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REVIEW ARTICLE



Metafluidic metamaterial: a review

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ABSTRACT

Metafluidic metamaterial is a metamaterial the optical response of which is dependent on fluid contributed metamolecules. The dependence originates either from a fluid background coupling to the metamolecule or from the resonance in a liquid structured metamolecule. Different liquid materials including water, liquid crystal, and liquid metals are applied to realize the metafluidic metamaterial. Sophisticated technologies like electric bias and microfluidic system have been used for active control of metafluidic metamaterials which provide a new platform for electromagnetic wave manipulation and metadvice realization. The liquid background and significant tunability of the metafluidic metamaterial promise numerous applications, such as material sensing, bio-detection, energy harvesting, and imaging, just to name a few.

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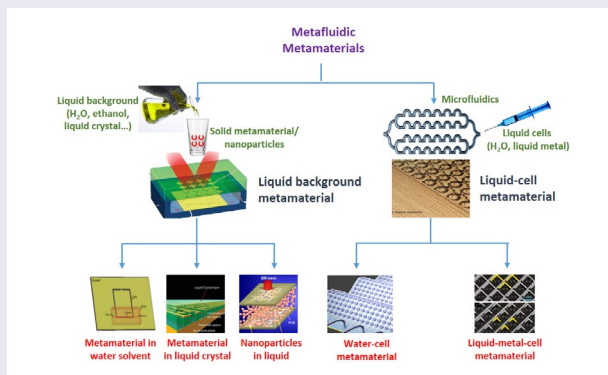
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78.67.Pt Multilayers, superlattices, photonic structures, metamaterials; 78.67.Bf Nanocrystals, nanoparticles, and nanoclusters; 78.20.Ci Optical constants (including refractive index, complex dielectric constant, absorption, reflection and transmission coefficients, emissivity); 41.20.Jb Electromagnetic wave propagation, radiowave propagation; 07.07.Df Sensors (chemical, optical, electrical, movement, gas, etc.), remote sensing



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1. Introduction

Metamaterial is an artificial material consisting of metamolecules arranged in an array of subwavelength period [1–3]. Metamolecule interacts with electromagnetic (EM) wave through rationally engineered structures such as split ring resonator [4,5], fishnet [6,7], and paired slabs [8]. Unique properties like negative refraction [9,10], strong optical activity [11–14] and extraordinary transmission [15–17] are realized through their interaction and open the door to a number of fascinating applications. Invisible cloaking [18–20] and transformation optics [21,22] were intensively studied by tailoring metamaterial refractive index in the cloaking space. Through metamaterial-based superlens [23] and hyper lens [24,25], diffraction limitation has been surmounted. Perfect absorption [26–28] or thermal emission [29] was obtained through index matching between the metamaterial and incident media. Polarizations of EM wave were manipulated through anisotropic [30,31] or chiral metamolecules [32,33]. Moreover, individual control of EM wave phase retardation at each metamolecule was realized via a special group of 2D metamaterial, or metasurface [34,35]. As a result, tailoring the EM wavefront becomes possible which explores metamaterial applications in the area of flat lens focusing [36,37], hologram [38,39] and imaging [40], etc.

The ever-increasing demand on optical information transmission and processing inspires the development of active metamaterial which manipulates the EM wave in real time. Numerous studies have been carried out to design the active metamaterial by either tuning the background refractive index or reconfiguring metamolecules. Semiconductors or phase transition materials are usually used as metamaterial substrate and their free carrier density or crystalline structure is controlled through electrical bias [41,42], optical pump [43,44], and thermal effect [45], etc. Metamaterial can also be reconfigured using micromachined technology [46,47] or soft substrate deformation [48,49] which actively manipulates the coupling between metamolecules and light.

Metamaterials are conventionally constructed using solid metal (Au, Cu, or Al, etc.) or high permittivity dielectrics (Si or TiO_2 , etc.) on solid substrate (Si, glass, Al_2O_3 , or PCB board etc.). Their permittivity tuning is highly constrained by material physical properties (free carrier density, bandgap, or crystalline phases, etc.) while metamolecule reconfiguration is also limited to material rigidity. Liquid, instead, can flow in an arbitrary structure and thus is able to tailor its EM wave response when designed into metamolecules. In addition, liquid can be replaced or mixed with other liquids so that the effective refractive index can be changed significantly. Moreover, as well known, many optically assisted applications such as bio-imaging, microorganism detection, chemical reaction, and energy harvesting are carried out in a liquid environment. Therefore, an inter-discipline of metamaterial and liquid will initiate another new era for active optical control and bio-sensing applications. Here in this paper, we reviewed the research progress of fluidic contributed metamaterials which is called metafluidic metamaterial.

Figure 1 illustrates different metafluidic metamaterial types according to their different internal fluid materials. First, liquid background metamaterials are discussed which are formed by embedding traditional solid metamaterials in a liquid. Water, as the most common liquid on earth, is widely considered because of its low cost, bio-compatibility, and miscibility with other chemical solutions for metamaterial tunability. Liquid crystal, the refractive index of which changes with its crystal orientation, is another promising tunable liquid medium. In addition, nanoparticle assembled metamaterials in liquid medium are also studied. The orientations and arrangements of suspended nanoparticles in liquid are tailored through different excitations, which realize flexible tunability for optical metamaterial.

The liquid cannot only be used for metamaterial background but also be shaped into resonant metamolecule structure. The liquid is constructed into a subwavelength artificial structure which usually flows through microfluidic channels and we name this type of metamaterials as liquid-cell metamaterial. Water, again, can serve as the resonant material because of its super high permittivity in microwave regime. In other EM wave regimes, liquid with metal property such as mercury, gallium, and allium alloys are proposed for metafluidic metamaterial. Their metamolecule can be changed by flowing the liquid metal in rationally designed channels.

In this review, the liquid background metamaterial is discussed in Section 2. The tuning and sensing function of this metamaterial are reviewed for different

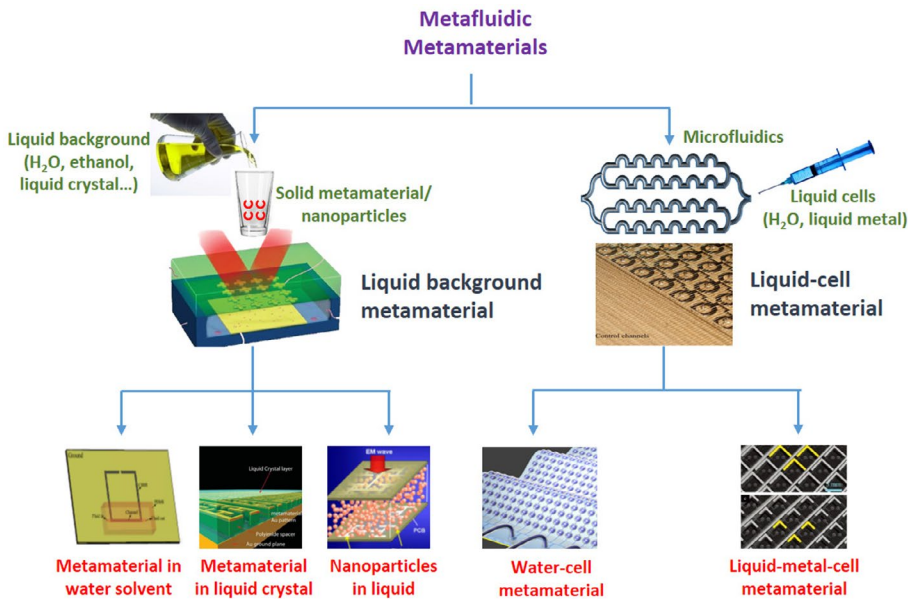


Figure 1. Metafluidic metamaterials categories.

Notes: The metafluidic metamaterial can be divided into the liquid background metamaterial [67] and the liquid-cell metamaterial. The liquid background metamaterial consists metamaterial in water solvent [56], metamaterial in LC [88] and nanoparticles in liquid [98]. The liquid-cell metamaterial consists of water-cell metamaterial [124] and liquid-metal-cell metamaterial [140].

liquid medium like water, ethanol and methanol etc. Liquid crystal (LC) background metamaterials and nanoparticle in liquid medium are also discussed. The liquid-cell metamaterial is reviewed in Section 3 for elements with different liquid materials including water and liquid metal. Different functions of the liquid-cell metamaterial are investigated afterward. The outlook and conclusions are given in Section 4.

2. Liquid background metamaterial

The liquid background metamaterial is a hybrid metamaterial, in which the traditional solid metamaterial is covered by a liquid medium. Metamaterials in different liquid mediums like water, ethanol, and LC have been proposed for either sensing different liquid types or inducing a tunable optical response. Nanoparticles suspended in liquid medium are assembled into another kind of liquid background metamaterial, which realizes large optical tunability through the particle arrangement manipulation in liquids.

2.1. Metamaterials in water solution

The refractive index of different liquids usually varies largely, which leads to different optical responses when used as the metamaterial background medium. Water, one of the most common materials on the earth, serves as an excellent metamaterial liquid background due to its non-toxicity and compatibilities to various bio-chemical applications. Other chemical solvents like ethanol, methanol, and oils, are also proposed to couple with the solid metamaterial. Two ‘conjugated’ functions are obtained from the background liquid coupling: one is to realize a tunable optical response through changing the liquid medium, the other is to characterize the composition and concentration of the liquid by analyzing metamaterial optical response.

Liquid background metamaterial is first proposed for tuning the response of microwave [50–52]. In these work, liquid is either loaded into a chamber to fully cover solid metamaterials, or injected into millimeter channels partially covering each metamolecule as shown in Figure 2(a) and (b). The channels are usually aligned with metallic gaps of metamolecules where high electric field is excited. Therefore, a slight change of refractive index at the gap location will induce a significant resonant frequency shift. It is demonstrated that the existing water in the background medium could induce a resonance shift of more than 100 MHz in the microwave regime [52]. Different microwave response are compared for different liquid mediums including ethanol [53], methanol [51], oil [54], and glucose [55], etc., which have significantly different resonant frequencies. In addition, the metamaterial’s resonance also differs when covered by chemical solvents with different concentrations. This can be used for both the optical response tuning and the liquid concentration analyzing [56–59]. For example, a tunable absorber

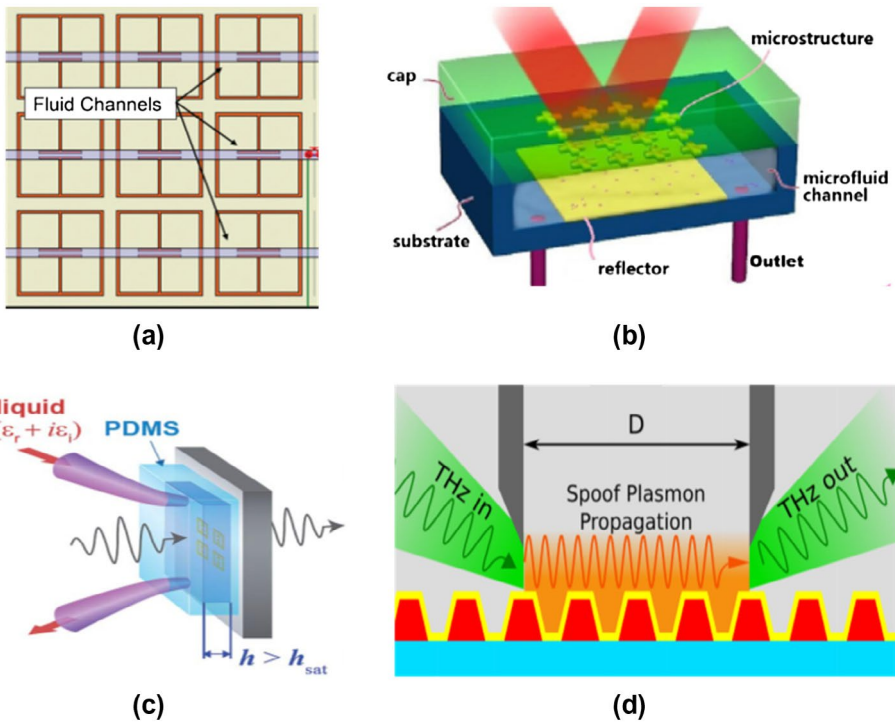


Figure 2. Metamaterials in water solvent.

Notes: (a) metamaterial with channeled fluidics in GHz regime [52]; (b) microfluidic sensing through absorbed THz spectrum from a liquid background metamaterial absorber [67]; (c) Aqueous solution sensing through transmitted THz signal from liquid background metamaterial [64]; (d) spoof plasmon based liquid background metamaterial for THz sensing [72].

realizes a linear frequency shift from 20% to 80%, which corresponds to an ethanol concentration from 0 to 100% [60]. Besides the liquid type and concentration control, thermal effect can also modify liquid refractive index thereby tuning the metamaterial response. The permittivity of water, for example, increases from about 30 to 55 at 15 GHz when temperature increases from 20 to 80 °C and lead to both large absorption coefficient change and resonant frequency shifts [61].

The liquid background metamaterial is also demonstrated in terahertz (THz) [62–64] and infrared (IR) regime [65]. THz wave, which does not damage biological samples due to its low photon energy, is a suitable source when exciting the metamaterial for biological liquid sample sensing [66]. Different metamaterial structures are proposed to increase the liquid detection sensitivity either through absorbed [67,68] or transmitted [64] THz signal as shown in Figure 2(b) and (c). Different liquid medium like water, gasoline, oil, and glycerin are well differentiated.

Similar sensing function can also be fulfilled using surface plasmon (SP) in the liquid environment [69]. IR or visible EM wave can be highly confined in a subwavelength scale through the SP which realizes a high sensitivity to surrounding media like chemical and bio-material [70,71]. In THz regime, subwavelength

structures are designed to mimic the SP and enhanced wave confinement for biological sensing is also demonstrated in the spoof SP structure as shown in Figure 2(d) [72,73].

2.2. *Metamaterials in LC*

LCs have dual properties of crystal and fluid. The crystal is usually anisotropic at room temperature, therefore, the change of the crystal orientation will result in a change of LC refractive index, which in turn, alters the response to EM wave. According to the order of the consisting crystals, LCs are formed in different phases, such as nematic phases, smectic phases, and chiral phases, etc., among which nematic phased LCs are the most common. Due to its unique properties, LCs have been widely applied in the electronic displays, thermometer, and other opto-electronic devices. In nematic LCs the crystal is in rod-shape and its directional order can be controlled by external stimulations such as thermal heating, pressure, magnetic and electric field, resulting good refractive index tunability. Therefore, LCs are widely used as the liquid background of the solid metamaterial.

The manipulations on the LC background metamaterial are first demonstrated in microwave regime [74–76]. The resonant frequency of the metamaterial is shifted under a DC voltage. A resonance shift of 9.91 GHz to 9.55 GHz with a response time of 300 ms was reported by changing the orientation of the nematic crystals with voltage from 0 to 100 V applied to the LC background metamaterial [76]. Despite the relatively slow response speed, the effective tuning of LC background metamaterial has promising applications for wavefront manipulation such as tunable gradient indexed lenses [77,78].

THz wave control through LC background metamaterial is realized by scaling down the solid metallic structure to micrometer size [79–81]. Compared to the manipulation in microwave regime, the control of THz wave can be obtained at a lower electrical voltage with much faster response because the required thickness of LC is much smaller. A tunable THz absorber was first demonstrated based on the LC background metamaterial [79]. The absorption was modified by 30% at 2.62 THz and the absorbing resonance shifted over 4% in bandwidth with a biased voltage as low as 4 V and a modulation frequency of 1 kHz. A following work which controls the transmission of the THz wave was also reported [82]. In this metamaterial, 12- μm thick LC was hybridized with a large planar metamaterial and realized a transmission change of 20% and a phase change of 40° at only 20 V. It is also found that the resonant frequency can be either blue shifted or red shifted depending on the applied modulation voltage frequency [83]. A shifting of 15 GHz is obtained by changing the modulation frequency between 19 and 22 kHz, which proves a new tuning method for the LC background metamaterials. As the resonant frequency depends on the orientation of the LCs in the metafluidic metamaterial, the angle of crystals can be in turn characterized [84], which could provide a feedback to future metafluidic metamaterial devices.

More potential applications of THz LC background metamaterials have been discussed such as the perfect absorber [85,86], polarization converter [87], and spatial light modulator (SLM) [88].

By further scaling down LC background metamaterials, the real time control of IR [89–94] and visible light [95–97] are realized as shown in Figure 3. The tunability can be fulfilled either from the optical nonlinear response or the electrical control of the LC. In addition, although most LC molecules are usually out-plane rotated, in-plane LC molecule rotation is achievable for efficient spectral tuning in a nanostructured metasurface [92]. The free control on LC orientation can lead to the development of compact multifunctional metamaterial-based devices.

2.3. Nanoparticle metamaterials in liquid

Traditional metamaterials are usually based on lithography techniques to fabricate microfluidic channels, which present significant challenges, especially for large-scale production and 3D structures. Mass production of bulk optical metamaterials can be realized from emerging nanoparticles in the bulk liquid. The

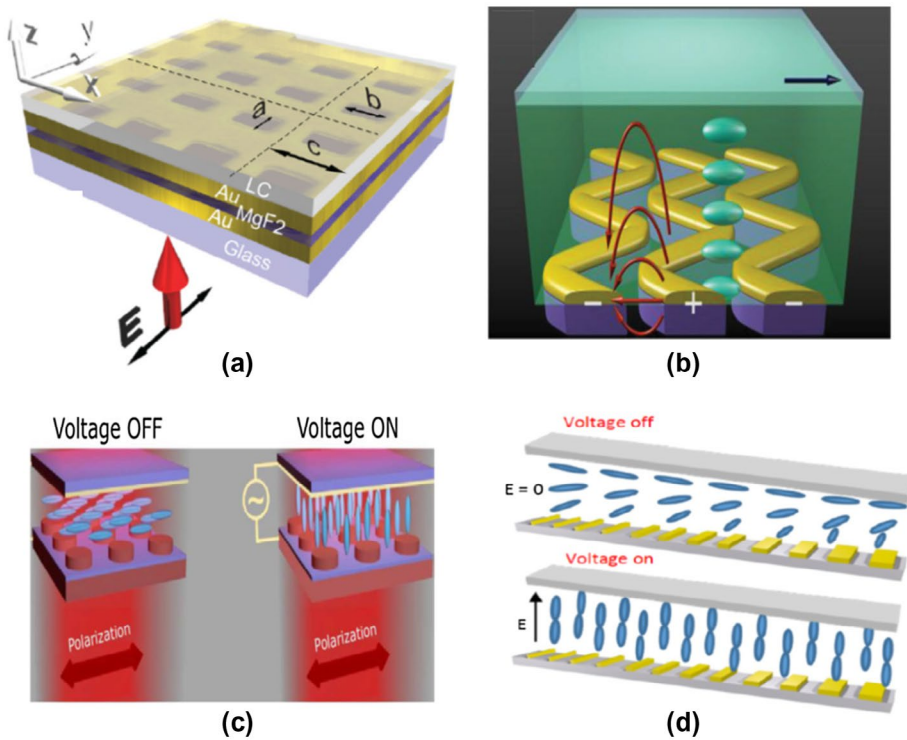


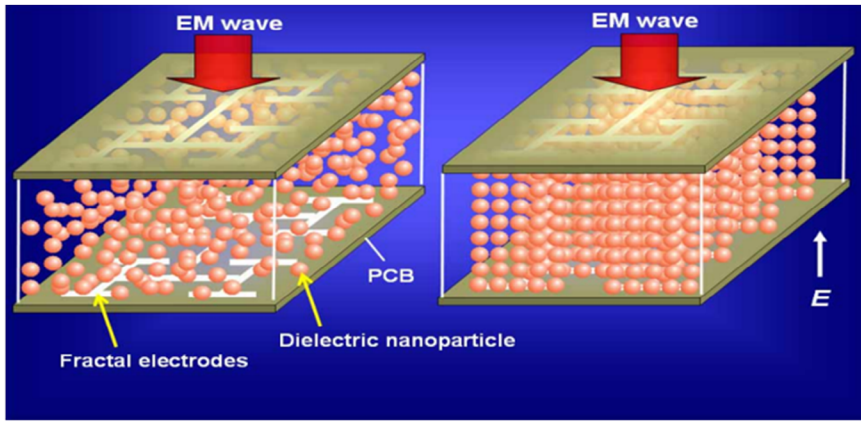
Figure 3. LC based metafluidic metamaterials in IR and visible regime.

Notes: (a) LC background metamaterials via optical nonlinear effect for IR light [94], (b) In-plane orientation control of LC in IR regime for efficient spectra tuning for IR light [92], (c) Electrically tunable LC background metamaterials coupled with dielectric metamaterial for IR light [93], (d) reflection control of the metafluidic metamaterials for visible light [97].

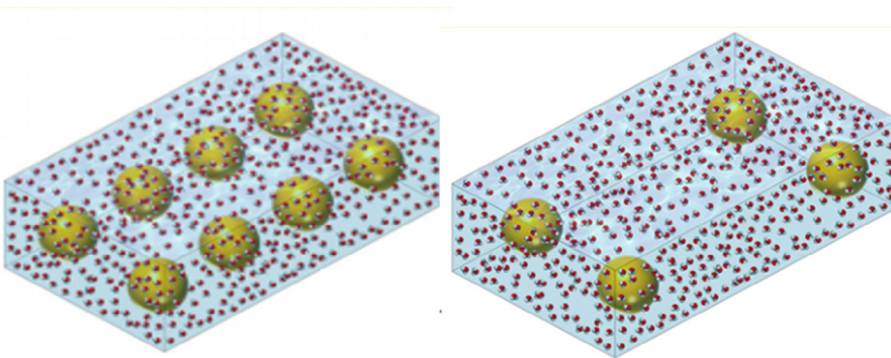
nanoparticles are designed as either the surrounding materials [98], or the resonant structures [99]. While the liquid provides the environment and support for suspension and reconfiguration of nanoparticles, thus a large tunability can be realized using external stimulus [100].

Electrorheological (ER) fluids, also called smart fluids consisting of nanometer- to micrometer-sized dielectric particles suspended in an insulating liquid, can be used as the surrounding material of the metamaterial. It can be abruptly changed from liquid to solid upon the application of an external electric field due to structural change when the particles align themselves along the field to form columns [101]. Apart from their controllable rheological properties, ER fluids have the characteristic of being anisotropic dielectric, with the dielectric constant increasing along the field direction while decreasing in the transverse direction [102]. This properties of ER suspensions are utilized to design tunable metafluidic metamaterials by controlling the status of an external electric field. A typical design of the ER-fluid-based metafluidic metamaterial is shown in Figure 4(a) [98]. A pair of printed circuit boards (PCB) with identical metallic fractal patterns was aligned face-to-face to form two electrodes connected to a direct current (DC) power supply. In the absence of the electric field, the particles were randomly suspended in the liquid; they migrated and formed columns between the two fractal electrodes when an external electric field was applied. In addition, the ER fluid can be designed with multilayer structures to realize 3D metafluidic metamaterials [103,104].

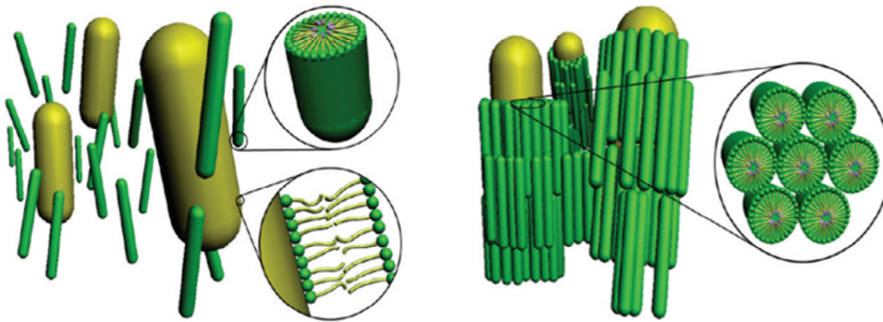
The ER-fluid-based metafluidic metamaterials are usually working in the microwave range, because the dielectric constant change of ER fluid using external electric field can only be observed up to the order of gigahertz [105]. The operating frequency can be increased to infrared, even visible range, by designing the nanoparticles as the resonant structures instead of surrounding materials. Gold nanorods are widely investigated in the metafluidic metamaterials incorporating with various liquid materials as shown in Figures 4(b) and (c), such as water [99], toluene [100], LC [106,107]. Using external stimulus, such as electric field, the spatial distribution, and orientation of nanorods can be controlled because of the dielectrophoretic effect. The field-controlled placement of nanorods causes optical effects such as varying refractive index and optical anisotropy (birefringence) [108]. At zero voltage, the nanorods are distributed uniformly across the area and show no alignment. When the ac voltage is applied, the gold nanorods move into regions of high electric field and align, creating an optically birefringent cloud near the electrode. Such effect induces gradient refractive index for polarized light that is decreasing from the high-field region to the low-field region, which has potential applications in cloaking [108,109], etc. The anisotropic effect of the nanorods can be eliminated using symmetric structures, for instance, nanosphere particles. For nanosphere structures, the alignment using electric field control is invalid. Terahertz phononic excitation is introduced via structural engineering [110]. It is also demonstrated that a cluster of silver nanoparticles has the ability to



(a)



(b)



(c)

Figure 4. Metallic nanoparticles based metafluidic metamaterial.

Notes: (a) ER-fluid-sandwiched structure without external electric field (left) and with it (right) [98]. (b) Gold nanosphere in water [110], (c) Gold nanorods in LC [107].

support Mie resonances as the dielectric material [111]. The plasmonic resonance of metal nanoparticles could be exploited to create an effective medium of high index that can be used to form Mie resonant magnetic meta-atoms. A densely packed nanoparticle composite might be characterized by a strong dispersion in its effective permittivity in the spectral vicinity of the plasmon resonance. By forming

nanoinclusions of a material with such high values of permittivity [112], Mie-type resonances arise that show signatures of magnetic dipoles. By arranging such nanoinclusions or meta-spheres into densely packed arrangements, a metafluidic metamaterial with a strong dispersion in its permeability can be obtained. In addition, using nanoparticle self-assembly technique, complex nanostructures is realized to produce three-dimensional geometries over a large scale [113,114].

Apart from the metallic nanoparticles, various dielectric nanoparticles are also used to design the metafluidic metamaterial. Aqueous suspensions containing different types of nanodiamonds are characterized in visible range having the property of photoluminescence, which paves the way for quantum optical applications [115]. A nanocarbon solid decorated with magnetic nanoparticles is dispersed in a host polymeric matrix, offering a flexible assembly framework, from nano to micrometric scales. Different components' composition, concentration, and spatial distribution can be adjusted to fine tune the effective permittivity and permeability of metafluidic metamaterials, being excellent candidates for the production of highly effective microwave absorbers for shielding applications [116].

3. Liquid-cell metamaterial

Liquid cannot only serve as the background of the metamaterial but also be shaped into a subwavelength structured metamolecule to form liquid-cell metamaterial. Liquid-cell metamolecules can respond to the EM wave similarly with traditional solid metamolecules through consisting liquid material with metallicity or high permittivity. On the other hand, unlike traditional metamaterials directly patterned on a solid substrate, the liquid-cell metamaterial is usually constructed by injecting liquid into a fluidic system with periodic channel structures. The channel width is in deep subwavelength, therefore, microfluidic technologies which supports micrometer sized channel systems are needed for the liquid structured metamaterial. According to injected liquid types, we categories the liquid-cell metamaterial into water-cell and liquid-metal-cell metamaterials.

3.1. Water-cell metamaterial

The fluidity and high permittivity of water in microwave range makes it a superior candidate to construct the liquid-cell metamaterial. Inspired by metamaterial with spaced metallic wires [117], metamaterial with spaced water wires are proposed. The water wire height can be tuned in real time, and therefore, modulates the refractive index of water based metamaterial [118]. The space between each water wire is also tuned to investigate the transition from photonic crystals to dielectric metamaterials [119] as shown in Figure 5(a). On the other hand, the water metamolecule can be effectively tuned through different excitations such as the thermal effect, mechanical pressure and more simply, gravity effect [120]. The gravity effect changes the metamolecule shape when the metamolecule is

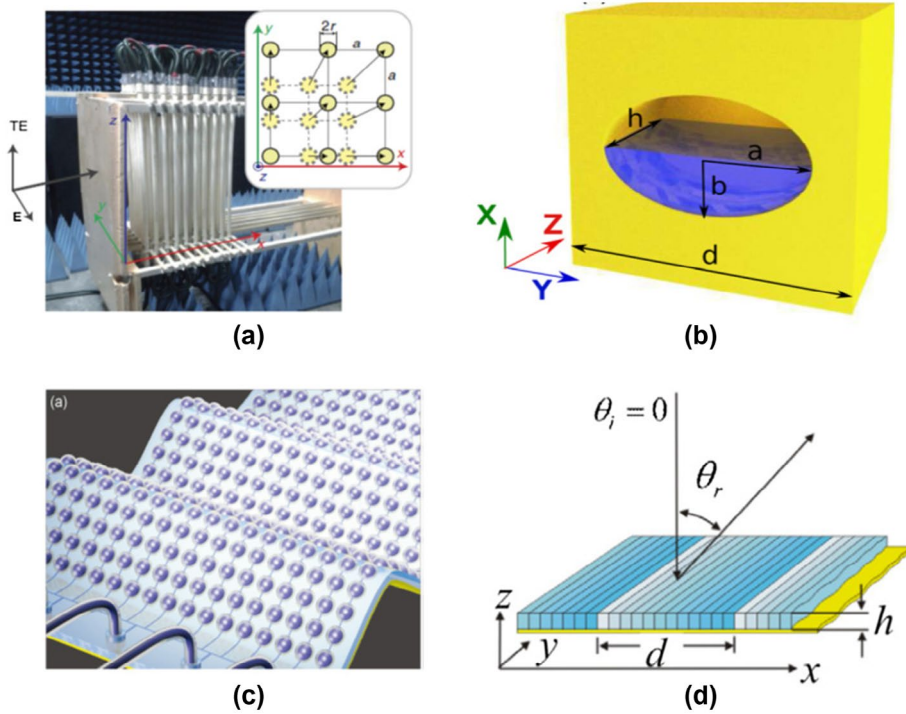


Figure 5. Water-cell metamaterials.

Notes: (a) Water resonators tunable via gravity [121]. (b) Water cylinders confined in tubes for bandgap tuning [119]. (c) Water resonators embedded in soft material [124]. (d) abnormal reflection from a compound liquid-based metasurface [131].

not isotropic in vertical direction. This tuning approach provides a simple way to manipulate the polarization responses of the water-cell metamaterial as shown in Figure 5(b) by simply rotating the two-dimensional metamaterial and reshaping the water filled in the metamolecule elliptical cylinder [121].

Although water enjoys the advantage of high real part of permittivity in microwave regime, its imaginary part is also high, which indicates a large absorption to the microwave. Hence, water-cell metamaterials are proposed as perfect absorbers for microwave [122–124]. The water can be patterned as droplet array with a metallic reflector at the backside which blocks the transmission of the microwave. The reflection of microwave is minimized by adjusting the size of the droplet to satisfy the impedance match between the metafluidic metamaterial and the ambient air. Surface wetting of the substrate is used to control the diameter and height of the droplet [123]. However, the simple water droplet patterning on the pre-treated surface is usually not stable due to gravity and evaporation, and real time tunability is hardly achievable. Recently, a new research work which designs the water-cell based metamaterial absorber device is proposed by integrating the water resonator with a microfluidic control system as shown in Figure 5(c) [124]. In this work, both the reconfiguration of the water resonator and the tunability of the chemical solution composition were investigated. The microfluidic system

fulfills the active tunability by controlling the water injection pressure, which is reliable for other water-cell metamaterial design as well.

Besides the reconfiguration, the perfect miscibility of water and other chemical solutions provides an alternative approach to change the material refractive index. The required index can be well addressed by mixing different liquids at specific ratio. This property can be perfectly applied to obtain a gradient indexed metamaterial, which is a promising approach to modulate the wavefront of the light. As shown in Figure 5(d), a metasurface with gradient refractive index is realized by mixing benzene and acetonitrile with different ratios at different metamolecule position and a 30° abnormal reflection is achieved [125].

3.2. Liquid-metal-cell metamaterial

Liquid metal is the metal or alloy with low melting points, which is in liquid form at room temperature. The dual property of fluidity and the metallicity enable the liquid metal to be widely applied in stretchable electronics, robots, and microfluidic sensors. The most commonly used liquid metal includes Mercury, Gallium, and Gallium alloy. Mercury has a lower melting point but a high toxicity, which is used in thermometer, medicine, and vapor lamps, etc. Gallium, as a low toxic material, is used as a replacement of Mercury in many areas. However, as its melting point is slightly higher than room temperature, the application of Ga as a liquid metal is somewhat limited. Gallium alloy is then proposed to achieve lower melting temperature while maintaining the metallicity. The typical Gallium alloy includes the eutectic gallium indium or ‘EGaIn’ (75% Ga, 25% In, by weight) and gallium indium tin, or ‘Galinstan’ (68% Ga, 22% In, 10% Sn, by weight). Table 1 compares the melting point and the conductivity of the above liquid metals. There are also other kinds of liquid metal like Cesium, Francium, and Rubidium, but usually they are not recommended for the above applications due to their toxicity, high chemical activity or radioactivity and will not be discussed in the review.

Similar with water, the liquid metal can also be well used for reconfigurable metamaterial due to its fluidity. The performance of single metamolecule consisting of Hg is firstly investigated in microwave regime [126], which modulate the wave transmission effectively. EGaIn is also used in a single metamolecule filling in a soft polymer polydimethylsiloxane (PDMS), and high tunability of the transmission dip from 10.2 GHz to 7.4 GHz is demonstrated through the metamolecule stretching [127]. The tunability of the liquid-cell metamaterials

Table 1. Conductivity and melting point comparison of liquid metals.

Liquid metal	Conductivity (S/m)	Melting point (°C)
Ga	7.1×10^6	29.76
Mercury	1×10^6	−38.83
Galinstan (68 wt% Ga, 22 wt% In and 10 wt% Sn)	3.46×10^6	−19
EGaIn (75 wt% Ga, 25 wt% In)	3.4×10^6	15.5

with metamolecule arrays on the soft substrate is demonstrated for the frequency selective surfaces or the GHz absorbers as shown in Figure 6(a) [128–130]. Two layered liquid metal metamaterial was later proposed by injecting the liquid metal into a double layered microfluidic channel as shown in Figure 6(c) [131]. The first THz liquid-cell metamaterial was demonstrated by injecting the micrometer size structured PDMS mold and an enhanced THz transmission was observed as shown in Figure 6(b) [132,133].

Large tunability of the liquid-metal-cell metamaterial is obtained due to the fluidity of the liquid metal. The most straightforward way is to reconfigure the liquid-cell metamaterial structure by applying different pressures in the liquid metal filled channel. Either the absorption or the transmission can be switched by changing the metal liquid filling state in the channel [133–135]. Compared to the solid metamolecule which has limited structure reconfiguration, the liquid-cell metamaterial can be reconfigured more flexibly using pre-patterned channel which can be designed as different complicated structures. Moreover, the reconfiguration is not limited in the surface plane. Flowing in a three-dimensional channel, the metal liquid can form a 3D liquid-metal-cell metamaterial which

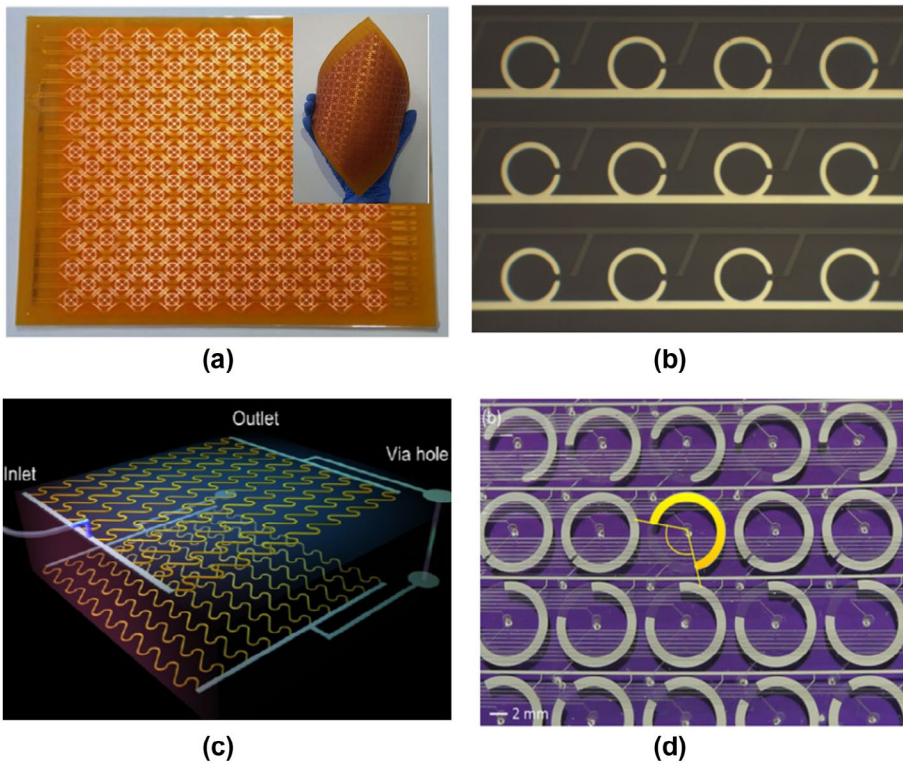


Figure 6. Liquid-metal-cell metafluidic metamaterials.

Notes: (a) EGaln metafluidic metamaterials for on soft substrate [130], (b) Reconfigurable EGaln metafluidic metamaterials in THz regime [133], (c) Multilayered metafluidic metamaterials with strong optical activity [131] (d) metafluidic metamaterials with individual tunable metamolecules through microfluidic system [137].

is firstly demonstrated using Gallium [136]. Because its melting point is a little higher than the room temperature, Gallium can be solidified after being injected in the channel and then cooling down. Another important tunability, the tuning on individual metamolecules, is also demonstrated using liquid-metal-cell metamaterial [137]. The metamolecules are randomly accessed by controlling the driving pressure on individual metamolecules. This is realized through a multi-layered microfluidic circuit which uses logical valves to switch ON/OFF the tunability of individual metamolecules as shown in Figure 6(d). As a result, a functional metadvice with arbitrary control on the incident EM wave could be obtained. Besides the mechanical pressure control, the liquid-metal-cell metamaterial can also be manipulated electrically using the electro-wetting or electrolytic reduction effect [138,139], which is not elaborated in this review.

The tunability of the liquid metal metamaterial opens the door to various functions on the EM wave control. Through pneumatic pressure, the symmetry of metamolecule can be varied which manipulates the EM wave polarization conversion as shown in Figure 7(a) [140]. The pressure can also control the height of the liquid metal in the microchannel and realizes a tunable absorber as illustrated in Figure 7(b)

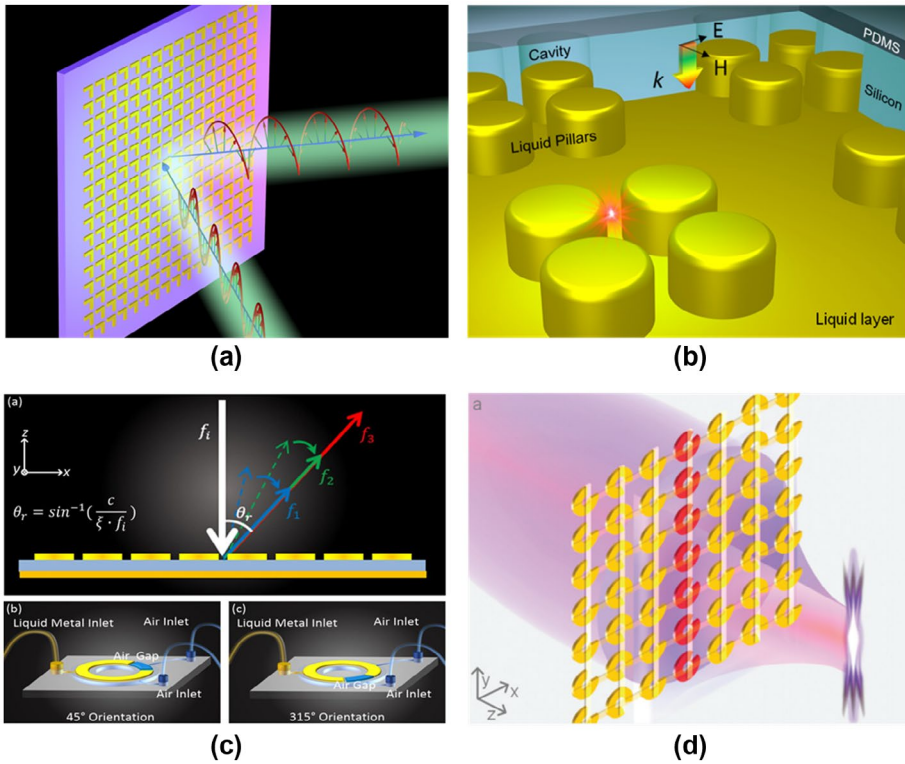


Figure 7. Liquid-metal-cell metafluidic metamaterials for different functions.

Notes: (a) Galinstan-based metafluidic metamaterials for polarization control [140]. (b) Mercury-based metafluidic metamaterials for THz wave control [141]. (c) Galinstan-based metafluidic metamaterials for beam steering [137]. (d) Mercury-based metafluidic metamaterials for a tunable flat lens [142].

[141]. A flexible control on the wavefront can be realized by rationally tailoring metamolecules individually according to the phase retardation requirement. As a result, novel functions such as beam steering and flat lens focusing can be achieved as shown in Figure 7(c) and (d) [137,142]. Based on this metamaterial, a flat lens consisting of Hg metamolecules with tunable focus length is demonstrated by tailoring the phase retardation of individual metamolecule in the liquid-cell metamaterial [142].

4. Conclusions and perspectives

In this review, recent progresses on tunable metafluidic metamaterials are presented. The reconfiguration and tuning of metafluidic metamaterials based on various types of liquids are discussed and different tuning methods are compared. The active manipulation on the microwave, THz wave, IR wave, and visible light are demonstrated through different metafluidic metamaterials. Specifically, water and chemical solutions like ethanol or methanol are good candidates for manipulating the background refractive index of metamaterial and thus tuning the EM wave response. In LC background metamaterials, the orientation of crystal changes the effective refractive index of metafluidic metamaterials and is usually polarization dependent. The orientation can be controlled by different excitations such as electrical voltage, magnetic field, thermal effect, and optical nonlinear effect. The nanoparticles based metafluidic metamaterials consist of nanometer-sized particles as resonant structures, which can easily push the operating frequency up to visible range. In the liquid-cell metamaterial, liquid are formed into different sized droplets or injected into predefined channels to form the metamolecules. Water-cell metamaterial and liquid-metal-cell metamaterial are reviewed which couple with EM wave from microwave to visible light.

Albeit above tunable metafluidic metamaterials were sophisticatedly developed, more potential work could be explored to improve the performance of the metafluidic metamaterials. For example, the high absorption of water metafluidic metamaterials for microwave regime could be further developed for stealth applications. In addition, 3D printed technology can be integrated with metafluidic metamaterials to realize a miniature 3D channels to enhance the coupling between the metafluidic metamaterials and the EM wave. With the development of fluidic manipulation technologies, especially from microfluidic to nanofluidic, it can be expected that metafluidic metamaterials will be further developed for the entire EM spectral range up to optical frequencies with stable performance. This will enable vast applications in holographic display, perfect absorber, compact sensor, wearable, and bio-compatible optical devices, etc.

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Disclosure statement

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