairs from a nonlinear metasurface, which is shown here. So, the 2D imaging of the object was obtained through quantum ghost imaging. and all optical scanning in the z and y directions, respectively, is okay. So, what is quantum ghost imaging? It is basically a technique that allows you to reconstruct an image of an object using light that does not directly interact with it. So, this is achieved by exploiting the correlations between the entangled photon pairs, where one photon interacts with the object while the other is detected to reveal information about the object's spatial distribution.

So, in Figure B, you can see the experimental data of 2D quantum imaging combining ghost imaging and optical scanning. So, the top and the bottom panel basically show the camera, which is the classical image of the object, and this one is basically the quantum, you know, reconstructed image from the coincidence measurement, okay. So, the unique properties of the metasurface basically enabled a hybrid quantum imaging approach. So, what we learn from here is that the quantum ghost imaging along the z direction, which is basically parallel to the stripes of the grating in this particular figure, was realized using the broad anti-correlated emission patterns of entangled photon pairs. Then all optical scanning along the y direction, which is basically perpendicular to the grating strips, was achieved by tuning the photon emission angles through adjustments to the pump laser wavelength based on the dispersion-dependent behavior of this non-local metasurface.

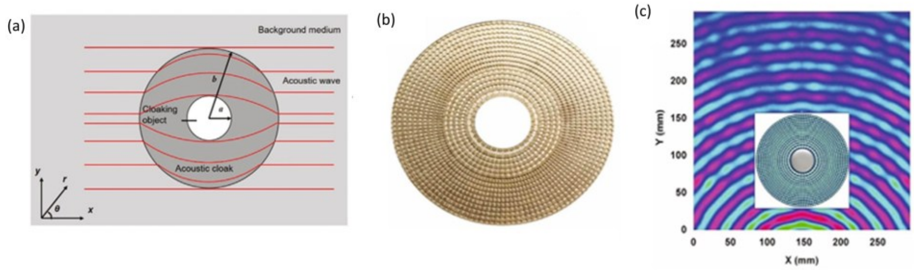
And based on these characteristics, the experimental implementation demonstrated the feasibility of high-resolution 2D imaging. Using a 1D detector array. So, you can see these are SPD single photon detectors, and here you have an SPD array. So, you can see the signal and the idler coming like this; this is the pump, okay. So, the single photons or the signal photons, these ones generated from the matter surface, basically pass through a 2D object that you see here, and that is where this particular object will be—any object that you want to image that will be kept here—and it will be detected by a bucket single photon detector (SPD), while the idler photons, which basically come this way, are detected by an SPD array in the z direction, right.

So, you have an array in the z direction. By measuring the coincidence as a function of the photon wavelengths, this 2D imaging data can be reconstructed. So, figure B basically presents the results of this 2D quantum imaging, combining ghost imaging for the z pixels and optical scanning images along the y. So, these are the Z pixels and these are the Y. This is where you are scanning optically, but the Z ones are basically the ghost pixels, and both are combined to give you the kind of, you know, image of the object.

Acoustic Metamaterials

Acoustic cloaking metamaterials (ACMs)

- Inspired by the electromagnetic cloak, the ACMs were firstly designed as a shell with a gradient bulk modulus and mass density, designed based on the cloaking solution, was capable of controlling the scattering of the compressional acoustic wave so that the wave would bypass the shell without scattering, thus an ACM is achieved, as shown in Fig.
- The cloak was fabricated by machining an aluminum plate into 16-step piecewise homogenous cylinders.
- Measured pressure field mappings of the AC at 60 kHz.



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So, with that, we move on to another application of metamaterials in a different domain, the acoustic domain. So, here are the acoustic metamaterials. They are basically inspired again by electromagnetic cloaking because we are taking the example of acoustic cloaking metamaterials (ACMs). So, they are primarily designed as a shell with a gradient bulk modulus, as you can see, and mass density. So, you have a gradient bulk modulus and mass density that allow the acoustic waves to bend around the object that you want to hide.

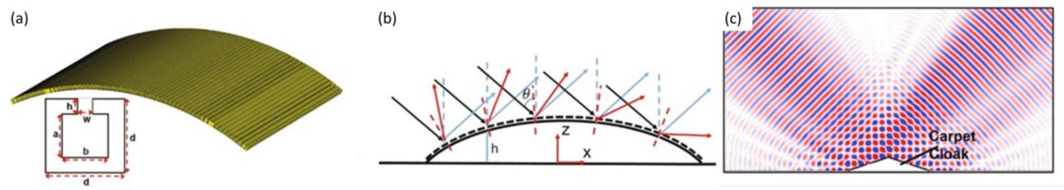
So, that is very similar to the concept that we saw in the previous lecture for light, okay. So, this particular clocking solution was capable of controlling the scattering of the compressed acoustic waves. So that the wave could bypass the shell without scattering, you see the way the waves were coming; they are exiting in the same manner as if there is nothing over here. Okay, so the cloak was fabricated by machining an aluminum plate into 16 steps. Piecewise homogeneous cylinders that give you gradient bulk modulus and mass density, as you can understand.

So, this is a zoomed diagram, and it shows the measured, you know, pressure field mapping of this particular cloak at 60 kilohertz. So, you can see that this object is not actually disturbing the field at all. So, the same concept can be further extended to create carpet cloaking. So, this is a new way to achieve acoustic invisibility that is also similar to cloaking, specifically carpet cloaking, which we saw in the previous lecture on the optical domain, where that lady was holding a carpet that was hiding her. The body in the path was revealing the background, okay.

Acoustic Metamaterials

Acoustic cloaking metamaterials (ACMs)

- Acoustic cloaking carpet (ACC) provides a new way to realize acoustic invisibility.
- In general, the 2D ACC is shaped like a carpet, on the surface of which a series of well-designed microstructures that could compensate for the phase distortion caused by the geometry of the cloaking carpet are imposed.
- Consequently, when the acoustic waves propagate to the cloaking carpet from a certain direction, the reflection orientation of the waves that should have been scattered becomes consistent (as shown in Fig. b), just like a mirror.
- Pressure field distributions when an acoustic Gaussian beam is an incident onto cloaked bump from top left with an incidence angle of 45 degrees.



So, the same kind of concept can be used here. So, in general, the 2D acoustic carpet cloaking is basically shaped like a carpet, on the surface of which there are a series of well-designed microstructures, as you can see here, that could basically compensate for the phase distortion caused by the geometry of the. Carpet cloaking is right. So, how it works is that the whole idea is to say if you want to hide something below the carpet. So, the elements on top of the carpet should scatter light in the same way that a normal surface without any objects would have scattered. So, that way, an object with a carpet on top will behave like a flat surface.

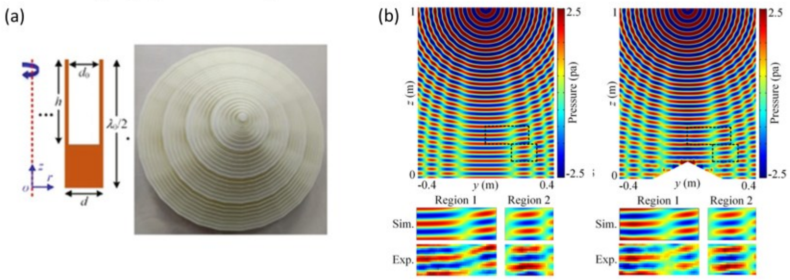
So, you have to manipulate the scattered waves in that particular manner, okay. So, here you can see that when the acoustic waves propagate to the cloaking carpet from a certain direction, the reflection orientation of the waves should be scattered and become consistent just like a mirror, as if it is coming from a flat surface. So, this is how it should look. So, assume there is nothing here; waves falling like this would have gone this way, right? That is how typical reflection would have worked. Now, you have an object here that you put the carpet cloak over to hide it.

So, with the carpet cloak, the reflected waves should also go in the same direction.

Acoustic Metamaterials

Acoustic cloaking metamaterials (ACMs)

- The 3D ACC is mostly cone-shaped, Fig. (a) provides a typical model fabricated by plastic using 3D printing.
- Cross-sectional illustration of the basic groove structure unit (left) of the and the sample of the ACC fabricated by 3D printing (right).
- Simulated and experimental total field distributions in the measured region 1 (left panels) and region 2 (right panels) for a spherical acoustic wave impinging on the flat ground and the object with the cloak.



Source: https://www.anl.gov/article/what-is-quantum-coherence.

So, you will not be able to see any objects over here. Right. So, people have also taken this further to make a three-dimensional acoustic cloaking metamaterial that is typically cone-shaped and can be fabricated using plastic through 3D printing techniques. So, this is the cross-sectional illustration of the basic grooved structure.

This is how the group looks, and this is the entire sample that has been fabricated. What you see here are the simulated and experimental results. So, these are the two regions. So, here you see this is basically a flat surface, and this is the flat surface with this particular carpet cloak on it, but the reflected field in region 1 looks similar; region 2 also looks similar. That means a flat ground and an object within a cloak basically look the same, which means you are able to hide that particular object.

So, here what is important to notice is that the spherical incident and the reflected fields strongly interfere with each other, resulting in discontinuous wave fronts, as you can see. In this particular figure. When the object is basically covered by the metasurface, the reflected and total field patterns are restored, respectively, to those of the case of the flat ground. So, that is the most important, and these results basically confirm the cloaking effect of the acoustic metasurface for a spherical incident wave.

Thermal Metamaterials

- Thermal metamaterials have unique capabilities of controlling heat transfer.
- Heat transfer and thermodynamics are now also of central importance to modern technologies including power generation and conversion, night vision, microelectronics, aerospace, etc.
- Thermal metamaterials could help dissipate heat in a deterministic manner and avoid local hot spots in advanced nanoscale devices.
- Few examples:
  - Thermal shields/camouflages protect an area from transient diffusive heat flow
  - Thermal concentrators can focus thermal flux on a small area
  - Thermal inverters (also called thermal rotators) change the direction of the thermal gradient in an area

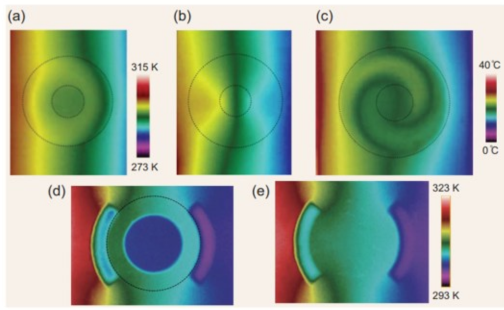
Source: Fan, J. *et al.*, 2021, Materials Today, 50, pp.303-328.

Next, we move on to another domain, which is thermal metamaterials.

So, thermal metamaterials also have unique capabilities for controlling heat transfer. So, heat transfer and thermodynamics are also now of central importance to modern technologies, including power generation and conversion, night vision, microelectronics, aerospace, etc. So thermal metamaterials could also help to dissipate heat in a deterministic or prescribed manner, and they can help you avoid local hotspots in advanced nanoscale devices. So heating also becomes very important, and by using thermal metamaterials, you can control the effect of heating, right? So you can think of some examples like thermal shields or camouflage to protect an area from transient diffusive heat flow. You can think of thermal concentrators that focus thermal flux on a small area. Thermal inverters, also called thermal rotators, can help you change the direction of the thermal gradient in an area.

Thermal Metamaterials

- Experimental demonstration of different thermal metamaterial devices.
  - (a) Cloak: Map between point and a region, eliminating thermal gradient
  - (b) Rotator/inverter: Change the direction of temperature gradient in a region
  - (c) Camouflage: Make one object appear to have another's properties — single conducting cylinder appears like two insulating segments
  - (d) Equivalent temperature profile of camouflage illusion, with two insulating segments actually present and no conducting cylinder



Source: Fan, J. *et al.*, 2021, Materials Today, 50, pp.303-328.

OK, so a couple of thermal metamaterial devices would be like cloaks, as they can map between a point and the region, eliminating the thermal gradient. So, you can hide some thermal sources by using a clock. The rotator inverter can change the direction of the temperature gradient, as we discussed. So, this is very important in night vision and military applications where you can make one object appear to have another object's property; something like a conducting cylinder may look or appear like two insulating segments.

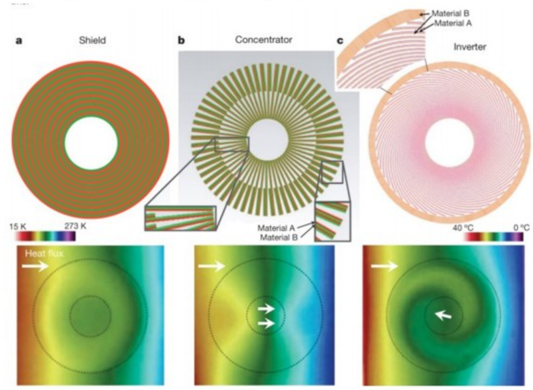
So, you can hide or disguise your weapons or something from the military perspective, right? So, you can also think of the equivalent temperature profile of the camouflage illusion with two insulating segments actually present in a non-conducting cylinder. So, that way you know you can hide bullets and all those things. So, these things are good for military applications.

Thermal Metamaterials

a) A thermal shield made of a concentric layered structure of latex rubber and silicone elastomer.

b) A thermal concentrator made of azimuthally alternating layers of latex and elastomer.

c) c) A thermal inverter made of a spiral arrangement of copper and polyurethane.



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Source: Sklan, S.R. and Li, B., 2018, National Science Review, 5(2), pp.138-141.

So, here are some examples. How they are made. So, a thermal shield is basically made of a concentric layered structure of latex rubber and silicon elastomer. So, this is a shield. So, you can see that this area is not getting the heat. It is basically shielded by this particular shield.

Next is the thermal concentrator. So, here is another way to basically focus more heat in the center. So, it is basically made of azimuthally alternating layers of latex and elastomers. So, you have material A and material B periodically altering azimuthally, okay. So, you can see whatever the flux is here; you can concentrate more over here, and then you can also have a thermal inverter made of this kind of spiral arrangement of copper and polyurethane, okay. So what happens here is that you can actually invert the thermal flux at the center.

So, three different metamaterials basically have three completely different applications. So that tells you the range of applications you can make metamaterials work for you. And the last topic that we will be covering today is mechanical metamaterials. Obviously, the mechanical properties in this case of a material are not basically determined by its chemical composition, but are also significantly influenced by the architecture of the constituents. So, although the strength of normal materials substantially degrades with reduced constituent density, natural cellular materials, something like honeycomb, and trabecular bone or sponge, are found to combine low weight and high strength simultaneously.

So that is something counterintuitive. So you are reducing the density, yet you are getting higher strength. So inspired by this, researchers have made ultra-light and ultra-stiff mechanical metamaterials through a network of nearly isotropic macro-scale unit cells that have high structural connectivity and nanoscale features, whose structural members are basically designed to carry loads in tension or compression. So, for the stretch-dominating structures, the scaling relationship between Young's modulus and yield strength with the material's density can be linear. Ah, in contrast to a bending-dominated structure, where the yield strength would vary exponentially with the density of the materials. So, this is something particularly for metamaterials in the mechanical domain, but it is important because these days, if you want to make a product for a particular application, you need to think of all these different aspects, not only the electromagnetics. I need to think about how the heat will be managed, how mechanically you will make the product rigid, and it should be able to withstand any external blow to still function properly.

Mechanical Metamaterials

- The mechanical properties of a material are not only determined by its chemical compositions, but also significantly influenced by the architecture of the constituent.
- Although the strength of normal materials substantially degrades with reduced constituent density, natural cellular materials (e.g., honeycomb, trabecular bone, sponge) are found to combine low weight and high strength simultaneously.
- Inspired by this, ultralight and ultra-stiff mechanical metamaterials have been realized through a network of nearly isotropic microscale unit cells with high structural connectivity and nanoscale features, whose structural members are designed to carry loads in tension or compression.
- For the stretch-dominated architectures, the scaling relationship between Young’s modulus and yield strength with materials density can be linear, in contrast to bending-dominated architectures where the yield strength would vary exponentially with the density of the materials.
- According to their unprecedented mechanical properties, mechanical metamaterials have been further classified into several categories, including ***auxetic metamaterials, penta-mode metamaterials, and chiral metamaterials.***

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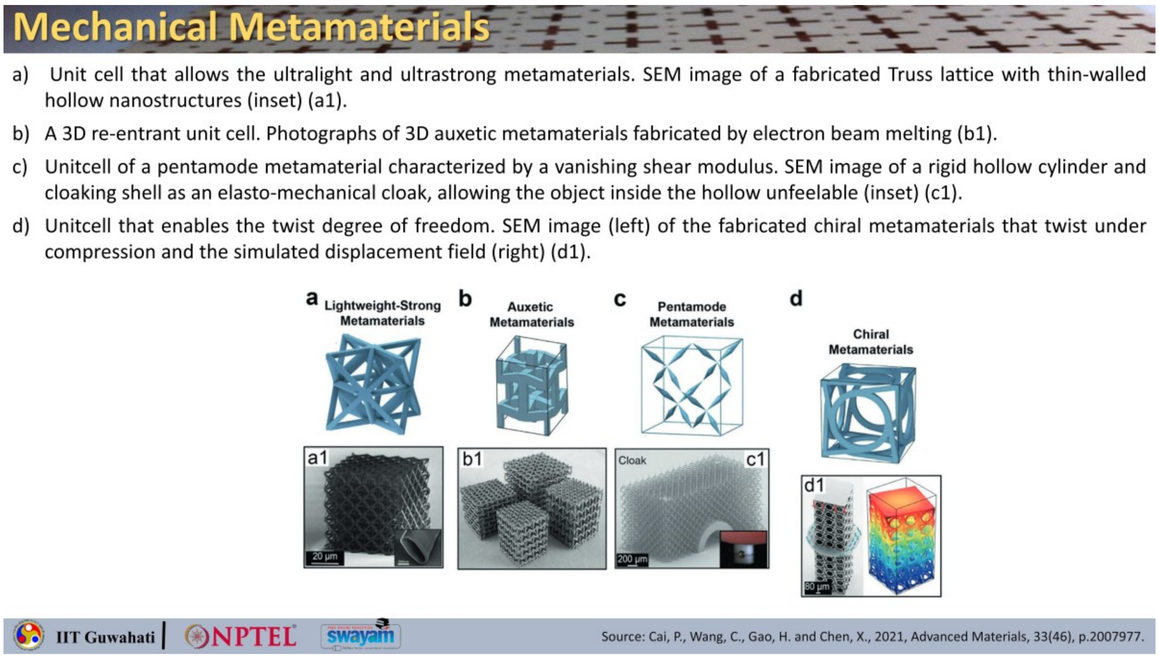
Source: Cai, P., Wang, C., Gao, H. and Chen, X., 2021, Advanced Materials, 33(46), p.2007977.

So, according to their unprecedented mechanical properties, these mechanical metamaterials have been further classified into several categories, such as auxetic metamaterials, pentamode metamaterials, and chiral metamaterials. So a lot of work is happening in this area as well as in the mechanical departments. So this is also something you have to understand: the metamaterial field is now getting into all different domains. So here you see a unit cell that allows ultra-light and ultra-strong metamaterials.

So the SEM image of the fabricated cross slat is within world hollow structures, as shown here. This is a 3D reentrant unit cell; the photographs of the auxetic metamaterials fabricated using electron beam melting are shown here. So, what is this particular truss? So, a truss is basically an assembly of members such as beams connected by nodes that create a rigid structure. A lattice truss basically provides increased structural stability due to its dispersion of forces, as it is typically designed with more units than is required. Now, when you come to exotic metamaterials, auxetic—sorry, auxetic metamaterials— they refer to a class of materials with zero or negative Poisson's ratio, which is defined as the ratio of minus epsilon t to epsilon l, where epsilon t is basically the transverse strain and epsilon l is the axial or longitudinal strain, right? So this is an example of pentamode metamaterial characterized by a vanishing shear modulus. So ACM's image shows a rigid hollow cylinder and cloaking shell as an electromechanical cloak, allowing objects inside this hollow to be unfillable. So you cannot actually go and touch that particular object that you are keeping here. So no mechanical pressure can actually reach it.



Similarly, you know the unit cells over here show chiral metamaterials. So, they enables the twist degree of freedom. So, the SEM image on the left shows the fabricated one; the twist under compression and the simulated displacement field are shown on the right. So, these chiral metamaterials are basically twisted when subjected to compressive forces, okay. So, usually, the lateral twist angle can reach 2 degrees per axial strain beyond the Cauchy elasticity, the typical ones, okay.

Some chiral metamaterials can also exhibit a negative Poisson's ratio. So, in addition, you can also think of origami and kirigami-inspired mechanical metamaterials, which are also attracting attention, and the deformation mechanism includes negative Poisson's ratio, multistability, ultra-large deformation, programmable stiffness, and so on. So, you can think of, you know, a mechanical engineering domain with these metamaterials, which are showing properties that are never found in natural materials. So, it's something very similar to what we discussed about the electromagnetic metamaterials.

So, with that, we will conclude our lecture. If you have any queries regarding this lecture, please mention the course name and the lecture number and email them to this particular email address. Thank you.