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A Review: MetamaterialsFrom Concepts To Technology

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Abstract— Electromagnetic (EM) metamaterials are artificially engineered media composed of sub-wavelength unit cells, which achieve exotic EM properties beyond the limits of natural materials and provide great freedom to manipulate EM wave. In recent years, the development of metamaterials continues to redefine the boundaries of materials science. This new type of artificial material—a newfrontier of science, which first emerged in the field of optics and photonics. Metamaterials are a new class of ordered composites that exhibits exceptional electromagnetic properties not readily observed in nature they exhibit negative permittivity and/ or negative permeability. Here, we review the progress on metamaterials. In the first section we give the brief introduction, In the second section we review the generalized metamaterials concepts including classification of metamaterials, different types of metamaterials and also give a comprehensive review on the recently proposed information metamaterials, including digital metamaterials and coding metamaterials. In the third section, we study the design of metamaterials and also include various numerical techniques and modeling methods of metamaterials. In fourth section we summarize the typical metamaterial devices such asantennas, absorbers, lenses, cloaks, and other devices, we review the research progress of metamaterial. Finally, an outlook of the future directionsof metamaterials is offered.

Keywords—Metamaterials(MTM), permittivity, permeability, Left-handed materials, Split Ring Resonator (SRR)

INTRODUCTION

In electromagnetic community the research into metamaterials has become a new promising paradigm. The unique properties of the metamaterials have significantly spurred the theoretical study of new physical concepts and phenomena with many scientific findings [1-5].Metamaterials are the artificial materials that can be used to control and manipulate the flow of light, sound and such generate other exceptional properties, not found in nature or in naturally occurring materials. In particular, artificial materials with both negative permeability and negative permittivity have attracted widespread interest in recent years. These composites are constructed from magnetic substratesand an array of metallic in dielectric and exhibit unusual electromagnetic properties such as inverted Snell's law and Doppler shift behavior with in a particular frequency range.

In 1898 JagadisChunder Bose was the first to attempt and explore the concept of "artificial" materials, when he attempted the first microwave experimenton twisted structures—geometries that were essentially artificial chiral elementsby today's terminology [6]. In 1914, Lindman worked on "artificial" chiral mediaby embedding many randomly oriented small wire helices in a host medium [7]. In 1948, Kock [8] made lightweight microwave lenses by arranging conductingspheres, disks, and strips periodically and effectively tailoring the effectiverefractive index of the artificial media. one of the most important contributions to this topic was made in 1967 by Russian physicist, Victor Veselago,he theoretically proposed Metamaterials[1]. In 1999, John Pendry practicallymakes first left-handed metamaterials (LHM) which did not follow the conventional right-hand rule [2]. Later then, David Smith and his colleaguesdemonstrated a new LHM that shows simultaneously negative permittivity and permeability in 2000 [3]. In July 2003, Richard W. Ziolkowski reported another metamaterial. This metamaterial comprised of a substrate with embedded capacitively loaded strips (CLSs) and square split ring resonators (SRRs)[4]. Many researchers have worked on metamaterials to extract their potential in various field and can design and control the properties of metamaterials so that can be synthesized and fabricated and it will help in the large advancement in the field of research.

GENERALIZED METAMATERIAL CONCEPT

CLASSIFICATION OF METAMATERIALS

It is appropriate to consider the classification of materials represented on figure 1 before turning to specific classification of metamaterial structures. On the basisof sign of permittivity and permeability, the materials can be divided into four categories. Metamaterials may have either negative permittivity or permeability or both.

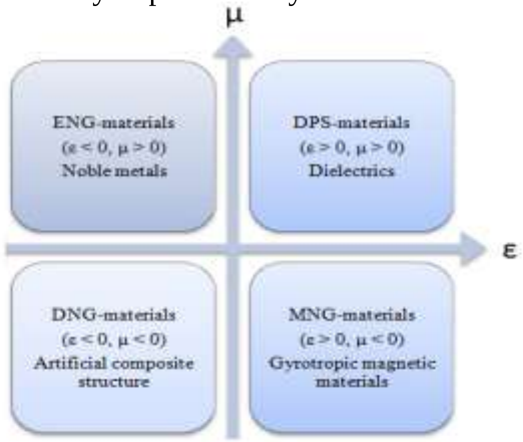

Figure 1: The general classification of physical materials depending on values of permittivity(ε) and permeability(μ)

I. First Quadrant

The region has positive permittivity and permeability ($\varepsilon > 0$, $\mu > 0$), represents Right Handed Material (RHM) or Double Positive (DPS). In the first quadrant the forward Propagation of wave takes place. It is commonly used material. These materials can be found in nature, such as dielectric materials, in which the electromagnetic waves can propagate.

II. Second Quadrant

This region has negative permittivity and positive permeability value ($\varepsilon < 0$ and $\mu > 0$). These materials representthe class ofmetamaterials known as Artificial Dielectrics.These materials can be used forreducing the size of antennas due to its highly negative dielectric value. It is alsocalled Epsilon NegativeMaterial (ENG).

III. Third Quadrant

This region represents the metamaterials with simultaneously negative permittivity and permeability($\varepsilon < 0$, $\mu < 0$). These are called Left Handed Materials (LHM) or Double Negative Material (DNG). Due tonegative μ and negative ε the refractive index of the medium is calculated to be negative, thus also termed as Negative Index Material (NIM) since due to backward wave propagation, such material could not be found in nature.

IV. Fourth Quadrant

This regionrepresents the materialswithpositivepermittivity value and negative permeability ($\varepsilon > 0$, $\mu < 0$). This class of metamaterials is called Artificial Magnetic or Mu Negative Material (MNG). These metamaterials can be used to increase the gain and to reduce the size of antenna.

TYPES OF METAMATERIALS

Metamaterials have been designed from radio frequencies up to optical frequencies, and different functions have been realized, e.g. negative refractive index (NRI), huge chirality, anisotropy and bianisotropy [9, 10]. As an interdisciplinary topic, metamaterials can be classified into different categories based on different criteria. On the basis of the sign of permittivity and permeability, metamaterials are broadly classified into Artificial Dielectric, Artificial Magnetics and Left Handed Materials From an operating frequency point of view, they can be classified as microwave metamaterials, terahertz metamaterials, and photonic metamaterials. From a spatial arrangement point of view, there are 1D metamaterials, 2D metamaterials, and 3D metamaterials. In this review we will concentrate on the electromagnetic properties, and introduce several important types of metamaterials in the microwave frequency range.

ARTIFICIAL DIELECTRICS

The artificial dielectric material was defined in this pioneering work as a composite reproducing, on amuch larger scale, processes occurring in the molecules of a usual dielectric. This involved arranging metallic elements in a three-dimensional (3D) array or lattice structure to simulate the crystalline lattices of dielectric materials. Such an array responds to radio waves just as a molecular lattice responds to light waves: Free electrons in the metal elements flow back and forth under the action of the alternating electric field. Metal elements called also as lattice inclusions or lattice particles become oscillatingdipoles similar to the oscillating molecular dipoles of a natural dielectric.This concept, however, probably was first suggested by Lord Rayleigh in his pioneering work [11]. Kock reproduced this concept for arrays of metal spheres and used that for practical applications. Then this concept was developed in an important work by M. M. Kharadly and W. Jackson [12].They calculated the effective permittivity of artificial dielectrics comprising metal ellipsoids, disks, or rods.

These materials have negative permittivity and positive permeability and these are also called Epsilon Negative Material (ENG). Natural occurring materials like gold or silver have a negative permittivity at very high frequencies but these materials also have an extremely large conductivity. There is no materials with largely real and negative permittivity in the microwave regime. The materials with negative permittivity in microwave regions and other regions can be generated artificially by arranging thin rods or cylinders in cubic lattice. The structure shows the negative permittivity below plasma frequency, when the electric field is applied parallel to the axis of rods.

ARTIFICIAL MAGNETICS

Magnetism without magnetic constituents has been known since 1940s due to works of S. A.Schelkunoff and H. T. Friis that suggested so-called split-ring resonators (SRRs). In these designs thebianisotropy was essentially (though not completely) compensated. Such double SRRs could be used to create artificial magnetic without chirality. In [13] one finds probably the firstexperimental demonstration of negative permeability in artificial microwave materials (1997).The design with strong capacitive coupling between loops suggested in [2] turned out, however,more appropriate for the artificial magnetism.Thestrong coupling of two loops allowed one to obtainthemagnetic resonance at lower frequencies.This means that the resonant frequency is lowenough toconsider the lattice of SRRs as a continuous medium. Because of its planar structure SRRs suggested and shown in Figure2(a)as well as SRRs suggested in [14] are perhaps very practical waysof creating artificial magnetism at microwaves. So-called Swiss roll metal scatterers reported in [15]and depicted in Figure 2(b) (right) turned out to bemore efficient as magnetic resonators but work atconsiderably lower frequencies.The amplitude and frequency bandwidth of magnetic response canbe enhanced by using very densely packed stacks of split rings, called metasolenoids [16].

These materials have negative permeability and positive permittivity and these are also called mu negative material (MNG). Artificial Magnetics exhibits negative permeability below plasma frequency. The first and the most widely-used MNG-structure is split-ring resonator (SRR) [5]. SRRs can be both round and square geometrically, are characterized as high-conductive resonant structure, in which the capacitance between the two rings balances the inductance. A time-varying magnetic field applied perpendicular to the rings surface induces currents that produce the secondary magnetic field. Some shapes of unit cells of MNG-material based on the SRR are shown on Figure 3.

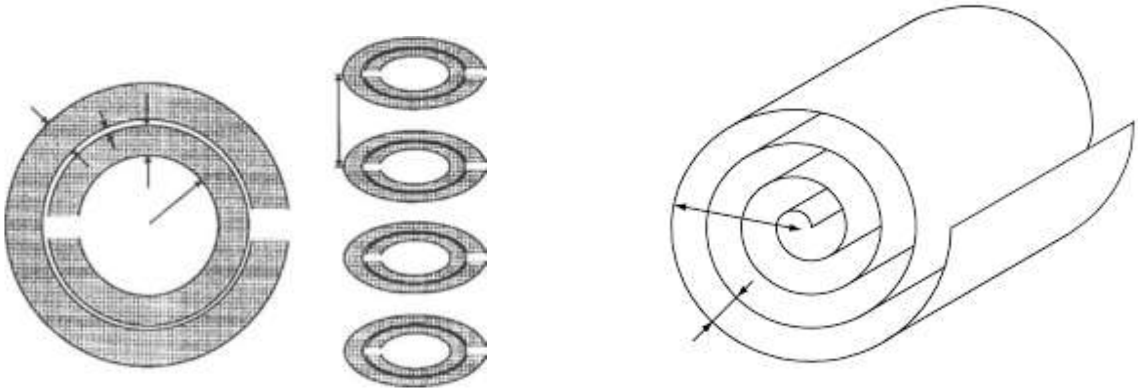

Figure 2.(a) SRRs in the 1990s. (From Pendry, J.B., Holden, A.J., Robins, D.J., and Stewart, W.J., *IEEE Trans.Microw. Theory*, 47, 2075, 1999) (b) Swiss rolls. (From Hardy,W.N. and Whitehead, L.A., *Rev. Sci.Instrum*., 52, 213, 1981 ;Wiltshire, M.C., Pendry, J.B., Young, I.R., et al., *Science*, 291, 849, 2001)

Figure 3. The first MNG-material unit cells: a) round, b) square

NEGATIVE-INDEX MATERIAL

The refractive index will be purely imaginary resulting in evanescent waves, when either ε or μ is negative. The refractive index is positive and thus results in forward wave propagation,when both the parameters are positive. The refractive index will be negative resulting in backward wave propagation, when both the parameters are negative,. The materials with simultaneous negative permittivity and permeability (Quadrant third) are called Negative Index Materials (NIM), these are also called Left Handed Materials or The Double Negative (DNG) Material.

CHIRAL MATERIALS

These materialsare comprised of particles whose mirror images cannot be superimposed. These are different from electromagnetic metamaterials in which both ε and μ are required to be negative for achieving negative index of refraction. But in these materials, either ε or μ or both are not required to be negative. Strong chirality can be achieved by negative refraction in chiral materials.

TUNABLEMETAMATERIALS

For metamaterials composed of artificially engineered unit cells, which are arranged periodically or non-periodically, the exotic EM properties of metamaterials originate exactly from the structure of unit cell, rather than the features of the constitutive materials [17]. As a consequence, the working band of metamaterials is usually fixed once the structure is determined. Moreover, the bandwidth is limited for metamaterials based on resonant elements. Thus, tunable metamaterials with adjustable operating frequency and wide bandwidth have attracted lots of attention [18–20]. Tunable metamaterials are usually achieved through tuning the constituent materials or surrounding media by temperature, electric field, or magnetic field, etc. Typical potential materials include superconductors, phase-transition materials, metal titanates, graphene, liquid crystals, magnetic materials, and so on [18,19, 21–26].

DIGITAL METAMATERIALS AND CODING METAMATERIALS

The conventional metamaterials based on effective medium theory exhibit strong capabilities in controlling the propagations of EMwaves. However, they are not well compatible with the information technologies because of their different description methods, i.e.,effective medium metamaterials are described using effective parameters, while the binary digitals 0 and 1 are usually used in information technologies, which will limit the applications of metamaterials in integrated circuits, communications, etc. Thus, it will largely advance the incorporation of metamaterials into information technologies if metamaterials can be digitally described. Moreover,compared with analog systems, digital systems exhibit remarkable advantages in noise interference and device parameter tolerancewhen the system structure becomes complex. Hence, novel metamaterials which are digitally described instead of being viewed as acontinuous medium have attracted lots of attention recently. In 2014, Engheta's group and Tie Jun Cui's group independently proposedthe concept of digital metamaterials [27,28]. Engheta et al. employed the binary metamaterial bits to construct a digital metamaterial[27]. Specifically, two types of metamaterial elements with different permittivity parameters (e.g., positive and negative permittivityrespectively) were defined as metamaterial bits, and the specific spatial distribution of such metamaterial bits formed a metamaterialbyte which achieved the desired effective EM parameters. A discretization processing is performed on thespace distribution functions of field, and then the effective permittivity parameters for each subwavelength-scaled building block(viewed as a metamaterial byte) can be retrieved. Next, the metamaterial byte is reconstructed by properly arraying the developedbinary metamaterial bits to match the effective parameters according to the effective medium theory. As an example, aplanar digital metamaterial byte and the equivalent cylinder structure with the same effective permittivity, and presents thecomparison of scattering fields for metamaterials constituted by digital bytes and homogeneous cylinders with the same effectivepermittivity. The similarity of the simulated scattering fields for both electric field polarizations proves the effectiveness of the digitalmetamaterial methodology. Afterwards, several devices such as digital convex lenses, flat graded-index digital lenses, and digitalhyperlenses were designed. However, it is noted that the core concept of this work is describing the effective media with binary digitals,and thus the developed metamaterials belong to the effective medium metamaterials. Moreover, each byte should be separatelydesigned according to the effective medium theory, which makes the scheme complex and limited to numerical simulationdemonstration.

At the same time, Cui et al. proposed the concepts of digital metamaterials and coding metamaterials from the perspective of informationscience without the involving of effective medium theory [28]. Similarly, metamaterial (or metasurface) elements aredigitally described with binary coding. However, the intrinsic difference is that the coding of the element is assigned according to itsphase response (or amplitude response) instead of permittivity, and hence the transmitted or reflected EM waves by a coding metamaterialcan be directly manipulated through changing the spatial pattern (coding sequence) of its constitutive elements. Thisconception has been successfully verified by numerical simulations and experiments. Specifically, for 1-bit coding, the digital states.

PLASMONIC METAMATERIALS

Surface plasmons are the collective oscillations of electrons existing at the interface of two materials with opposite signs of the real part of dielectric functions. At optical wavelengths, metals such as gold and silver usually exhibit negative real part of dielectric functions, and hence surface plasmons can be excited at the interface of metal and dielectrics (such as air). For surface plasmons, it can be divided into two types: one is surface plasmon polariton (SPP) mode, the propagation mode along the metal-dielectric interface; the other is called localized surface plasmon (LSP) mode, the localized mode existing in nano-scale metallic particles [29,30].

DESIGN OF METAMATERIAL

Design of metamaterial cell consists of split ring resonators and metal strip. Split ring resonators are responsible for negative permeability and also for forward and backward wave propagation. There are different types of SSR, circular split ring resonators and square split ring resonators. A single cell SRR has a pair of enclosed lops with gaps in loops which are opposite to each other. These loops may be circular or square or gapped as needed.The loops are etched on a dielectric substrate which are made of non-magnetic metals like copper and loops are separated by small gap. Due to splits in the ring structures can support wavelengths much larger than the diameter of the rings. The small gaps between loops raises to large capacitance which are reason for reducing resonating frequency. The dimensions of the structure are small compared to resonant wavelength which are responsible for low radiative losses and high quality factors. Different split ring resonators are shown below.

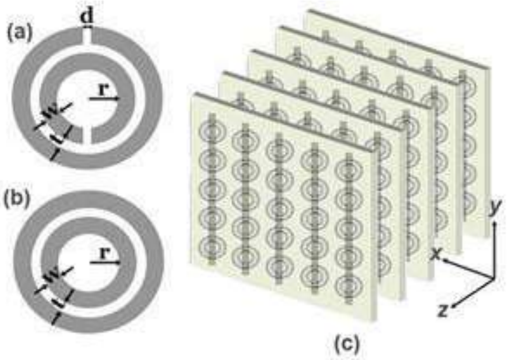

Figure 4 . Schematics of **(a)** a single split ring resonator(SRR) **(b)** a ring resonator with splits closed (CSRR) **(c)** PeriodicCMM composed of SRRs on one side, wires on the other side ofdielectric board.

The metallic wire which is on other side of substrate isresponsible for negative permittivity. The SSRs and metallicstrips are optimised to fabricate a cell with optimumdimensions which results in negative parameters.

NUMERICAL TECHNIQUES AND MODELING METHODS OF METAMATERIALS

There are many complex problems, which can be easily solved by numerical methods only. Various Computational electromagnetic simulators based on Maxwell equations are used to test antennas and wave propagation in complex media. On modeling of metamaterials theresearcher should be aware about several special considerations. So, for the efficientdevelopment of a device, several modeling techniques are used [31]. Some of the methods are discussed below.

A. Finite Difference Time Domain (FDTD) method

FDTD is an efficient and robust method that used to model a variety of frequency dispersive and non-dispersive materials with electromagnetic wave interaction [32]. It gives straight forward method to model complex periodic structures and commerce with the characteristics of metamaterials over a wide frequency band because it is a time domain solver. The FDTD algorithm gives accuracy in both time and space.

B. Finite-Element Method (FEM)

To solve the problems of inhomogeneous anisotropic materials and complex structures the finite-element method (FEM) is used. It eliminates the problem of spurious solutions by expanding the angular and transverse field components with the node-based scalar and edge-based vector basis functions respectively [33].

C. Transmission Line Method (TLM)

There are many numerical methods and theories that describe the properties of different structures of wire metamaterials. The modeling of metamaterials is much important with this method and is also very difficult task. TLM model permits the design of different structures based on conducting thin-wires [34].

TYPICAL METAMATERIAL DEVICES

Man-made meta-atoms: Natural materials consist of large quantities of fundamental particles, atoms or molecules. Themacroscopic electromagnetic (EM) properties of a material are usually presented by the electric permittivity and the magnetic permeability. In contrast, metamaterial are composed of periodically or non-periodically arranged unit cells of manmade meta-atoms. These meta-atoms are essentially sub-wavelength electric or/and magnetic resonators which response to the external electromagnetic fields as harmonic oscillators [35]. The followings are some applications of metamaterial.

Antennas: Metamaterials Antennas are the type of Antennas in which Metamaterials is to be used for increases the performance of the Antenna system, there is the coating of metamaterials is used for the radiation enhancement and venture up the emanated power. Metamaterials having negative permeability may allow for some properties like high directivity, and better optional frequency, and radiate power enhancement is possible with the use of Metamaterials in an antenna system. Metamaterials consist of an inherent property that are used to control electromagnetic radiation, and increases achieve bandwidth by using superstrate of Metamaterials over conventional patch antenna. Zero refractive index material is mostly used for making high directivity antennas [36].

Absorbers: A Metamaterial absorber is intended to efficiently absorb electromagnetic radiation such as light. As Metamaterial is an advance in materials science. Hence, Metamaterials absorbers offer benefits over conventional absorbers such as further miniaturization, wider adaptability, and increased effectiveness. Metamaterial applications as absorber include Radar Absorbers, [37] spatial light modulators, emitters, sensors, infrared camouflage, wireless communication, and use in solar photovoltaic and thermophotovoltaics. A structure is designed to broaden the bandwidth of metamaterial absorber composed of a patterned square metallic patch and a metallic ground plane separated by a dielectric layer [38]. The conductivity of the metal and the thickness of the dielectric layer determine the bandwidth of the metamaterial absorber [39].

Super lens: A Super lens is a lens which uses Metamaterial to go beyond the diffraction limit. A twodimensional Luneburg lens based on bulk Metamaterial is composed by a number of concentric layers. By the variation the geometric dimensions of unit cells in each layer, the gradient refractive index profile required for the modified Luneburg lens can be achieved. From a point source the cylindrical waves generated at the focus point of the lens could be transformed into plane waves as desired in the microwave frequency. Modification in Luneburg lens can realize wide-angle beam scanning when the source moves along the circumferential direction inside the lens [40].

Cloaks: Metamaterial cloaking is the usage of Metamaterial in an invisibility cloak. This is oftenachieved by manipulating the paths traversed by light through a novel optical material. The propagation and transmission of specified parts of the light spectrum direct and control by metamaterials and demonstrate the potential to render an object seemingly invisible. Metamaterial cloaking, based on transformation optics, describes the process of shielding something from view by controlling electromagnetic radiation. A new pi-shaped metamaterial unit cell that exhibits more than a 2 GHz wideband Near Zero Refractive Index (NZRI) property in the microwave region. The metamaterial was utilized as the design of three types of cloak shapes (rectangular-shaped, eyeshaped, and triangular shaped) for hiding a metal cylinder. It had been found that, for all the three types of shapes, the metal object could be cloaked in the C-band region by reducing the normalized scattering width to below zero, where the material was showing near zero refractive index property [41].

Sensors: Artificially structured metamaterials on a size scale smaller than wavelength of external stimuli, and they can exhibit a strong localization and enhancement of fields, which may provide novel tools to enhance the sensitivity and resolution of sensors, and open new doors in sensing design aspect. There are various metamaterial sensors which can be used for specific application. These sensors are Biosensor (microwave, terahertz, plasmonic), Thin-film sensor, Wireless strain sensor, etc [42]. A microwave sensor based on an artificial transmission line is used for non-invasive blood glucose monitoring.

WMD Detectors: To detect the presence of chemical explosives Army and Air force researchers use metamaterials, biological agents, and contamination. The same structure and science is used for cargo and screening passenger.

PROGRESS O**N METAMATERIALS**

1967: Theoretically proposed by Vesalogo

1999:First negative Mu material by Pendry

2000:First Metamaterial by Smith

2002:First Resonant antenna was manufactured by Lucent Technology.

2003: Metamaterials employing photonic crystal, and Methods of fabricating electromagnetic metamaterials.

2005: Metamaterials as an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties.

2009:Miniaturized structures for optical frequencies

2010: Metamaterials are used as artificial media structure.

2015:Metamaterials are used as manmade media providing electromagnetic properties on-demand.

2017:A software enables Metamaterial-based satellite antenna is now commercially available.

2018 Space-time-coding digital metasurface.

2019: Metamaterials as real time processor.

CONCLUSIONS AND FUTURE

In conclusion, we reviewed the recent progress of metamaterials from the aspects of metamaterials and its types with applications. The field of metamaterials is a synthetic field of research and a young field of research with top talent from microwave and optical sciences, materials science, acoustics, nanotechnology and high-performance computing all attracted by the subject. Since the beginning of the century, many research papers have been written on the subject of Metamaterials. So there has a great area of Research and development for the creating new technologies and future development with the development of fabrication structure that offers the exciting possibilities for the new design of the component, devices, and improvement in their silent properties.

Then, what is the road ahead for metamaterials? We may suggest three key words: new physics, new devices and new systems. Aspreviously discussed, metamaterials have been extended to many other fields including acoustics, mechanics, and theomotics, and alsolots of new physics in metamaterials such as topological properties and nonlinearity are been revealed. Thus, it is significant to keepexploring the new physics and new phenomena in metamaterial systems. On this basis, metamaterials functional devices will bedeveloped and applied. One of the directions is the integration of metamaterials with on-chip technology. Holographic imaging system has been developed based on information metamaterials at microwavefrequencies, and if the operating frequency can be increased to millimeter or terahertz frequencies, the imaging resolution will beremarkably improved. The key technical problem to be overcome is designing and processing the metamaterial elements with real-timeswitchable coding states. Novel communication systems based on both the plasmonic metamaterials and information metamaterials inthe microwave frequency region can also be expected in the near future.

Fromdigital coding metamaterials to programmable metamaterials. Owing to the real-time switchable coding states of the digital elements,the programmable metamaterials truly become real-time information processing systems. Digital information can be stored and directlymodulated to the far-field radiation patterns, and thus communications can be performed free of carrier waves. Moreover, digital signalprocessing and operation methods can be applied to the information metamaterials to achieve the flexible and diversified control of EMwaves. Nevertheless, an overwhelming breakthrough which can be expected in the near future must be the achievement of smartX. Fu, T.J. Cui Progress in Quantum Electronics 67 (2019) 10022334. metamaterials. By combining the information metamaterials, smart materials, and artificial intelligence technology, smart metamaterialswhich may possess the abilities of learning, perception, adaptation, etc., can respond differently to different environmentssuch as automatic switching among cloaking, communication, and radar detection. Thus, various exotic and science fiction stories maybecome reality in such a world constructed by smart metamaterials as what we have already observed and attained from the currentmetamaterials.

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