Dispersion engineering in metamaterials and metasurfaces

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Abstract
Dispersion engineering is essential for spectral utilization in electromagnetic systems. However, it is difficult to manage the dispersions in both natural materials and traditional electromagnetic waveguides since they are tightly related to fine structures of atoms, molecules and causality. The emergence of metamaterials and metasurfaces, which are made of subwavelength inclusions offers tremendous freedom to manipulate the electromagnetic parameters of materials and modes. Here, we review the basic principles, practical applications and recent advancements of the dispersion engineering in metadevices. The contributions of dispersion management in metadevice-based super-resolution imaging/nanolithography systems, planar functional devices, as well as the broadband perfect absorbers/polarization converters are discussed in depth. The challenges faced by this field as well as future developing trends are also presented in the conclusions.

Keywords: dispersion engineering, metamaterials, metasurfaces, surface plasmon

(Some figures may appear in colour only in the online journal)
to manipulate the electromagnetic waves at the structured interfaces. Compared to metamaterials, metasurfaces have much smaller thickness and thus are far easier to fabricate. Due to the ultrathin profile and design flexibility, they are widely exploited as functional devices, such as holograms [6–8], phase-front shapers [9–12], spectral filters [13–15], perfect absorbers [16, 17] and polarization converters [18, 19].

Thus far, various kinds of metamaterials and metasurfaces have been proposed to realize the phase, amplitude, or polarization modulation. In this review, we concentrate on the metamaterials and metasurfaces associated with dispersion engineering, including the fundamental theory, constructing methods, and their applications. This paper is organized as follows: in section 2, we give an overview of the fundamental theory of dispersion engineering in metamaterials and metasurfaces. Section 3 presents a few applications taking advantage of dispersion engineering capability, which include super-resolution imaging/nanolithography systems, planar functional devices, and broadband absorbers/polarization converters. Finally, conclusions of the current results and outlook for future development are given in section 4.

2. Dispersion in metamaterials and metasurfaces

As artificial materials constructed by periodic subwavelength units, the metamaterials can be described by effective material parameters including effective permittivity, permeability and refractive index. Due to the intrinsic resonance of the building blocks of metamaterials, their effective material parameters exhibit strong dispersion, as shown in figure 1(a). Different kinds of building blocks, such as metallic continuous lines [20], resonant rings [21], cut-wire pairs [22] and fishnets [23] were proposed to manipulate the dispersion properties of metamaterials with geometric shapes and sizes. Artificial materials with negative permittivity, negative permeability, or even double negative values have been realized in a wide spectrum ranging from electromagnetic waves to mechanical waves.

Hyperbolic metamaterial is a particular simple 3D metamaterial which is normally constructed by anisotropic multi-layered metal-dielectric structures. The effective permittivity of hyperbolic metamaterials can be manipulated both in the horizontal and longitudinal directions, when the materials and the fill ratio of alternating layer vary. The effective permittivity in the horizontal ($\varepsilon_\parallel$) and longitudinal ($\varepsilon_\perp$) directions can be described by [24]

$$
\varepsilon_\perp = \frac{\varepsilon_m d_q + \varepsilon_d d_d}{d_m + d_d}, \quad \frac{1}{\varepsilon_\parallel} = \frac{d_m/\varepsilon_m + d_d/\varepsilon_d}{d_m + d_d}
$$

where subscript $m$ and $d$ represent the metal and dielectric, respectively. According to equation (1), the topology of the frequency contour can be engineered from a closed elliptical dispersion ($\varepsilon_\parallel > 0, \varepsilon_\perp > 0$) to a hyperbolic one ($\varepsilon_\parallel\varepsilon_\perp < 0$) as shown in figures 1(b) and (c) [25]. The origin of this special dispersion modulation is attributed to the coupling of the excited surface plasmon polaritons (SPPs) between the neighboring layers [24, 25]. The hyperbolic dispersion brings many exotic phenomena such as directive transmission, spatial frequency filtering and negative refraction [24–27]. As a practical application of these effects, the hyperbolic dispersion of SPP coupling mode could be used to achieve far-field imaging of subwavelength objects and super-resolution lithography [28–32]. Recently, hyperbolic dispersion is also realized in the metasurfaces [33, 34]. It is found that the structured graphene monolayer and planar metallic grating can support a SPP propagation mode with hyperbolic dispersion, which opens new venues for extreme light confinement and unusual propagation and guidance.

Metasurfaces are usually considered as a thin artificial interface which change the electromagnetic boundaries. Different from metamaterials, the bulk material parameters such as permittivity and permeability are less important or even meaningless in case of the single-layered metasurfaces with two dimensional configurations. As an alternative, sheet impedance is often exploited in the characterization of light-matter interactions, which can be engineered at will by designing the unit cells in the metasurface, as shown in figure 2(a). Various applications, including broadband perfect absorbers and polarization converters, are realized by using this design strategy [18, 35–40].

Special electromagnetic modes propagating along the horizontal direction can also be excited during the interaction between the illuminate light and the metasurface structures. As shown in figures 2(b) and (c), the propagation modes in plasmonic and dielectric waveguides are two typical electromagnetic modes.

The use of surface structure to manipulate the plasmonic modes can date back to 1902, when an abnormal phenomenon now called Wood’s anomaly was reported [41]. This particular electromagnetic mode exists at the interface between the metal and dielectric, and could have very large propagation constant compared to that in vacuum when the resonant condition is satisfied, as shown in figure 2(c). The large wave vector of the mode dramatically shortens the effective wavelength, thus enables a variety of applications in super-resolution imaging/nanolithography [42–45] and integrated optical planar devices, such as the plasmonic lenses [46–49], deflectors [50], optical vortex generators [51, 52] and planar structural color devices [13, 53]. A subwavelength dielectric waveguide was also adopted to construct high efficiency metasurfaces due to the lower electromagnetic loss of the dielectric materials compared to metal. Metadevices made of TiO$_2$ [54, 55] and Si [56–58] nanofilms, which work at visible wavelengths and near-infrared wavelengths respectively, are considered to be the promising candidates for achieving high efficiency planar optical systems.

Considering the fact that comprehensive overviews of traditional metamaterials have been given in many reviews and books [59–63], in the following we mainly confine our contents to the dispersion engineering of recent emerging metasurfaces.
### 3. Applications of metasurface dispersion engineering

#### 3.1. Super-resolution imaging and nanolithography

The diffraction limit sets a fundamental barrier to achieve high resolution imaging and lithography, which are continuously pursued by optical researchers. In order to surpass the diffraction limit, tremendous efforts have been made in developing various super-resolution techniques [64–68]. The discovery of the SPPs in metallic structures brings a new approach to overcome the barrier due to its unique SPP mode dispersion [69, 70]. The dispersion equation of the symmetric SPP mode (defined according to the symmetry of the longitudinal electric fields) in insulator/metal/insulator (IMI) structure is [50, 71]:

\[
\tanh\left(\sqrt{\beta^2 - \varepsilon_1 k_0^2} h/2\right) = -\frac{\varepsilon_2}{\varepsilon_1} \sqrt{\beta^2 - \varepsilon_1 k_0^2}.
\]  

\[ (2) \]

where \(\varepsilon_1\) and \(\varepsilon_2\) are the permittivity of the metal and dielectric, respectively. Figure 3(a) presents the dispersion curves of plasmonic mode at a single metal–dielectric surface and in the thin metallic film with different thicknesses. When the resonant condition is satisfied, the horizontal wave vector increases dramatically, so that the effective wavelength of the mode is shortened correspondingly. For example, the effective wavelength in a 20 nm thick Ag film is only ~38 nm when a 375 nm laser illuminates on it, as shown in the dispersion curve in figure 3(a). This short wavelength promises a resolution ~19 nm. Combining this short wavelength effect and the amplification of evanescent wave induced by the plasmonic mode dispersion, the concept of superlens firstly proposed by Pendry in 2000 [72], was experimentally demonstrated both in super-resolution imaging [45, 73, 74] and nanolithography [42, 75–77]. With a single layered Ag film, an imaging resolution of 89 nm has been successfully obtained for 365 nm laser source (figure 3(b)) [45]. In 2004, Luo et al utilized a structured silver film to image the standing wave fields onto the photoresist, and a lithographic pattern with 50 nm line width was experimentally achieved at a wavelength of 436 nm (figure 3(c)) [42]. As an alternative to the complex and costly modern projection lithographic techniques [78–80], the superlens-based plasmonic lithography has been greatly developed during the last decade [44, 75, 81–83]. A resolution of 22 nm...
Figure 2. Dispersion in metasurfaces. (a) Effective impedance dispersion in metasurfaces. (b) Schematic and (c) dispersion diagrams of plasmonic and dielectric waveguides.

Figure 3. Applications of dispersion engineering in super-resolution imaging and nanolithography. (a) Dispersion of SPP on semi-infinite silver and silver films with different thicknesses, the refractive index of the surrounding dielectric is 1.7. Reprinted from [84], with the permission of AIP Publishing. (b) Schematic of super-resolution imaging system with superlens. From [45]. Reprinted with permission from AAAS. (c) Schematic of plasmonic nanolithography system with superlens. Reprinted from [42], with the permission of AIP Publishing. (d) 3D plot of hyperbolic dispersion diagram for multilayered metamaterial [85]. (e) Schematic of interference structure with planar hyperbolic metamaterial [85]. (f) SEM image of the resist pattern with half pitch of 45 nm. (d)–(f) [85] John Wiley & Sons. © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) SEM images of the curved hyperlens for nanolithography and (h) the fabricated pattern. (g), (h) Reproduced from [28] with permission of The Royal Society of Chemistry.
with single-step exposure for 365 nm light source, was demonstrated recently by introducing a reflective Ag film to form a metal/insulator/metal (MIM) cavity [44].

When the metallic films are stacked to multilayers, the excited SPP modes in the neighboring layers will couple each other as shown in figure 3(d). By geometry designing and materials selection, an engineered dispersion with hyperbolic form will be obtained. This particular dispersion of the multilayered metamaterial can also be used to achieve super-resolution lithography and far-field imaging of subwavelength objects by taking advantages of its short wavelength effect, spatial frequency filtering and directive transmission effect [28–32]. For example, Liang et al explored a planar hyperbolic metamaterial composed of SiO$_2$/Al films to squeeze bulk plasmon polaritons by filtering out the low spatial frequency components (figures 3(e)). Large area and uniform deep subwavelength interference patterns with half pitch of 45 nm ($\approx \lambda/8$) were demonstrated (figures 3(f)) [85]. Making use of the directive transmission effect of the hyperbolic dispersion, the image of the object can be magnified or demagnified, and the near-field information could be transferred to the far field nearly diffraction-freely with curved multilayers. In 2007, Liu et al reported a far-field curved hyperlens that can project a nano-object into a sub-diffraction-limit image [29]. Capitalizing on the demagnifying imaging capability of the curved multilayers, nanolithography with demagnified patterns compared to mask were demonstrated recently [28, 30]. Figure 3(g) presents the configuration of the demagnifying projective lens, a sub-diffraction resolution of about 55 nm line width, about 1.8 demagnification factor at a wavelength of 365 nm was experimentally obtained (figure 3(h)).

It is worth mentioning that the dispersion of the plasmonic mode can also be engineered through coupling between the propagating surface plasmon and localized surface plasmon mode [86, 87]. The additional anticrossing in the dispersion spectrum makes it attractive for applications due to its wide tunability.

3.2. Broadband and achromatic planar functional devices

Planar and lightweight optical devices and systems are the pursuing goal for optical engineering. However, the traditional laws of refraction and reflection constrain the optical devices, e.g. lenses and mirrors, to have curved shapes. Great effort has been devoted to construct planar optical systems. The Fresnel zones and photon sieves are two typical examples, which manipulate the light in a planar way [88, 89]. However, the low diffraction efficiency and strong chromatic dispersion limit the practical use of these devices. Along with the rapid developments of nano-fabrication and nano-optics, new types of flat devices based on metallic nanoslits and dielectric nanofins have been proposed recently. A single metallic nanoslit can be treated as a MIM waveguide, with the dispersion equation very similar to that of a metallic slab. For MIM waveguide, $\varepsilon_1$ and $\varepsilon_2$ in equation (2) present the permittivity of the dielectric and metal respectively, and the tanh changes to coth. The dispersion diagrams for Ag/air/Ag structure with different air gaps are plotted in figure 4(a). It can be seen that the dispersion
properties are successfully engineered by changing the width of the air gap and the horizontal wave vector increases when the width of air gaps decreases \[46, 71\]. By properly arranging the nanoslits with space-variant width, a gradient phase can be generated along the exit plane, and the classic Snell’s law is generalized to a new form, i.e. the so-called generalized law of reflection and refraction \[9, 46\]. Based on this method, Verslegers \emph{et al} experimentally demonstrated a flat plasmonic lens based on an array of nanoslits on a thin metallic film as shown in figure 4(b) \[48\]. Subsequently, this one dimensional design of the flat lens was extended to two dimensions by different groups, in which the lenses are polarization-independent \[49, 90\]. Other flat functional devices can also be realized by MIM plasmonic structures \[13, 51–53\]. For example, taking advantage of the near-linear dispersion of antisymmetric mode in MIM waveguide (as the indicated shaded region in figure 4(a)), color filter capable of filtering white light into individual colors across the entire visible spectrum was demonstrated \[13\]. The most significant advantages of MIM resonator color filters over other plasmonic nanostructures are their high efficiency and the ultrahigh spatial resolution (closed to the diffraction limit) \[53, 91\]. Similar to the dispersion engineering in plasmonic devices, the dispersion of the waveguide mode in dielectric nanopillars can also be modulated \[54, 55, 92–95\]. Using this method, titanium dioxide and silicon-based dielectric metasurfaces were obtained at visible wavelengths and near-infrared wavelengths respectively. Due to the low material loss, dielectric metasurfaces are promising for practical applications in planar optical systems. A variety of devices, such as planar lenses \[54–56\], Bessel beam and optical vortex generators \[56, 92, 93\], and even multifunctional devices and systems \[57, 94, 95\] have been realized in recent several years.

Large chromatic dispersion is a critical barrier which hampers the widespread prospective applications for many metasurfaces. Achromatic metasurfaces for several discrete wavelengths were proposed by utilizing space-division multiplexing \[99, 100\], wavelength-division multiplexing \[96\] and also multilayer stacking \[101\]. Recently, various approaches have been demonstrated to realize achromatic metasurfaces over a continuous bandwidth through dispersion management. Generally, the phase dispersion of an achromatic metasurface at the exit plane can be written as \[96\]:

\[
\varphi(r, \lambda) = -\frac{2\pi}{\lambda}(\sqrt{r^2 + f^2} - f) + C(\lambda) \tag{3}
\]

where \(f\) is the focal length, and \(C(\lambda)\) can be set as an arbitrary value to optimize the elements for linear optics applications. By making use of the compensation between the structural dispersion of MIM waveguide and material dispersion of metal, Li \emph{et al} theoretically demonstrated that the plasmonic nanoslits structures can be used to construct broadband achromatic lenses \[102\]. In the near-infrared frequency, the Drude dispersion of the gold counteracts the dispersion of the propagation SPP mode, which makes the achromatic condition, i.e. equation (3) satisfied. The designed metasurfaces can focus the near-infrared light over a continuous bandwidth broader than 1 \(\mu\)m (figure 4(c)). The limitation of this method is the fabrication difficulty of the nanoslits at high aspect ratios. Taking advantage of the dispersion engineering of dielectric nanomaterials, an achromatic reflective metasurfaces operating in visible light was obtain (figure 4(d)) \[97\]. The phase dispersion of the nanopillars was engineered by modulating their geometric parameters, and a particle swarm optimization algorithm was utilized to optimize the distribution of the nanopillars. The working bandwidth of this metasurfaces is around 60 nm, which is not broad enough for practical purposes due to the limited design freedom of the structure. Very recently, Wang \emph{et al} employed the integrated-resonant unit element with smooth and linear phase dispersion combining with geometric phase to design broadband achromatic flat optical lens (figures 4(e) and (f)) \[98\]. The main advantage of this kind of structures comparing with the nanopillars is the increased design freedom in dispersion engineering. An achromatic converging metalens within a broad bandwidth from wavelength of 1200 to 1680 nm was demonstrated. It is worth noting that the dispersion engineering of phase-type metasurfaces has been greatly extended. Metasurface lenses with positive, zero, and hyper-negative dispersion can be custom-tailored at will capitalizing on their design flexibility \[103, 104\].

3.3. Broadband perfect absorbers and polarization converters

The strong resonance of the traditional metamaterials and metasurfaces results in the narrow band response in frequency domain. However, metadevices working in broadband or even ultra wideband are desired and pursued in various practical applications. The dispersion of electromagnetic modes plays an important role in almost all kind of structured devices. In order to obtain the broadband response of the metadevices, the dispersion of electromagnetic modes needs to be engineered. Here, we take the reflective metasurfaces as an example to derive the electromagnetic behaviors when the illuminate wave interacts with the metasurfaces. The metasurface is treated as a two dimensional sheet with effective admittance \(Y = \sqrt{\varepsilon_1/\mu_1}\), as shown in figure 5(a). The electromagnetic wave illuminates from medium 1 to medium 2 through the metasurface. The permittivity and permeability of medium 1 and medium 2 are \(\varepsilon_1, \mu_1\) and \(\varepsilon_2, \mu_2\), respectively. The tangential electric field in the transmission and reflection direction is \(A_t\) and \(B_r\), \(i\) represents index of the corresponding medium. The effective admittance of medium 1 and medium 2 is \(Y_t\) and \(Y_r\), respectively. A ground plane is added, so that all the electromagnetic energy will be reflected. The thickness of the medial dielectric layer is \(d\). Assuming no magnetic materials are used in the design, and light is normally illuminated from free space, we can obtain \(Y_1 = Y_0 = \sqrt{\varepsilon_0/\mu_0} = 1/377\). By solving the Maxwell equations with the boundary conditions, the reflection coefficient can be written as:

\[
\hat{r} = \frac{\hat{B}_1}{\hat{A}_1} = \frac{(1 - \sqrt{\varepsilon_2} - Y_s/Y_0) - (1 + \sqrt{\varepsilon_2} - Y_s/Y_0)\exp(2ikd)}{(1 + \sqrt{\varepsilon_2} + Y_s/Y_0) - (1 - \sqrt{\varepsilon_2} + Y_s/Y_0)\exp(2ikd)} \tag{4}
\]

The phase shift of the reflection is:

\[
\Phi_r = \arg\left(\frac{(1 - \sqrt{\varepsilon_2} - Y_s/Y_0) - (1 + \sqrt{\varepsilon_2} - Y_s/Y_0)\exp(2ikd)}{(1 + \sqrt{\varepsilon_2} + Y_s/Y_0) - (1 - \sqrt{\varepsilon_2} + Y_s/Y_0)\exp(2ikd)}\right). \tag{5}
\]
Figure 5. Applications of dispersion engineering in broadband perfect absorbers. (a) Schematic of reflective metasurfaces. (b) Unit cell of broadband absorber based on metasurface dispersion engineering [35]. (c) Retrieved sheet impedance and the corresponding impedance of an ideal absorbing sheet [35]. (d) Absorption at normal incidence as a function of frequency [35]. (b)–(d) Reproduced with permission from [35]. © 2012 Optical Society of America. (e) Photographs of the microwave broadband absorber [39]. (f) Simulated wave impedance of the microwave absorber as a function of frequency [39]. (e), (f) Reprinted with permission from [39]. Copyright 2013 by the American Physical Society.

Figure 6. Applications of dispersion engineering in broadband polarization converters. (a) Photograph of the fabricated broadband polarization converter [105]. (b) Sheet impedances retrieved from S parameters (denoted as Re. A and Re. B) and the corresponding optimal impedance (denoted as Op. A and Op. B) [105]. (a), (b) Reprinted from [105], with the permission of AIP Publishing. (c) Perspective view of the broadband polarization converter through two dimensional dispersion engineering [36]. (d) Simulated polarization conversion ratio (PCR) from LCP to LCP (blue line) and measured polarization conversion ratio from x- to y-polarization (red asterisk) [36]. (e) Volumetric current flows at $f_1 = 6.5$ GHz under the x-polarization [36]. (f) Volumetric current flows at $f_2 = 5.3$ GHz under the y-polarization [36]. (c)–(f) Reproduced from [36], CC BY 4.0.
From equations (4) and (5), we obtain both the amplitude and phase responses after the electromagnetic waves interact with the reflective metasurfaces. This is an important guidance in the design of metasurfaces to obtain a broadband response.

The amplitude modulation of the reflective electromagnetic waves with subwavelength structures can be used to realize the perfect absorber. For broadband absorber designing, the dispersion equation can be written as:

\[ |r(\omega)| = 0. \tag{6} \]

Based on this dispersion relation and the desired working band, one can derive the ideal dispersion curve of \( Y' \) for the electromagnetic absorbing sheet. The ideal dispersion curves of the real and imaginary part of effective impedance \( Z_e \) (reciprocal of \( Y' \)) for the working band from 9 THz to 55 THz are plotted in figure 5(c). In order to construct a dispersion relation to mimic the one of the ideal absorbing sheet, a metasurface composed of cross structure was proposed (figures 5(b) and (c)) [35]. A nearly perfect absorber with absorption greater than 97% was achieved over a one-octave bandwidth in infrared (figure 5(d)). It is worth noting that the effective permittivity of meta-surface is modulated from the Drude model of a normal metal to the Lorentz modal when the sheet impedance is converted to the effective permittivity [35]. Ye et al extended the concept of dispersion engineering to the microwave band (figures 5(e) and (f)) [39]. By deliberately controlling the dispersion and dissipation, a bandwidth of 39% with the absorption better than 99% was experimentally observed.

The phase modulation can be employed in polarization converter by controlling the phase difference between the polarized components in the two orthogonal horizontal directions. For broadband polarization converter, the dispersion equation can be written as:

\[ \Phi_x(\omega) - \Phi_y(\omega) = \text{const.} \tag{7} \]

When const. in equation (7) equals \( \pi/2 \) and \( \pi \), the function of the polarization converter, corresponds to quarter-wave plate and half-wave plate, respectively. Similar to the design process in broadband perfect absorber, one can derive the ideal dispersion curve of \( Y' \) for the electromagnetic sheet. The ideal impedance \( Z_e \) of both the half-wave plate (Op. A) and quarter-wave plate (Op. B) is obtained based on equations (5) and (7) for the working band from 3 GHz to 18 GHz, as shown in figures 6(b). Aiming at this dispersion diagram, metasurface with \( 'T' \) shaped unit is adopted to excite the Lorentzian resonances, so as to compensate the variation of propagation phase shift induced by frequency change (figures 6(a) and (b)) [105]. A polarization transformation with bandwidth ratio larger than 3:1 was demonstrated with 90% transformation efficiency. Two-dimensional dispersion engineering in the metamaterials was also implemented for further enlarging the bandwidth of the polarization conversion (figures 6(c) and (d)) [36]. Two different Lorentzian resonant modes were excited for different polarizations (figures 6(e) and (f)), thus an achromatic half-wave plate with a 5:1 bandwidth ratio was experimentally obtained in the microwave band. It should be noted that more resonant modes can be artificially introduced to expand the working bandwidth further at the cost of increasing the complexity of the structures. Furthermore, this strategy can also extend to the design of polarization converters working in transmission mode [18].

4. Conclusions and outlooks

In summary, we have reviewed the principles and applications of dispersion engineering in metamaterials and metasurfaces. Comparing to that of the traditional devices, the management of dispersion in metadevices has much more degrees of freedom due to their design flexibility during the construction of the artificial structures and ability of manipulation at a subwavelength scale. As a result, this emerging realm brings us not only the various exciting applications, but also help to overcome the fundamental limitations of classic diffraction, reflection and refraction theory. Nevertheless, there is still plenty of space to explore as a newly born realm. Future works might be focused on the further applications and in-depth theory of the metadevice-based dispersion engineering. For example, the dimension of manipulation can be increased from one or two dimensions to three or even more dimensions, so that the performances of the metadevices and metasystems can be improved further. Dynamical manipulation is pursued to overcome the limitations of the existing metadevices which have merely static responses to the environmental electromagnetic fields [106–110]. Active materials can be introduced to the metadevices, so that dynamical dispersion engineering can be realized. Furthermore, the extension of dispersion engineering from electromagnetic waves to mechanical waves [111, 112], and even matter waves [113] are still open to be explored. We definitely believe that the dispersion engineering will have more applications in both scientific and engineering areas.

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