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Metamaterials for Revolutionizing Modern Applications and Metasurfaces

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ABSTRACT

Metamaterials, artificial structures engineered to possess properties not found in naturally occurring materials, are revolutionizing modern applications across various fields. These materials, composed of periodic or aperiodic arrangements of unit cells, manipulate electromagnetic waves in unprecedented ways, enabling unique control over wave propagation, refraction, and absorption. Metamaterials have paved the way for transformative advancements in optics, telecommunications, and medical imaging.One of the most promising areas of metamaterial research is the development of metasurfaces—two-dimensional analogs of metamaterials that consist of ultra-thin layers of nanostructures. Metasurfaces offer significant advantages in terms of compactness and ease of integration into existing technologies. They are capable of manipulating light at sub-wavelength scales, leading to innovative applications such as flat lenses, holograms, and beam steering devices. In telecommunications, metasurfaces enable the development of high-efficiency antennas and filters, enhancing signal quality and reducing interference. In medical imaging, metamaterials improve the resolution and depth of imaging techniques, facilitating more accurate diagnostics. Additionally, metamaterials are being explored for cloaking devices, which can render objects invisible by guiding light around them.As research progresses, the potential for metamaterials and metasurfaces to revolutionize various industries continues to expand, promising a future where the manipulation of electromagnetic waves is limited only by our imagination..

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INTRODUCTION

Metamaterials, engineered with meticulous microscopic structures, possess the extraordinary ability to manipulate electromagnetic waves, sound, and other phenomena in ways that defy conventional materials.[1-3] These artificial marvels, derived from the Greek word “meta” meaning “beyond,” offer unprecedented control over light, unleashing transformative potential across diverse fields.[2] By carefully tailoring their subwavelength “metamolecules,” metamaterials exhibit exotic properties like negative refraction, empowering novel optics applications such as superlenses for ultra-high-resolution imaging and holography,[1-3] as in Fig. 1.

This introduction seamlessly integrates a metamaterials as advanced materials, paving the way to explore their evolution, fabrication techniques, emerging electromagnetic wave manipulation capabilities for functional metadevices like antennas, cloaking, absorbers, and lithography applications. It also touches upon the challenges and prospects, underscoring

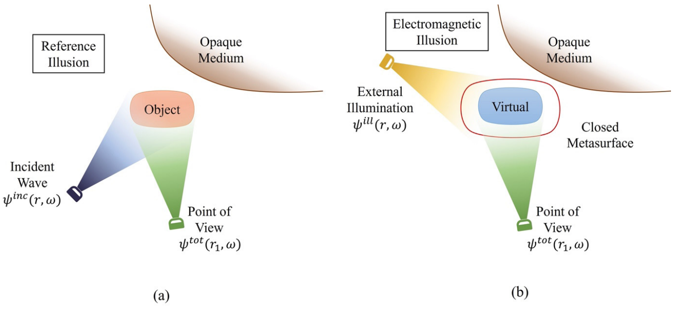

Fig. 1: Electromagnetic Illusions

metamaterials' pivotal role in shaping the future of physics, engineering, and interdisciplinary innovation.

METAMATERIALS AND THEIR CLASSIFICATION

A metamaterial (from the Greek word μετά*meta*, meaning "beyond" or "after", and the Latin word *materia*, meaning "matter" or "material") is any material engineered to have a property that is rarely observed in naturally occurring materials.They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics.These materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures.Their precise shape, geometry, size, orientation and arrangement gives them their smart properties capable of manipulating electromagnetic waves: by blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials.[4-14]

The history of metamaterials begins with artificial dielectrics in microwave engineering as it developed just after World War II. Yet, there are seminal explorations of artificial materials for manipulating electromagnetic waves at the end of the 19th century. Historically, and conventionally, the function or behavior of materials can be altered through their chemistry. However, at the end of the 20th century, this description was expanded by John Pendry, a physicist from Imperial College in London. Pendry discovered that the radiation absorption property did not come from the molecular or chemical structure of the material, but from the long and thin, physical shape of the carbon fibers. He realized rather than conventionally altering a material through its chemistry, the behavior of a material can be altered by changing its internal structure on a very fine scale, less than the wavelength of the applied electromagnetic radiation. Scientists view this material as "beyond" conventional materials, hence the Greek word "meta" was attached, and these are called metamaterials.[15]

A. Classification Based on Physical Properties

Metamaterials can be classified based on the real parts of their constitutive parameters, i.e., their permittivity and permeability.[16]

1. **Negative-index metamaterials (NIM)** are characterized by a negative index of refraction. Other terms for NIMs include "left-handed media", "media with a negative refractive index", and "backward-wave media". NIMs where the negative index of refraction arises from simultaneously negative permittivity and negative permeability are also known as double negative metamaterials or double negative materials (DNG).[17]
2. **Single negative (SNG) metamaterials** have either negative relative permittivity (εr) or negative relative permeability (μr), but not both[19]. They act as metamaterials when combined with a different, complementary SNG, jointly acting as a DNG.
3. **Hyperbolic metamaterials (HMMs)** behave as a metal for certain polarization or direction of light propagation and behave as a dielectric for the other due to the negative and positive permittivity tensor components, giving extreme anisotropy.The material's dispersion relation in wavevector space forms a hyperboloid and therefore it is called a hyperbolic metamaterial. The extreme anisotropy of HMMs leads to directional propagation of light within and on the surface.[18]
4. **Electromagnetic bandgap metamaterials (EBG or EBM)** control light propagation.This is accomplished either with photonic crystals (PC) or left-handed materials (LHM).PCs can prohibit light propagation altogether.Both classes can allow light to propagate in specific, designed directions and both can be designed with bandgaps at desired frequencies.[19]
5. **Chiral and/or bianisotropic metamaterials** generally exhibit a chiral and/or bianisotropic electromagnetic response as a consequence of 3D geometrical chirality.3D-chiral metamaterials are composed by embedding 3D-chiral structures in a host medium and they show chirality-related polarization effects such as optical activity and circular dichroism.[20]
6. **Frequency selective surface-based metamaterials** block signals in one waveband and pass those at another waveband.They have become an alternative to fixed frequency metamaterials, allowing for optional changes of frequencies in a single medium, rather than the restrictive limitations of a fixed frequency response.[21]

B. Classification Based on Dimensionality

The dimensionality of the range of components that form the bulk (3D) structures is another criterion for metamaterial classification.[22] They are structures that have a large number of constituent elements in any given direction.The materials on the surface (i.e., 2D) are

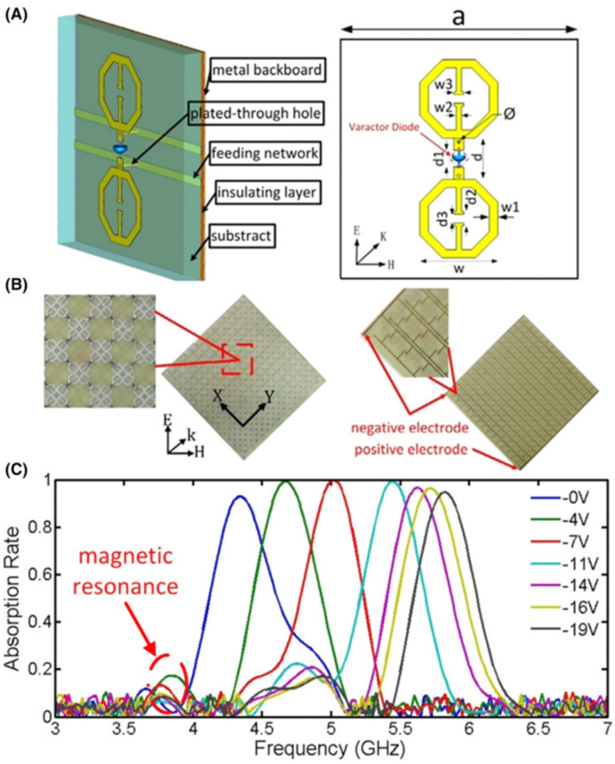

Fig. 2: Metamaterials and Metasurfaces

equivalent to the case where a thin film structure is made of 1–3 constituents only.Surface-type metamaterials are generally called metafilms or metasurfaces. Optical waveguide with nano inclusions and plasmonics and polaritonic nano-chains are considered as linear (1D) structures as in Fig. 2.

EVOLUTION OF METAMATERIALS

A. Historical Background

The history of metamaterials can be traced back to artificial dielectrics in microwave engineering, which emerged shortly after World War II. However, the seminal explorations of artificial materials for manipulating electromagnetic waves date back to the end of the 19th century. In 1904, Horace Lamb and Arthur Schuster noted the possibility of negative phase velocity accompanied by an anti-parallel group velocity.

It was not until 1967 that V.G. Veselago from the Moscow Institute of Physics and Technology considered the theoretical model of a medium that is now known as a metamaterial. Thirty-three years later, the properties of metamaterials became a subdiscipline of physics and engineering.

In 2000, a team of researchers at the University of California, San Diego (UCSD) produced and demonstrated the first metamaterials, which exhibited unusual physical properties never before observed in nature. These materials obeyed the laws of physics but behaved differently from conventional materials. Advances in fabrication and computation capabilities during the 1990s allowed these first metamaterials to be constructed, initially testing the effects described by Victor Veselago 30 years earlier in the microwave frequency domain.

B. Recent Developments and Market Forecast

The latest research indicates that the global metamaterial technologies market reached a value of USD 6.74 million in 2023. It is expected to achieve USD 26.18 million by 2030, exhibiting a compound annual growth rate (CAGR) of 21.39% during the forecast period [23].

The market growth is anticipated to rise considerably between 2021 and 2028, driven by the rising adoption of strategies by key players. The report covers a research time span from 2019 to 2030, combining extensive quantitative and qualitative analysis to provide a comprehensive overview of the global metamaterial technologies market from different perspectives, including sales, revenue, growth rate, region, product type, and downstream industry.[17]

Several factors are driving the growth of the metamaterial technologies market, including the increasing demand for antennas and radars in the defence sector due to growing safety requirements and the need for detecting obstacles in low visibility conditions. Conventional resonant and broadband antennas are being gradually replaced by metamaterial antennas in wireless communications due to their suitability for emerging applications such as radio frequency identification systems.

Moreover, increasing capital investments from private and public sectors, technological advancements and modernization in product techniques, and rising research and development (R&D) activities are providing growth opportunities for the market. The focus on utilizing metamaterial technologies in various sectors, such as aerospace, defence, healthcare, biomedical applications, passive radiative cooling solutions for power plants, electronically scanned array self-driving cars and drones, and smart metamaterial antennas for 5G networks and satellites, is further driving market growth.[24]

FABRICATION TECHNIQUES FOR METAMATERIALS

A. Photolithography

Photolithography is a widely used fabrication technique in the semiconductor industry, and it is also employed in the fabrication of metamaterials as in Fig. 3. In this process, a photoresist, a light-sensitive material,

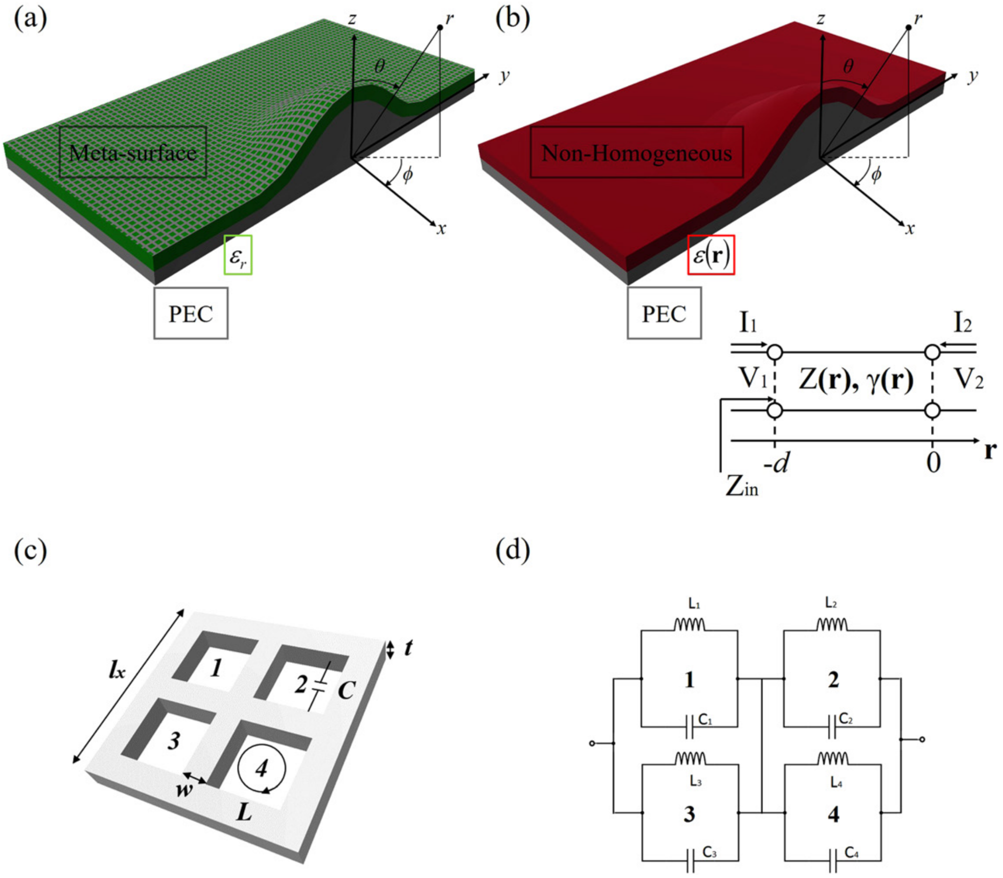

Fig. 3: Curvilinear MetaSurfaces for Surface Wave Manipulation

is deposited on a substrate. The photoresist is then exposed to light through a patterned mask, which causes chemical changes in the exposed areas. The exposed areas are either removed (positive photoresist) or remain (negative photoresist) during the subsequent development process, creating the desired pattern on the substrate. This technique is well-suited for processing photoresists and can produce highly precise patterns.

B. Shadow Mask Lithography

Shadow mask lithography, also known as stencil lithography or shadow masking, is a fabrication technique that utilizes stencil metal plates or shadow masks to designate where a metal is deposited upon a substrate. The shadow mask serves as a medium for achieving custom designs onto a substrate without the need for photolithography processes. This method works by masking certain areas of a substrate while exposing others to be deposited with metal. Shadow masks are typically made of thin stainless steel or nickel sheet metal. Creating shadow masks can be challenging, as the required machining can be difficult, and it may result in jagged edges. For high-precision designs, shadow masking may present difficulties, as small feature sizes are often harder to obtain compared to photolithography fabrication methods. However, shadow masking offers a more mechanical mechanism for transferring designs and can significantly reduce production costs by eliminating the need for expensive photoresists and solvents.

C. Soft Lithography

Soft lithography is a collection of fabrication methods based on using a patterned layer of polydimethylsiloxane (PDMS), a soft and flexible polymer.This technique extends the possibilities of conventional photolithography by allowing the processing of a wide range of elastomeric materials, including polymers, gels, and organic monolayers.PDMS is widely used in soft lithography due to its useful properties, such as low cost, biocompatibility, low toxicity, chemical inertness, and mechanical flexibility.Soft lithography encompasses various techniques, including replica molding, capillary molding, microcontact printing, and microtransfer molding.These techniques enable the patterning of biocompatible polymers, the duplication of 3D structures, and the transfer of molecular inks onto substrates

D. Electron Beam Lithography

Electron beam lithography (EBL) is a high-resolution patterning technique widely used for fabricating nanostructures.In this process, a focused beam of electrons is used to expose a resist material, creating the desired pattern.EBL offers a high-resolution patterning capability without the need for masks.However, the fabrication of three-dimensional (3D) nanostructures using EBL can be challenging due to alignment errors that occur during the overlay process.To address this issue, researchers have developed strategies such as newly designed alignment marks and calibrators to minimize alignment errors and achieve sub-20 nm EBL overlay accuracy.This technique has been used to fabricate complex 3D nanostructures inspired by metamaterials and plasmonic structures for optical applications

E. Three-Dimensional Fabrication Techniques

Additive manufacturing (AM) techniques, also known as 3D printing, play a crucial role in the fabrication of metamaterials. These techniques offer form-freedom, which is essential for creating the often highly complex microarchitectures required for realizing unusual properties and advanced functionalities in metamaterials as in Fig. 4. AM techniques have evolved from rapid prototyping to the fabrication of fully functional parts with complex geometries and high fidelities. Recent developments in AM have expanded the length scales, types, and number of co-printed materials, enabling the fabrication of metamaterials with resolutions ranging from a few nanometers to submillimeters.[25]

However, two major challenges need to be addressed in future studies: the long fabrication times for objects with dimensions much larger than the printing resolution, and the limited number of materials that can be processed with small-scale AM techniques. Indirect AM techniques, such as creating molds, masks, or stamps using AM and then applying them to scale up the manufacturing of target devices, have been employed to address these limitations to some extent. Nonetheless, it is crucial to develop AM machines specifically designed for scalable manufacturing of metamaterials and novel, bespoke materials that can be processed using ultrahigh resolution AM techniques.[26]

Emerging Functional Metadevices

A. Tunable and Reconfigurable Metadevices

Metasurfaces, ultrathin metamaterials constructed by planar meta-atoms with tailored electromagnetic (EM) responses, have attracted tremendous attention due to

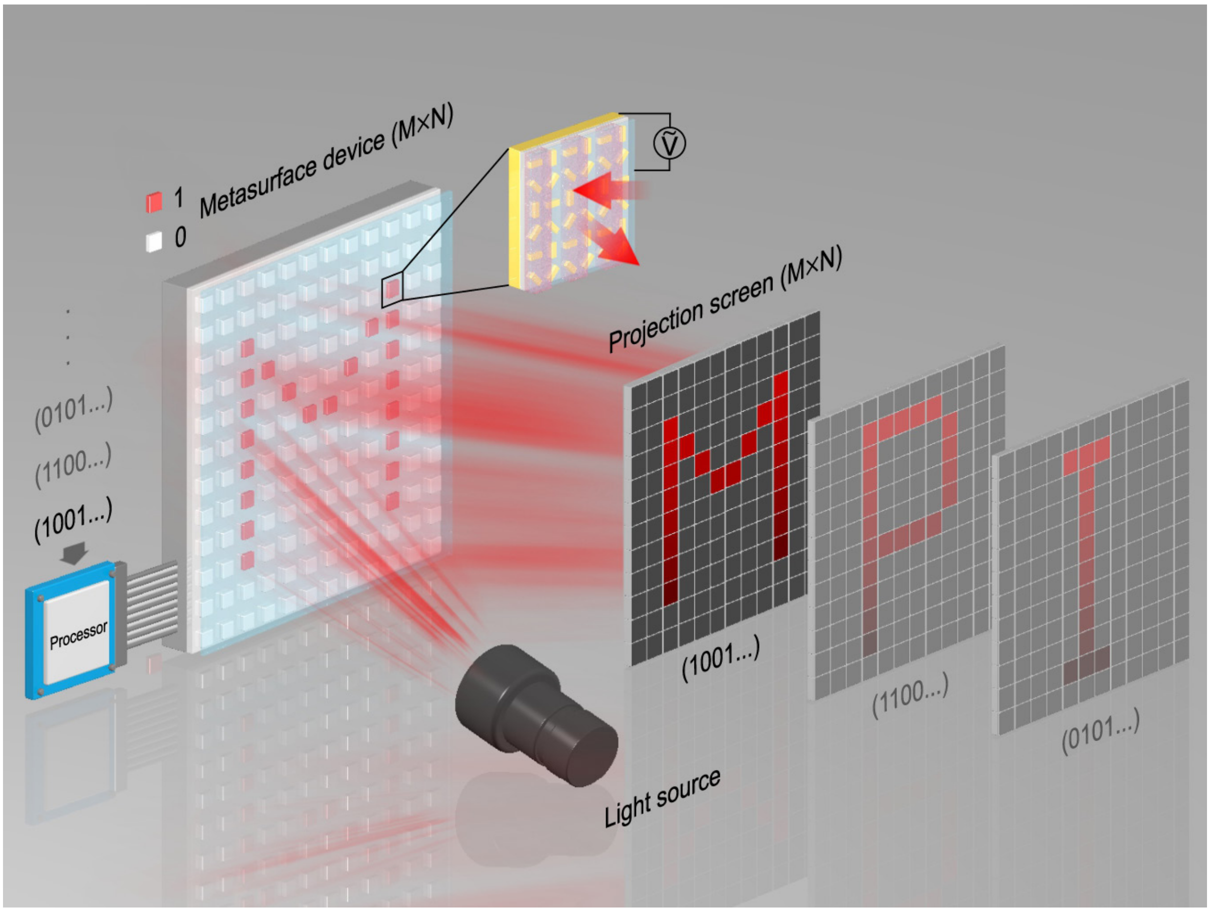

Fig. 4: Electrically-controlled digital metasurface device

their exotic abilities to freely control EM waves. With active elements incorporated into metasurface designs, one can realize tunable and reconfigurable metadevices with functionalities controlled by external stimuli, opening a new platform to dynamically manipulate EM waves.

Available approaches to realize homogeneous tunable and reconfigurable metasurfaces, which can offer uniform manipulations on EM waves, can be categorized into different classes based on external stimuli applied. Electrically tunable metasurfaces (ETMs) have garnered enormous research interest, thanks to the maturity of electronic and semiconductor technologies, allowing the integration of meta-atoms with different electrically sensitive materials (e.g., varactor/PIN diodes, liquid crystals, doped semiconductors, 2D materials, and conducting transparent metals). This has enabled the realization of many high-performance active metadevices with functionalities tuned dynamically in different frequency domains.

Mechanically switchable metasurfaces (MSMs) can be realized through mechanically changing the geometrical structures of constitutional meta-atoms or altering the distances between adjacent meta-atoms or between meta-atoms and their substrate, manipulating the near-field interactions between meta-atoms and enabling dramatic modifications on the EM properties of the whole metasystem. Optical modulation through ultrafast light pulses provides another way to realize active metasurfaces typically constructed with meta-atoms involving optically sensitive materials like semiconductors, whose conduction carriers (and dielectric constants) strongly depend on external optical pumping. Thermally tunable metasurfaces (TTMs) can be achieved by combining passive metasurfaces with thermally sensitive materials (e.g., phase-change materials, liquid crystals, and superconductors).

Incorporating MEMS/NEMS techniques in metamaterial designs enables the manipulation of the structural configurations of metamaterial unit cells in real time. By combining MEMS actuators with metamaterials, the electromagnetics, mechanics, electronics, thermal dynamics, and fluidic dynamics work in synergy to create tunable and reconfigurable metamaterials, which are functional metadevices for applications such as EM wave modulation and sensing.Compared with conventional optical devices, metadevices are design-driven and have unprecedented advantages, including enhanced performance, a large dynamic tuning range, design flexibility, fast response, and compactness.

Using MEMS and NEMS actuators, one can structurally reconfigure meta-atoms to modulate their resonant frequency, amplitude, and phase in steady and dynamic fashions [25].For different applications, meta-atom designs and actuation mechanisms may be optimized to maximize the resonant frequency shift, amplitude modulation depth, or phase coverage.

B. Electro-Optical Metadevices

An active metadevice capable of efficient real-time control of radiation with electric signals was first developed for the terahertz part of the spectrum. It consisted of a gold metamaterial array fabricated on a semiconductor substrate, effectively forming a Schottky diode, where the dielectric properties of the substrate can be controlled by injection and depletion of carriers. An electric signal applied to the metamaterial affects the high-frequency conductivity of the substrate in critical areas near the metamolecules, thus affecting their resonant response as shown Fig. 5.

Graphene is another favored material for constructing metamaterials with electro-optical capability, particularly in the infrared and terahertz domains, by exploiting the modification of the electromagnetic response by an applied voltage. Such a terahertz electro-optical modulator, consisting of engineered graphene microribbon arrays, was recently demonstrated.

Tunability and a strongly nonlinear response can be achieved in metamaterials by infiltrating them with liquid crystals. Electrical control of negative permeability in microwave metamaterials infiltrated with nematic liquid crystals was experimentally demonstrated for a periodic array of split-ring resonators, showing a reversible change of the transmission resonance with a maximum shift of about 210 MHz.

C. Phase-Change Metadevices

A radical change in the arrangement of atoms is called a structural phase transition or phase change. Phase-change functionality of semiconductor chalcogenide glass has been used for decades in optical compact disks and DVDs, where the rewritable memory function is underpinned by a transition from amorphous to crystalline phase. Phase-change functionality in polymorphic metals can also provide a way to achieve nanoscale optical and plasmonic switching devices that can be fast and require little energy to activate.

Hybridizing vanadium dioxide with a metamaterial shows 20% temperature-activated tuning of the transmission in the terahertz range. Similar switching has also been

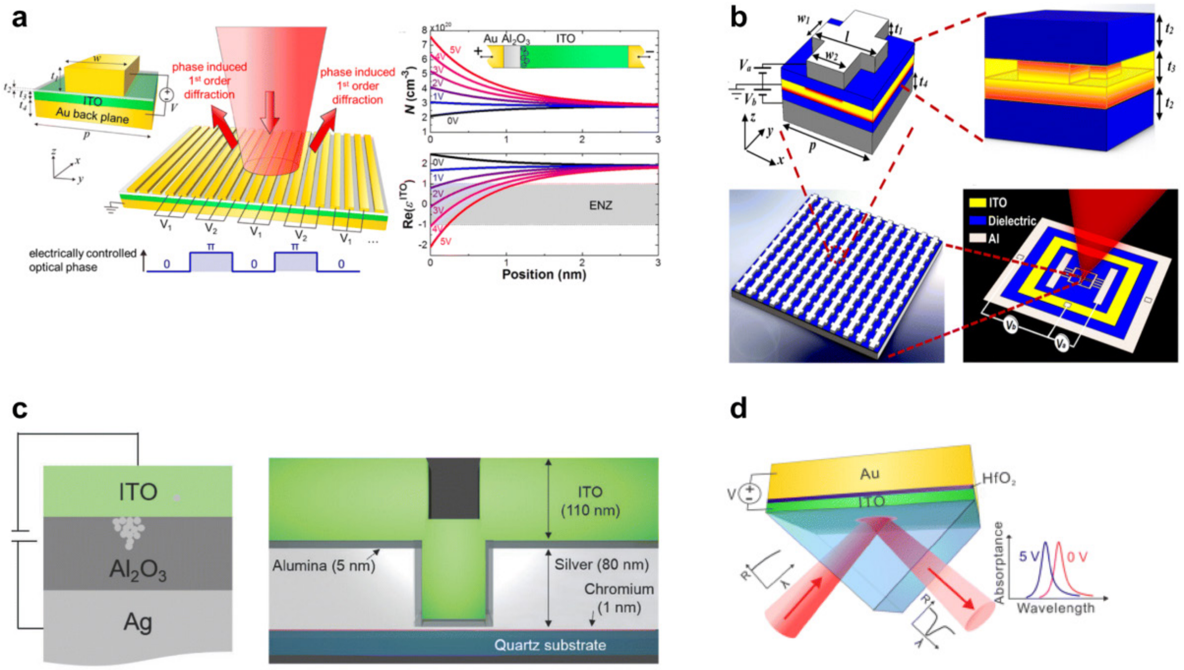

Fig. 5: Tunable metasurfaces for visible and SWIR applications

demonstrated in the near-infrared using a dual-bar gold metamaterial array. A form of electrically activated memory function and persistent frequency tuning of a metamaterial, which allows lasting modification of its response by using a transient stimulus, have also been demonstrated in a hybrid VO2 metadevice in the terahertz part of the spectrum.

Switching has been demonstrated by exploiting the frequency shift of a narrowband Fano resonance mode of a plasmonic planar metamaterial that was induced by a change in the dielectric properties of an adjacent 200-nm-thick film of chalcogenide glass. The material used was a new gallium lanthanum sulphide chalcogenide glass, which was bistable and silicon-on-insulator compatible. An electrically stimulated transition between amorphous and crystalline forms of the glass brings about a 150-nm shift in the near-infrared resonance, providing transmission modulation with a contrast ratio of 4:1 in a layer of subwavelength thickness.

More recently, the resistive-switching of phase-change cells incorporated into a type of Fabry-Perot resonator structure was shown to provide the capability for new types of high-resolution, fast, and non-volatile optoelectronic color displays and holograms. Another interesting recent development that also exploits the large change in optical properties resulting from a switch between amorphous and crystal states is that of phase-change metadevices. Here, phase-change materials are typically used as a form of switchable dielectric that, in combination with optical metasurfaces, can provide a wide range of novel functionalities such as beam steering with no moving parts, ‘perfect’ infrared absorbers and modulators, and planar and re-configurable thin-film lenses as shown Fig. 6.

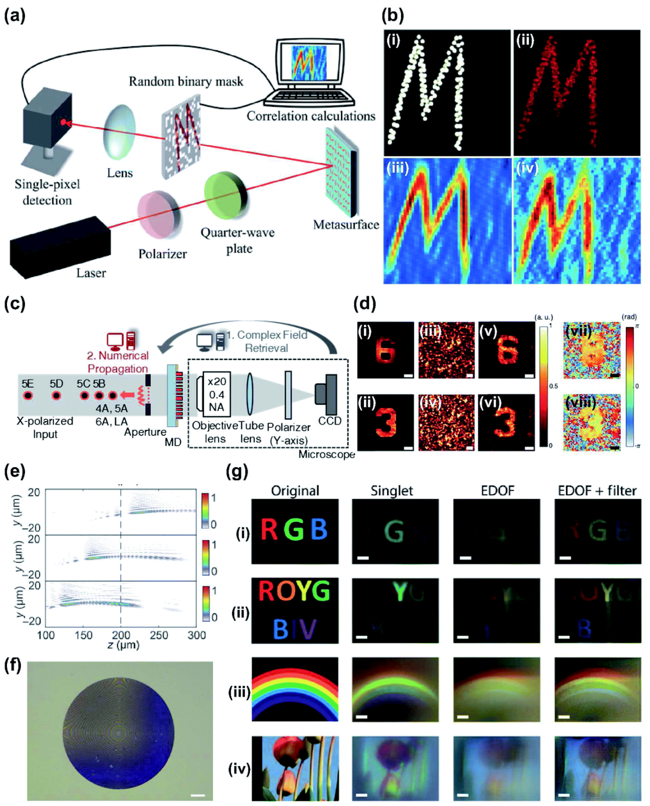

Fig. 6: Metasurfaces-based imaging

APPLICATIONS OF METAMATERIALS AND METASURFACES

Metamaterials and metasurfaces have garnered significant attention due to their exceptional ability to manipulate electromagnetic (EM) waves, enabling a wide range of applications across various domains. These engineered materials possess unique properties not found in natural materials, making them highly versatile for controlling the amplitude, phase, and polarization of reflected and transmitted EM waves.

A. Antennas and Polarization Converters

One of the prominent applications of metamaterials and metasurfaces lies in the field of antennas and polarization converters. These materials can be employed to enhance the efficiency of antennas by manipulating the radiation patterns and improving the directivity. Additionally, metasurfaces can be designed to convert the polarization of EM waves, enabling the development of polarization converters for various applications

B. Radar Cross-Section (RCS) Reduction and Absorbers

Metamaterials and metasurfaces have demonstrated remarkable capabilities in reducing the radar cross-section (RCS) of objects, making them less detectable by radar systems. This property finds applications in stealth technology and cloaking devices. Furthermore, these materials can be engineered to act as ideal absorbers, efficiently absorbing EM waves across a wide range of frequencies. This characteristic has applications in energy harvesting, thermal management, and electromagnetic shielding.

C. Superlenses and Cloaking

The unique properties of metamaterials and metasurfaces enable the development of superlenses, which can overcome the diffraction limit and achieve super-resolution imaging capabilities.This technology has potential applications in microscopy, lithography, and medical imaging. Additionally, metamaterials can be employed in cloaking devices, which can render objects invisible to EM waves by bending and guiding the waves around the object.

D. Wave Manipulation and Guiding

Metasurfaces possess the ability to block, absorb, concentrate, disperse, or guide EM waves on their surface and in space, from microwave to visible frequencies.By designing impedance cells to manipulate phase or group velocity, surface waves can be controlled and guided in specific directions. This property finds applications in the design of microwave and optical lenses, such as Luneburg and fish-eye lenses, for antenna systems and planar microwave sources.

E. Elimination of Scattering and Energy Harvesting

Metamaterials and metasurfaces can be engineered to eliminate scattering of EM waves, enabling the development of devices with reduced electromagnetic interference.Furthermore, these materials can be utilized for energy harvesting applications, where they can efficiently capture and convert EM waves into usable forms of energy as shown Fig. 7.

These are just a few examples of the numerous applications of metamaterials and metasurfaces, which continue to expand as research in this field progresses. Their unique properties and ability to manipulate EM waves make them promising candidates for revolutionizing various industries, including telecommunications, defense, energy, and biomedical technologies.

CHALLENGES AND FUTURE PROSPECTS

A. Fundamental Challenges

The main challenge in the field of metamaterials and metasurfaces is to gain a deep understanding of the fundamental principles underlying these technologies, including design theory, fabrication methods, and effective modulation of their performance. Achieving this comprehensive understanding is critical for enabling precise manipulation of electromagnetic waves, the design of advanced electromagnetic devices, and the development of other functional applications.

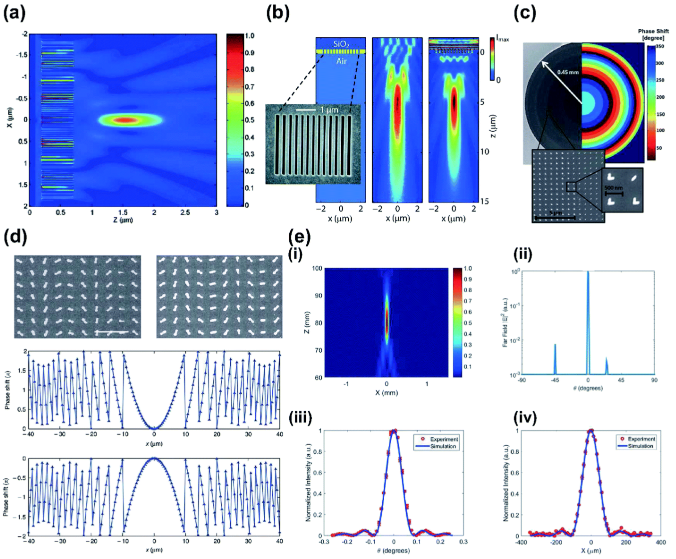

Fig. 7: Miniaturized optical components

B. Practical Implementation Challenges

In addition to the fundamental challenges, the practical implementation of metamaterials and metasurfaces presents several obstacles. These include high fabrication costs, material stability issues, and the need for integrated performance optimization. Addressing these challenges is crucial for the widespread adoption and commercialization of these technologies.

C. Fabrication Limitations

Though various fabrication techniques, such as photolithography, soft lithography, and three-dimensional (3D) printing, have been developed for creating metamaterial structures, these methods are not yet versatile and mature enough. Some of these techniques are complex, involving multiple manufacturing steps that impact the structural resolution, while others are restricted by the types of materials employed or the choice of suitable substrates. Additionally, transfer techniques are dependent on surface chemistry, further limiting their applicability. Achieving high-resolution patterns below 0.1 μm on highly curved substrates using a fusion of complex techniques like soft lithography and photolithography remains a significant technological challenge.

D. Nonlinear Optical Applications

Advancements in the field of plasmonic resonance due to metamaterial networks can be employed in the optical part of the spectrum to increase the nonlinear response of nearby semiconductor or dielectric layers. Fano-type resonances promoted by plasmonic nanostructures have demonstrated more than a tenfold increase in nonlinearity.This technique allows for the engineering of nonlinearity in materials like graphene at predefined wavelengths within a wide range, enabling applications such as optical switching and pulse shaping.

E. Future Prospects and Opportunities

Despite the challenges, the field of metamaterials and metasurfaces holds immense potential for future growth and innovation. As research continues, new applications and market segments are expected to emerge, driving the demand for these advanced materials. The report highlights the different types of metamaterials, including electromagnetic, acoustic, and optical metamaterials, as well as their subclasses such as metasurfaces, photonic metamaterials, and tunable metamaterials.

The report also examines the applications of metamaterials in various market segments. For instance, in the acoustics segment, metamaterials are being utilized for sound insulation and vibration damping, offering superior performance compared to traditional materials. The report identifies key growth areas and untapped opportunities in the metamaterials market, helping businesses and investors align their strategies accordingly [26]-[27].

CONCLUSION

The realm of metamaterials and metasurfaces has unleashed a revolutionary paradigm in manipulating and harnessing electromagnetic waves. With their engineered microscopic structures, these artificial marvels transcend the limitations of conventional materials, enabling unprecedented control over light propagation, phase, and polarization. From cloaking devices and superlenses to tunable antennas and energy harvesters, the applications of metamaterials span diverse fields, catalyzing interdisciplinary breakthroughs. While challenges persist in fundamental understanding, practical implementation, and fabrication techniques, the future prospects of metamaterials are boundless. Continuous research and innovation will undoubtedly unravel new avenues, propelling these advanced materials into realms yet unexplored. As we delve deeper into the world of metamaterials, we embark on a journey that redefines the boundaries of physics, engineering, and technology, paving the way for a future where the extraordinary becomes reality.

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