Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-1
Lecture-5

Lec 5: Overview of Metamaterials Technology

Hello students, welcome to Lecture 5 of the online course on Introduction to Microwave and Optical Metamaterials.

Lecture Outline

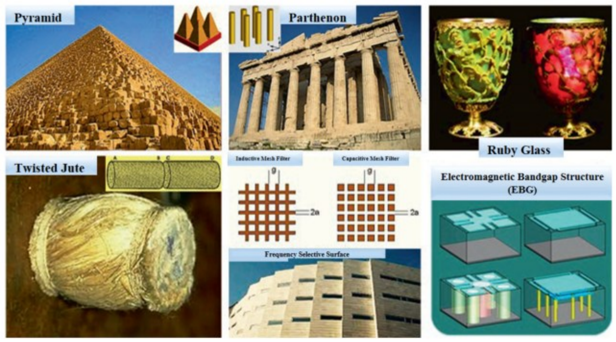
- Metamaterials in History
- Evolution of Metamaterials Technology —A Market Study
- Metamaterials Technology in Different Consumer Sectors
  - Medical
  - Automotive
  - Aeroscape
- Overview of Metamaterial Fabrication Techniques
  - Photolithography
  - Shadow Mask Lithography
  - Electron Beam Lithography

Today's lecture will be an overview of metamaterials technology. Here is the lecture outline. We will briefly look into the history of metamaterials, discuss the evolution of metamaterial technology with the help of a market study, and see how metamaterials technology features in different consumer sectors such as medical, automotive, and aerospace. We will also talk about metamaterial fabrication techniques such as photolithography, shadow mask lithography, and electron beam lithography, just to inform you and give you an idea of how things are actually made.

Metamaterials in History

- The origins of metamaterials can be traced to various historical examples such as *pyramid brick walls*, the *columns of the Parthenon*, *medieval ruby glass*, and *twisted jute fibers*.

- These early examples have significantly influenced the conceptual foundation of metamaterials in contemporary technologies — such as communication, imaging, sensing, stealth, and quantum devices — through the use of frequency-selective surfaces, electromagnetic bandgap structures, and related innovations.



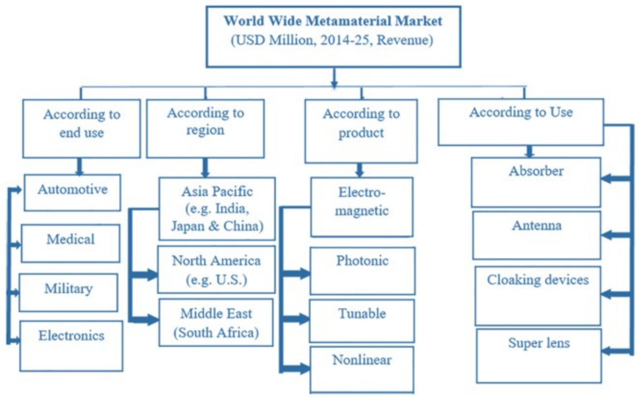
Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

So, the origin of metamaterials can be traced to various historical examples such as pyramid brick walls, the columns of the Parthenon, medieval ruby glass, and twisted jute fibers.

So, these are basically early examples. That has significantly influenced the conceptual foundation of metamaterials in contemporary technologies such as communication, imaging, sensing, stealth, and quantum devices. Through the use of frequency selective surfaces, electromagnetic bandgap, and other related innovations. So, these are the frequency selective surfaces and these are electromagnetic Kelly programmable band gap structures.

Evolution of Metamaterials Technology —A Market Study

- In 2016, it is estimated that the worldwide metamaterial market size was USD 316 million.
- But in recent days, there has been an increasing requirement for better quality parts with durability properties, which are driving the growth of the metamaterial medium market worldwide.



IIT Guwahati | NPTEL swayam

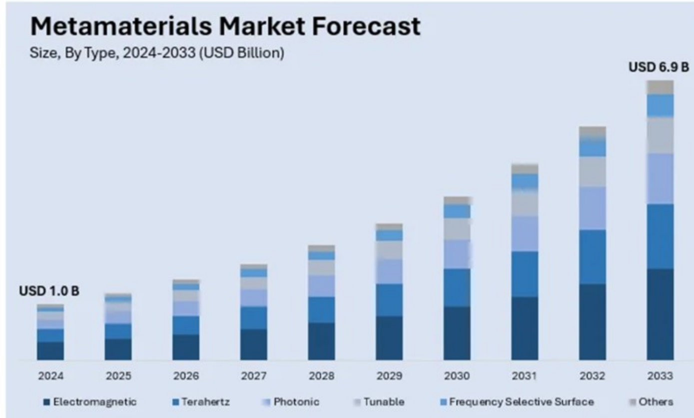
Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

So, in 2016, there was a market study that basically presented the worldwide metamaterial market, and the estimate showed that the market size in 2016 was around 316 million. But in recent days, there has been an increasing requirement for better quality parts with durability properties. So that has also fueled the growth of the metamaterials medium market worldwide. So the Grandview research has classified this worldwide metamaterial market based on end use, different regions, and product, and finally, you can see their particular usage from this figure. So, what do you see is that if you consider end use in different sectors like automotive, medical, military, and electronics, these are the domains where metamaterials are used.

Region-wise, mainly in Asia, specifically India, Japan, and China, as well as North America, the Middle East, and South Africa. There is a huge market. According to the product, if you think of metamaterials, there is a big segment in electromagnetic metamaterials and photonics. Then there are tunable metamaterials and nonlinear metamaterials. The majority of the applications are focused on absorbers, metamaterial antenna design, cloaking devices, and making superlenses.

Evolution of Metamaterials Technology —A Market Study

- The global metamaterials market size was valued at *USD 1.0 Billion in 2024*.
- Looking forward, the metamaterials market to reach *USD 6.9 Billion by 2033*, exhibiting a *CAGR of 23.31%* from 2025-2033.
- North America currently dominates the market, holding a market share of over 42.2% in 2024.

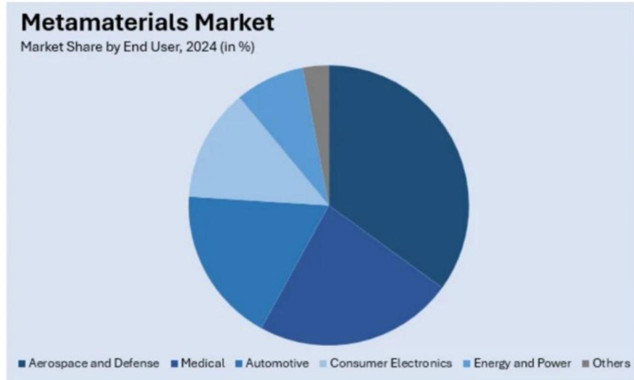


IIT Guwahati | NPTEL swayam Source: https://www.imarcgroup.com/metamaterials-market.

So in 2024, the global metamaterial market size was valued at 1 billion US dollars. If you see that it is 2014, sorry, 2024. Now looking forward, the metamaterials market is projected to reach 6.9 billion US dollars by 2033. So, that is basically going to exhibit a growth rate or CAGR of 23.31 percent from 2025 to 2040. So, currently, North America is dominating the market, holding a share of around 42 percent in 2024. And here you can also see the colors representing different sectors, such as electromagnetic metamaterials; then you have terahertz metamaterials, photonic metamaterials, different tunable metamaterials, frequency selective surfaces, and other applications. So, all are growing, and as you can see, terahertz and photonics metamaterials are also going to be equally prominent in the market as the other array of microwave metamaterials. So, the market is primarily driven by technological advancements in nanotechnology and photonics, increasing demand in the wireless communication and defense sectors, expanding the applications toward healthcare and sustainable solutions, educational and research initiatives, and different customization potential across various areas.

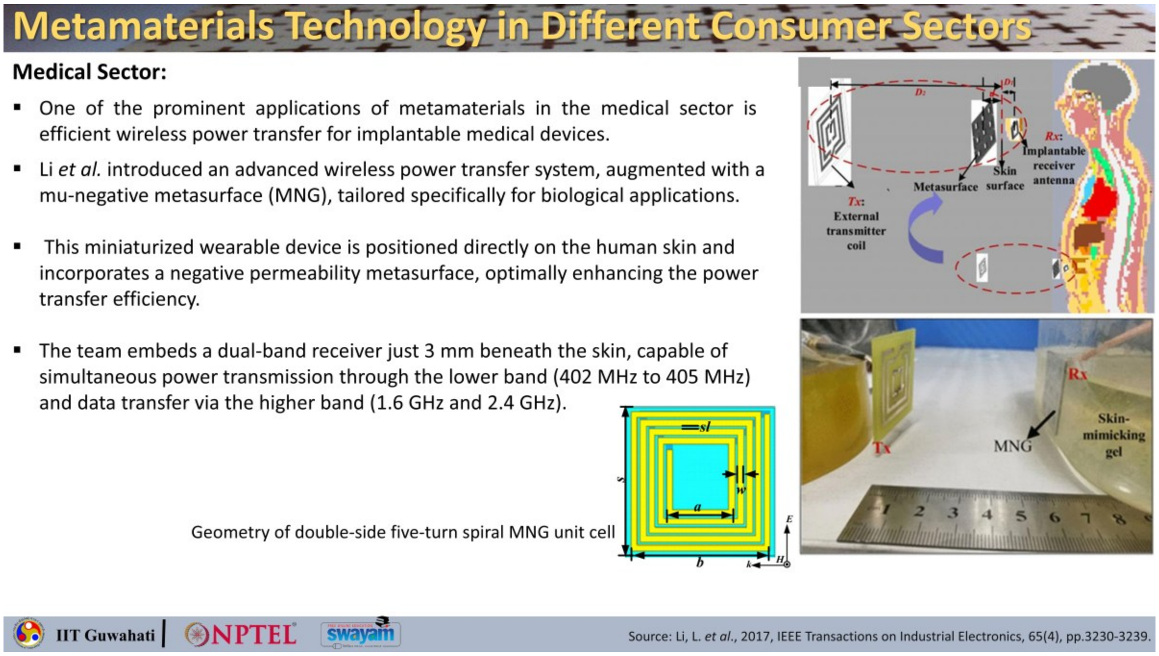
Evolution of Metamaterials Technology —A Market Study

- Aerospace and Defense lead the market with around *29.7% of market share in 2024*.
- The use of metamaterials in aerospace and defense is pivotal.
- In these industries, these materials enhance the capabilities of communication systems, radar, and stealth technology.
- Their unique properties enable the development of advanced antennas and radar systems with improved performance, reduced size, and increased frequency bandwidth.



Industries. Every industry requires a metamaterial or a material where you can tune the properties of that material based on your application, and that is where the metamaterial market is basically catering to. Now aerospace and defense lead the market with almost 30 percent of the market share in 2024, as you can see from here. Next come the medical, automotive, consumer electronics, energy and power, and various other applications. So, the use of metamaterials in the aerospace and defense sector is pivotal.

This particular industry's metamaterials can be used to enhance the capability of communication systems, radar, and also make stealth technology feasible. Their unique properties enable the development of advanced antennas and radar systems with improved performance, reduced size, and increased frequency bandwidth. So they are also very critical to stealth technology. Which is a very, very important technology in today's world. Adding the development of materials that can effectively reduce the radar cross section of any aircraft or missile.



So, this application is key for modern defense strategies that rely on minimally detectable technology. The medical sector is one of the important sectors as well, where the prominent applications of metamaterials are mainly towards efficient wireless power transfer for implantable medical devices. So, Lee *et al.* Introduced an advanced wireless power transfer augmented with a negative permittivity metasurface, or you can call it a mu-negative metasurface MNG, which is tailored specifically for biological applications. So, this miniaturized wearable device is positioned directly on the human skin, and it incorporates a negative permeability metasurface that basically increases the, you know, power transfer efficiency.

So, this is how it looks. So, if you zoom in on this, you will see that this is an external transmitter coil. Okay, and then here is your implantable receiver antenna. Okay, and before the antenna, you are basically putting this boundary, which marks the skin; this is your metasurface. So, what happens is the team basically embeds a dual-band receiver just 3 mm beneath the skin, capable of simultaneous power transmission through the lower band.

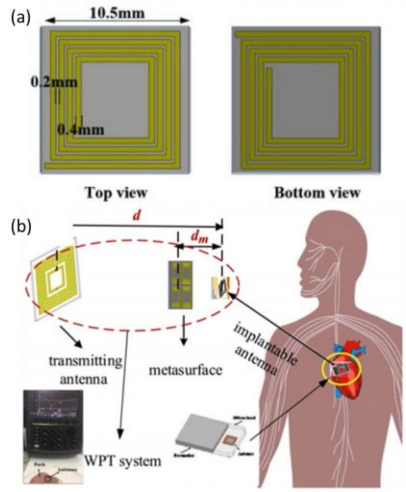
Typically, they were using 402 megahertz to 405 megahertz, and the data transfer via the higher band, which is between 1.6 gigahertz and 2.4 gigahertz. So, this was used for power transmission; this was used for data transmission. So, here I can show you the unit cell that they used.

So, this is basically a double-sided, 5-turn spiral mu-negative metamaterial unit cell, and the metasurface is essentially a metamaterial; do not get confused: a metasurface is just a 2D version of the metamaterial. So, here you can see the MNG metasurface has an overall dimension of 3 mm by 30 mm, and it has an array of 3 by 3 unit cells that are fabricated on an F4B substrate with a dielectric constant of around 2.65. And the design parameters here, you can see that this particular length is 10 mm, a is 4.6 mm, b is around 9.4 mm, sl is the gap between the lines around 0.2 mm, the width of each line is around 0.4 mm, and t, which is basically t, is around 1 mm. So, to ensure seamless wireless power transfer or power connectivity, they utilize a conformal strongly coupled magnetic resonator coil as a transmitter. Here is another clear experimental setup shown. So, this is basically the transmitter.

Metamaterials Technology in Different Consumer Sectors

Medical Sector:

- Wang *et al.* introduce a new wireless power transfer (WPT) system by integrating it with a miniaturized metasurface to enhance the WPT efficiency and extend the lifetime of the implantable device.
- The metasurface element has a size of 10.5 mm × 10.5 mm × 1 mm.
- F4B is selected as the substrate with dielectric constant of 2.65, and the planar reverse spiral structure is implemented on both sides of it.
- The MNG metasurface has a strong magnetic resonant behavior, which can improve the transfer efficiency of the WPT system.
- Integration of the metasurface array significantly bolsters the PTE and effective transmission distance even with the human body's inherent absorption capabilities.



The conceptual illustration of WPT system with metasurface.

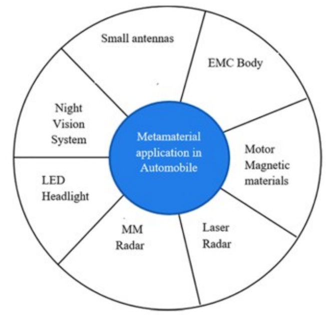
IIT Guwahati | NPTEL swayam Source: Wang, M. *et al.*, 2020, IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, 5(1), pp.2-8.

Wang et al. introduce a new wireless power transfer (WPT) system by integrating it with a miniaturized metasurface to enhance the WPT efficiency and extend the lifetime of the implantable device. The metasurface element has a size of 10.5 mm × 10.5 mm × 1 mm. F4B is selected as the substrate with dielectric constant of 2.65, and the planar reverse spiral structure is implemented on both sides of it. The MNG metasurface has a strong magnetic resonant behavior, which can improve the transfer efficiency of the WPT system. Integration of the metasurface array significantly bolsters the PTE and effective transmission distance even with the human body's inherent absorption capabilities.

Metamaterials Technology in Different Consumer Sectors

Automotive sector:

- Recently, there is more requirement of a new material in the automotive field (i.e. high-performance magnetic & absorbing as well as shielding materials) for operating the motors using electricity and to ensure electromagnetic compatibility.
- Performance absorbing and shielding materials are needed to ensure electromagnetic compatibility.
- In addition, many more materials (photonic metamaterials) enhance the capability of automobile optical devices.
- Toyota Central research and development Lab, reported that metamaterials provide highly contribution in the use of automobile such as mobile communication antennas, radar scanning, new magnetic materials for the application of electric motors *etc*.
- The use of industrialization includes early-stage applications, driving applications, and other such as a tyre pressure monitoring system, EMC body application *etc*.



Metamaterial applications in Automobile field.

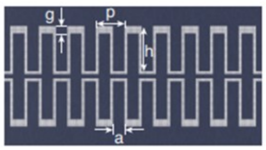
Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

Automotive Sector: Recently, there is more requirement of a new material in the automotive field (i.e. high-performance magnetic & absorbing as well as shielding materials) for operating the motors using electricity and to ensure electromagnetic compatibility. Performance absorbing and shielding materials are needed to ensure electromagnetic compatibility. In addition, many more materials (photonic metamaterials) enhance the capability of automobile optical devices. Toyota Central research and development Lab, reported that metamaterials provide highly contribution in the use of automobile such as mobile communication antennas, radar scanning, new magnetic materials for the application of electric motors etc. The use of industrialization includes early-stage applications, driving applications, and other such as a tyre pressure monitoring system, EMC body application etc.

Metamaterials Technology in Different Consumer Sectors

Automotive sector:

- An example of physiological monitoring using metamaterials in real-life driving scenarios.
- The structural parameters of the unit cells are h = 16 mm, p = 10 mm, a = 4 mm, g = 5 mm, and the substrate layer consists of a polyester fabric substrate (ε_r = 1.5) with thickness t = 1 mm.
- The sensor is attached to the center of the seat belt at the subject's thoracic region, and connected to the lightweight software-defined radar using coaxial cables.
- Metamaterial supports confined microwave surface waves that are modulated by subtle local physiological motions, which are sensitively transduced into changes in the phase of the transmitted signal.



Designed Metamaterial

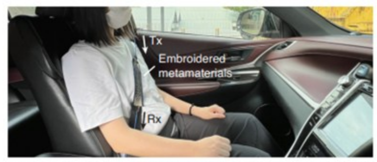


Image of the experimental setup inside a vehicle

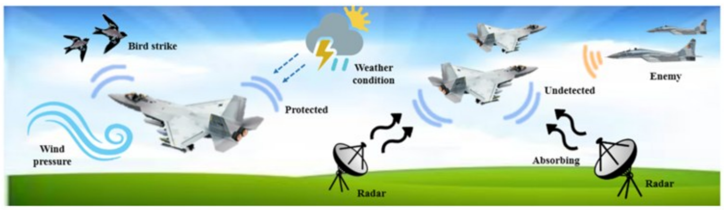
Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

An example of physiological monitoring using metamaterials in real-life driving scenarios. The structural parameters of the unit cells are h = 16 mm, p = 10 mm, a = 4 mm, g = 5 mm, and the substrate layer consists of a polyester fabric substrate (ε_r = 1.5) with thickness t = 1 mm. The sensor is attached to the center of the seat belt at the subject's thoracic region, and connected to the lightweight software-defined radar using coaxial cables. Metamaterial supports confined microwave surface waves that are modulated by subtle local physiological motions, which are sensitively transduced into changes in the phase of the transmitted signal.

Metamaterials Technology in Different Consumer Sectors

Aerospace sector:

- Metamaterials have emerged as transformative materials in the aerospace sector, offering unprecedented control over electromagnetic, acoustic, and mechanical properties.
- Their engineered structures enable innovative solutions for lightweight design, improved stealth capabilities, meta-domes, vibration damping, thermal management, and advanced communication systems.
- The commercial market for metamaterial-based components and subsystems in aerospace and defense was projected to reach approximately $250 million by 2020, with rapid growth expected to drive it to $2.3 billion by 2025.



An illustration of meta-dome

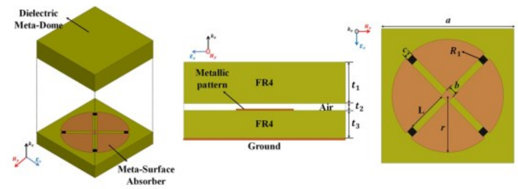
Source: Jeong, H., Nguyen, T.T. and Lim, S., 2018, Scientific Reports, 8(1), p.17893.

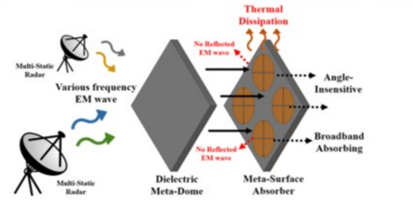
Aerospace Sector: Metamaterials have emerged as transformative materials in the aerospace sector, offering unprecedented control over electromagnetic, acoustic, and mechanical properties. Their engineered structures enable innovative solutions for lightweight design, improved stealth capabilities, meta-domes, vibration damping, thermal management, and advanced communication systems. The commercial market for metamaterial-based components and subsystems in aerospace and defense was projected to reach approximately $250 million by 2020, with rapid growth expected to drive it to $2.3 billion by 2025.

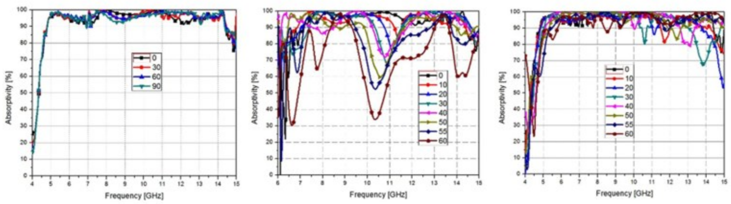
Metamaterials Technology in Different Consumer Sectors

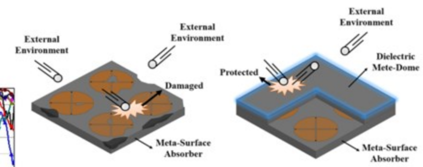
Aerospace sector:

- The structure consists of a metasurface absorber and a dielectric meta-dome, both with FR4 substrate.









Structure roles as absorbers and meta-domes.

IIT Guwahati | NPTEL swayam

Source: Jeong, H., Nguyen, T.T. and Lim, S., 2018, Scientific Reports, 8(1), p.17893.

The illustrated meta-dome to not only enhance broadband radar-absorbing structure and, but also to protect the structure from the external environment. For example, meta-domes are placed on radar-absorbing structures to protect them from mechanical damage. The meta-dome structure has broadband absorptivity in addition to its protecting properties and polarization insensitivity.

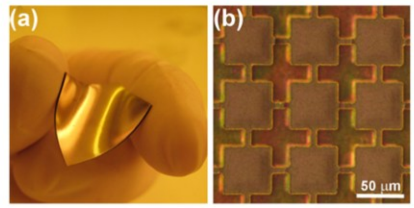
Meta-dome : t_1=t_3=2.4mm, t_2=0.4, a = 14 mm, L = 3.02 mm, r = 4 mm, b = 0.5 mm, c = 0.35 mm, R_1 = 150 Ω.

The normal incidence was insensitive to 0°–90° polarization with 90% absorptivity for 4.8–14.4 GHz. The meta-dome was angle insensitive 0°–40° for oblique incidence in TE mode and 0°–60° in TM mode.

Overview of Metamaterial Fabrication Techniques

Photolithography:

- Photolithography is a technique of microfabrication, which can be used to synthesize metamaterials that work at terahertz frequencies.
- This technique has been commonly used in the manufacturing of single and multilayer metamaterials, since it is able to fabricate high-resolution subwavelength structures at wavelength 30 μm – 3 mm with minimal complication.
- Fig. (a) and (b) show a multilayered fishnet metamaterial developed using a microfabrication process on PDMS.
- The resonators were patterned into the metal (200 nm gold thin films, with an adhesion layer) deposited on spin-coated PDMS substrates post curing.
- Often, micron scale resolution patterns obtained by this technique are further encapsulated with a thin layer of PDMS to avoid delamination of metal layers.



Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

Photolithography is a technique of microfabrication, which can be used to synthesize metamaterials that work at terahertz frequencies. This technique has been commonly used in the manufacturing of single and multilayer metamaterials, since it is able to fabricate high-resolution subwavelength structures at wavelength 30 μm – 3 mm with minimal complication.

Fig. (a) and (b) show a multilayered fishnet metamaterial developed using a microfabrication process on PDMS. The resonators were patterned into the metal (200 nm gold thin films, with an adhesion layer) deposited on spin-coated PDMS substrates post curing. Often, micron scale resolution patterns obtained by this technique are further encapsulated with a thin layer of PDMS to avoid delamination of metal layers. Polydimethylsiloxane (PDMS), also known as dimethylpolysiloxane or dimethicone, is a silicone polymer with a wide variety of uses, from cosmetics to industrial lubrication and passive daytime radiative cooling.

Overview of Metamaterial Fabrication Techniques

Photolithography: Steps

- Fabrication of multilayered flexible terahertz metamaterials started with a bare silicon substrate as a sacrificial wafer.
- A polyimide solution was spincoated onto the substrate and baked at 180°C in a convection oven for 30 min as a flexible metamaterial substrate.
- A negative photoresist was spin-coated and patterned using conventional photolithography.
- Au/Cr (90 nm/10 nm) was then evaporated and patterned as 'I'-shaped array structures.
- Repeating the polyimide coating and curing processes, single-layered metamaterials were fabricated.

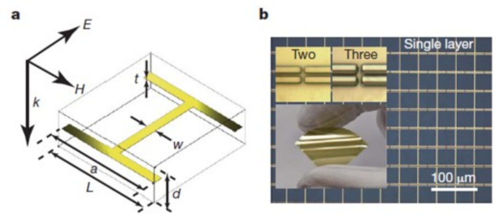


Fig. (a) Unit cell structure of the high-index metamaterial, made of a thin 'I'-shaped metallic patch symmetrically embedded in a dielectric material. (b) Optical micrograph of fabricated single-layer metamaterial.

IIT Guwahati | NPTEL swayam Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

Fabrication of multilayered flexible terahertz metamaterials started with a bare silicon substrate as a sacrificial wafer. A polyimide solution was spincoated onto the substrate and baked at 180ºC in a convection oven for 30 min as a flexible metamaterial substrate.

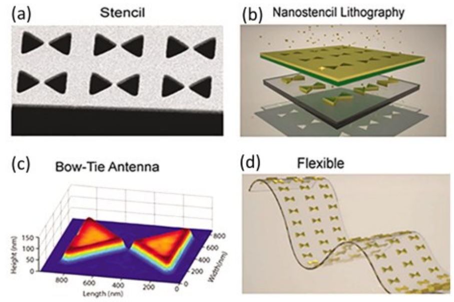
A negative photoresist was spin-coated and patterned using conventional photolithography. Au/Cr (90 nm/10 nm) was then evaporated and patterned as 'I'-shaped array structures. Repeating the polyimide coating and curing processes, single-layered metamaterials were fabricated.

The curing process hardens or toughens a process through a chemical reaction or physical action, resulting in a more stable substance. The curing of the polyimide layers was conducted at 350 ºC using an open-ended quartz tube furnace under an inert atmosphere to convert the polyamic acid into a fully aromatic and insoluble polyimide. Multilayered metamaterials on the silicon substrate were obtained by repeating the above single-layer processes until the desired number of metamaterial layers was stacked. Finally, the flexible terahertz metamaterials were fabricated by peeling off the metamaterial layers from the silicon substrate. The incident terahertz wave is directed downwards, with the polarization of the wave indicated by the arrows. Top insets, higher-magnification micrographs, showing the alignment of constituent metamaterial layers for double- and triple-layer metamaterials. Bottom inset, photograph of a flexibility test for the fabricated metamaterials.

Overview of Metamaterial Fabrication Techniques

Shadow Mask Lithography

- Shadow mask lithography is an acid-free fabrication technique employed to create planar and multiple layer micro- and nano-scale features.
- This technique involves direct deposition on to a substrate through a stencil during the deposition of thin metal films or oxides without the need of any photolithography and etching processes.
- This is analogous to the screen-printing approaches utilized in the manufacture of T-shirts.
- A stencil is prepared [Fig. (a)], usually made by through substrate etching of a silicon wafer or an aluminum foil.
- The stencil is placed either in direct contact or in close proximity to the substrate [Fig.(b)].



Fabrication sequence in the SML technique.

Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

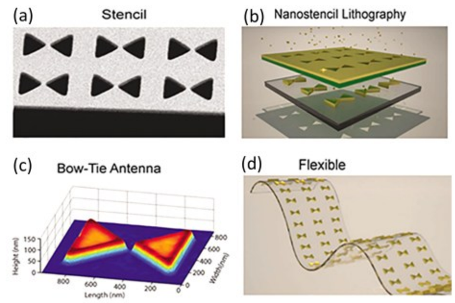
Shadow mask lithography is an acid-free fabrication technique employed to create planar and multiple layer micro- and nano-scale features. This technique involves direct deposition on to a substrate through a stencil during the deposition of thin metal films or oxides without the need of any photolithography and etching processes.

This is analogous to the screen-printing approaches utilized in the manufacture of T-shirts. A stencil is prepared as shown in Figure a, usually made by through substrate etching of a silicon wafer or an aluminium foil. The stencil is placed either in direct contact or in close proximity to the substrate as shown in Figure b.

Overview of Metamaterial Fabrication Techniques

Shadow Mask Lithography

- Subsequently, metal or dielectric layers as required are deposited, predominantly by electron beam evaporation, to utilize its inherent line-of-sight deposition characteristics to create a 1:1 copy of the stencil on the substrate.
- Using the shadow mask lithography, features as small as 100 nm wide can be patterned on arbitrary substrates including polymers and plastics that are mechanically fragile and/or chemically sensitive [Figs.(c) and (d)].
- This approach enables large area nanopatterning with high throughput. The stencils are reusable and demonstrate repeatable results with high-throughput replication of patterns.



Fabrication sequence in the SML technique.

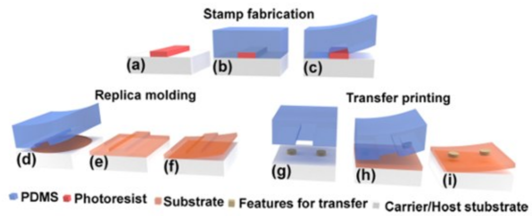
Subsequently, metal or dielectric layers as required are deposited, predominantly by electron beam evaporation, to utilize its inherent line-of-sight deposition characteristics to create a 1:1 copy of the stencil on the substrate. Using the shadow mask lithography, features as small as 100 nm wide can be patterned on arbitrary substrates including polymers and plastics that are mechanically fragile and/or chemically sensitive as shown in Figures c and d. This approach enables large area nanopatterning with high throughput. The stencils are reusable and demonstrate repeatable results with high-throughput replication of patterns.

However, the resolution of the realized patterns often deteriorate over repeated cycles of deposition due to the contact and proximity placement of stencil with the substrate during the deposition.

Overview of Metamaterial Fabrication Techniques

Soft lithography

- Soft lithography is an alternative fabrication technique, which allows multi-scale patterning of micro- and nano-scale patterns on polymers.
- Soft lithography is an inexpensive technique that can overcome some of the disadvantages encountered during photolithography.
- These include patterning structures below the diffraction limit and the need for high energy radiation.
- The soft lithography process typically requires an elastomeric which is fabricated by casting PDMS onto a "master" structure.
- The master features can be defined using the appropriate lithography technique for the pattern size. The stamp fabrication is completed by peeling off the PDMS with the embedded features of the master [Fig.(c)]



Illustrated schematics of two common soft lithography processes.

Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

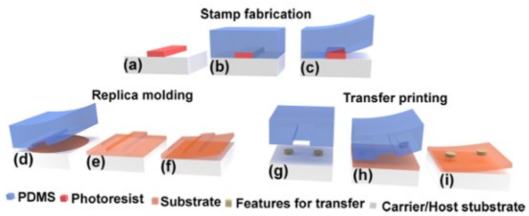
Soft lithography is an alternative fabrication technique, which allows multi-scale patterning of micro- and nano-scale patterns on polymers. Soft lithography is an inexpensive technique that can overcome some of the disadvantages encountered during photolithography. These include patterning structures below the diffraction limit and the need for high energy radiation.

The soft lithography process typically requires an elastomeric stamp which is fabricated by casting PDMS onto a "master" structure. The master features can be defined using the appropriate lithography technique for the pattern size. The stamp fabrication is completed by peeling off the PDMS with the embedded features of the master, as shown in Figure c.

Overview of Metamaterial Fabrication Techniques

Soft lithography

- Replica molding allows for high resolution patterning of any polymer compatible with the PDMS stamp which even include polymers that are not photolithographically definable.
- The pre-polymer is simply applied onto a carrier [Fig. (d)] and the stamp pressed firmly onto the surface.
- Post curing and removal of the stamp, an inverted copy of the stamp is fabricated, which can be removed from the carrier to form a free standing design [Figs. (e) and (f)].



Illustrated schematics of two common soft lithography processes.

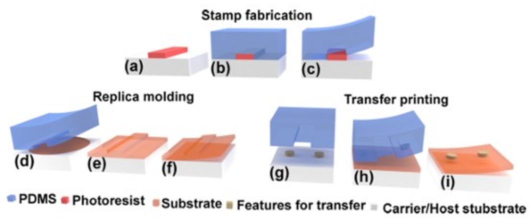
Source: Ali, A., Mitra, A. and Aïssa, B., 2022, Nanomaterials, 12(6), p.1027.

Replica molding allows for high resolution patterning of any polymer compatible with the PDMS stamp which even include polymers that are not photolithographically definable. The pre-polymer is simply applied onto a carrier as shown in Figure d and the stamp pressed firmly onto the surface. Post curing and removal of the stamp, an inverted copy of the stamp is fabricated, which can be removed from the carrier to form a free standing design as shown in Figures e and f.

Overview of Metamaterial Fabrication Techniques

Soft lithography

- Transfer Printing: Features of any desired materials, such as semiconductors, functional oxides, or metals, can be prepared on a silicon substrate. This allows for the use of established patterning techniques and high process temperatures.
- Subsequently, the patterns are "picked up" by the elastomeric stamp [Fig. (g)] and placed onto the substrate of choice [Fig. (h)].
- The substrate can then be released from the carrier [Fig. (i)].
- The transfer printing method is very powerful but requires precise control over the adhesion of the features to the donor substrate, the stamp as well as the target substrate.



Illustrated schematics of two common soft lithography processes.

Transfer Printing: Features of any desired materials, such as semiconductors, functional oxides, or metals, can be prepared on a silicon substrate. This allows for the use of established patterning techniques and high process temperatures. Subsequently, the patterns are "picked up" by the elastomeric stamp as shown in Figure g and placed onto the substrate of choice as shown in Figure h. The substrate can then be released from the carrier as shown in Figure i.

The transfer printing method is very powerful but requires precise control over the adhesion of the features to the donor substrate, the stamp as well as the target substrate. By using soft lithography techniques, limitations of plastic substrates such as high temperature expansion, poor adhesion, low processing temperature and chemical instabilities can be overcome. Additionally, these techniques are suitable for a wide range of structure sizes and enable patterning on non-planar surfaces.

Overview of Metamaterial Fabrication Techniques

Electron beam lithography (EBL)

- EBL uses the extremely small wavelength of a beam of electrons at high accelerating voltages to obtain nanoscale patterns.
- Analogous to conventional photolithography, where a photoresist layer is exposed to ultra-violet (UV) light, the EBL technique requires the exposure of an electron beam resist, PMMA, or ZEP520A, by a high-energy electron beam.
- This causes a scission in the organic structure that is subsequently developed using a standard developing solution, whereby the exposed region dissolves completely in the developer.
- Subsequently, deposition of metal and/or dielectric layers is carried out following which the resist is dissolved to obtain the nanoscale patterns.
- This approach utilizes the "lift-off" process, and so, the initial pattern defined by EBL needs to be the inverse of the desired pattern.
- EBL provides the highly desirable ability to create nanoscale features below the diffraction limit of the standard photolithography processes and does not require a physical mask to transfer the patterns.

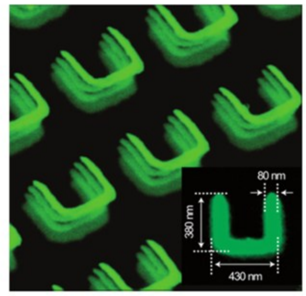
EBL uses the extremely small wavelength of a beam of electrons at high accelerating voltages to obtain nanoscale patterns. Analogous to conventional photolithography, where a photoresist layer is exposed to ultra-violet (UV) light, the EBL technique requires the exposure of an electron beam resist, PMMA, or ZEP520A, by a high-energy electron beam. This causes a scission in the organic structure that is subsequently developed using a standard developing solution, whereby the exposed region dissolves completely in the developer.

Subsequently, deposition of metal and/or dielectric layers is carried out following which the resist is dissolved to obtain the nanoscale patterns. This approach utilizes the "lift-off" process, and so, the initial pattern defined by EBL needs to be the inverse of the desired pattern. EBL provides the highly desirable ability to create nanoscale features below the diffraction limit of the standard photolithography processes and does not require a physical mask to transfer the patterns.

Overview of Metamaterial Fabrication Techniques

Electron beam lithography (EBL)

- For metamaterials, the EBL technique is employed to fabricate sub-wavelength resolution resonators operating at optical wavelengths.
- Figure shows a multi-layered metamaterial comprising of 4 layers of gold SRRs developed on a photoconductive polymer (PC403) substrate using the EBL technique.
- While EBL is a powerful technique to achieve nanometer and sub-micron features, it has major limitation in creating large area, high performance metamaterials.
- These are long writing times due to the serial nature of the technique, stitching errors impacting periodicity, and the low stability of the electron beam.
- Additionally, the serial patterning process gives rise to issues such as instability of the beam due to drifting.
- Finally, the stability and accuracy of the electron beam blanking are important factors that influence the effectiveness of this technique.



For metamaterials, the EBL technique is employed to fabricate sub-wavelength resolution resonators operating at optical wavelengths. Figure shows a multi-layered metamaterial comprising of 4 layers of gold SRRs developed on a photoconductive polymer (PC403) substrate using the EBL technique. While EBL is a powerful technique to achieve nanometer and sub-micron features, it has major limitation in creating large area, high performance metamaterials.

These are long writing times due to the serial nature of the technique, stitching errors impacting periodicity, and the low stability of the electron beam. Additionally, the serial patterning process gives rise to issues such as instability of the beam due to drifting. Finally, the stability and accuracy of the electron beam blanking are important factors that influence the effectiveness of this technique.

The beam blanker is an external voltage source that is used to switch the electron beam “ON” and “OFF” while patterning the nanoscale features. During the large writing times that typically accompany this method, any fluctuations in the current can give rise to inconsistent exposure, and result in variable developing times for PMMA as well as introduce geometrical errors.

This is all for the fifth lecture. We will start the discussion of “Basic Electromagnetic theory” in next lecture. If you have any doubts/queries regarding any part of the lecture, you can send your queries at deb.sikdar@iitg.ac.in. Thanks!