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Published in:
ADVANCED OPTICAL MATERIALS

DOI:
[10.1002/adom.202001000](https://doi.org/10.1002/adom.202001000)

Published: 03/12/2020

Document Version
Peer reviewed version

Please cite the original version:
Li, W., Qi, J., & Sihvola, A. (2020). Meta-Imaging: from Non-Computational to Computational. *ADVANCED OPTICAL MATERIALS*, 8(23), [2001000]. <https://doi.org/10.1002/adom.202001000>

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Meta-imaging: from Non-computational to Computational*Wenzhi Li, Jiaran Qi*, and Ari Sihvola*

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Keywords: metasurfaces, metamaterials, imaging, computational imaging

Imaging equipment is one of the most powerful tools for human to explore the world. Devices utilizing various portions of the electromagnetic spectrum are developed to reveal the fine details of objects and extend the sensing range. Recently, the advent of metamaterials/metasurfaces has significantly advanced the evolution of both imaging components and techniques. Many promising imaging methods based on metamaterials/metasurfaces arise owing to their superior spatial modulation capabilities over the electromagnetic waves. This review focuses on applications of metamaterials/metasurfaces in the electromagnetic/optical imaging, and summarize the recent developments of metamaterial/metasurface imaging in a new perspective, which can be categorized into the non-computational and the computational ones. Firstly, the purposes, principles, methodology of non-computational meta-imaging are presented, which covers the evanescent-wave-collecting lens with sub-diffraction-limited imaging potentials and the focal metalens with Fourier transformation functionalities. Secondly, the principles of various computational meta-imaging methodologies are elucidated, including mainly the Born approximation, the synthetic aperture radar, and the ghost imaging. Finally, a brief conclusion and prospects to meta-imaging will be provided.

1. Introduction

Human curiosity drives people to develop a variety of tools to explore the world. Imaging equipment is one of the most important tools. For the curiosity of the microscopic world, people invented the microscope; for the curiosity of outer space, people invented the telescope. However, traditional imaging devices are usually bulky, heavy and with diffraction limit, which greatly limits the pace of human exploration of the world, and do not meet the requirements of miniaturization and integration in modern imaging system. In order to overcome these shortcomings, metamaterials/metasurfaces were proposed to realize the functions of traditional imaging devices.

Metamaterials are artificial media composed of periodic/aperiodic subwavelength metal/dielectric structures (i.e. meta-atom). This class of media possess electromagnetic properties not present in the constituent materials and have yielded breakthrough electromagnetic phenomena. The capability of tailoring effective electric permittivity and magnetic permeability responses leads to a wide range of accomplishments, such as enhanced nonlinearity,^[1] and electromagnetic cloak.^[2] However, high losses, strong dispersion and difficulty of micro- and nano-fabrication of three-dimensional (3D) meta-atoms have hindered the progress of bringing metamaterials into practice.

To overcome the shortcomings of bulk metamaterials, planar metamaterials or metasurfaces, were proposed.^[3-4] Metasurfaces, composed of single-layer or multiple-layer stacks of planar meta-atoms with subwavelength thickness, control electromagnetic wave via the tailored surface impedance or abrupt phase variation instead of phase accumulation through propagation. Metasurfaces can be readily fabricated using existing technologies such as lithography and nanoprinting methods since they are a class of planar material. Besides, the subwavelength thickness in wave propagation direction not only brings smaller volume, making it easier to be integrated, but also suppresses losses. Metasurfaces have drawn great attention in the

metamaterial community and shown high potential in applications, such as light bending,^[5-6] beam focusing,^[7-8] and computational holograms.^[9]

One of the most fascinating applications among all potential applications of metamaterials/metasurfaces is imaging. The properties of metamaterials/metasurfaces provide new design paradigms for imaging devices. Imaging paradigms using metamaterials/metasurfaces can be classified into two groups: non-computational metamaterial/metasurface imaging and computational metamaterial/metasurface imaging, as shown in **Figure 1a** and **1b**.

Non-computational imaging is a “what you see is what you get” imaging method, i.e., the measurements of the detectors directly represent the image of the object. However, computational imaging is different. The relation between the measurements of the detector and the object is not a straightforward one-to-one mapping. The measurements require further processing to obtain an image which is the one-to-one mapping of the object. Postprocessing on the measurement data can not only image the object as done by non-computational imaging, but also retrieve 3D and/or polarization information which are difficult to acquire using non-computational techniques.

Assuming both non-computational and computational imaging systems are linear, a mathematical model, generalizing their image formation description, can be given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

where, $\mathbf{y}$ is the measurement vector, representing the output of detector(s), $\mathbf{x}$ is the object vector, representing the information of the object to be imaged, $\mathbf{H}$ is the transfer matrix that maps the information of the object to the output of the detector, $\mathbf{n}$ represents the noise term. For non-computational imaging systems, the transfer matrix $\mathbf{H}$ is ideally an identity matrix, that's, a point-to-point mapping between the object and the output of detector, leading to “what you see is what you get”, and thus the system performance (or the transfer matrix) is well-defined which

will not be deteriorated significantly by small noise. For computational imaging systems, $\mathbf{H}$ is usually filled with complex elements and necessarily requires inversion to deduce the object from the measurements. In addition, in some cases, the transfer matrices of the computational systems are ill-posed that small noise will considerably deteriorate the system performance, and thus diversity mechanisms are exploited to make the system performance more stable (see Section 3.1). We have to recognize that the computational imaging systems are not always significantly superior to the non-computational ones. However, the computational imaging systems are capable of capturing more information of a scene as mentioned above. Besides, as we deploy an imaging system, we have to deal with many constraints in reality, such as cost, system size and weight, preventing us from using a non-computational imaging system. A typical example of computational imaging systems that reconcile these practical constraints is the synthetic aperture radar (SAR), especially when a SAR imaging system is deployed in an airplane or satellite to realize an effectively huge antenna aperture with high resolution and all-weather imaging capability.

In essence, computational imaging shifts the burden of hardware to software. Therefore, implementing a computational imaging method is to balance the capabilities of hardware and software through joint design and optimization of all components of an imaging system. Metamaterials/metasurfaces become an excellent candidate for computational imaging hardware because of flexibility and freedom in controlling electromagnetic waves.

There have been a few good reviews focusing on metamaterials/metasurfaces-based imaging,^[10-11] as the metamaterial community rapidly grows. Here, we provide a distinct perspective on the progress of this field over the past two decades. In this review, we summarize the recent developments of metamaterial/metasurface imaging which are categorized into two classes, i.e., the non-computational and the computational ones. It should be noted that we only focus on the applications of metamaterials/metasurfaces in the electromagnetic/optical imaging.

Thermal imaging, acoustic imaging and other methods are not considered. Hereinafter, the so-called metamaterial/metasurface imaging is referred to as meta-imaging. Firstly, we present the purposes, principles, methodology of non-computational meta-imaging. Secondly, we discuss the principles of the computational meta-imaging methodologies, including mainly the Born approximation, the synthetic aperture radar, and the ghost imaging. Besides, we introduce practical examples of the computational meta-imaging. Finally, we draw a brief conclusion and give prospects to meta-imaging.

2. Non-computational Meta-imaging

In this section, we discuss on non-computational meta-imaging systems which can be classified into two categories: evanescent-wave-collecting lens and focal metalens. The former including perfect lens, superlens, and hyperlens is capable of collecting evanescent wave and thus form sub-diffraction-limited image, while the latter is a type of metamaterial/metasurface-based lens with both focusing and Fourier transformation functionalities.

2.1. Imaging by Evanescent-wave-collecting Lens

In 1873, Abbe discovered the fact that an optical system such as a microscope and a telescope is unable to resolve two spots apart less than half a wavelength, i.e., the diffraction limit.^[12] Such a limitation of the resolution results from the fact that the evanescent wave carrying fine features smaller than half a wavelength decays exponentially away from an object to be imaged, and thus a traditional optical imaging system cannot resolve the subwavelength features.

As the first attempt to overcome diffraction limit using metamaterials, perfect lens,^[11] made up of negative index material (NIM), was introduced to recover the fine details of an object by magnifying the evanescent wave. If the refractive index of the lens equals -1 , its transfer function will be proportional to $\exp(i\mathbf{k}\cdot\mathbf{r})$, where $\mathbf{r}$ denotes the displacement vector and the wave vector $\mathbf{k}$ is purely imaginary, leading to exponentially enlarged evanescent wave. Implementing the NIM is, nevertheless, difficult in reality. Therefore, superlens was proposed under the quasi-static limit, and experimentally demonstrated in the visible.^[13-16] **Figure 2a** shows an optical

silver superlens. The corresponding results of the superlens are shown in Figure 2b with an average 89 nm line width, or a quarter of the illuminating wavelength 365 nm. However, both perfect lens and superlens are ‘near-sighted’,^[17] that is, they rely on atomic force microscope or near-field scanning optical microscope to achieve sub-diffraction-limited imaging rather than a traditional far-field microscope.

To implement far-field sub-diffraction-limited imaging using a conventional microscope, far-field superlens (FSL) and hyperlens were proposed.^[18-27] A representative FSL, shown in Figure 2c, was composed of a silver slab and a nano-scale grating. The silver slab enhances the evanescent wave while the grating converts the evanescent wave to the propagating one according to the grating law by shifting the incident wave-vector, k_{in} , into a certain diffraction order

$$k = k_{in} \pm \frac{2m\pi}{p} \quad (2)$$

where m is the corresponding diffraction order and p is the grating period. The sub-diffraction-limited information can be captured in the far-field region since the evanescent wave (with higher k) is converted to the propagating one (with lower k). Two line-sources of 50 nm width separated by a 50 nm gap are clearly resolved at incident wavelength of 377nm by the FSL with a conventional microscope, as shown in Figure 2d.

The operating principle of hyperlens is different from FSL. As a typical example, hyperlens shown in Figure 2e was composed of uniaxially anisotropic metamaterials governed by a hyperbolic dispersion, which reads

$$\frac{k_t^2}{\varepsilon_z} + \frac{k_z^2}{\varepsilon_t} = k_0^2 \quad (3)$$

where k_t and k_z are the transversal and the longitudinal wave numbers, and ε_t and ε_z have different signs, denoting the transversal and the longitudinal permittivities. It indicates that a hyperlens also supports the propagation of evanescent waves. Furthermore, a hyperlens is

capable of far-field magnification owing to the geometry deformation of the structure, such as obliquely cut or curved contour.^[22] Figure 2f shows the imaging results of the magnifying optical hyperlens (Figure 2e). Two lines of 35 nm width spaced 150 nm are magnified as a 350-nm-spacing image while the conventional microscope is with diffraction limit of 260 nm. Experimentally, hyperlenses with curved shape were demonstrated from the ultraviolet to the visible. However, the obliquely cut or curved geometries may bring troubles to certain imaging applications such as biological imaging, since the image plane is not parallel to the object plane. Therefore, a planar hyperlens based on transformation optics is more feasible to capture sub-diffraction-limited details,^[28-32] owing to the alignment of these two planes.

2.2. Imaging by Metamaterial/Metasurface Focal Lens

All the aforementioned lenses, despite realizing super-resolution imaging, are incapable of focusing a plane wave, due to the absence of a phase compensation mechanism. In this section, we focus on how to implement a metamaterial/metasurface-based focal lens, not only capable of sub-diffraction-limited or at least diffraction-limited focusing, but also Fourier transformation.

2.2.1 Bulk Metalens

A metamaterial-based lens achieving sub-diffraction-limited focusing needs to satisfy two requirements.^[33] The first one is supporting the propagation of waves with higher spatial frequencies that carry sub-diffraction-limited information. Besides, a bidirectional coupling mechanism is needed to convert the waves with higher spatial frequencies from air to metamaterial and vice versa in order to avoid total reflection. The second requirement is that phase compensation mechanism should process two types of phase change. One is the geometric phase accumulated when the wave propagates in the metamaterial, and the other is the phase variation introduced by bidirectional coupler or curved geometry.

Three types of bulk metalens are shown in **Figure 3**.^[33-35] In Figure 3a,^[33] the bulk metalens is composed of nonperiodic plasmonic waveguide coupler (PWC) and hyperbolically or

elliptically dispersive metamaterial, referred as PWC bulk metalens. Triple resolution enhancement compared with conventional lens was achieved when illuminated by both a normally and an obliquely incident plane wave. The magnification and demagnification capabilities of this bulk metalens were also demonstrated, and coincide with conventional lens. In Figure 3b,^[34] a metamaterial immersion lens (MIL) is illustrated. Same as conventional lenses, the MIL has a shaped metamaterial-air interface to compensate the phase change to focus an incoming plane wave: the convexity claims ownership of the elliptically dispersive metamaterial, and the concavity leads to the hyperbolically dispersive metamaterial. In Figure 3c,^[35] gradient index (GRIN) metalens is presented, where the focusing problem is treated as a light bending task. From the transformation optics point of view, this can further be regarded as a refraction variation problem. Tracking the trajectory of every ray, the refraction profiles of GRIN metalens can be accordingly calculated. Both elliptically and hyperbolically dispersive GRIN metalenses for both internal and external focusing are studied. Finally, a resolution of $\lambda/6$ in the GRIN metalens and that around $\lambda/2$ in the air at $\lambda=830$ nm were achieved for normal- and tilted-incident plane-wave illumination.

2.2.2 Flat Metalens

High losses according to the Kramers-Kronig relations, strong dispersion due to the required exotic effective electromagnetic parameters, and difficulty in fabricating the complicated 3D structures, have hindered practical applications of metamaterials. As their two-dimensional variants, metasurfaces attract great attention in the metamaterial community. It is mainly attributed to the fact that the subwavelength thickness of metasurfaces effectively diminishes the abovementioned issues of metamaterials. Relying on tailored surface impedance which introduces desired abrupt phase change instead of accumulated geometric phase change via light propagation in optical components, metasurface can greatly suppress losses. Hence, metasurfaces are currently playing an increasingly significant role in the general field of metamaterials researches.^[3-4]

Flat metalenses are a class of focal lenses made of metasurfaces, on which a phase profile $\varphi(r)$ at frequency ω to focus a normally incident plane wave can be derived from the generalized laws of reflection and refraction.^[5-6, 36] Assuming a time-harmonic factor of $e^{i\omega t}$, a simplified version of which by properly selecting the coordinate system reads

$$\sin \theta_i - \sin 0 = \frac{c}{\omega} \frac{d\varphi(r)}{dr} \quad (4)$$

where all variables are self-explanatory in **Figure 4a**. Substituting $\sin \theta_i = (r^2 + f^2)^{-1/2} \times r$ into Equation (4), we have

$$\frac{r}{\sqrt{r^2 + f^2}} = \frac{c}{\omega} \frac{d\varphi(r)}{dr} \quad (5)$$

Therefore, solving the differential Equation (5) leads us to the phase profile:

$$\varphi(r) = \frac{\omega}{c} \sqrt{r^2 + f^2} + \varphi_0 \quad (6)$$

where r is the radial distance from a particular point on the flat metalens to its center, f is the focal length, c is the light speed, and φ_0 is the reference phase at the center. A flat metalens was first experimentally demonstrated using V-shaped metal optical antenna at the wavelength of $1.55 \mu\text{m}$, as shown in Figure 4b with its scanning electron microscope (SEM) image and phase profile.^[37] However, the focusing efficiency is approximately 1%, preventing the proposed metalens from practical application. Flat metalenses with higher efficiency could be realized based on Babinet's principle,^[38] all-dielectric meta-atom,^[39] and reflect-array.^[38] Based on the Pancharatnam-Berry (PB) phase theory,^[41-42] flat metalenses functioning as focusing or diverging lens depending on the handedness of the incident circular polarization was presented.^[43-44] As shown in Figure 4c, under the left circularly polarization (LCP)/the right circularly polarization (RCP) illumination, the transmitted light of the cross-polarization can be focused by the metalens on the right/left side of the focal plane. Besides, Huygens' flat metalenses whose impedance profiles can be calculated by generalized sheet transmitted condition were proposed,^[45-48] introducing an alternative route to design flat metalenses. Ke

Chen et al. proposed a Huygens' flat metalens,^[46] composed of varactor-loaded meta-atoms and can focus an incident plane wave into spatially varying focal spots, as shown in Figure 4d. Besides the electrical tunability assigned by varactors, there are other reconfigurable metalenses with distinct operational mechanisms, e.g., zoom metalens,^{[49][50]} stretchable metalens,^[51] microelectromechanical systems (MEMS) metalens,^[52] phase-change-material-based metalens,^[53] and so on. We believe these novel reconfigurable metalenses will provide more possibility to design non-computational meta-imaging systems. Moreover, a metalens for focal plane array passive millimeter wave (PMMW) imaging at microwave regime was reported, and a single-channel imager based on the metalens and a radiometer in Figure 4e exhibited promising imaging qualities.^[54] All these flat metalenses provide the characteristics of high efficiency, compact size and ease of fabrication, paving a bright avenue to realize compact imaging systems.

2.2.3. Aberration-free Flat Metalens

In geometrical optics, the path of light ray is studied by the Gaussian theory. In this theory, only those points and rays are considered which lie in the immediate neighborhood of the optical axis; terms involving the second and other higher powers of off-axis distances are neglected. However, as lenses are constructed with large aperture and large field, the assumptions of the theory are not satisfied. Aberrations, resulting from the terms in powers higher than second, will occur to reduce resolution of the imaging system and even to degrade the image quality. Typically for a flat metalens, aberrations can be categorized into the following two classes. On one hand, the chromatic aberration is related to the frequency dispersion mismatch of the ~~geometric~~ phase to be compensated and the abrupt phase variation offered by the meta-atom constituting the flat metalens. On the other hand, the monochromatic aberrations primarily including spherical aberration and coma are attributed to the angular dispersion of the reflection or the transmission property of the meta-atom, as well as the idealized design methodology,

such as the classical geometric optics which only considers the geometric phase compensation on the principal axis.

Conventional lens-based imaging systems, such as microscopes, telescopes, suffer from aberrations and often rely on corrections by cascading compound lenses, giving rise to increased system size, weight and cost. However, metasurface, due to capability of tailoring electromagnetic responses at sub-wavelength scale, is able to minimize different aberrations without introducing extra lenses. Synthesizing flat metalenses with advanced design methodology does allow imaging free from aberrations.

A) Chromatic aberration-free metalenses: Chromatic aberration correction is one of the first efforts to diminish the aberration effects associated with metasurfaces in non-computational imaging systems. As shown in Equation (6), the phase profile of a focal metalens is dependent on not only radial distances but also operating frequency. Therefore, eliminating chromatic aberration is not to design a meta-atom with a constant phase response, but to engineer its dispersion across a wide range of frequency to meet the variation of the required phase profile with the wavelength.

The mechanism of realizing an achromatic flat metalens is the phase compensation, and a systematic and general methodology was proposed in Ref.^[55] Expanding Equation (6) as a Taylor series near the operating frequency ω_0 , we have

$$\varphi(r, \omega) = \varphi(r, \omega_0) + \left. \frac{\partial \varphi(r, \omega)}{\partial \omega} \right|_{\omega=\omega_0} (\omega - \omega_0) + \left. \frac{\partial^2 \varphi(r, \omega)}{2 \partial \omega^2} \right|_{\omega=\omega_0} (\omega - \omega_0)^2 + \dots \quad (7)$$

To achieve achromatic flat metalenses in a given bandwidth $\Delta\omega$ with the central operating frequency at ω_0 , one needs to design meta-atoms capable of providing phase delay imposed by Equation (5) and compensating the phase associated with group delay $\partial\varphi(r, \omega)/\partial\omega$, group delay dispersion $\partial^2\varphi(r, \omega)/\partial\omega^2$, and other higher-order terms. **Figure 5a** shows the comparison of chromatic and achromatic metalenses, that's, metalenses without and with phase compensation.

Besides, the phase response of meta-atoms is required to be frequency- and position-dependent which is also shown in Figure 5a.^[56]

As a simplified version of Equation (7), realizing a linear phase response with respect to frequency, that is, compensating only the group delay while forcing group delay dispersion and other higher-order terms to be zero, is a straightforward way to accomplish an achromatic flat metalens, which can be realized by multiple resonances,^[57-62] or by compensation between the structure dispersion and material dispersion.^[63] In essence, the linear phase methodology presented is applied to compensate the phase retardation of propagation in free space since the phase accumulation in free space is proportional to the frequency for a given focal length.^[58] Aieta et al. reported an experimental result of the simplified version by engineering dispersion of a meta-atom, as shown in Figure 5b.^[58] The spectrum of the meta-atom has three resonances at wavelengths 1300, 1550 and 1800 nm, respectively, resulting from the individual resonators and from the coupling between the resonators, as depicted in upper panel of Figure 5b. The resonances lead to a linear phase response at the three wavelengths, namely, the dispersion of the meta-atom compensates the wavelength-dependent phase retardation in free space. In addition, creating libraries of meta-atoms to provide diverse phase dispersions is convenient to implement broadband achromatic flat metalenses.^[64] Shrestha et al. created phase dispersion libraries of meta-atoms shown in Figure 5c to construct broadband achromatic metalenses. Numerical optimization methods,^[65-66] such as genetic algorithm and machine learning, are also powerful tools to realize phase compensation, although they may provide little physical insights. However, it should be noted that the aforementioned aberration corrections are rather complicated tasks, which not only require tedious full-wave construction of an appropriate meta-atom library, but also tend to sacrifice significantly the system efficiency.

Alternatively, multiplexing meta-atoms^[67-70] consisting of different meta-atoms resonating at different wavelengths as well as stacked multi-layer meta-atoms^[71-72] were proposed to eliminate chromatic aberrations. Instead of the phase compensation, the working principle of

the multiplexing meta-atoms (or the multi-layer ones) is the weak coupling among different interleaved meta-atoms (or multiple layers). A sub-meta-atom should be designed to resonate only at a given wavelength so that the spectral crosstalk is minimized. When chromatic illumination is incident on a flat metalens composed of interleaved meta-atoms, different wavelengths couple with the corresponding sub-meta-atoms and are then funneled into the same focal spot. As illustrated in **Figure 6a**, the multiplexing meta-atom consists of three meta-atoms that are, respectively, optimized at red (633 nm), green (532 nm) and blue (430 nm). Three colors are focused at the same focal plane. Stacked multi-layers flat metalenses work in a similar way with every layer corresponding to a particular wavelength, as shown in Figure 6b. However, such a configuration can only realize achromatism at a set of discrete wavelengths, preventing them from a wider range of applications.

B) Monochromatic aberration-free metalenses: Another type of aberration is the monochromatic one, which includes spherical aberration, coma, astigmatism, and field curvature. Flat metalenses avoid spherical aberration inherently due to the capability of tailoring phase responses of meta-atoms at will.^[73] Narrow field of view (FoV), resulting from other monochromatic aberrations, is instead a more important issue hindering flat metalenses from practical applications. An aplanatic metalens fabricated on a curved surface was proposed to focus light without coma and spherical aberration.^[73] However, patterning meta-atoms on the curved surface is challenging. Therefore, a diffraction-limited doublet metalens,^[74] as shown in **Figure 7a** with an angle-of-view larger than $60^\circ \times 60^\circ$ and 70% focusing efficiency has been demonstrated in the near-infrared. The doublet metalens consists of two metasurfaces fabricated on opposite sides of the same substrate, where one operating as a corrector plate while the other one focusing light. Both phase profiles of the two metasurfaces are optimized by the ray tracing approach. The principle of the doublet metalens is based on fisheye lens yet replaces the smaller aperture with the metasurface corrector plate. The conception of doublet metalens was also demonstrated in the visible region.^[75] Later, a Huygens flat metalens with an unprecedented >

170° angle-of-view and capable of correcting primary aberrations was proposed, as illustrated in Figure 7b.^[76] The design processing of the Huygens flat metalens is similar to the doublet metalens yet relies only on a single metasurface, leading to a lower cost imaging system. In addition to imaging in laboratory, a wide FoV metalens was reported recently to perform outdoor imaging.^[77] As shown in Figure 7c, the metalens is integrated into a commercial camera and used to capture the outdoor scene under natural sunlight instead of illumination in a laboratory.

Herein, we discuss some limitations of the abovementioned flat metalenses. One of them is the chromatic point spread function deterioration resulting from variation of efficiency of a metalens with wavelength, even though chromatic and monochromatic aberrations are absent. As reported in Ref,^[55] the images formed under white-light illumination is bluish due to the higher efficiency of the metalens at shorter wavelengths than that at longer ones. Therefore, a metalens with a uniform efficiency over a continuous broadband is more suitable for imaging than one with extremely high efficiency at a particular wavelength yet with lower efficiency at other wavelengths. Although the average efficiencies of the metalens may be lower, improvement of image quality can be achieved. Another limitation is that image distortions exist even for flat metalenses without spherical aberration, coma, astigmatism and field curvature, as shown in Figure 7a. This phenomenon, known as geometric distortion, is particularly common when metalenses are applied to record an image in a wide field of view. These reported flat metalenses without monochromatic aberrations operate only in a narrow bandwidth. Finally, single-layer achromatic flat metalenses are often limited to perform qualified imaging in moderate or small numerical aperture (NA) regions due to the discrepancy of the required large group delays and high efficiency. This discrepancy can be alleviated by integrating an extra flat metalens into an imaging system, yet at the cost of system compactness.^[78-79] Hence, realizing a broadband aberration-free metalens (including both

chromatic and monochromatic aberration-free) with a large NA remains further research challenges.

2.2.4. *Super-oscillation Flat Metalens*

An attempt to break the diffraction limit based on a flat metalens is to achieve the so-called super-oscillation,^[80-81] which is mathematically referred to as that a band-limited function contains local oscillations faster than its fastest Fourier components. The mechanism of super-oscillation to realize sub-diffraction-limited imaging can be considered as shifting the energy within Airy disk from the main beam to the side lobes, as shown in **Figure 8a**. Figure 8b shows the criterion of the Rayleigh diffraction limit and super-oscillation.^[82] There is a tradeoff between image resolution and quality. In other words, a higher resolution can be achieved by narrowing the main beamwidth, whereas the side-lobe energies will dominate over the main-beam leading to a lower signal to noise ratio. Thus, the field of view of a super-oscillation flat metalens (SFML) is often quite limited to prevent the sidelobe distortions of image qualities. Moreover, this restriction usually delivers very small focal intensity and is utterly fragile to phase-profile aberrations, calculation precision, and fabrication errors.^[80]

Both optimization and optimization-free methods to design SFML have been proposed. Optimization methods include particle swarm algorithm,^[83-84] linear programming methods,^[85] and multi-objective genetic algorithm.^[86] Taking the genetic algorithm (GA) as an example, the design process can be described as follows. To initialize GA, a population of lenses with different transmission functions called genomes are randomly generated. The viability of each individual of the population is evaluated by a fitness function associated with a set of given parameters, such as full width at half maxima, side-lobe level, and wavelength, and sorted by the fitness. Then, preference is given to the individuals with higher fitness. Then, a new population is created by crossover, mutation of the previous population. This procedure is repeated until a certain criterion is reached. However, the size of the SFML designed by the

optimization methods are limited due to the computational burden. Furthermore, these methods provide little physical insights into the operational mechanisms of SFML.

Alternatively, the optimization-free methods enable us to analytically design an SFML with physical explanation. Since the field of view of an SFML is limited in a certain region, prolate spheroidal wave functions (PSWF),^[87-88] a set of band-limited functions, which are orthogonal and complete on a finite interval and across the infinite open interval, are suitable for synthesizing the lenses. The design procedure of an SFML using PSWF was shown in Ref.^[89] Besides, Newton theory and Schelkunoff super-directive antenna theory were also applied to unveil the fundamental physics, and enable us to design a focal super-oscillation spot while pushing the high sidelobe away from the center.^[82, 90-92]

SFMLs have no need to be placed in the near field to collect the evanescent wave, different from the evanescent-wave-collecting lenses, but are restricted by a narrow view of field due to the inherent sidelobes with higher energies.^[93-95] An imaging system with an SFML is illustrated in Figure 8c.^[94] The system includes a Xe-lamp, an optical collimator (AL1), an iris, three same achromatic lenses (AL2, AL3, AL4), a mirror, two linear polarizers (LP1, LP2), an SFML (the metasurface), and a CCD. The imaging results of the system are shown in Figure 8d. As can be seen, an object 'E' cannot be resolved by the system without the SFML. However, as the SFML inserted, the system is capable of resolving the object 'E' but with a narrow field of view due to high-intensity side lobes. Therefore, how to realize a flat metalens with a wider field of view and capable of breaking diffraction limit remains a future work.

3. Computational Meta-imaging

For a non-computational imaging system, every component can be designed independently. In contrast, the definition of a computational imaging system is that its design systematically incorporates optics, optoelectronics, and signal processing, and its performance is determined through joint design and optimization.^[96] A comparison between non-computational and computational imaging is shown in Figure 1. We reiterate that the computational imaging

system needs either pre-processing or post-processing, in contrast to the non-computational imaging ones which design and optimize all imaging components sequentially and independently.

In reality, an imaging system has many design constraints such as size, weight, power, and cost. Metamaterial/metasurface-based computational imaging system, compared with the non-computational one, shifts the burden from hardware to software, and may bring the following advances: 1) lower profile, 2) lower cost, 3) reduced complexity of the imaging system, and 4) without mechanically moving parts. Besides, objects to be imaged can be three-dimensional, polarized, and time-variant in the context of computational meta-imaging, in contrast to non-computational meta-imaging where the objects are implicitly assumed to be planar and scalar.

In this section, we mainly discuss the principles, design and realization of a computational meta-imaging system based on Born approximation, ghost imaging, and synthetic aperture radar (SAR). In addition, other computational methods are listed as practical examples at the end of this section to show the versatility of computational meta-imaging systems.

3.1. Born Approximation

We begin with the scattering and inverse scattering point of view. In the context of scattering, a uniform medium serves as the background medium, which is usually either vacuum or air. The scattering object (in imaging system it is the object to be imaged), or scatterer has different properties from the background and can be viewed as a collection of induced sources. We denote the electric field of an incoming electromagnetic wave on a scatterer as the incident field $\mathbf{E}_i(\mathbf{r}, \omega)$. Due to the existence of the scatterer, the electric field distribution, denoted as total field $\mathbf{E}_t(\mathbf{r}, \omega)$, is different from incident field $\mathbf{E}_i(\mathbf{r}, \omega)$. We define the difference between the total field and the incident field as scattering field and denote it as $\mathbf{E}_s(\mathbf{r}, \omega)$.

For simplicity, we consider only an isotropic and non-magnetic scatterer (the object to be imaged) with arbitrary shape in the vacuum. It is noted that extending the results of this

discussion to more general cases can be done. Assume that the incident field $\mathbf{E}_i(\mathbf{r}, \omega)$ incident on the scatterer, the scattering field $\mathbf{E}_s(\mathbf{r}, \omega)$ can then be expressed as

$$\mathbf{E}_s(\mathbf{r}, \omega) = \mathbf{E}_t(\mathbf{r}, \omega) - \mathbf{E}_i(\mathbf{r}, \omega) = \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \omega^2 [\varepsilon(\mathbf{r}', \omega) - \varepsilon_0] \mu_0 \mathbf{E}_i(\mathbf{r}', \omega) d\mathbf{r}' \quad (8)$$

where ω is the angular frequency, ε is the relative permittivity of the scatterer, ε_0 and μ_0 are the permittivity and the permeability of air, V denotes the volume enclosing the scatterer, and $\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}')$ is tensor Green's function in free space.^[97] In computational meta-imaging, two situations usually occur. In the first one, the properties of the scatterer, including shape, permittivity, and incident field are completely known. Equation (8) is then a Fredholm linear integral equation of the second kind.^[98] Such a situation is called direct scattering problem.^[92] The second situation to which we should pay more attention is that the incident field is known while the properties of the scatterer are not. We need to solve an inverse scattering problem so as to deduce information of the scatterer from measurements of the scattering field, that is, to acquire an image of a scatterer.^[99] Equation (8) becomes a Fredholm linear integral equation of the first kind, which is nonlinear since unknown quantities are on both sides of the equation.^[98] However, it can be simplified to a linear equation under certain conditions.

We consider Born approximation to simplify the inverse scattering problem governed mathematically by Equation (8).^[97] Under Born approximation, the total field of a scatterer can be approximated to the incident field, i.e., $\mathbf{E}_t(\mathbf{r}, \omega)|_V \approx \mathbf{E}_i(\mathbf{r}, \omega)|_V$, and thus Equation (8) can be simplified as

$$\mathbf{E}_s(\mathbf{r}, \omega) = \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \omega^2 [\varepsilon(\mathbf{r}', \omega) - \varepsilon_0] \mu_0 \mathbf{E}_i(\mathbf{r}', \omega) d\mathbf{r}' \quad (9)$$

Here, the only unknown quantity is the scatterer, defined as $\varepsilon(\mathbf{r}', \omega)$. In a practical imaging system, a measurement of a detector at a given point is often not a vector response yet a scalar response of the scattering field. For example, if we use a small antenna to measure the scattering field, the result of measurement is either the voltage or the current rather than the scattering

field vector. The vector-to-scalar processing can be boiled down to that a linear operator R performed on the scattering field vector:

$$g(\omega) = R[\mathbf{E}_s(\mathbf{r}, \omega)] = \kappa(\omega) \int_V \mathbf{E}_i^R(\mathbf{r}', \omega) [\varepsilon(\mathbf{r}', \omega) - \varepsilon_0] \mathbf{E}_i^T(\mathbf{r}', \omega) d\mathbf{r}' \quad (10)$$

where κ is a normalized factor, $\mathbf{E}_i^R(\mathbf{r}', \omega)$ is the incident field if the detector (usually a low gain antenna) operates as a transmitter, and $\mathbf{E}_i^T(\mathbf{r}', \omega)$ is the actual incident field. More details regarding Equation (10) can be referred to Ref.^[100] Discretizing the volume V into N voxels and ignoring the normalized factor, we have

$$g(\omega) = \sum_i^N E_i^T(r_i, \omega) E_i^R(r_i, \omega) \Delta\varepsilon(r_i, \omega) \quad (11)$$

Although the scatterer is isotropic in the discussion above, all equations can be generalized to a more universal situation by introducing tensor permittivity and tensor permeability while keeping a similar form.^[101] After conducting M times measurements, we acquire an M by N matrix by stacking Equation (11). We call each column a measurement mode. To obtain the maximal information of the scatterer, the metamaterial aperture should be capable of providing distinct measurement modes that can be implemented by one of the following operations: 1) sweeping frequencies, 2) changing E_i^T or E_i^R , or both, 3) performing 1) and 2), simultaneously. One thing should be noted that the matrix acquired by Equation (11) is usually ill-posed, that is, straightforwardly inverting the matrix results in numerical nonsense.^[102] This issue can be estimated by two parameters. One is the condition number which will often trend to extremely large as ill-posed matrices are encountered. The other one is the ranks of the transfer matrices which directly determine the amount of independent information that the imaging system can assess. Therefore, diversity mechanisms, e.g., frequency, reconfigurability, are applied to improve the performance of the imaging systems.

A typical representation of a Born approximation-based meta-imaging system (BAMS) is shown in **Figure 9a**.^[103] Metamaterial apertures are sources of incident field and perform

preprocessing. Detectors are usually low-gain and wideband antennas, allowing the BAMS to receive scattered field from all directions at all operating frequencies so as to collect the information of the scatterer(s) as much as possible. Sweeping over all measurement modes of the metamaterial apertures results in all measurements, and thus, we can acquire a linear system. Solving the linear system with a regularization, i.e., performing postprocessing, we acquire the image of the object. The regularization is necessary in general since the inverse scattering problem is often ill-posed.^[102] Owing to the preprocessing, such a computational meta-imaging system requires no mechanical parts and performs directly three-dimensional imaging,^[104-106] and even polarimetric imaging.^[107] The reason why metamaterial aperture can perform preprocessing is that each element of a metamaterial aperture can be regarded as a dipole with Lorentz-type response, of which polarizability can be expressed as

$$\chi(\omega) \propto \frac{\omega^2}{\omega^2 - \omega_0^2 + j\gamma\omega} \quad (12)$$

where ω_0 and γ are the angular resonance frequency and the damping frequency, respectively.^[103-104] There are two methods to retrieve all parameters: 1) theoretical calculation based on surface equivalence principles and coupled-mode theory, 2) numerical simulation.^[101] The resonant frequencies of the metamaterial elements are randomly distributed over a large bandwidth such that the radiation patterns of the metamaterial aperture spatially change as frequency varies. In addition, each element should have a high Q factor associated with the damping coefficient so as to keep each measurement mode as distinct as possible. However, improving Q value results in low radiation efficiency which determines the signal to noise ratio (SNR).

Cavity-backed metamaterial aperture was proposed to reconcile the discrepancy between high Q value and SNR, as shown in Figure 9b and 9c.^[109-112] We can understand the operating principle of cavity-backed metamaterial aperture from a perspective of cavity-type feeder, that

is, the rapid variation of modes of a cavity with the variation of the input frequency is equivalent to that the excitation of the metamaterial aperture alters quickly, leading to the fast variation of the radiation pattern, and thus the correlation between two measurement modes is reduced and the distinction grows. Besides, the arrangement of metamaterial elements can be optimized to increase the possible measurement modes.^[113] Cavity-backed metamaterial aperture based on 3D printing was proposed to circumvent the requirement of conventional expensive and time-consuming fabrication techniques.^[114] Array of cavity-backed metamaterial aperture was used to achieve an improvement of measurement modes.^[115]

Although the abovementioned metamaterial apertures operate well in practice, correlations between measurement modes are heavily dependent on randomness, making it difficult to control the measurement modes in advance to reduce the measurement complexity, e.g., the measurement times. A more elegant method to generate sufficient measurement modes employs reconfigurable metamaterial/metasurface apertures (RMMA), where each constitutive element is electrically tunable.^[116-120] In microwave regime, by attaching one or several diodes/varactors to each metamaterial element, RMMA is capable of real-time dynamic regulation. Leaky-wave antenna and machine learning theory can be applied to optimize the measurement modes.^[121-122] Besides, cavity-backed RMMAs were demonstrated as effective measurement-mode generators.^[123-124] RMMAs have also been realized in terahertz,^[118] infrared and optical bands.^[125-127] Figure 9d shows an infrared meta-imaging system. Light transmitted through the object are processed by a metasurface. Meta-atoms of the metasurface are tunable due to being integrated with graphene, and thus, the metasurface, following mask patterns, is able to process the light. The imaging result is acquired by postprocessing the measurements collected by MCT.

It should be noted that Born approximation is valid for weak scatterers.^[97, 99] Moreover, it might be burdensome for the software if we intend to image a large region since one needs to discretize the region into a numerous set of pixels/voxels based on the diffraction limit.^[128] Decreasing the number of pixels/voxels may be considered but at the cost of lower image

resolution. Compressive sensing (CS) algorithms can reconcile the discrepancy between computational burden and resolution, yet are subject to sparse scenes.^[129-130]

3.2. Synthetic Aperture Radar

The range and the cross-range resolution of a given metamaterial aperture read

$$\delta_r = \frac{c}{2B}, \quad \delta_{cr} = \frac{\lambda R}{D} \quad (13)$$

where c is the speed of light, B is the bandwidth of the transmitted signal, λ is the wavelength, D is the effective size of the aperture, and R is the distance from the object to the aperture.^[131]

The range and cross-range resolution are the resolution in the direction perpendicular to and parallel to the metamaterial aperture, respectively, as shown in **Figure 10a**. The Equation (13) indicates that increasing the effective size of the metamaterial aperture leads to resolution improvement. However, increasing size may result in higher cost and fabrication difficulty in practice.

Synthetic aperture radar (SAR) provides an alternative solution.^[132-138] As illustrated in Figure 10a, the virtual aperture is synthesized with effective dimension larger than the physical metamaterial aperture which moves at xoy -plane to take coherent processing of multiple interrogations of an object/objects. Assuming M scattering points, SAR system can be mathematically expressed as

$$g = \sum_m \gamma_m a_m e^{-j\omega \frac{R_m}{c}} \quad (14)$$

where g is the received signal, γ_m is the reflection coefficient, a_m represents antenna gain and round-trip path loss between the m th scattering point and the receiver, R_m is the length of the round-trip path, ω is angular frequency of the transmitted signal and c is the speed of light. Advances of metamaterial aperture for SAR imaging compared with conventional SAR hardware platforms (such as phased array) are lower cost, light weight, lower energy cost, much more compact.^[134] Besides, metamaterial-based SAR provides not only stripmap and spotlight

modalities as conventional SAR does, but also enhanced resolution stripmap and diverse pattern stripmap modalities.^[134]

A typical experimental set-up of SAR meta-imaging system is shown in Figure 10b.^[136] A dynamic metasurface antenna operating in X-band (10-13.7GHz) moves parallel to the cross-range dimension while its main beam scans the imaging plane. A bistatic transfer function S_{21} is collected by a vector network analyzer (VNA) and then postprocessed to form the SAR image of the imaging plane. Figure 10c shows another situation called inverse SAR (ISAR): the object is on a moving stage while the metamaterial aperture remains stationary.^[137] Since the movements are mutual, the imaging processes on both situations presented in Figure 10b and 10c are the same.

There are also some other types of SAR meta-imaging system. MIMO SAR can be used to reconcile the trade-off between high resolution and large imaging area, and has been experimentally demonstrated with metamaterial apertures.^[139-140] Instead of translating a metamaterial aperture, rotational SAR can be another approach to enhance SAR imaging quality.^[141] With assistance of graphic processing unit, the post processing of SAR data is accelerated with an improvement of cross-range and range resolution compared with standard SAR.^[142] Range decoupling algorithm was used to accelerating SAR imaging.^[143] Single frequency SAR was implemented to achieve 3D imaging.^[144]

In fact, the Born approximation and SAR are almost the same in the mathematical sense.^[135, 145] From a mathematical point of view, SAR is nothing different from Born approximation yet with a moving compensation due to the movement of metamaterial aperture. This point will be clearer, as we compare Equation (11) with Equation (14): $\Delta\epsilon(r_i, \omega)$ vs γ_m , $E_i^T(r_i, \omega)E_i^R(r_i, \omega)$ vs $a_m e^{-j\omega R_m/c}$. Therefore, SAR can be considered as the counterpart of Born approximation in time domain since it assumes that the antenna patterns are invariant the same as the assumption of Born approximation.

3.3. Ghost Imaging

Both Born approximation and SAR imaging modalities require complex signal measurements, that is, recording the amplitude and the phase of scattered fields. As frequency increases from microwave to optics, accurate measurements of phase may be difficult and make the system more complex and more vulnerable to noise.^[146-150] ~~Therefore, a phaseless imaging method can not only reduce complexity but also improve stability of the computational imaging system.~~ Computational ghost imaging method can instead perform intensity-only imaging with single pixel.^{[151][152]} In addition, computational ghost imaging, compared with traditional optical imaging systems, is more attractive due to its prominence of higher resolution, higher detection, and more robustness.^{[153][154]}

~~In contrast to two methods mentioned above that rely on reliable phase measurements,~~ Ghost imaging retrieves the object information from correlation of light intensity fluctuations.^[155-156] In ghost imaging systems, one beam is split into two: one referred as to the object beam is transmitted through or reflected by the object, and then detected by a bucket detector; the other one referred as to the reference beam is directly detected by a high spatial-resolution detector array. An image of the object is formed by correlation calculation of light intensity recorded by the bucket detector and the detector array. Computational ghost imaging (CGI) simplify ghost imaging system with removing the detector array and using only the bucket detector, since the reference beam can be calculated by Fresnel diffraction integral.^[157]

Single-pixel CGI have been initially demonstrated to produce promising results for 2D and 3D imaging.^{[152][153]} Later, single-pixel CGI with a high efficiency metasurface was demonstrated at optical region both computationally and experimentally, as illustrated in **Figure 11a**.^[158] Such an imaging system is capable of both imaging and optical encryption. In microwave region, RMMA play the role of diffusing media or spatial light modulators in the optical ghost imaging systems.^[159-160] The microwave ghost imaging system is illustrated in Figure 11b. The image of the object is deduced by the fluctuation of electromagnetic wave intensity between the two RMMA measured by a VNA.

3.4. Other Computational Meta-imaging Methods

In this section, we will summarize several computational meta-imaging methods without diving into the principles and analysis, to demonstrate the diversity of computational meta-imaging and refer readers for further reading.

Diffuser imaging. Inhomogeneity of a sample, such as biological tissue, scatters light, limiting accordingly the resolution and the depth of field of an optical system. Based on memory effect,^[161-162] using a disordered medium layer (a diffuser) to capture the scattering light instead of a lens can realize an image of the sample close to diffraction limit,^[163] and a 3D image reconstruction.^[164-165] However, time-consuming characterization, instability with time, and limited memory-effect range could be critical drawbacks for diffuser imaging systems associated with the conventional disordered layers. Replacing those layers with a metasurface diffuser can alleviate these problems and thus make the imaging system more robust, as illustrated in **Figure 12**.^[166]

PSF-designer imaging. A linear, shift-invariant optical system can be fully characterized by its point spread function (PSF). Designing a PSF with particular properties leads to an imaging system with desired properties. An extended depth of focus (EDOF) metasurfaces with parabolic phase profile plus a cubic phase term, leading to an invariant PSF across the entire visible regime, could perform in-focus full-visible-spectrum direct imaging with the white light, as shown in **Figure 13a**.^[167] Moreover, a double-helix PSF (DH-PSF) which rotates as an object to be imaged moves along axis can uniquely encode the object distances.^[168] A Huygens' metasurface with the DH-PSF was fabricated and applied to image a scene with a conventional camera, as depicted in Figure 13b and 13c. The image of the scene with depth information was generated by calculating the power cepstrum of measurements taken by the camera.^[169]

Dispersive Fourier Imaging. Dispersive Fourier transformation (DFT) is an emerging measurement technique which can be applied to real-time spectroscopy, laser scanning, and analog-to-digital conversion and imaging.^[170] Dispersive Fourier imaging system is capable of

achieving ultrafast imaging. However, dispersive components limit the system power efficiency and thus degrade the system performance. With a gap-plasmon metasurface grating integrated into the system, higher power efficiency is achieved compared with the use of conventional gratings,^[171] as illustrated in **Figure 14**. Implementing such a system with all electronic components without optical dispersive components is also possible.^[172]

Light-field Imaging. Light-field imaging theory describes light intensity distribution as a plenoptic function $P(\theta, \varphi, \lambda, t, x, y, z)$. This function governs how light rays pass through the space with the spherical coordinates (θ, φ) , and how light intensity varies with wavelength λ , time t and spatial coordinates (x, y, z) .^[173] It allows us to form an image of a scene with depth information (that's 3D imaging). Conventional light field camera (LFC) utilizes microlens array, suffering from aberrations and large size. However, LFC composed of achromatic metalens array has inherent advantages, such as aberration-free, large depth of field, compact size, and dynamic imaging.^[174-175] As shown in **Figure 15**, the image formed the metalens array on the sensing plane is captured and rendered to acquire the reconstructed images with different depths (the flowers and the person). Moreover, a metalens array enables the retrieval of the polarimetric and the phase profiles of the incident beam.^[176]

4. Conclusion

We review meta-imaging from the non-computational to the computational perspectives in this paper. Metamaterial/metasurface provides a remarkable platform for designing and realizing imaging devices which is capable of controlling amplitude, phase and polarization of electromagnetic waves at will and gives more flexibility and freedom to designers. Recently, analog computation using metamaterials/metasurfaces has become an emerging field,^{[177][178][179][180]} which can perform mathematical operations (e.g., differentiation and integration) and signal processing, and pave a way to overcome the speed and energy limitations of digital techniques. However, since these metamaterials/metasurfaces do not focus on the

imaging purposes, we do not categorize these thrilling achievements as ‘computational imagers’ discussed in this review.

Metamaterial/metasurface-based lens provides a powerful tool to direct imaging, i.e., non-computational imaging. Super resolution imaging beyond diffraction-limit has been realized by perfect lens and superlens. Farfield superlens and hyperlens were proposed to acquire super-resolution image in the farfield since perfect lens and superlens form an image in the near field. Bulk metalens fills the gap that metamaterial-based lens cannot focus plane wave. However, the application of 3D metamaterial is hindered in practice due to high loss, manufacturing difficulty, and strong dispersion. Therefore, metasurface draws great attention from metamaterial community. Metasurface-based lens (flat metalens) is not only with lower loss and suitable for integration and miniaturization in modern electromagnetic imaging systems, but also can be designed to diminish aberrations. However, the flat metalenses suffer from some limitations, such as being incapable of super resolution with wide view of field and image distortion. Overcoming these limitations may motivate future studies.

Besides, we have also shown the impact of computation on meta-imaging. The marriage of advanced computational algorithms and versatile metamaterial hardware platforms, compared with non-computational meta-imaging, provides low cost, reduced complexity, and more intelligent imaging systems. One can balance the capability of hardware and software, and thus retrieve not only a 2D image of the object but also more information, such as depth and polarization.

Non-computational and computational meta-imaging techniques pave a new way to image the real world, and have been demonstrated with great potential in various practical situations. We envision that the development of meta-imaging from devices to algorithms will bring a revolution in next-generation imaging products. For the non-computational meta-imaging, multi-task imaging could be a potential hotspot, where the multiplexing metasurfaces are capable of maximizing their potentials. Sub-diffraction-limited meta-imaging methods with

improved efficiency and extended field of view is definitely another challenge to be accomplished. Besides, compact and highly efficient aberration-free meta-imaging approaches are in great demand. For the computational one, many territories deserve to be cultivated, where the unprecedented properties of metamaterials/metasurfaces will fully unlock the potentials of advanced algorithms, or greatly simplify the hardware complexities of computational imaging systems.

Acknowledgements

This work was partially supported by National Natural Science Foundation of China under Grant no. 61671178 and no. 61301013.

Received: ((will be filled in by the editorial staff))

Revised: ((will be filled in by the editorial staff))

Published online: ((will be filled in by the editorial staff))

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Figure 1. Non-computational and computational imaging. a) Non-computational meta-imaging (red dashed box) vs computational meta-imaging (blue dashed box). b) The diversity of meta-imaging.

Figure 2. Evanescent-wave-collecting lenses. a) An optical silver superlens and b) its corresponding result. c) Experimental set-up of FSL and d) the subwavelength imaging results. e) Magnifying optical hyperlens and f) the imaging of line pair object. a) and b) Reproduced with permission.^[14] Copyright 2005, American Association for the Advancement of Science. c) and d) Reproduced with permission.^[19] Copyright 2007, American Chemical Society. e) and f) Reproduced with permission.^[24] Copyright 2007, American Association for the Advancement of Science.

Figure 3. Three typical bulk focal metalenses. a) The PWC illuminated by the normally and the obliquely incident plane wave, respectively, b) the MIL and c) the GRIN. a) Reproduced with permission.^[33] Copyright 2010, AIP Publishing. b) Reproduced with permission.^[34] Copyright 2010, Optical Society of America. c) Reproduced with permission.^[35] Copyright 2011, American Physical Society.

Figure 4. Flat metalenses. a) Schematics used to derive the phase profile of a metalens. Media on both side of the metalens are supposed to be air, i.e., refractive index $n = 1$. b) SEM image of the a flat metalens with 3 cm focal distance and the corresponding phase profile and the results of focusing of the metalens. c) The imaging results of the handness-dependent flat metalenses. d) A Huygens' metalens and its meta-atom. e) Experimental set-up of a PMMW imaging system and the image (left lower) of the 'HIT' metal pattern (right lower) taken by the metalens for PMMW. b) Reproduced with permission.^[37] Copyright 2012, American Chemical Society. c) Reproduced with permission.^[43] Copyright 2018, Optical Society of America. d) Reproduced with permission.^[46] Copyright 2017, John Wiley and Sons. e) Reproduced with permission.^[54] Copyright 2018, AIP Publishing.

Figure 5. Chromatic aberration-free flat metalenses based on phase compensation. a) The comparison of chromatic and achromatic metalenses and the phase profile of a metalens at different wavelengths. b) Scattering efficiency Q_{scat} (upper panel) for one meta-atom with geometry $s = 1$ mm, $t = 400$ nm, $w_1 = 300$ nm, $w_2 = 100$ nm, and $g = 175$ nm, and focal lengths of the metalens as a function of wavelength (lower panel). The inset in lower panel is the schematic of the meta-atom with two coupled rectangular dielectric resonators. c) Schematics of meta-atom archetypes: Generation 1A, Generation 1B and Generation 2, and the corresponding calculated phase and dispersion libraries of the three types of meta-atom (lower row). a) Reproduced with permission.^[56] Copyright 2017, S. Wang et al. b) Reproduced with permission.^[58] Copyright 2015, American Association for the Advancement of Science. c) Reproduced with permission.^[64] Copyright 2018, S. Shrestha et al.

Figure 6. Chromatic aberration-free flat metalenses based on multiplex meta-atoms and stacked multi-layers. a) The SEM image of the metalens (top left) and schematic illustration of multiplexing meta-atoms (top right). The measured results at the focal plane are shown in the bottom row. b) Schematic illustration of a stacked three-layers metalens (left). The measured intensity profile (top right) of and imaging demonstration (bottom right) of the metalens under chromatic illumination. a) Reproduced with permission.^[67] Copyright 2018, American Chemical Society. b) Reproduced with permission.^[71] Copyright 2018, O. Avayu et al.

Figure 7. Monochromatic aberration-free flat metalenses. a) Schematic of a doublet metalens (left) and image taken with the doublet (right). b) Schematic of imaging setup of a monochromatic singlet metalens (left) and the corresponding imaging results at angles ranging from 0° to 82°. c) SEM image of the metalens with FoV up to $\pm 15^\circ$ (left) and its imaging result. a) Reproduced with permission.^[74] Copyright 2016, A. Arbabi et al. b) Reproduced with permission.^[76] Copyright 2019, Optical Society of America. c) Reproduced with permission.^[77] Copyright 2020, J. Engelberg et al.

Figure 8. Super-oscillation Flat Metalenses. a) Schematic drawing of a super-oscillation flat metalens and its intensity profile at focal plane. b) The criterion of the Rayleigh diffraction limit and super-oscillation: spot size as a function of numerical aperture (NA). The black and white curves are Rayleigh and super-oscillation criteria, respectively. c) The experimental set-up of an SFML imaging system. d) Panels from left to right are object 'E', its images without and with SFML, respectively. b) Reproduced with permission.^[82] Copyright 2013, John Wiley and Sons. c) and d) Reproduced with permission.^[94] Copyright 2018, John Wiley and Sons.

Figure 9. Born approximation meta-imaging. a) Schematic diagram of a BAMS. b) A cavity-backed BAMS includes a transmitting cavity-backed metamaterial aperture and four receiving probes. c) In order from top to bottom: 3D schematic drawing of and front view of BAMS, and imaging results of a mannequin. d) Schematic illustration of an infrared meta-imaging system. M1, M2: flat mirrors, BS: beamsplitter, P: polarizer, M3: parabolic mirror, MCT: mercury-cadmium-telluride single-pixel detector. The infrared RMMA and imaging result are shown at top right corner and at bottom left corner. a) Reproduced with permission.^[103] Copyright 2015, Optical Society of America. b) Reproduced with permission.^[109] Copyright 2015, AIP Publishing. c) Reproduced with permission.^[112] Copyright 2017, J. N. Gollub et al. d) Reproduced with permission.^[126] Copyright 2018, B. Zeng et al.

Figure 10. SAR meta-imaging system. a) Schematic of SAR meta-imaging system. b) A typical experimental set-up of SAR meta-imaging system in laboratory. c) An ISAR meta-imaging system (top) and its experimental results (last two rows). b) Reproduced with permission.^[136] Copyright 2017, Optical Society of America. c) Reproduced with permission.^[137] Copyright 2017, Optical Society of America.

Figure 11. Ghost meta-imaging system. a) Experimental set-up of single-pixel CGI with a high efficiency metasurface. (b) Computational microwave GI configuration with two RMMAAs. a) Reproduced with permission.^[158] Copyright 2017, H. C. Liu et al. b) Reproduced with permission.^[159] Copyright 2018, Optical Society of America.

Figure 12. Schematic illustration of diffuser meta-imaging. The metasurface diffuser scatters light from the object, generating a speckle pattern. Since the properties of the metasurface diffuser is known, the image can be retrieved from the speckle pattern after SSM method applied. Reproduced with permission.^[166] Copyright 2018, Optical Society of America.

Figure 13. PSF-designer meta-imaging. a) In-focus full-visible-spectrum direct imaging results under white light, which are the original object (left), the images formed by a single metasurface functioning as a lens (center) and by an EDOF metasurface (right). b) Schematic illustration of the creation of a DH-PSF with a phase mask formed by a metasurface. c) In order from left to right: the rotation angle of DH-PSF in dependence of point source distance D , the photograph of target scene, the retrieved depth information of the scene. a) Reproduced with permission.^[167] Copyright 2018, S. Colburn et al. b) and c) Reproduced with permission.^[169] Copyright 2019, C. Jin et al.

Figure 14. Dispersive Fourier Imaging. a) The experimental set-up. b) The whole pattern of 1951 USAF test chart. c) The reconstructed image corresponding to the red dashed box in b). a), b) and c) Reproduced with permission.^[171] Copyright 2014, AIP Publishing.

Figure 15. Experimental set-up light-field meta-imaging. Reconstructed images with different depths of focus are rendered from the images captured from the sensing plane. Reproduced with permission.^[174] Copyright 2019, Springer Nature.

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This review focuses on applications of metamaterials/ metasurfaces in the electromagnetic/ optical imaging, and summarize the recent developments of metamaterial/metasurface imaging in a new perspective, which can be categorized into the non-computational and the computational ones. The former includes sub-diffraction-limited and aberration-free imaging, while the latter shows the impact of computation on imaging.

Keyword metasurfaces, metamaterials, imaging, computational imaging

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Title Meta-imaging: from Non-computational to Computational

ToC figure