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REVIEW ARTICLE

Subwavelength electromagnetics

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Abstract Subwavelength electromagnetics is a discipline that deals with light-matter interaction at subwavelength scale and innovative technologies that control electromagnetic waves with subwavelength structures. Although the history can be dated back to almost one hundred years ago, the flourish of these researching areas have been no more than 30 years. In this paper, we gave a brief review of the history, current status and future trends of subwavelength electromagnetics. In particular, the milestones related with metamaterials, plasmonics, metasurfaces and photonic crystals are highlighted.

Keywords electromagnetics, subwavelength scale, metamaterials, plasmonics, photonic crystals

1 Introduction

Since James Maxwell founded his equations in 1860s, the interactions of electrics and magnetics are known to form a new kind of wave. These electromagnetic waves include many different types, such as visible, infrared light, microwave and radio waves. The Maxwell's theory, however, did not consider the interaction of electromagnetic waves and matters. As a result, Maxwell did not even obtain the correct Fresnel's equations from his theory. Soon after, Hendrik Antoon Lorentz proposed his famous "electronic theory" and gave the first electromagnetic theory of Fresnel's equation [1].

Lorentz's theory, as well as others like Drude and Debye et al., gave a well description of the frequency dispersion of natural materials such as metals and glasses [2]. In almost the entire 20th century, people were searching for natural materials for various electromagnetic (commonly related to the relatively low frequency spectrum) and optical applications. For example, many works have been done to search for magnetic materials for radar absorbing materials during and after the World War II [3]. In the optical regime, high performance gain materials are highly wanted for lasers [4]; meanwhile, optical transparent material with high static conductivity is also a big challenge [5]. Recently, the searching for low-loss plasmonic material in both the visible and infrared spectrum has attracted many attentions [6]. Nevertheless, natural occurring materials often cannot fulfill the demanding of people. Since the microscopic structures are fixed, intrinsic limits exist in these materials [7].

As said by Richard Feynman in 1959 [8]: "Up to now, we have been content to dig in the ground to find materials … when we have some control of the arrangement of things on a small scale we will get enormously greater range of possible properties that substances can have, and of different things that we can do." In fact, the last century has witnessed a lot of efforts that have been devoted to design artificial materials with on-demanding properties. As early as the dawn of 20th century, some pioneering work has been done for complex materials. Maxwell-Garnett has given a model to describe the effective permittivity of diluted metallic particles immersed in dielectric background, which has been studied by Faraday in earlier experiments. Nevertheless, the mixing principle still seems not so strong to revolute the development of electromagnetics [9].

Owing to the pioneering work of Veselago, Pendry and Smith et al., we have seen the emerging of metamaterials in the last decades, which are artificially structured materials with electromagnetic properties not existing in nature [10–14]. The dimensions of the metamaterial unit cells are much less than the operating wavelength, so its property can be well characterized by the effective permittivity and permeability. Based on these exotic permittivity and permeability, one could then construct a sub-diffraction perfect lens with only a piece of metal sheet and make Harry Porter's invisibility cloak with properly arranged metals and dielectrics [15–17].

Although it was often thought the root of metamaterials

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is the concept proposed by Veselago, it was soon recognized that the history can be dated back to 1898 when Bose made an artificial chiral material in the microwave regime with twisted jute [18]. Furthermore, we also noted that the metamaterials are intrinsically connected with other topics such as plasmonics, photonic crystals as well as metasurfaces (Fig. 1). For example, the first metamaterial superlens is made of a single layer of noble metal, and the amplification of evanescent wave is actually related to the excitation of surface plasmon (SP) modes, which have been predicted as early as in 1957 [19]. Besides, the impedance sheet as well as frequency selective surface (FSS) can be considered as early types of metasurfaces [20,21].

Whatever the initial motives and development history, from our current point of view, the metamaterials, plasmonics, metasurfaces and photonic crystals can be all put into a category called "subwavelength electromagnetics", since all these structures have characteristic dimensions in the subwavelength scale.

The following will give a concise review of the recent development of these areas. Since photonic crystals have been discussed and reviewed many times in the literatures, it will not be included except for some particular cases where they are interconnected with other topics.

2 Transformation of the electromagnetic fields with metamaterials and metasurfaces

In 2006, Pendry et al. and Leonhardt proposed a method to achieve on-demand control of the electromagnetics with metamaterials [16,22]. By utilizing the form invariance property of Maxwell's equations under coordinate transformation, they demonstrate that a piece of metamaterials in one space can be equivalent to another space with completely different geometry and shape. As shown in Fig. 2(a), the first cloak device was constructed in the microwave range in the same year [17].

Soon after, it was recognized that there is an intrinsic bandwidth limitation for the cloak devices [26]. As an attempt to broaden the bandwidth, other technologies such as conformal transformation and carpet cloak have been proposed by Li and Pendry [27]. In general, there are mainly two researching directions. On the one hand, the transformation optics have been extended to other fields such as acoustic waves and heats [28,29]. On the other hand, there are extensive researches devoted to carpet cloaks in the visible regime (Figs. 2(b)−2(d)), which transform a small bump into a flat mirror to camouflage [23–25]. More recently, metasurface-based surface cloaks and related technology are demonstrated by various groups [30,31]. However, although these technologies seem to greatly reduce the detection probability by enemies [31], the perfect cloaking condition was only met at one single wavelength [30]. To obtain broadband surface cloaking with metasurface, the chromatic dispersion should be addressed [32,33].

We note that there are some applications where the bandwidth is not a necessary requirement. For example, in the monochromatic sub-diffraction imaging, the transformation optics provided the concept of hyperlens, which can magnify objects much smaller than the wavelength to the far-field [34].Then conventional microscopy can be utilized to capture the output of hyperlens to achieve far-field super-resolution imaging. Recently, the hyperlens was

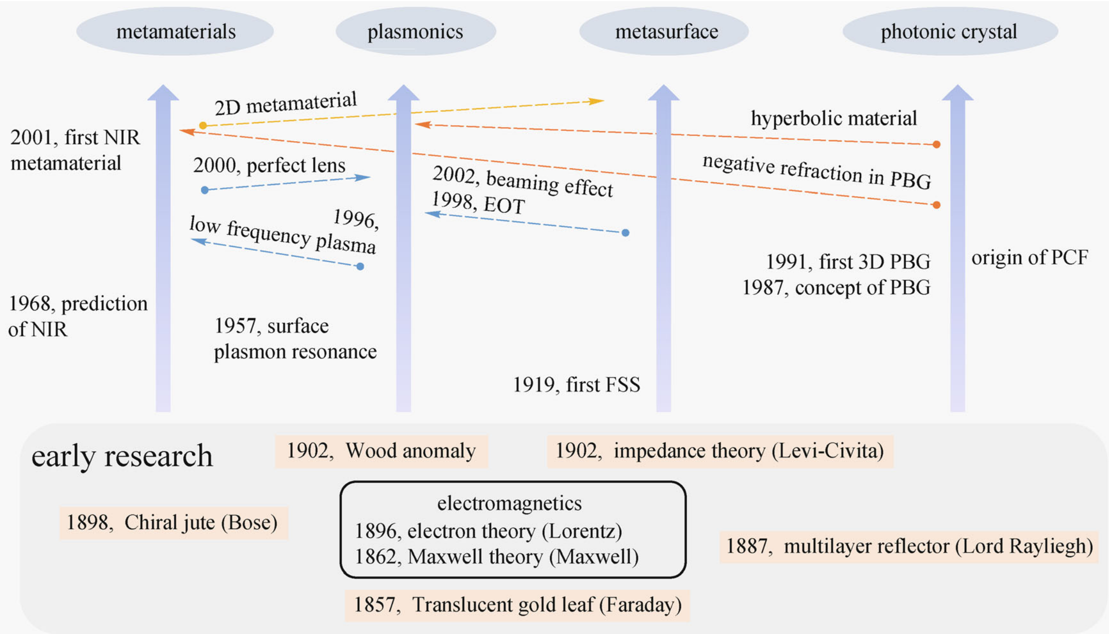
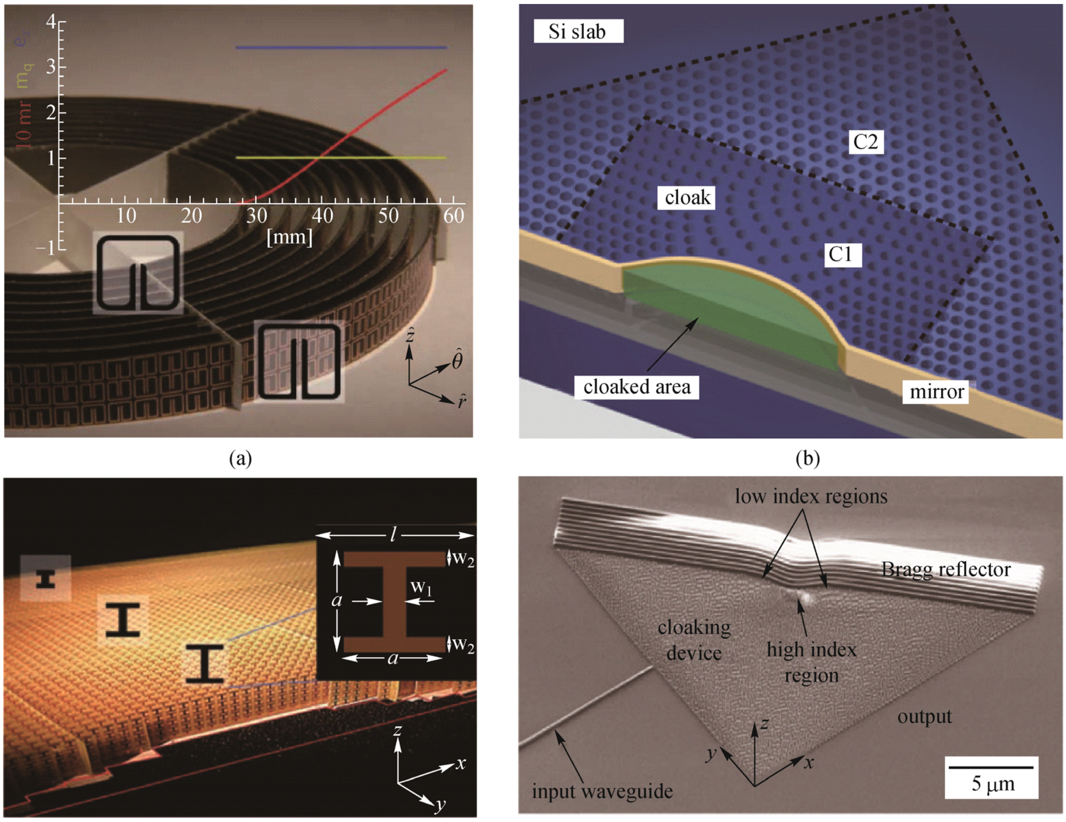


Fig. 1 Brief history of the subwavelength electromagnetics



(a) (b)

(c) (d)

Fig. 2 Various transmissive and reflective cloaks based on transformation optics [17,23–25]

also introduced into the plasmonic lithography system, which could shrink the patterns on the masks (see Fig. 3). It should be noted that although the original concept of hyperlens is based on the cylindrical wave expansion method [35], it can be seen as a direct result of the coordinate transformation and could be extended with the transformation optics [36].

Owing to the fantastic dispersion diagram, hyperbolic metamaterials can be used to tailor the optical transfer functions and even photonic density of states [37]. Based on the fact that only evanescent wave could propagate through such materials, we recently demonstrated an interference lithography technique which use high spatial components to obtain sub-diffraction periodic patterns [38]. At a wavelength of 365 nm, a half pitch of 45 nm ($\lambda/8$) was demonstrated in experiments. We also showed that deeper resolution up to 22.5 nm ($\lambda/16$) and a variety of complex interference patterns are feasible.

3 Meta-surfaces and the revisitation of the electromagnetic boundary problem

Metasurfaces, as originally called metamaterial surfaces or 2D metamaterials [39,40], sometimes refer to metamaterials with thickness much smaller than the wavelength. From a historical view, however, we noted that the emerging of metasurfaces can be dated back to the days when metamaterials are not known to us. For example, the FSSs, which were designed in antennas systems to selectively reflect or transmit the signals depending on their frequencies, are actually metasurfaces. It is known to us that the first FSS could be found in 1919 when Marconi used dipoles array to reflect microwaves [41]. Also, an ultrathin metallic slab could also be considered as metasurface which was studied by Faraday in 1857 [9] and used as resistive sheet in Salisbury and Jaumann absorbers [3].

In essence, the metasurfaces should be considered as a modification of the electromagnetic boundary conditions [42]. As given in our previous discussion, the metasurface boundary theory can perfect interpret all of the current phenomena [21]. As such, metasurfaces can replace metamaterials in many conditions. Owing to the reduction in fabrication challenge, thickness and weight, metasurface is thought to be a promising candidate for the next-generation integrated optical and electromagnetic devices [43]. In the following, we would like to give some discussion on the recent development of metasurfaces.

3.1 Ultrathin broadband absorbers

The electromagnetic absorbers based on resistive sheet were invented during the World War II. Although these

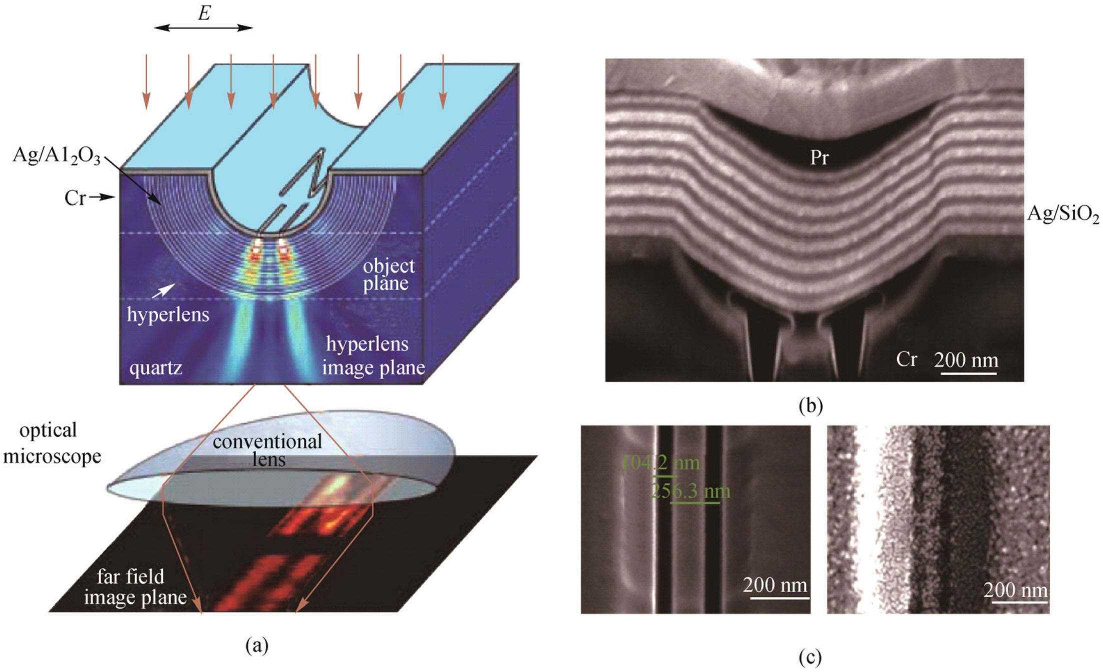


Fig. 3 Sub-diffraction imaging and lithography based on hyperlens. (a) Schematic of the hyperlens for far-field imaging [34]; (b) cross-section of the scanning electron microscopy (SEM) of the hyperlens for plasmonic lithography; (c) SEM of the patterns on the mask and photoresist (Pr)

materials can efficiently absorb electromagnetic waves based on interference in theses resistive sheets, the overall thickness of these materials are typically comparable to or even much larger than the operation wavelength [44]. In the last decades, three types of metamaterial configurations were proposed to achieve ultrathin absorber.

As depicted in Figs. 4(a) and 4(b), the first type is based on the high impedance surface or so-called artificial magnetic conductors (AMCs) [45]. It is well known that when the metallic ground plate (perfect electric conductor, PEC) in the Salisbury absorber is replaced with ideal magnetic conductor, one could obtain frequency-independent absorber across the entire radio, microwave, terahertz and even the infrared region of the electromagnetic spectrum [46]. With mushroom structures, the first AMC was constructed in 1999 by Sievenpiper and Yablonovitch et al. [47]. Such AMCs have enabled the development of ultrathin absorbers [39] as well as low-profile antennas [40].

The second type thin absorber was proposed in 2008. Landy and Padilla et al. pointed out when the permittivity and permeability of a metamaterial are tuned to be simultaneously very lossy and large, only a small thickness is sufficient to absorb almost entire incoming wave energy [48]. Since the impedance is matched to the environment, there will be no reflection at the entrance surface. However, this interpretation is controversial [49,50]. First, only infinite permittivity and permeability could guarantee the so-called "perfect" absorption; second, there are many problems when one try to homogenize a thin slab with effective electromagnetic parameters.

The third type ultrathin absorber is based on the magnetic resonance induced in parallel metallic plates [49,51]. We noted that this high magnetic resonance can be also described using high refractive index (Fig. 4(c)), which can explain the wide-angle absorption ability.

Along with many works that devoted to the ultrathin absorbers, it was recognized that the narrow bandwidth of such absorbers may severely restrict their practical applications [52]. In fact, there is a compromise between the thickness and bandwidth owing to the Kramers-Kronig relation [53]. Even in the early day of 20th century, Planck has noted that a perfect absorber must have sufficient thickness, so that the original concept of Kirchhoff's black body is not true ("... the supposition that bodies can be imagined which, for infinitely small thicknesses, completely absorb all incident rays, and neither reflect nor transmit any"). As such, the thickness-bandwidth limitation of absorber can be called "Planck's limit" [20].

In fact, the bandwidth limits for the absorbers and AMC have the same origin, which have been discussed in previous literatures. In particular, Rozanov gave a concise description of the bandwidth and thickness of an arbitrary absorber backed by a PEC plate [53]. Brewitt-Taylor proposed similar equations for AMCs [54].

When the PEC ground plane is removed in the traditional absorber, the bandwidth problem should be reconsidered. In 2012, we proposed a method to break the

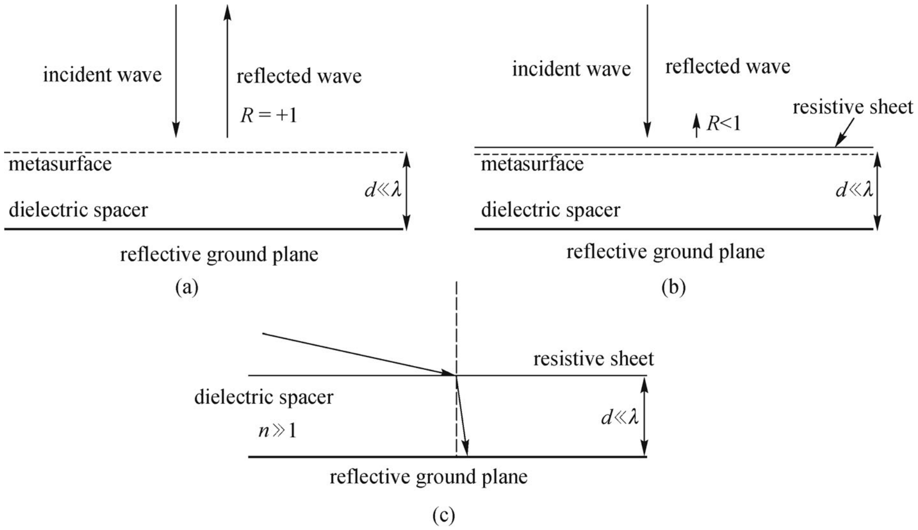


Fig. 4 (a) and (b) Schematic of the ultrathin absorber based on the combination of AMC and resistive sheet [39]; (c) ultrathin wide angle absorber based on high index metamaterials

above thickness-bandwidth limitation [55].Using the concept of coherent perfect absorber, we found that a resistive sheet can absorb all of the electromagnetic radiations ranging from the radio frequency to the visible regime (Fig. 5). The thickness of this absorber can be as small as 0.3 nm. This theoretical prediction was experimentally demonstrated recently in the microwave regime [56]. It was also shown that a single layer of graphene with thickness of 0.34 nm can also perform the same functionality [57].

3.2 Antennas with extremely low profiles

The whole history of electromagnetics is accompanied with the design of antennas, which are indispensable for transmitting and receiving electromagnetic signals. Recently, the concept of antennas were extended to the optical region, where optical antennas refer to metallic or dielectric nanostructures that could convert the electromagnetic waves between propagating and bounding components [58]. In the meanwhile, traditional methods used by the microwave engineers have also been demonstrated to be useful for optical analysis [59].

On the other hand, emerged concepts such as zero index, plasmonic beaming effect and defect in photonics crystals have enabled the design of many novel directive antennas [60–62]. Many types of metasurfaces have been used to improve antenna performances such as side lobe level [63,64], polarization agility [65] and others [66–68]. However, most of these antennas have fixed radiation which could not be actively tuned. As a result, one of the current main trend of subwavelength antennas is to design lightweight, low-profile, high-efficient phased array. As shown in a recent work [69] (and reference therein), we recently demonstrated that the scanning range of metasurface-based phased array could exceed±60° for both directions, while the polarization states can be dynamically tuned (Fig. 6).

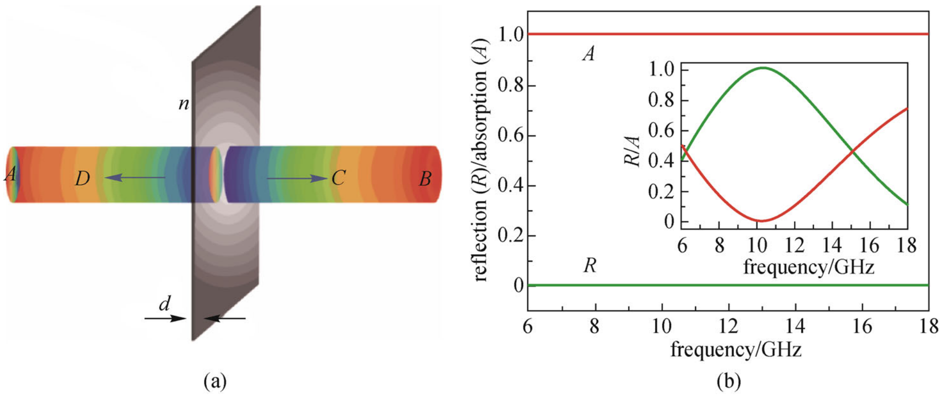


Fig. 5 Metasurface-based ultra-broadband coherent perfect absorber. (a) Schematic description [55]; (b) experimental demonstration in the microwave regime [56]

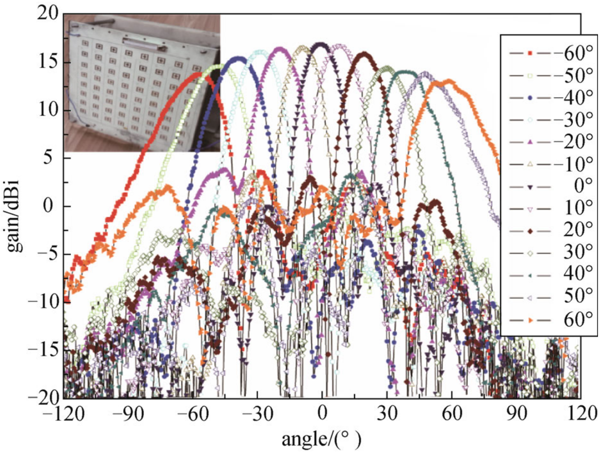


Fig. 6 Active metasurface for beam scanning in the microwave frequency [69]. The overall thickness of the antenna is 3.89 mm, and the operational frequency is designed to be 5.4 GHz. The mean insertion loss is less than 4.5 dB

3.3 Achromatic polarizers and high efficient spin-orbit interaction

One of the major applications of the subwavelength metamaterials and metasurfaces is the control of polarization state [70–73].To increase the polarization conversion efficiency and working bandwidth, reflective meta-surfaces (or meta-mirrors) have been proposed by various groups [74–78]. Zhou et al. proposed a circular polarizer based on an ultra thin metasurface reflector [74]. Pors et al. also obtained similar phenomenon at optical frequencies using orthogonally oriented electrical dipoles [75]. Compared to the transmissive polarization transformers, the meta-mirrors have much smaller thickness due to the large anisotropy as well as higher energy efficiency since no complicated anti-reflection technique is required.

Owing to the intrinsic resonance, meta-mirrors are often realized in narrow frequency band. To overcome this problem, we designed a dispersive ultrathin meta-mirror to extend the bandwidth [76,78]. It is shown that the operation bandwidth and frequency selectivity of metasurfaces can be increased significantly with fully released dispersion management capability in two dimensions (Fig. 7). Multiple resonance mechanism was employed to match the effective impedance of the meta-mirror with the ideal impedance, and significantly broaden the operating bandwidth. Experimental results demonstrated that this meta-mirror worked well from 3.2 to 16.4 GHz with polarization conversion efficiency higher than 85%.

The polarization tuning ability of metasurface can result in high efficient phase modulation techniques via the spin-orbital interaction, a quantum process related to the vectorial property of electromagnetic fields [79,80]. In 1984, Berry proposed that an adiabatic polarization can introduce a phase shift [81]. Since the phase is associated with circular polarization, it can be termed as one kind of optical spin-orbit interaction. This idea was further developed by Hasman et al., with various kinds of

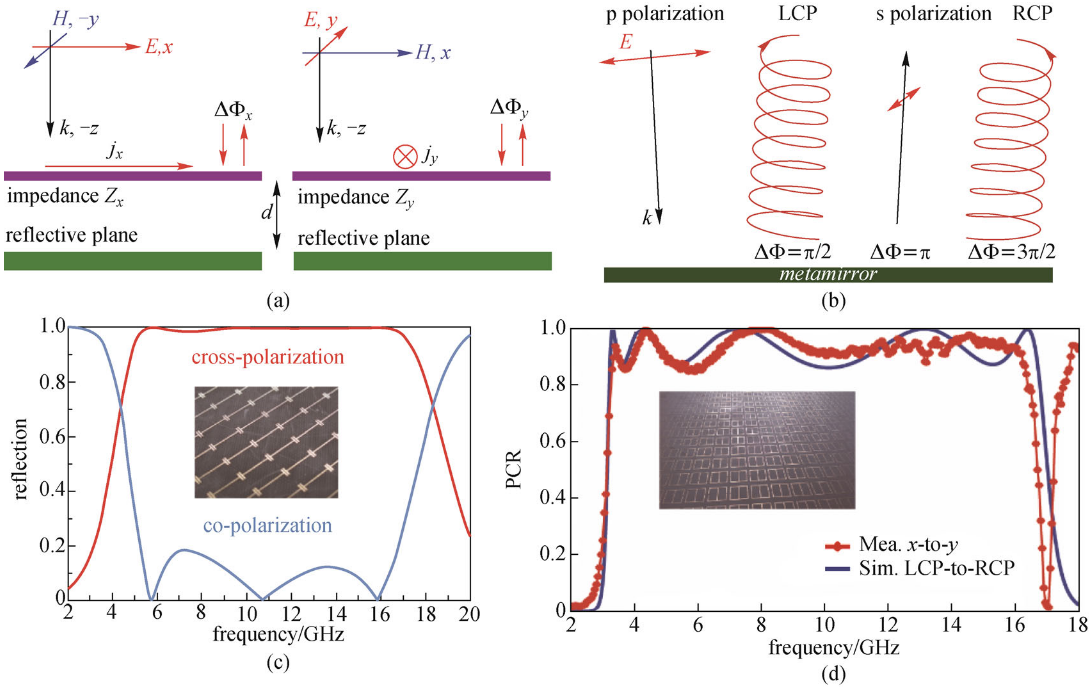


Fig. 7 Schematic of the anisotropic meta-mirror in (a) x and y directions; (b) schematic of polarization transformation for a p-polarization incident wave; (c) and (d) reflection coefficients for co-polarized and cross-polarized components for two microwave samples [76,78]

applications, such as beam splitter, optical vortex generation and focusing lens [82].

Traditionally, the spin-orbital interaction is related to the circular polarization. To overcome this problem, Capasso et al. proposed a novel phase shifting mechanism with linearly polarized illumination [83]. By varying the angle and length of V-shaped nano-antennas, arbitrary modulation of phase shift and amplitude transmission was demonstrated. We have shown that the physical process here is a combination of the spin-orbit interaction and circuit-induced phase shift in the metallic nano-antennas [20]. Similar with the case of circular polarization, such antennas have low energy efficiency because there always has one component with the same polarization as the incident one. By properly tuning the geometrical parameters of each antenna, broadband phase change could be achieved, although the phase was not rigorously achromatic [84].

Very recently, we proposed and demonstrated the concept of broadband virtual shaping at the visible, infrared and microwave spectrum by tailoring the spatial-temporal property of spin-orbit interaction in cascaded metasurfaces [31]. When electromagnetic waves impinge on the designed metasurface, they are completely reflected to predefined directions to avoid being detected. Resorting to the dispersion engineering techniques in metasurface-based polarizers, the bandwidth was dramatically enhanced. The design principle provided a new route for the control of electromagnetic wave for applications ranging from laser beam shaping to 3D holographic display and conformal camouflage. We also demonstrated that this approach could be utilized in complex objects owing to the flexibility of the metasurface.

3.4 Catenary optics

The spin-orbit interaction in metasurface provides a vital mean by which the phase could be controlled. In previous designs, geometric phase is generated by sub-wavelength antennas and the phase profile is not continuous in the horizontal plane. Recently, we proposed a unique structure which can generate geometric phase continuously [85,86]. As illustrated in Fig. 8, the structure can be obtained by connecting two catenary curves with a vertical shift. Each catenary curve is described by the “catenary of equal strength”, as derived in 1826 by Davies Gilbert.

The optical catenary can serve as a unique building block of metasurfaces to produce continuous and linear phase shift covering [0, 2π]. Via catenary arrays, planar optical devices were designed and experimentally characterized to generate beams carrying various phase profiles. Furthermore, these devices can operate in an ultra-broadband spectrum since the anisotropic modes associated with the spin-orbit interaction are almost independent of the incident light frequency.

In particular, we show that these catenaries can enable

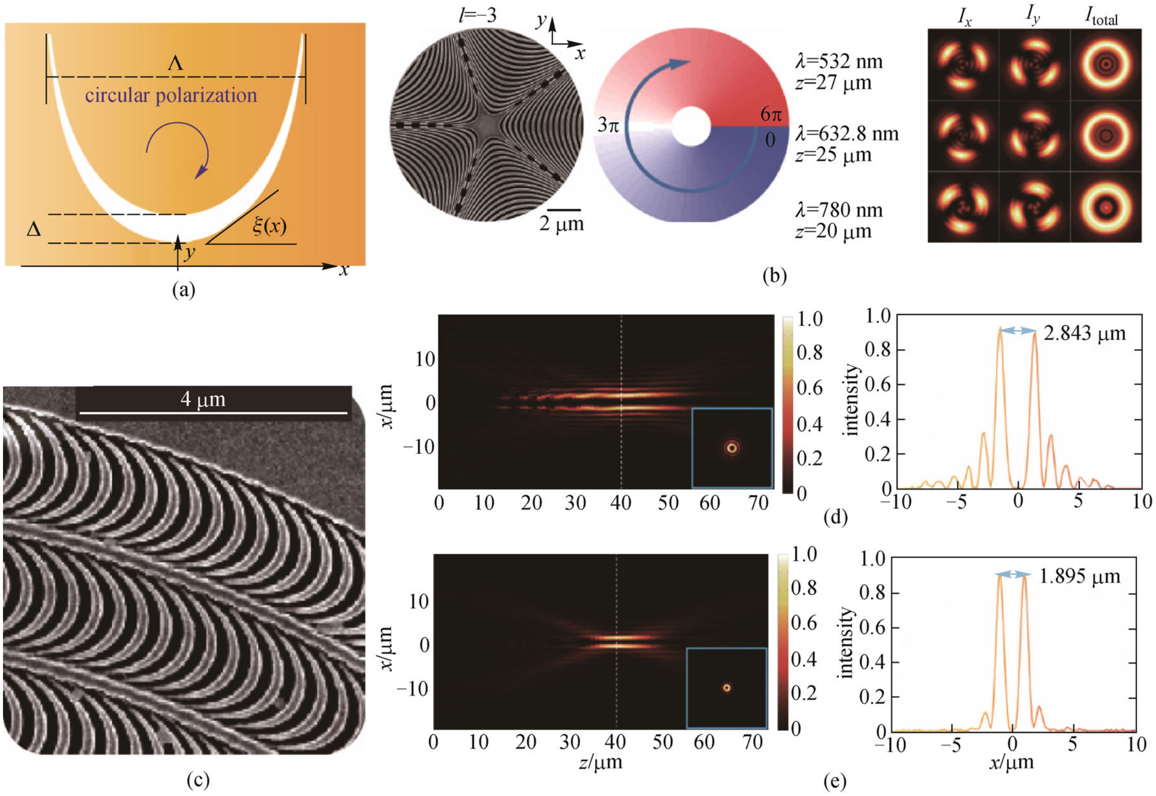


Fig. 8 Catenary optics based perfect optical elements [85]. (a) Schematic of the catenary aperture; (b) catenary array for perfect OAM generation; (c) SEM image of the catenary lens; (d) and (e) measurement of the Bessel beam generator and flat lens carrying OAM

the generation of perfect orbital angular momentum (OAM), which are of central importance for future wireless communication systems. Unlike OAM beams formed by spiral phase plates, computer-generated holograms, optical nanoantenna arrays, ring resonators, and even chiral forms, catenary OAM beams have broader bandwidth and can be created from nanometers-thick structures.

Similar with the OAM generation, catenary structures can also be used as powerful generators for high-order Bessel beams (HOBBs) [87], i.e., Bessel beams carrying OAM. The diffraction-free property of the Bessel beam, combined with the (theoretically) infinite freedoms of OAM, makes the HOBBs become a promising alternative for high-speed optical and quantum communications systems. Besides, the particular shape of the HOBBs and its ability to retain over an extended propagation distance in a propagation-invariant manner makes it useful in optical manipulation.

Although the catenary-based metasurface is very flexible in the tuning of phase shift, the polarization conversion efficiency is not high enough for many applications. It was shown that the theoretically predicted upper limit 25% is the intrinsic obstacle for its further improving [86]. In the last several years, it was demonstrated that the coherent property could be used to dynamically change the light-matter interaction on the metasurface [55,88]. Recently, a coherent control method is utilized to surpass the intrinsic efficiency limit of the metasurface in transmission mode and realize dynamic control over the generalized Snell's law [89,90], providing a promising route to the practicality of a variety of devices based on metasurface structures.

4 Electromagnetic surface waves at metallic surfaces

Plasmonics is a major part of the field of subwavelength electromagnetics, which explores how electromagnetic fields can be confined on the nanoscale [91,92]. Plasmonics is based on the interaction between electromagnetic radiation and conduction electrons at metallic interfaces or in small metallic nanostructures, leading to dramatically enhanced optical nearfields and other exotic properties.

In classic theory, the collective excitations called surface plasmons (SPs) are just surface waves that locates at the boundary of metals and dielectrics [20]. Analytic approaches have been developed a century ago by Zenneck and Sommerfeld et al. [93].

4.1 Perfect lens and plasmonic sub-diffraction lithography

One of the most promising applications of SPs is to construct superlens and hyperlens to break the notoriously diffraction limit [94]. In 2000, Pendry proposed the concept of perfect lens, in which the amplification of evanescent waves and perfect imaging could be obtained by a negative refraction index slab [15]. Pendry also suggested that a metallic thinfilm can be used as a near perfect lens. We note that this can be partially attributed to the short wavelength characteristic of SPPs on a sliver film, which was first demonstrated in 2003 [95]. Subsequently, plasmonic nanolithography technique was proposed to achieve a resolution of half-pitch 50 nm at a wavelength of 365 nm (~1/9 wavelength) [96,97].

The silver lens has some practical limits, such as large optical loss and the sensitivity on surface roughness and film thickness. To address these issues, some important techniques such as the reflective plasmonic lens are proposed [98,99]. Based on the reflective amplification of evanescent wave, we experimentally achieved 50 nm line width at a wavelength of 365 nm [98]. As shown in Fig. 9, we also shown that the plasmonic cavity lens can be utilized to achieve high aspect profile for 32 and 22 nm half-pitch patterns [100]. The profile depth of half-pitch 32 nm resist patterns was enhanced to be about 23 nm, much larger than previous results.

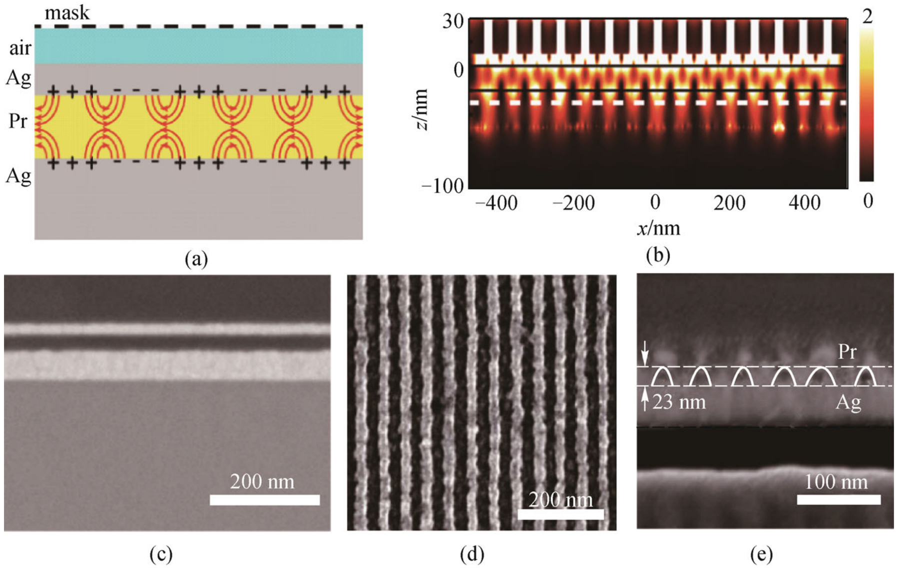
The reflective lens brings significant improvement of the imaging and lithography performance. In the optical theory, this can be interpreted using the metasurface-assisted imaging model [20]. Interestingly, we noted that there are natural analogies in the eyes of many night living animals, such as cats, wolfs and bowls [101]. It is well known that there are reflective layers in the bottom of the retinas, so the energy efficiency can be boosted in the night.

It should be noted that the short wavelength property of SPs could also be utilized to realized flat plasmonic lens operating at the meso-fields and far-fields [20,102]. By utilizing the super-oscillatory effect, one could construct sub-diffraction lens systems at far-fields [103,104]. The nonlinear two SP absorption can also be utilized to make smaller patterns [105].

4.2 Plasmonic Fano resonances

One interesting application of the subwavelength structures is to mimick the physical processes in cosmology and quantum effects. As previously shown, the transformation optics bear some intrinsic similarities with the general relativity, thus one could model the light behaiviors in black holes [106] and gravitational lenses [107] with metamaterials. On the other hand, many quantum effects such as electromagnetic induced transparency (EIT) and Fano resonance were also intensively studied [108,109].

The famous Fano resonance was discovered by Ugo Fano in 1961 when he was studying the quantum mechanical process of the autoionizing states of atoms [110]. Different from a Lorentzian resonance, the Fano resonance exhibits an asymmetric shape as a result of the quantum interference between broadband spectra with discrete states. In its classic analogy, Fano resonance



(a) (b) (c) (d) (e)

Fig. 9 Plasmonic reflective lenses for 32 and 22 nm lithography nodes [100]. (a) Schematic of plasmonic modes in the cavity lens; (b) simulation results; (c) cross section of the fabricated lens; (d) SEM of the fabricated dense lines of 32 nm half-pitch; (e) cross section of the dense lines in (d)

exhibits the characteristics of both a sharp resonance peak and a strong local field enhancement, forming the basis of many applications such as biological sensing and nonlinear photonics [111–113].

Recently, Fano resonance was exploited as a novel method to obtain a narrower focus spot beyond the diffraction limit [114]. Complicated mode matching theory shows that the full-width at half-maximum (FWHM) of the x component electric field intensity can be decreased to 0.036λ. However, such performance is just comparable to a negative refraction lens. Furthermore, one-dimensional focusing and a limitation on size placed by nanofabrication technology hamper the practical application of this design.

More recently, we proposed an alternative approach to realize sub diffraction focusing with evanescent wave amplification at 633 nm [115]. It is shown that a ring-disk complementary structure possesses significant plasmonic Fano resonance when a plasmon excitation meets a spectrally broad spectrum. This coupling leads to abrupt π phase change and amplitude modulated electromagnetic fields exiting the structure, which contributes to a deep subwavelength field confinement.

5 Concluding remarks

Subwavelength electromagnetics is an old and new researching area, which has grown so much in recent years that a complete discussion of all aspects in a single paper is almost impossible. Nevertheless, the main directions in future research are becoming much clearer for us. As shown in Fig. 10, the nonlinear and quantum phenomena are still the frontiers of subwavelength electromagnetics. Besides, smart electromagnetic materials and systems will be one of the most promising developing directions, where on-demand applications could be realized. Furthermore, the dynamics of non-electromagnetic waves such as acoustic wave and matter wave in the subwavelength scale should attract more attentions in the future.

As a final remark, we would discuss the development tendencies of some particular sub-disciplines which we think would have huge influence and applications:

1) Metamaterials and metasurfaces. As we mentioned, one of the major drawbacks of metamaterials is the narrow bandwidth. For applications such as sensors and thermal bolometers, the bandwidth is not a problem, the goal of metamaterials is just to improve the efficiency and reduce the cost, which is indispensable for commercial implementation of metamaterials. On the other hand, although many efforts have been devoted to the dynamic tunable metamaterials, the current stage is still far from satisfactory. In future, many efforts should be given to the combination of various fundamental materials such as semiconductors, phase-changing materials, graphene and other two-dimensional materials to achieve active and even smart materials (Fig. 10).

2) For plasmonics, the main challenge is the commercial implementation of plasmonic devices in practical systems. For example, plasmonic lithography system beyond the 22 and 16 nm nodes could be an affordable alternative for the fabrication of integrated circuits and other nanoscale devices. Other promising directions should be the quantum and nonlinear plasmonics, where rich new physics can and should be explored.

3) Bio-mimetic subwavelength systems. Although one

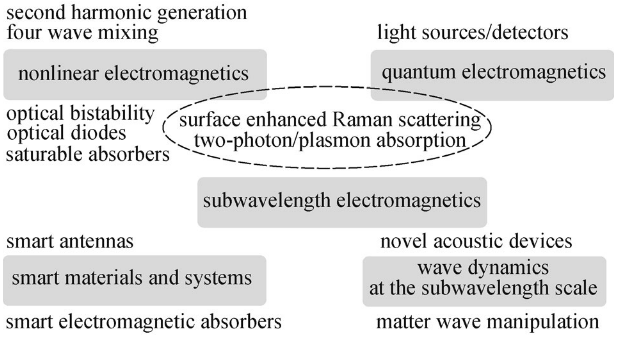


Fig. 10 Future trends of subwavelength electromagnetics

of the main directions of subwavelength electromagnetics is to exploit structures to obtain properties not occurring in nature, we must admit that many exotic and useful things actually exist in nature and especially in living beings, which we were not able to discover owing to the lack of proper instruments [116]. With the ever developing cutting edge technology, we should be able to learn more things from the nature. It is thus an urgent task to bring the biomimetic method to the subwavelength worlds.

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