Electromagnetic Architectures: Structures, Properties, Functions and Their Intrinsic Relationships in Subwavelength Optics and Electromagnetics

Xiangang Luo\textsuperscript{1,2}*, Mingbo Pu\textsuperscript{1,2}, Yinghui Guo\textsuperscript{1,2}, Xiong Li\textsuperscript{1,2}, and Xiaoliang Ma\textsuperscript{1,2}

Prof. X. G. Luo, Prof. M. B. Pu, Prof. Y. H. Guo, Prof. X. Li, Prof. X. L. Ma
State Key Laboratory of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, P.O. Box 350, Chengdu 610209, China.
School of Optoelectronics, University of Chinese Academy of Sciences, Beijing 100049, China.
E-mail: lxg@ioe.ac.cn

Keywords: electromagnetic architectures, structural-functional relationship, subwavelength structures, metasurface

In recent years, with the development of photonic crystals, metamaterials, metasurfaces, and other related disciplines, the relationship between the structures and functionalities of artificial optical/electromagnetic materials and devices has become a research hotspot. This article reviews the optical/electromagnetic properties and performance of typical artificial micro/nanostructures. Based on the analogy of mechanics and optics/electromagnetism, the concept of “Electromagnetic Architectures” is proposed. In particular, we reviewed several typical methods for the study of optical/electromagnetic structural-functional relationships, including semi-classical analytical models, heuristic optimization methods, deep neural networks, topological optimization methods, etc. The viewpoint of this paper may push further researches on the structural-functional relationship of artificially structured materials and devices, and find broad application prospects in imaging, communication, photonic chips, among many others.
1. Historical remarks

For quite a long time, structures and functions of matters are the core of physics researches. From celestial bodies and buildings to the atomic and molecular structure of common materials, the structures of various scales determine their basic functions, wherein the underlying physical laws of the interaction between substances are called "structural-functional relationship". For example, the law of universal gravitation determines that most celestial bodies are approximately spherical in shape and move in nearly elliptical orbits.

Meanwhile, the molecules in crystals reach equilibrium states under the action of many molecular forces, thereby forming regular and orderly structures, which determine their mechanical, thermal, electromagnetic, and optical properties. Under the classical optical theoretical framework, the surfaces of both the refractive and reflective lenses are shaped to be curved to bend the light trajectory. The curved profile and large weight of refractive/reflective lenses and mirrors hinder the development of next-generation optical systems, especially in integrated space telescopes and wearable optical devices and systems.

In recent years, with the development of micro/nanofabrication technology, it has been discovered that artificial structures have many physical properties not occurring in traditional materials. It is expected to achieve many disruptive functions through artificial structures, such as photonic bandgap, negative refractive index, sub-diffraction imaging, etc. Therefore, research directions such as photonic crystals, metamaterials, and surface plasmons have become research hotspots in the field of optics and electromagnetics during the past two decades.

Humans have a long history of changing optical and electromagnetic properties through artificial structures. For example, structural color was created by light interactions with certain nanostructures that strongly influence the light scattering properties. As shown in Figure 1, due to the surface plasmon absorption effect of metal particles, the late Roman (4th century AD) Lycurgus cup exhibits different colors under transmission and reflection.

This article is protected by copyright. All rights reserved.
The emergence of new optical materials has not only advanced the development of electromagnetic antennas, but also promoted the concept of microwave antennas. On the one hand, optical structures have been used for more than a century, and from an electromagnetics research perspective, they are promising. For example, the Chinese Magic Mirror (1th century BC) has provided many new and marvelous opportunities. (TCO), two-dimensional (2D) materials, phase-change materials, and so on) have become the cornerstone of many optical systems. In principle, such a device can be regarded as one early type of hologram.

In optical engineering, both flat and curved mirrors have already been made in ancient Greece and China. However, although lenses could be constructed from transparent materials with curved surfaces, the specific law of light refraction is not clear. In 1621, Snell proposed the law of refraction of light, revealing that the angle of refraction is inversely proportional to the refractive index of a substance, thus laying the foundation for the structural design of various lenses and mirrors. The structures, materials, and combination of various lenses and mirrors are key to determining the performance of optical systems. Traditionally, the basic materials for optical applications are mainly transparent glasses, reflective metals, and optical thin films. The emergence of new optical materials (e.g., transparent conducting oxides (TCO), two-dimensional (2D) materials, phase-change materials, and so on) in past decades has provided many new and marvelous opportunities.

Since the 1860s when Maxwell predicted that light is an electromagnetic wave, optical research from the perspective of electromagnetics has become a promising direction. For more than one hundred years, optical, electronic, and electromagnetic technologies have promoted each other. On the one hand, optical structures are constantly being used in electromagnetic antennas, and on the other hand, the concept of microwave antennas has also...
been extended to the optical band.\textsuperscript{[10]} The emergence of optical antennas brings great freedom for the control of light fields. Related investigations have pushed the development of several new research directions, including photonic crystals, surface plasmons, metamaterials, metasurfaces, etc. In essence, these research fields all exploit structured materials to achieve functionalities that are difficult to achieve with traditional materials and devices. Among them, photonic crystals rely on the periodic arrangement of structural materials, forming energy bands similar to electronic crystals through the interference of electromagnetic waves.\textsuperscript{[11]} Metamaterials and metasurfaces are usually composed of periodic or aperiodic array structures with a lattice constant much smaller than the wavelength.\textsuperscript{[12]} Since the period is much smaller than the wavelength, there is no energy band in the frequency band of interest. Although the concept of photonic crystals was not formally proposed until 1987,\textsuperscript{[1]} its research history can be traced back to 1887 when Rayleigh discovered that periodic multilayer dielectric films are completely reflected within a certain range of wavelengths.\textsuperscript{[13]} The multilayer film is a widely used optical micro-nano structure, which can be regarded as a one-dimensional (1D) photonic crystal. 2D photonic crystals are often used as photonic crystal waveguides,\textsuperscript{[14]} which are of great importance in integrated photonics. In contrast, three-dimensional (3D) photonic crystals can not only realize the full bandgap but also can lead to new functions such as photonic topological insulators through special structures.\textsuperscript{[15,16]} Besides, inspired by superlattices, photonic crystals are sometimes called dielectric superlattices and have important applications in nonlinear optics and other fields.\textsuperscript{[17,18]}

Metamaterials in the narrow sense generally refer to negative refraction materials, which were first proposed by V. G. Veselago, and finally realized at the beginning of this century.\textsuperscript{[19,20]} In the broad sense, metamaterials include artificial materials with peculiar equivalent electromagnetic parameters, which can be traced back to the spiral wave plate proposed by Bose in 1897.\textsuperscript{[21]} In 1919, Marconi used a dipole antenna to achieve a prototype of a frequency selective surface (FSS), which is also a generalized low-dimensional

This article is protected by copyright. All rights reserved
metamaterial.\textsuperscript{[22]} Different from natural materials whose properties are primarily determined by the chemical constituents and bonds, metamaterials offer a significantly broader range of material properties by engineering the geometries and arrangements of the subwavelength building blocks (meta-atoms) and thus promise widespread potential applications. Thus far, metamaterials have been realized in the microwave, terahertz, infrared and visible ranges to exhibit many exotic properties, including but not limited to negative/zero/high refractive index, strong chiral, and anisotropic response as well as perfect absorption. For example, the use of plasmonic materials with negative dielectric permittivity is one of the most feasible ways to circumvent the diffraction limit and achieve localization of electromagnetic energy (at optical frequencies) into nanoscale regions as small as a few nanometers. As a result, like Feynman’s statement on nanotechnology, there is plenty of room at the bottom that has not been utilized in traditional optics.\textsuperscript{[23]}

Although gradient index metamaterials offer a feasible way to construct planar lenses and other miniature optical devices, their sizes are usually bulky and the thickness is larger than the operation wavelength. As a result, there has been growing interest in planar, subwavelength-thick planar optical devices with multifunction. Fortunately, the recently emerging metasurfaces (two-dimensional metamaterials) are proved to be able to produce phase discontinuity within a vanishing thickness of structured materials, thus makes it possible to construct lightweight and flat optical elements. The difference between metamaterials and metasurfaces can be understood in the context of constitutive relations and boundary conditions of Maxwell equations. As a result, it was expected that the first generation of practical metamaterial devices will utilize metasurface implementations.

Materials with tunable properties upon external stimuli are crucial for the realization of versatile platforms with reconfigurable functionalities. For instance, by changing the lattice constant of a complex Au nanorod array fabricated on stretchable polydimethylsiloxane (PDMS) substrate,\textsuperscript{[24]} a metasurface that can continuously tune the wavefront has been
demonstrated in the visible range. Meanwhile, vanadium dioxide (VO₂)-based hybrid metamaterials have been shown to have tunable resonances resulting from the VO₂ phase transition at THz and IR frequencies. As another kind of phase change material, germanium-antimony-tellurium (GeₓSbᵧTe₂, GST) has also been utilized to develop reconfigurable metamaterials and metasurfaces, owing to the good stability, high-speed and reversible switching performance. GST undergoes a phase change from the amorphous state to the crystalline state through pumping by ultrafast femtosecond laser beams or by thermal heating, with remarkable dielectric property differences between the two states. In particular, the degree of crystallization can be gradually obtained by applying controllable amounts of external excitation, giving rise to greater flexibilities to access continuous refractive index control. The combination of these characteristics with specifically designed metasurfaces can provide new functionalities toward active electromagnetic perfect absorbers, polarization manipulation, beam steering, and dynamic planar lens.

From the development history of structured functional materials such as photonic crystals and metamaterials, it can be seen that the central tenet is the spatial control of the material units and their arrangement and interaction. Therefore, we proposed a concept of Electromagnetic Architectures to recapitulate these broad research areas. Here we use electromagnetic rather than optics to emphasize that the involved frequency bands cover the entire electromagnetic spectrum, including ultraviolet, visible, infrared, terahertz, and microwave. As illustrated in Figure 2, for spatial-temporal shaping applications, six important parameters must be carefully controlled, including the amplitude, phase, angular frequency, polarization state, wavevector, and group velocity. For instance, by manipulating the wavevector, one could break the classical diffraction limit and achieve super-resolution imaging. By the combination of the wave vector and polarization manipulation, both dynamic and geometric phases could be realized, forming the basis of gradient-phase flat optics.

This article is protected by copyright. All rights reserved
Furthermore, with on-demand dispersion engineering of the group velocity, broadband applications have also been realized.\textsuperscript{36,37}

As shown in Figure 3, it is worth noting that there is a certain analogy between mechanical structure and electromagnetic and optical structure, including the crossroads and cross waveguides, the mechanical catenary and optical catenary, as well as the mechanical and optical spiral structure.\textsuperscript{38} Take the catenary structure as an example, Hooke pointed out that the catenary function is the true mathematical and mechanical form of arched buildings in the early 1670s. As we all know, the stable form of the cable bridge under the action of gravity follows the catenary function. By turning it upside down, one could obtain an arch with stable mechanical properties. Many famous buildings, including the Gateway Arch and the roof of Washington Airport,\textsuperscript{39} are made of the catenary-shaped arch. In classical physics, the law of refraction of light can be derived from Fermat's principle through the principle of least action. If the light is transmitted in a linear gradient medium, the trajectory of the light is just the catenary curve.\textsuperscript{40} Interestingly, when light is irradiated on the microscopic "equal-intensity catenary",\textsuperscript{41} the light wave will obtain "equal-phase gradient", resulting in spin-related deflection.\textsuperscript{42} It can be seen from the above examples that mechanics, optics, and electromagnetism have many similarities in mathematics, and various advanced mathematical methods are also used to study the structural-functional relationship. To make the article more concise, the following part of this article mainly discusses the optical and electromagnetic properties of sub-wavelength structures.

This paper is organized as follows: In Section 2, we first give the classifications and properties of typical artificial structures according to their roles in electromagnetic manipulation. In Section 3, several representative methodologies for the research of structural-functional relationships are discussed. Finally, some conclusions and outlooks are presented. It should be noted that this review is just a guideline for the study of structural-
functional relationship in subwavelength structured materials and devices. More details can be found in the references therein.

2. Properties of typical artificial structures

This section briefly introduces the characteristics of various typical subwavelength structures and provides a basis for studying the structural-functional relationship between subwavelength structures and optical/electromagnetic functions.

2.1. Classification of subwavelength structures

Without the loss of generality, electromagnetic structures could be divided into three categories depending on their arrangement in space. The first kind of structure is single or few structures, which could act as miniaturized devices.\textsuperscript{[42–44]} For instance, single V-shaped or catenary-shaped nanoantennas could convert normally incident electromagnetic waves into unidirectional waveguiding modes.\textsuperscript{[45,46]} Few nano-antennas or nano-apertures could be utilized to collimate light waves to predefined directions.\textsuperscript{[43,47]}

The second kind of structure is a periodically arranged pattern array with identical geometric properties. Some typical examples include the century-old FSS,\textsuperscript{[22]} photonic crystals,\textsuperscript{[11]} negative-index metamaterials, and metasurface perfect absorbers.\textsuperscript{[48,49]} Note that the lattice constant of photonic crystals is larger than the operational wavelength to produce photonic bandgap, while it should be in the deep subwavelength scale to enable effective index approximation of metamaterials. However, in many follow-up studies, the concept of metamaterials is broadened and the deep subwavelength condition is often discarded.

The third kind of structure is a gradient array with space-variant unit elements. The early gradient artificial structured materials in antenna engineering may date back to the 1940s-1960s, where metallic plates and waveguides are utilized as lens antennas.\textsuperscript{[50,51]} Beginning from the late 1980s, as a result of the mature printable microstrip antennas, various reflectarrays with space-variant metallic structures have been proposed to realize flat antennas.\textsuperscript{[52–54]} Meanwhile, in the optical bands, as a consequence of the development of
micro- and nano-fabrication techniques, subwavelength gradient structures were proposed and fabricated to introduce abrupt phase shift.\cite{55-59} Along with the emergence of metamaterials, transformation optics, and metasurfaces, gradient subwavelength structures have been developed explosively during this century. Typical examples include the invisibility cloaks,\cite{60,61} hyperlenses,\cite{62,63} metalenses,\cite{64} etc.

**Figure 4** shows some typical unit structures for electromagnetic engineering. Figures 4(a) and (b) illustrate two classes of elements usually used to obtain isotropic and anisotropic optical functionalities. In FSSs, the transmission and reflection spectrum could be interpreted using equivalent circuit models and transmission line theory. These metasurfaces may be considered as impedance sheets composed of equivalent inductors and capacitors. The geometric shape and size of the elements will then determine the equivalent circuit parameters, e.g., inductance $L$, capacitance $C$, and resistance $R$.

**Figure 4(c)** shows two kinds of planar chiral elements, i.e., the spiral and gammadion,\cite{65,66} which have different responses for opposite circular polarizations. Figure 4(d) shows two kinds of basic elements used for quasi-continuous phase modulation.\cite{67,68} Since small pieces in these elements have space-variant sizes and orientations, smooth geometric and propagative phase shifts would occur naturally. Note that although the characteristic dimensions are smaller than the wavelength, the whole sizes are often larger than one wavelength, thus a single element may act as basic elements of metagratings, which could bend light to almost arbitrary direction with high efficiency.

In a structured array of basic elements, the electromagnetic coupling of adjacent structures has a great influence on electromagnetic properties. **Figures 5(a) and (b)** show two types of lattices that are usually adopted in current researches. If the optical functionality is sensitive to the variation of symmetry, the two kinds of lattices would have completely different performances. For instance, if the isotropic polygonal elements in Figure 5(a) are placed at the lattices, the anisotropic coupling between the adjacent elements would induce

This article is protected by copyright. All rights reserved
nontrivial and lattice-dependent geometric phases, which are referred to as generalized geometric phase.\textsuperscript{[60]} Note that the electromagnetic coupling in the subwavelength scale can be described using catenary-shaped intensity distribution for both metallic and dielectric elements.\textsuperscript{[70,71]}

2.2. Structures for effective electromagnetic parameters

Distinct from naturally occurring materials whose optical constants are determined by the inherent molecules and atoms, the electromagnetic properties of artificially structured materials are mainly determined by the geometries and arrangements of building blocks, which offer unprecedented freedom to tailor the effective materials parameters. For electromagnetic applications, these properties include the effective permittivity $\varepsilon_{\text{eff}}$, permeability $\mu_{\text{eff}}$, refractive index $n_{\text{eff}}$, and impedance $Z_{\text{eff}}$. The refractive index and impedance can be calculated using the permittivity and permeability, which are stemming from the electric and magnetic resonances of the subwavelength structures and lie at the heart of effective medium approximation. It has been shown that Lorentzian resonances may be viewed as possible building blocks for engineering any desired metamaterial response, for example, simultaneous negative permittivity and permeability by use of metallic cut-wires and split-ring resonators of different parameters.\textsuperscript{[2,20]} Many novel physical phenomena and application prototypes, such as negative refraction,\textsuperscript{[20]} sub-diffraction imaging,\textsuperscript{[72]} and cloak,\textsuperscript{[60]} have been demonstrated based on metamaterials.

In the late 1990s, J. Pendry proposed to use metallic rods and rings to control the effective permittivity and permeability in the microwave frequencies,\textsuperscript{[73,74]} which was subsequently combined to realize an effective negative index.\textsuperscript{[2,20]} From then on, many efforts have been paid to increase the operational frequencies to terahertz, infrared, visible, and even ultraviolet bands. Meanwhile, many new kinds of structures have been put forward, including the nanorods pair,\textsuperscript{[75]} fishnet structure,\textsuperscript{[76,77]} the metal-dielectric multilayers,\textsuperscript{[78]} and so on.
Structures exhibiting a near-zero index of refraction at the frequency of interest were defined as zero-index media, including epsilon-near-zero (ENZ), $\varepsilon \approx 0$,[79–82] mu-near-zero (MNZ), $\mu \approx 0$, and epsilon -and-mu-near-zero (EMNZ), $\mu \approx 0$ and $\varepsilon \approx 0$, according to their predominant electromagnetic response. Among them, the metallic mesh of thin wires is the simplest type of metamaterials potentially used to form ENZ medium, since the Drude-like dispersion behavior can be tuned by adjusting the radius and period of the wires.[73]

Besides negative index materials and near-zero index materials, artificial materials with unnaturally high index or chirality are also of particular importance for phase and polarization control. To obtain a high index, metallic patches or slits arrays with narrow gaps and large capacitance are usually adopted.[83,84] To realize chiral response, traditional planar structures are not suitable anymore. Instead, 3D spiral structures or multilayered metallic structures placed in a helical way are required.[85] The earliest such structures may be date back to the 1890s when Bose proposed to use helical jute as polarizers in the microwave and millimeter-wave frequencies.[23] In the optical regime, Robbie et. al., have found the chiral optical response in sculptured dielectric thin films characterized by helical columns with pitches comparable to the visible light.[86] More recently, gold helices with stronger chiral responses are created using direct laser writing into a positive-tone photoresist followed by electrochemical deposition of gold.[85]

Among the varieties of metamaterials proposed, hyperbolic metamaterials (HMMs) have rapidly gained a central role in nanophotonics. HMMs refer to mediums whose permittivity and permeability tensor elements (along principal axes) are of opposite signs, resulting in the hyperbolic equifrequency contour (EFC), including Type I hyperbolic metamaterials ($\varepsilon_x > 0$ and $\varepsilon_z < 0$) and Type II hyperbolic metamaterials ($\varepsilon_x < 0$ and $\varepsilon_z > 0$).[87] Many novel and unique properties result from this hyperbolic EFC. First, hyperbolic EFC gives rise to omnidirectional negative refraction for a certain polarization of the electromagnetic wave. Second, hyperbolic metamaterials can support the transmission of evanescent wave.

This article is protected by copyright. All rights reserved.
components and transform them into propagating waves. This property forms the basis for the so-called hyperlens, enabling subwavelength imaging in the far-field. Finally, the hyperbolic EFC is shown to greatly enhance the photonic density of states in a broad range of frequencies, paving the way for boosting the efficiency of photonic devices. Several different structures have been shown to implement the HMMs, including layered metal-dielectric structures in planar profile,\textsuperscript{[88]} curved and fishnet profile, as well as a lattice of metallic nanowires embedded in a dielectric matrix, termed nanowire array.\textsuperscript{[89]}

2.3. Structures for surface impedance matching

In general, metamaterials are 3D in nature, so they are described by an effective refractive index. However, the refractive index is not well suited for the description of 2D metamaterials, or the so-called metasurfaces. When the thicknesses of metasurfaces become much smaller than the wavelength or are virtually zero, they act as modified boundary conditions, which could be treated as effective impedances.\textsuperscript{[90]} The structures and material compositions of the metasurface will determine the value of impedance.

According to electromagnetic theories, dielectric metasurfaces must have non-negligible thicknesses to perform functionalities, thus the surface impedance approach is widely utilized only in metallic metasurfaces. Since the impedance could be described using equivalent circuits and almost frequency independent parameters such as capacitance, inductance, and resistance, it has provided a versatile approach to control electromagnetic waves in a wide frequency range.\textsuperscript{[91–94]} It was also shown that such an approach can also be extended to the optical regime.\textsuperscript{[95,96]}

For a metasurface described by its impedance, a proper change of the structural parameters could also result in a gradient phase. In this case, the reflection and transmission phase of a single layer metasurface could be obtained using electromagnetic boundary conditions described by the generalized Fresnel’s equations.\textsuperscript{[90]}
Phase modulation is one of the most important tasks of functional optical materials and devices. In traditional optical technologies, the phase accumulation is accomplished by varying either the thickness or the refractive index of the lenses. Such a phase shift mechanism is called dynamic phase and results in large thickness and weight for the large-aperture optical system. Optical researchers have paid much effort to find out new ways to circumvent this barrier. Nowadays, it has been known that subwavelength structures could modulate the phase shift locally, which leads to the so-called generalized law of reflection and refraction: \[ n_1 k_0 \sin \theta_1 + \nabla \Phi (T) = n_2 k_0 \sin \theta_2 \]

where \( \nabla \Phi \) is the phase gradient in the metasurface plane, which is determined by the geometric structure and spatial distribution, and may be changed at different time \( T \) by external stimuli, leading to the adaptive tuning of the law of refraction and reflection. \( n_1 \) and \( n_2 \) are the refractive index of media at the incident and transmit sides. \( \theta_1 \), \( \theta_2 \), and \( \theta_3 \) are the angles for the incident, refracted, and reflected light. Local and gradient phase modulation is the key to realize generalized reflection and refraction. Three kinds of structures and phase
shift mechanisms have been proposed, i.e., propagation phase, geometric phase, and circuit induced resonance phase, as indicated in Figure 6.

Different from the propagation phase accumulation in traditional optical materials and macrostructures, abrupt phase change can occur at a thin interface and a typical example is the plasmon phase retardation through narrow slits drilled in a thin metallic film. The underlying reason is that coupled plasmonic mode is excited in the metallic slits, whose propagation constant is generally several times that in the free space. With the shrinking of the metallic slit width, the propagation constant of coupled plasmonic mode increases sharply. Therefore, when the plasmonic phase retardation through two subwavelength metallic slits with unequal widths are opposite with each other, an extraordinary Young’s interference (EYI) could be observed, i.e., a dark stripe appeared at the center of the interference pattern. Since the propagation constant of plasmonic slits is related to their width, transversal phase gradient can be easily implemented by drilling a series of slits of different widths through a thin metallic film. Several plasmonic phased devices, such as plasmonic flat lenses \[^{[58]}\] and beam deflectors \[^{[100]}\] have been realized based on metallic slit arrays with variant widths, which were experimentally demonstrated in the visible band. In parallel with the plasmonic approach, high-index dielectric nanopillars also provide a means to localize light into the subwavelength scale. Similar to the plasmonic metal-insulator-metal (MIM) waveguide, the propagation constant at a given frequency is dependent on the width and used materials, which promises the local phase modulation for dielectric metasurfaces. \[^{[102,103]}\] Owing to the respective advantages (e.g., low cross-talk and low loss), both plasmonic and dielectric structures have been widely utilized in local phase modulation.

The second phase shift mechanism is the orientation-dependent geometric phase, which can be simply expressed as $\phi = 2\sigma \xi$, where $\sigma = \pm 1$ denotes the left and right-handed circularly polarized (LCP and RCP) incidence and $\xi$ defines the orientation angle of nanoslits or stripes. Such phase change results from the spin conversion that accumulates a Pancharatnam–Berry

This article is protected by copyright. All rights reserved
Recently, an approach to realize high-order geometric phases was proposed using meta-atoms with high-fold rotational symmetries. Broadband angular spin Hall effect of light and optical vortices were experimentally demonstrated by using plasmonic metasurfaces consisting of space-variant nanoapertures with C2, C3, and C5 rotational symmetries, which provides a fundamentally new understanding of the geometric phase as well as light-matter interaction in nanophotonics. The third approach for local phase modulation is based on the local resonance in complex metallic or dielectric structures. For example, for a V-shaped metallic antenna supporting symmetric and antisymmetric modes with different amplitude and phase due to their distinctive resonance conditions, the scattered light can have a polarization different from that of the incident light. Accompanied with the polarization conversion, a local phase shift within $\pi$ is generated, which can be adjusted by changing the arm length and the open-angle of a V-shaped metallic antenna. By exploiting the mirror structure of an existing antenna, one could create a new antenna whose cross-polarized radiation has an additional $\pi$ phase shift. Similarly, C-shape split-ring resonators were also developed for realizing local phase modulation.

Different from the V- and C-shaped metallic antennas, H- and I-shaped metallic antennas do not rely on polarization conversion. Nevertheless, to covering $2\pi$ phase shift and improving the manipulation efficiency, reflective configurations are generally adopted with strong magnetic resonance. Meanwhile, it has been shown that a high-index dielectric...
resonator can support both electric and magnetic dipolar Mie-type modes and exhibit very low intrinsic losses in the optical band. Thanks to the superimposing of the electric and magnetic resonances at the same frequency, a phase shift covering the whole $2\pi$ range can be realized.\footnote{113}

An effective method to simultaneously tailor the phase-amplitude or phase-polarization is combining two kinds of phase shift mechanisms in a single metasurface, i.e., both the geometric parameters and spatial orientation of subwavelength structures are varied. In recent years, the concept of asymmetric photonic spin-orbit interactions (PSOIs) has been proposed to achieve spin-decoupled multifunctional meta-devices by merging propagation phase and geometric phase in plasmonic metasurfaces\cite{93} and dielectric metasurfaces.\cite{34,35,114–116} Besides independent control of the wavefront of opposite-handedness, asymmetric PSOIs can also allow independent amplitude modulation by adopting super-atoms as building blocks,\cite{117–119} which may be utilized for chiral imaging and elliptical polarizers. The symmetry breaking of PSOIs is attributed to the opposite spin dependence of the propagation phase and geometric phase. By employing their opposite frequency dependence, broadband achromatic metalenses have also been realized in multiple spectral bands,\cite{120–123} where the geometric phase and propagation phase are utilized to independently control phase and dispersion, respectively. More interesting, by suppressing the propagation phase in all-dielectric catenary-like streamline structures, a maximum diffraction efficiency approaching 100% is obtained in ultrawide spectral and angular ranges, and wide-angle ($178^\circ$) diffraction-limited imaging has also been realized using a single planar metadevice.\cite{124,125} Besides, multistate wavefront tunable meta-devices have also been realized based on phase-change meta-atoms, in which the combination of the two phases can increase the function complexity while decreasing the design complexity.\cite{126}

2.5. Structures for spectral filtering

This article is protected by copyright. All rights reserved
Besides phase, frequency and wavelength are key parameters to describe electromagnetic waves. Since the full electromagnetic spectrum covers the visible, infrared, ultraviolet, terahertz, and microwave, the tuning of frequency response is of critical importance for applications such as materials characterization, multispectral imaging, and biochemical sensing, etc. In the early days, spectral filtering is typically accomplished with the help of natural dyes, which often suffer from low transmittance, poor selectivity, and bad expansibility. Along with the development of micro- and nano-optics, it was demonstrated that structured materials could be designed as spectral filters at almost arbitrary frequencies in the entire electromagnetic spectrum. Since the frequency response is mainly determined by the structures, the structural color filters may become more stable than natural dyes.

First of all, according to the interference theory, optical multilayered films can be designed as low-pass, band-pass, band-stop, and other kinds of filters. Since the design of multilayers is well understood in the textbook, it will not be discussed in detail in this review. Nevertheless, it should be mentioned that these simple multilayered films are the basis of the 1D photonic crystal. Also, special film stacks such as the metal-dielectric multilayers with thickness much smaller than the wavelength could lead to many novel phenomena such as spatial frequency filtering, subwavelength interference, and sub-diffraction-limited imaging.

One of the most simple spectral filtering multilayer configurations is the Fabry-Perot resonators, which can be modified to construct space-variant color filters for multispectral imaging. Another is the plasmonic holes or slits array, which could be used as compact color filters as a result of the surface-plasmon-assisted extraordinary optical transmission. The transmission peak wavelength is proportional to the lattice constant of the hole arrays and thus the transmitted color can be selected by simply adjusting the lattice. Since surface plasmons can be seen as one kind of guided mode, other types of modes have
also been utilized as color filters. For instance, because dielectric guided-mode resonances bear lower losses and higher quality factors, a narrower spectral response is achievable.\textsuperscript{134}

Dynamic color tuning is a very important and fascinating direction in the field of structural colorations due to its possible applications in stealth, anti-counterfeiting, displaying techniques, etc. Tensile substrate (e.g., polydimethylsiloxane, PDMS) has been introduced into conventional plasmonic structures to demonstrate dynamic tunable structural colors via mechanical deformation. Recently, it is of great interest to develop dynamic structural colors by integrating phase-change materials in artificial structures, opening up more opportunities for further advancement.\textsuperscript{[27,136–139]}

One development trend of structured color filters is the integration of color filtering and other functionalities in a single device.\textsuperscript{140–142} For instance, by combining the plasmonic resonance and geometric phase in reflective metasurface, Zhang et al. proposed a novel approach to realize simultaneous structural color and holography.\textsuperscript{143} Under incoherent white light, the metasurface appears as a polarization- and angle-encoded full-color image with flexibly controlled hue, saturation, and brightness, while switching to multiwavelength holograms under coherent laser illumination. Lim et al. developed a monolithically integrated pixel that overlays a structural color element onto a diffractive phase plate to achieve structural color and hologram simultaneously.\textsuperscript{144}

Besides the aforementioned applications, subwavelength structures are also of particular importance for local field enhancement associated with applications such as biochemical sensing\textsuperscript{145} and nanolithography.

2.6 Structures for reconfigurable functionalities

Reconfiguration is another essential goal for Electromagnetic Architectures because dynamic manipulation of light waves with ultrahigh spatial and ultrafast temporal control can lead to entirely new applications and physics.\textsuperscript{146} However, for most existing subwavelength structures, the function is usually fixed once the structure is fabricated. The emergence of
reconfigurable subwavelength structures enables lightweight, integrated, and flat hardware for optical/quantum communication and computation, light detection and ranging (LiDAR) for autonomous vehicles,\textsuperscript{[147,148]} or other dynamic display applications such as augmented reality and holography.\textsuperscript{[149,150]}

Mechanical actuation offers an effective way to tune the optical properties of structures by reconfiguring their position, orientation, or spatial arrangement. Micro-electro-mechanical (MEMS) technology\textsuperscript{[151,152]} offers high-precision control of position and orientation of meta-devices at sub-nanometer and sub-degree angles. For example, varifocal metalenses have been demonstrated by combining one fixed and one movable metalens.\textsuperscript{[151,153]} Compared with traditional bulky optical elements, the negligible mass of metadevices allows higher operating frequency, which shows great potential for reconfigurable metadevices and digital optics.

Subwavelength structures can also be fabricated on a stretchable substrate such as PDMS. Under an external mechanical force, the arrangement of nanostructures and the spacing will change with the force, resulting in the change of its phase gradient and spectrum response. With such flexible substrate, varifocal metalenses,\textsuperscript{[24]} dynamic holograms,\textsuperscript{[154,155]} and tunable structural colors\textsuperscript{[135,156]} have been demonstrated. As shown in Figure 7a, with the increase of the stretching amount of the PDMS substrate (up to 30\%), the peak wavelength of the resonance will experience redshift, realizing dynamic tunable structural colors.

Compared with the aforementioned mechanical methods, solid-state reconfiguration enables higher tuning frequency and stability. In the microwave region, solid-state tunable structures can be realized by using active elements such as diodes and adjustable capacitors.\textsuperscript{[157–159]} In the optical region, the small wavelength makes it hardly applicable and one of the main ways of constructing solid-state tunable structures is to use reversible materials such as liquid crystals,\textsuperscript{[160,161]} phase-change materials,\textsuperscript{[126,136,137,162–164]} and others,\textsuperscript{[165,166]} whose refractive indices can dynamically respond to heat, electric, optical, or chemical stimulations. In general, solid-state tunable metadevices can be classified into two
categories: pixel control and global control. For the former case, the amplitude or phase of each pixel can be independently controlled through the integrated circuit. Commercial spatial light modulators belong to the former but suffer from problems of low switching rate and small field of view. In recent years, many efforts have been paid on decreasing the size of an independent pixel and increasing switching frequency by combining subwavelength structures and reversible materials like liquid crystals\cite{160} and indium tin oxide.\cite{166} As shown in Figure 7b, a recent study shows that the switching rate can reach up to a high level (~5.4 MHz) but an independent pixel still consists of several nanostructures, resulting in large pixel size.\cite{166}

In contrast, global control requires the same stimulation on the whole device. As a result, it can effectively avoid the aforementioned problems but suffers from another problem of fewer functions. For amplitude or spectral control, one can realize multiple even unlimited levels by giving different degrees of external stimulation,\cite{27,136–138,162} such as different temperature and voltage. Although this action can also cause different phase shifts, practical applications usually require multiple independent wavefronts, which is of great challenge for pure propagation-phase design.\cite{163} Switchable-PSOI-based metasurfaces have been proposed to code multichannel information into different function states,\cite{164,165} but the interlaced arrangement would cause problems of high-order diffraction, low efficiency, and small field of view. Recently, Zhang et al. proposed a methodology to realize multistate switchable PSOIs (Figure 7c), namely, symmetric PSOIs, asymmetric PSOIs, and no PSOIs, by employing polyatomic phase-change resonators,\cite{126} in which phase-change independent geometric phase and phase-change dependent propagation phase can be independently controlled. By merging the two phases, the design complexity can be effectively reduced and all elements can contribute to the wavefront control.

3. Methodologies for the research of structural-functional relationships

The governing equation of electromagnetic and optical problems is Maxwell’s equations. To find the structural-functional relationships of structured materials and devices, Maxwell’s...
equations must be rigorously solved. Combining with the constitutional relations of materials and the boundary as well as the initial conditions, the electric and magnetic fields in any given place could be calculated either analytically or numerically. In some special cases such as planar and cylindrical multilayers, when the structures are simple enough that all electromagnetic fields could be decomposed into orthogonal eigenmodes, analytic or semi-analytic solutions of Maxwell’s equations are possible. In other cases, problems must be numerically solved using rigorous coupled-wave analysis (RCWA), finite difference time domain (FDTD) method, finite element method (FEM), or other similar approaches.

In the following, we first discuss some analytical, semi-analytical approaches, and then the numerical ones. Furthermore, some more advanced concepts such as deep learning and topological optimization are also introduced.

3.1. Analytical and semi-analytical approaches

The transfer matrix method (TMM) is a powerful tool to investigate light propagation through layered media. Within the framework of TMM, the electric or magnetic fields in one layer are related to those in the successive layer through a transmission matrix and a propagation matrix, which connects the fields across an interface and propagating over a distance within a homogeneous medium and can be mathematically expressed as:

\[
\begin{bmatrix}
a_j \\
b_j
\end{bmatrix} = M_{j,j+1} \begin{bmatrix} a_{j+1} \\ b_{j+1} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} e^{ik_jd_j} & 0 \\ 0 & e^{ik_{j+1}d_{j+1}} \end{bmatrix} \begin{bmatrix} 1+K & 1-K \\ 1-K & 1+K \end{bmatrix} \begin{bmatrix} a_{j+1} \\ b_{j+1} \end{bmatrix}
\]

\[
= \frac{1}{2} \begin{bmatrix} (1+K)e^{ik_{j+1}d_{j+1}} & (1-K)e^{-ik_jd_j} \\ (1-K)e^{ik_jd_j} & (1+K)e^{-ik_{j+1}d_{j+1}} \end{bmatrix} \begin{bmatrix} a_{j+1} \\ b_{j+1} \end{bmatrix}
\]

where \(a_j\) and \(b_j\) represent the field coefficients along with different propagation directions, \(k_j\) is the wavevector, and \(d_j\) is the thickness of \(j\)th layer. Here, the harmonic oscillation phase-convention of \(\exp(ikx-\omega t)\) has been assumed, where \(\omega\) and \(t\) denote the angular frequency and time. As a consequence of continuous boundary conditions, the parameter \(K\) is respectively
expressed as \( \frac{k_{j+1}e_j}{k_{j+1}e_{j+1}} \) for transverse magnetic (TM) and transverse electric (TE) polarization. For the stack of \( N \) multilayers, the TMM relates both the incoming and the outgoing waves on one side of the multilayers to those on the other side of the multilayers.

With the TMM, one can easily calculate the optical spectra such as reflection \( (R) \), transmission \( (T) \), and absorption \( (A) \).

TMM has been utilized to investigating photonic band structures,\(^{[167]} \) constructing broadband angular selectivity,\(^{[168]} \) plasmonic filters, reconfigurable color reflector,\(^{[136]} \) absorptive and radiative cooling materials. For special curved multilayer film systems, the TMM is still applicable using different eigenmodes. For example, Richmond proposed a solution of the field in a cylindrical multilayer\(^{[169]} \) by using the cylindrical Bessel function to obtain the transmission coefficient between adjacent layers.

Although the fabrication of multilayers is simple without structure patterning, the electromagnetic manipulation flexibility is restricted by the limited materials. On the contrary, when artificial effective conductive or impedance layers are locating at the interfaces, more design freedom can be obtained so that one can flexibly engineer the whole dispersion of the multilayers and develop broadband and wide-angle metamaterials such as absorbers,\(^{[49,95,170]} \) polarization converters,\(^{[91,105]} \) wide-angle focusing and imaging.\(^{[171]} \) Assuming the effective conductivities of the alternative layers and subwavelength patterned layer are \( Y_1, Y_2, \) and \( Y_s \), then the transfer matrix between can be expressed as

\[
\begin{bmatrix}
a_{j+1} \\
b_{j+1}
\end{bmatrix} = M_{j+1,j} \begin{bmatrix}
a_{j} \\
b_{j}
\end{bmatrix} = \frac{1}{2Y_1} \begin{bmatrix}
(Y_1 + Y_2)e^{i\theta_j} & (Y_1 + Y_2)e^{i\theta_j} \\
(Y_1 - Y_2)e^{-i\theta_j} & (Y_1 - Y_2)e^{-i\theta_j}
\end{bmatrix} \begin{bmatrix}
a_{j} \\
b_{j}
\end{bmatrix}
\]

(4)

where \( Y_1 = (\varepsilon_i)^{1/2}Y_0 \) and \( Y_0 \) are the impedance of the free space. For thin metallic patterns, equivalent circuit theory could be leveraged for qualitative analyses of the equivalent impedance/conductivity.

This article is protected by copyright. All rights reserved
To quantitatively determine the equivalent surface impedance/conductivity, a generalized Fresnel equation has been established, which bridges a link between the equivalent surface impedance/conductivity and the transmission and reflection coefficients. Generally, full-wave simulations are required to obtain these transmission and reflection coefficients of subwavelength patterns. For some regular metallic structures, e.g., 1D metallic meshes, it has been shown that the equivalent impedance/conductivity can be described by a catenary dispersion function with satisfactory accuracy. Specifically, the normalized admittance $Y_{\text{eff}}$ is characterized by

$$ Y_{\text{eff}} = \frac{1}{Z_{\text{eff}}} = -i \frac{2p \left( n_1^2 + n_2^2 \right)}{\lambda} \ln \text{csc} \left( \frac{\pi w}{2p} \right), $$

where $Z_{\text{eff}}$ is the surface impedance, $p$ is the period of the grating, $w$ is the width of the slit, $\lambda$ is the wavelength, $n_1$ and $n_2$ are the refractive indexes for the background materials. Note that the right side of Equation (5) is similar to the mechanical “catenary of equal strength”, which follows the function $y = \Lambda \text{ln}(|\text{csc}(\pi y/\Lambda)|)/\pi$ and different from the normal catenary function, i.e., $y = \alpha \cosh(x/\alpha)$. Apart from simple metallic 1D gratings, many complex structures could also be described using the catenary dispersion function, providing an efficient way to understand the broadband electromagnetic response of these functional metasurfaces. With the catenary dispersion theory, the design efficiency of structured functional materials can be greatly improved since time-consuming full-wave simulations and parameter sweeps are avoided.

For subwavelength slits drilled in a thick metallic film, one can approximately take them as truncated MIM waveguides. In the visible band, the near-field coupling between decaying evanescent waves along the two metal-insulator interfaces of the MIM waveguide causes the formation of the symmetric and asymmetric catenary field. By matching the field distributions at the interfaces, the dispersion relations of coupled SPPs can be also obtained.

This article is protected by copyright. All rights reserved.
with ease.\textsuperscript{[37]} Details about catenary dispersion and field can be found in a recent review and a book.\textsuperscript{[38,173]}

Different from metallic slits arrays that each slit can be taken as an isolated plasmonic waveguide, the coupling between adjacent dielectric nanostructures make it difficult to accurately describe their electromagnetic responses through the full-analytical method. Alternatively, RCWA, a semi-analytical method in computational electromagnetics, is most typically applied to solve scattering from periodic dielectric structures. In 1981, Moharam\textsuperscript{[174]} first proposed the RCWA method for vector analysis of electromagnetic wave diffraction problems of sub-wavelength or resonant gratings. RCWA is often utilized to investigate the electromagnetic response of periodic gratings or unit cells of metamaterials/metasurfaces\textsuperscript{[102,175–178]}. Since RCWA can be easily implemented numerically, the simulation times will be greatly reduced compared to the full-wave simulation, which is preferred in the parameters sweeping of periodic subwavelength structures.

3.2. Heuristic optimization methods

For simple subwavelength structures, e.g., V-, I-, and C- shaped metallic antennas, as well as periodic rectangular and circular dielectric nanopillars, the geometry parameters are few and the mapping relationship between the geometries and electromagnetic responses is simple. In these situations, the structural-functional relationship can be easily established after a series of parameter sweeping. Then, desired optical modulations can be realized by searching a simple look-up table repeatedly at each pixel of the structured functional materials.

For complex structures that possess a couple of design freedoms, it is not easy to obtain the optimal design. Some nature-inspired optimization methods have been developed and introduced to the electromagnetics community. Here we mainly focus on two optimization techniques. One is the genetic algorithm (GA), which seeks to evolve designs based on the principles of natural selection. The other is particle swarm optimization (PSO), which is an artificial realization of the social intelligence of insect swarms. The GA begins with a
population of randomly generated individuals and is an iterative process in which the population in each iteration is called a generation. In each generation, the fitness of each individual in the population is evaluated, which is usually the value of the objective function. More suitable individuals are randomly selected from the current population, and the genome of each individual is modified (recombined and possibly stochastically mutated) to form a new generation. This new generation of candidate solutions is then used in the next iteration of the algorithm. Typically, the algorithm terminates when the maximum number of generations has been created or a satisfactory fitness level has been achieved.

Alternatively, a basic variant of the PSO algorithm works by a group (called a swarm) of candidate solutions (called particles). These particles move through the search space according to a few simple formulas. The motion of the particles is guided by their own best-known positions in the search space and the best-known position of the entire swarm. These will guide the movement of the group when an improved position is found. This process is repeated, and by doing so, it is hoped but not guaranteed that a satisfactory solution will eventually be found. PSO has been utilized in designing broadband achromatic metalens, where the phase shift, group delay and group delay dispersion of light at each coordinate of the metalens should be elaborately optimized. It should be noted that although these methods have made great successes, however, are typically restricted to optimizing a relatively small number of geometric parameters, and scale poorly with additional degrees of freedom.

3.3. Deep learning
The past decade has witnessed the rise of deep learning with unprecedented impact on a plethora of research topics. As a data-driven method, deep learning can produce fast and accurate designs without the need for case-by-case, time-consuming numerical calculations. Among the various machine learning techniques, deep neural network (DNN) based approaches have shown great promise for solving non-intuitive design and optimization
problems. Since multiple hidden layers and sufficient hidden units are utilized, DNNs can be
used to uncover hidden relations between variables, such as between nanophotonic structure
geometries and their electromagnetic (EM) responses. Well-trained DNNs can directly set up
a mapping from geometrical design to optical properties of target photonic devices, and vice
versa. Beginning with the random initialization, the model parameters in DNNs are iteratively
optimized according to a specific loss function during the training process until convergence
occurs and the generalized model can predict unseen data. As shown in Figure 8, a series of
subwavelength devices has been designed via deep learning method, including chiral
metamaterials,[181,182] self-adaptive microwave cloak,[183] all-dielectric metalens,[184]
plasmonic nanostructures,[185] as well as silicon photonic device.[186] Among them, the
networks in Figures 8(a), (b), and (c) respectively focus on the structural-functional
relationship at the unit cells, meta-molecules, and functional devices level. Various network
models include multilayer perceptron, convolutional neural networks, recurrent neural
networks, and deep generative models have been leveraged and more information can be
found in recent reviews.[187,188]

Another important issue that should be noted is that today’s computing hardware is
inefficient at implementing neural networks, in large part because much of it was designed for
von Neumann computing schemes. Recently, fully optical neural networks, both interferences
and diffractive types have been proposed,[189,190] which, in principle, could offer an
enhancement in computational speed and power efficiency over state-of-the-art electronics for
conventional inference tasks. Inspired by the diffractive deep neural network,[190] where each
layer’s neurons were physically encoded using the relative thickness of each 3D-printed
neuron, metasurfaces with powerful local phase modulation ability may find potential
applications in diffractive all-optical neural networks.

3.4. Topology optimization and adjoint simulation

This article is protected by copyright. All rights reserved
One intriguing feature that distinguishes artificially structured materials from conventional optical components is their multifunctional capability owing to the more degrees of freedom in structural parameters. Especially, for multifunctional metasurfaces operated under different illuminations, the large number of design parameters and intricate electromagnetic intercoupling make the design of multifunctional artificial structured materials a complex task, as shown in Figure 9. Over the past two decades, there have been increasing interest in topology optimization (TO) combined with adjoint and gradient-descent methods for freeform electromagnetic structures design in various scenarios, including photonic crystals, microcavity, multilayer thin films, waveguides, metasurfaces, and other applications. This approach allows the topology of the electromagnetic structures to change in a free-form way, opening up large design space, while converging comparatively quickly to an optimal solution. The audiences may refer to recent reviews for more details.

As a gradient-based optimization algorithm, the TO process begins by defining a design region with a random and continuous distribution of permittivity $\varepsilon$ between different materials, i.e., $\varepsilon = \varepsilon_a + \rho(\varepsilon_b - \varepsilon_a)$, where $\varepsilon_a$ and $\varepsilon_b$ are the permittivities of materials and $\rho \in [0,1]$ denotes the relaxation parameter. The optimization goal is to find an optimal permittivity distribution that satisfies the user-defined figure-of-merit (FOM), such as the intensity of the electric field at the focus for metalens. Therefore, how the change of $\varepsilon$ affects the FOM during each iteration should be investigated. Different from the conventional approaches that achieve it by changing the permittivity of each cell in sequence and performing a time-costing simulation depending on the number of unit cells, gradient-based adjoint simulation can calculate the gradient of FOM ($\nabla$ FOM/$\partial\varepsilon$) at each pixel through only two full-field simulations with the help of Born approximation, greatly alleviating the restriction above. Then, the distribution of permittivity at each pixel can be once updated (similar to the backpropagation
used in training neural networks), with the changes proportional to the gradient. Applying the process above iteratively can then lead to a local optimum.[125,222]

Although the nonintuitive and nontrivial functionalities of freeform metasurfaces enabled by adjoint-based TO have recently attracted considerable interest and reached the stage of an explosion, there is still a non-negligible challenge for practical application. Specifically, the small features spontaneously appearing in the optimization process make the freeform metasurfaces impossible for high-throughput manufacturing with photolithography technology. Instead, most of the devices are experimentally fabricated by using electron-beam lithography, which greatly limits the applications of TO-based metasurfaces. Therefore, we should re-examine the optimization procedure as the TO is performed and additional considerations should be employed to solve the above challenge. Typical solutions include pixelation of topology structure with a size larger than the smallest feature size or using erosion and dilation operations to increase the robustness to fabrication imperfections.[223–225]

4. Conclusions and Outlooks

In summary, we have reviewed the history and recent advances of structured electromagnetic and optical functional materials and devices. Based on the similarity of functional structures and architectonics, the term Electromagnetic Architectures was proposed. It is shown that the construction of structured materials and devices has drawn many inspirations from the construction of buildings. In both cases, the structures determine the functionalities. So it is of critical importance for us to find out the most suitable structures for particular applications.

In our opinion, future research directions of Electromagnetic Architectures may include but not limited to the following aspects:

1. More rapid and efficient approaches to explore possible combinations of materials and structures to realize functionalities required by potential practical applications.
classical models and deep learning are promising candidates, but the prediction accuracy and extendibility need to be further increased.

2. Fast and accurate fabrication of large-area functional devices with minimal critical dimensions smaller than several hundreds of nanometers. Owing to the replicative nature, imaging nanolithography and nanoimprint are very promising in these applications.

3. Dynamic and fast modulation of optical functionalities via electrical and optical approaches. Although there have been many efforts to realize tunable structured devices, the tuning speed, and pixel numbers are still limited.

Finally, it should be noted that although our discussion is focused on electromagnetic structures, similar concepts may be extended to other researching areas, such as mechanics, acoustics, thermal physics, and quantum physics, etc.

Acknowledgements

This work was supported by the National Natural Science Funds of China under Grant Nos. 61975210 and 61875253, Chinese Academy of Sciences Youth Innovation Promotion Association under Grant Nos. 2019371

References

[1] E. Yablonovitch, Physical Review Letters 1987, 58, 2059.
[2] D. Smith, W. Padilla, D. Vier, S. Nemat-Nasser, S. Schultz, Phys. Rev. Lett. 2000, 84, 4184.
[3] J. B. Pendry, Phys. Rev. Lett. 2000, 85, 3966.
[4] I. Freestone, N. Meeks, M. Sax, C. Higgitt, Gold Bulletin 2007, 40, 270.
[5] D. B. Swinson, The Physics Teacher 1992, 30, 295.
[6] X. Luo, Engineering Optics 2.0: A Revolution in Optical Theories, Materials, Devices and Systems, Springer Singapore, 2019.
[7] K. Shportko, S. Kremers, M. Woda, D. Lencer, J. Robertson, M. Wuttig, Nat Mater 2008, 7, 653.
[8] Arash Nemati, Qian Wang, Minghui Hong, Jinghua Teng, OEA 2018, 1, 180009.
[9] J. C. Maxwell, Philosophical Transactions of the Royal Society of London 1865, 155, 459.
[10] P. Bharadwaj, B. Deutsch, L. Novotny, Advances in Optics and Photonics 2009, 1, 438.
[11] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, R. D. Meade, *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, Princeton and Oxford, 2008.

[12] Y. Xu, Y. Fu, H. Chen, *Nature Reviews Materials* 2016, 1, 16067.

[13] Lord Rayleigh, *Philosophical Magazine Series 5* 1887, 24, 145.

[14] S. G. Tikhodeev, A. L. Yablonskii, E. A. Muljarov, N. A. Gippius, T. Ishihara, *Phys. Rev. B* 2002, 66, 045102.

[15] Y. Yang, Z. Gao, H. Xue, L. Zhang, M. He, Z. Yang, R. Singh, Y. Chong, B. Zhang, H. Chen, *Nature* 2019, 565, 622.

[16] A. B. Khanikaev, S. Hossein Mousavi, W.-K. Tse, M. Kargarian, A. H. MacDonald, G. Shvets, *Nat Mater* 2013, 12, 233.

[17] S. John, *Physical Review Letters* 1987, 58, 2486.

[18] S. Zhu, Y. Zhu, N. Ming, *Science* 1997, 278, 843.

[19] V. G. Veselago, *Sov. Phys. Usp.* 1968, 10, 509.

[20] R. Shelby, D. Smith, S. Schultz, *Science* 2001, 292, 77.

[21] D. T. Emerson, *Microwave Theory and Techniques, IEEE Transactions on* 1997, 45, 2267.

[22] B. A. Munk, *Frequency Selective Surfaces*, Wiley, New York, 2000.

[23] R. P. Feynman, *Engineering and science* 1960, 23, 22.

[24] H.-S. Lee, R. Agarwal, *Nano letters* 2016, 16, 2818.

[25] D. Wang, L. Zhang, Y. Gu, M. Q. Mehmood, Y. Gong, A. Srivastava, L. Jian, T. Venkatesan, C.-W. Qiu, M. Hong, *Scientific Reports* 2015, 5, 15020.

[26] D. Wang, L. Zhang, Y. Gong, L. Jian, T. Venkatesan, C. Qiu, M. Hong, *IEEE Photonics Journal* 2016, 8, 1.

[27] T. Driscoll, S. Palit, M. M. Qazilbash, M. Brehm, F. Keilmann, B.-G. Chae, S.-J. Yun, H.-T. Kim, S. Y. Cho, N. M. Jokerst, D. R. Smith, D. N. Basov, *Appl. Phys. Lett.* 2008, 93, DOI 10.1063/1.2956675.

[28] M. A. Kats, R. Blanchard, S. Zhang, P. Genevet, C. Ko, S. Ramanathan, F. Capasso, *Phys. Rev. X* 2013, 3, 041004.

[29] V. K. Mkhitarian, D. S. Ghosh, M. Rudé, J. Canet-Ferrer, R. A. Maniyara, K. K. Gopalan, V. Pruneri, *Advanced Optical Materials* 2017, 5, 1600452.

[30] Y. Chen, X. Li, X. Luo, S. A. Maier, M. Hong, *Photon. Res.* 2015, 3, 54.

[31] T. Li, L. Huang, J. Liu, Y. Wang, T. Zentgraf, *Opt. Express* 2017, 25, 4216.

[32] C. H. Chu, M. L. Tseng, J. Chen, P. C. Wu, Y.-H. Chen, H.-C. Wang, T.-Y. Chen, W. T. Hsieh, H. J. Wu, G. Sun, D. P. Tsai, *Laser Photonics Rev.* 2016, 10, 986.

[33] Q. Wang, B. T. F. Rogers, B. Gholipour, C.-M. Wang, G. Yuan, J. Teng, N. I. Zheludev, *Nat Photon* 2016, 10, 60.

[34] F. Zhang, M. Pu, J. Luo, H. Yu, X. Luo, *Opto-Electronic Engineering* 2017, 44, 319.

[35] J. P. Balthasar Mueller, N. A. Rubin, R. C. Devlin, B. Groever, F. Capasso, *Physical Review Letters* 2017, 118, 113901.

[36] W. T. Chen, A. Y. Zhu, F. Capasso, *Nature Reviews Materials* 2020, 5, 604.

[37] M. Pu, Y. Guo, X. Ma, X. Li, X. Luo, *Advanced Optical Materials* 2019, 7, 1801376.

[38] X. Luo, *Catenary Optics*, Singapore Springer, 2019.

[39] N.d.

[40] J. Evans, M. Rosenquist, *Am. J. Phys.* 1986, 54, 876.

[41] D. Gilbert, *Phil. Trans. R. Soc. Lond.* 1826, 116, 202.

[42] X. Luo, M. Pu, X. Li, X. Ma, *Light: Science & Applications* 2017, 6, e16276.

[43] A. G. Curto, G. Volpe, T. H. Taminiau, M. P. Kreuzer, R. Quidant, N. F. van Hulst, *Science* 2010, 329, 930.

[44] H. Aouani, M. Rahmani, M. Navarro-Cia, S. A. Maier, *Nat Nano* 2014, 9, 290.

[45] D. Vercruyssse, P. Neutens, L. Lagae, N. Verellen, P. V. Dorpe, *Acs Photonics* 2017, 4.

[46] J. Jin, X. Li, Y. Guo, M. Pu, P. Gao, X. Ma, X. Luo, *Nanoscale* 2019, 11, 3952.

This article is protected by copyright. All rights reserved
H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal, T. W. Ebbesen, *Science* **2002**, *297*, 820.

V. G. Veselago, E. E. Narimanov, *Nature Materials* **2006**, *5*, 759.

Q. Feng, M. Pu, C. Hu, X. Luo, *Opt. Lett.* **2012**, *37*, 2133.

W. E. Kock, *The Bell System Technical Journal* **1948**, *27*, 58.

D. Berry, R. Malech, W. Kennedy, *Antennas and Propagation, IEEE Transactions on* **1963**, *11*, 645.

D. M. Pozar, T. A. Metzler, *Electronics Letters* **1993**, *29*, 657.

J. Huang, in *Antennas and Propagation Society International Symposium, 1995. AP-S Digest, IEEE*, **1995**, pp. 582–585.

J. Huang, J. A. Encinar, *Reflectarray Antennas*, John Wiley & Sons, New Jersey, **2008**.

P. Kipfer, M. Collischon, H. Haidner, J. Schwider, **1994**, pp. 2169–8.

F. T. Chen, H. G. Craighead, *Opt. Lett.* **1995**, *20*, 121.

P. Lalanne, S. Astilean, P. Chavel, E. Cambril, H. Launois, *Opt. Lett.* **1998**, *23*, 1081.

H. Shi, C. Wang, C. Du, X. Luo, X. Dong, H. Gao, *Opt. Express* **2005**, *13*, 6815.

L. Verslegers, P. B. Catrysse, Z. Yu, J. S. White, E. S. Barnard, M. L. Brongersma, S. Fan, *Nano Lett.* **2009**, *9*, 235.

D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith, *Science* **2006**, *314*, 977.

J. Valentine, J. Li, T. Zentgraf, G. Bartal, X. Zhang, *Nat. Mater.* **2009**, *8*, 568.

Z. Liu, H. Lee, Y. Xiong, C. Sun, X. Zhang, *Science* **2007**, *315*, 1686.

J. Sun, T. Xu, N. M. Litchinitser, *Nano Letters* **2016**, *16*, 7905.

M. Khorasaninejad, F. Capasso, *Science* **2017**, *358*, eaam8100.

D. Wang, Q. Huang, C. Qiu, M. Hong, *Science China Physics, Mechanics & Astronomy* **2015**, *58*, 084201.

G. Ru, R. L. Nelson, Q. Zhan, *Opt. Lett.* **2011**, *36*, 4533.

M. Pu, X. Li, X. Ma, Y. Wang, Z. Zhao, C. Wang, C. Hu, P. Gao, C. Huang, H. Ren, X. Li, F. Qin, M. Gu, M. Hong, X. Luo, *Sci. Adv.* **2015**, *1*, ea500396.

Z. Li, E. Palacios, S. Butun, K. Aydin, *Nano Letters* **2015**, *15*, 1615.

X. Xie, M. Pu, J. Jin, M. Xu, Y. Guo, X. Li, P. Gao, X. Ma, X. Luo, *Physical Review Letters* **2021**.

M. Pu, X. Ma, Y. Guo, X. Li, X. Luo, *Opt. Express* **2018**, *26*, 19555.

M. Pu, Y. Guo, X. Li, X. Ma, X. Luo, *ACS Photonics* **2018**, *5*, 3198.

P. A. Belov, Y. Hao, S. Sudhakaran, *Phys. Rev. B* **2006**, *73*, 033108.

J. Pendry, A. Holden, W. Stewart, I. Youngs, *Phys. Rev. Lett.* **1996**, *76*, 4773.

J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, *IEEE Trans. Microwave Theory Tech.* **1999**, *47*, 2075.

V. M. Shalaev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, A. V. Kildishev, *Optics Letters* **2005**, *30*, 3356.

J. Valentine, S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov, G. Bartal, X. Zhang, *Nature* **2008**, *455*, 376.

S. Xiao, V. P. Drachev, A. V. Kildishev, X. Ni, U. K. Chettiar, H.-K. Yuan, V. M. Shalaev, *Nature* **2010**, *466*, 735.

T. Xu, A. Agrawal, M. Abashin, K. J. Chau, H. J. Lezec, *Nature* **2013**, *497*, 470.

M. Silveirinha, N. Engheta, *Phys. Rev. Lett.* **2006**, *97*, DOI 10.1103/PhysRevLett.97.157403.

M. Z. Alam, I. De Leon, R. W. Boyd, *Science* **2016**, *352*, 795.

M. Z. Alam, S. A. Schulz, J. Upham, I. De Leon, R. W. Boyd, *Nature Photonics* **2018**, *12*, 79.

Y. Li, I. Liberal, N. Engheta, *Sci Adv* **2019**, *5*, eaav3764.

This article is protected by copyright. All rights reserved
[83] M. Choi, S. H. Lee, Y. Kim, S. B. Kang, J. Shin, M. H. Kwak, K.-Y. Kang, Y.-H. Lee, N. Park, B. Min, *Nature* 2011, 470, 369.
[84] J. T. Shen, P. B. Catryssse, S. Fan, *Physical Review Letters* 2005, 94, 197401.
[85] J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, K. Bade, V. Saile, G. von Freymann, S. Linden, M. Wegener, *Science* 2009, 325, 1513.
[86] K. Robsie, M. J. Brett, A. Lakhtakia, *Nature* 1996, 384, 616.
[87] A. Poddubny, I. Iorsh, P. Belov, Y. Kivshar, *Nat Photon* 2013, 7, 948.
[88] C. Lv, W. Li, X. Jiang, J. Cao, *Europhysics Letters* 2014, 105, 28003.
[89] C. R. Simovski, P. A. Belov, A. V. Atrashchenko, Y. S. Kivshar, *Advanced Materials* 2012, 24, 4229.
[90] X. Luo, *Sci. China: Phys., Mech. Astron* 2015, 58, 594201.
[91] M. Pu, P. Chen, Y. Wang, Z. Zhao, C. Huang, C. Wang, X. Ma, X. Luo, *Appl. Phys. Lett.* 2013, 102, 131906.
[92] A. K. Zadeh, A. Karlsson, *IEEE Trans. Antennas Propagat.* 2009, 57, 2307.
[93] Y. Guo, M. Pu, Z. Zhao, Y. Wang, J. Jin, P. Gao, X. Li, X. Ma, X. Luo, *ACS Photonics* 2016, 3, 2022.
[94] Y. Huang, J. Luo, M. Pu, Y. Guo, Z. Zhao, X. Ma, X. Li, X. Luo, *Advanced Science* 2019, 6, 1801691.
[95] M. Pu, C. Hu, M. Wang, C. Huang, Z. Zhao, C. Wang, Q. Feng, X. Luo, *Opt. Express* 2011, 19, 17413.
[96] N. Engheta, *Science* 2007, 317, 1698.
[97] C. Pfeiffer, A. Grbic, *Phys. Rev. Lett.* 2013, 110, 197401.
[98] M. Decker, I. Staude, M. Falkner, J. Dominguez, D. N. Neshev, I. Brener, T. Pertsch, Y. S. Kivshar, *Advanced Optical Materials* 2015, 3, 813.
[99] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, Z. Gaburro, *Science* 2011, 334, 333.
[100] Y. Chen, X. Li, Y. Sonnefraud, A. I. Fernández-Dominguez, X. Luo, M. Hong, S. A. Maier, *Sci. Rep.* 2015, 5, 8660.
[101] L. Lin, X. M. Goh, L. P. McGuinness, A. Roberts, *Nano Letters* 2010, 10, 1936.
[102] A. Arbabi, Y. Horie, M. Bagheri, A. Faraon, *Nat. Nanotechnol.* 2015, 10, 937.
[103] M. Khorasaninejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, F. Capasso, *Science* 2016, 352, 1190.
[104] M. V. Berry, *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 1984, 392, 45.
[105] Y. Guo, Y. Wang, M. Pu, Z. Zhao, X. Wu, X. Ma, C. Wang, L. Yan, X. Luo, *Sci. Rep.* 2015, 5, 8434.
[106] X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, *Science* 2012, 335, 427.
[107] X. Zhang, Z. Tian, W. Yue, J. Gu, S. Zhang, J. Han, W. Zhang, *Adv. Mater.* 2013, 25, 4567.
[108] F. Qin, L. Ding, L. Zhang, F. Monticone, C. C. Chum, J. Deng, S. Mei, Y. Li, J. Teng, M. Hong, S. Zhang, A. Alù, C.-W. Qiu, *Science Advances* 2016, 2, DOI 10.1126/sciadv.1501168.
[109] L. Liu, X. Zhang, M. Kenney, X. Su, N. Xu, C. Ouyang, Y. Shi, J. Han, W. Zhang, S. Zhang, *Advanced Materials* 2014, 26, 5031.
[110] S. Sun, K.-Y. Yang, C.-M. Wang, T.-K. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W.-T. Kung, G.-Y. Guo, L. Zhou, D. P. Tsai, *Nano Lett.* 2012, 12, 6223.
[111] S. Sun, Q. He, S. Xiao, Q. Xu, X. Li, L. Zhou, *Nat. Mater.* 2012, 11, 426.
[112] M. Pu, P. Chen, C. Wang, Y. Wang, Z. Zhao, C. Hu, X. Luo, *AIP Adv.* 2013, 3, 052136.

This article is protected by copyright. All rights reserved
[113] M. I. Shalaev, J. Sun, A. Tsukernik, A. Pandey, K. Nikolskiy, N. M. Litchinitser, *Nano Lett.* **2015**, *15*, 6261.

[114] R. C. Devlin, A. Ambrosio, N. A. Rubin, J. P. B. Mueller, F. Capasso, *Science* **2017**, *358*, 896.

[115] Q. He, F. Zhang, M. Pu, X. Ma, X. Li, J. Jin, Y. Guo, X. Luo, *Nanophotonics* **2021**, *10*, 741.

[116] Y. Guo, S. Zhang, M. Pu, Q. He, J. Jin, M. Xu, Y. Zhang, P. Gao, X. Luo, *Light: Science & Applications* **2021**, *10*, 63.

[117] F. Zhang, M. Pu, X. Li, P. Gao, X. Ma, J. Luo, H. Yu, X. Luo, *Adv. Fun. Mater.* **2017**, *27*, 1704295.

[118] S. Wang, Z.-L. Deng, Y. Wang, Q. Zhou, X. Wang, Y. Cao, B.-O. Guan, S. Xiao, X. Li, *Light: Science & Applications* **2021**, *10*, 24.

[119] Q. Fan, M. Liu, C. Zhang, W. Zhu, Y. Wang, P. Lin, F. Yan, L. Chen, H. J. Lezec, Y. Lu, A. Agrawal, T. Xu, *Phys. Rev. Lett.* **2020**, *125*, 267402.

[120] S. Wang, P. C. Wu, V.-C. Su, Y.-C. Lai, C. Hung Chu, J.-W. Chen, S.-H. Lu, J. Chen, B. Xu, C.-H. Kuan, T. Li, S. Zhu, D. P. Tsai, *Nat. Commun.* **2017**, *8*, 187.

[121] W. T. Chen, A. Y. Zhu, V. Sanjeev, M. Khorasaninejad, Z. Shi, E. Lee, F. Capasso, *Nat. Nanotechnol.* **2018**, *13*, 220.

[122] S. Wang, P. C. Wu, V.-C. Su, Y.-C. Lai, M.-K. Chen, H. Y. Kuo, B. H. Chen, Y. H. Chen, T.-I. Huang, J.-H. Wang, R.-M. Lin, C.-H. Kuan, T. Li, Z. Wang, S. Zhu, D. P. Tsai, *Nat. Nanotechnol.* **2018**, *13*, 227.

[123] F. Zhang, M. Zhang, J. Cai, Y. Ou, H. Yu, *Appl. Phys. Express* **2018**, *11*, 082004.

[124] F. Zhang, M. Pu, X. Li, X. Ma, Y. Guo, P. Gao, H. Yu, M. Gu, X. Luo, *Adv. Mater.* **2021**, *33*, 2008157.

[125] M. Xu, M. Pu, D. Sang, Y. Zheng, X. Li, X. Ma, Y. Guo, R. Zhang, X. Luo, *Optics Express* **2021**, *29*, 10181.

[126] F. Zhang, X. Xie, M. Pu, Y. Guo, X. Ma, X. Li, J. Luo, Q. He, H. Yu, X. Luo, *Adv. Mater.* **2020**, *32*, 1908194.

[127] M. Song, D. Wang, S. Peana, S. Choudhury, P. Nyga, Z. A. Kudyshev, H. Yu, A. Boltasseva, V. M. Shalaev, A. V. Kildishev, *Applied Physics Reviews* **2019**, *6*, 041308.

[128] H. A. Macleod, *Thin-Film Optical Filters*, CRC Press, Boca Raton, 2010.

[129] X. Luo, D. Tsai, M. Gu, M. Hong, *Adv. Opt. Photon.* **2018**, *10*, 757.

[130] C. Williams, G. S. D. Gordon, T. D. Wilkinson, S. E. Bohndiek, *ACS Photonics* **2019**, *6*, 3132.

[131] E. Laux, C. Genet, T. Skauli, T. W. Ebbesen, *Nat Photon* **2008**, *2*, 161.

[132] T. Xu, Y.-K. Wu, X. Luo, L. J. Guo, *Nat. Commun.* **2010**, *1*, 59.

[133] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, P. A. Wolff, *Nature* **1998**, *391*, 667.

[134] A. F. Kaplan, T. Xu, L. J. Guo, *Applied Physics Letters* **2011**, *99*, 143111.

[135] S. Song, X. Ma, M. Pu, X. Li, K. Liu, P. Gao, Z. Zhao, Y. Wang, C. Wang, X. Luo, *Adv. Opt. Mater.* **2017**, *5*, 1600829.

[136] M. Jafari, L. J. Guo, M. Rais-Zadeh, *Adv. Opt. Mater.* **2019**, *7*, 1801214.

[137] P. Hosseini, C. D. Wright, H. Bhaskaran, *Nature* **2014**, *511*, 206.

[138] H. Liu, Z.-H. Wang, L. Li, Y.-X. Fan, Z.-Y. Tao, *Sci. Rep.* **2019**, *9*, 5751.

[139] C. Ji, K.-T. Lee, T. Xu, J. Zhou, H. J. Park, L. J. Guo, *Adv. Opt. Mater.* **2017**, *5*, 1700368.

[140] Q. Wei, B. Sain, Y. Wang, B. Reineke, X. Li, L. Huang, T. Zentgraf, *Nano Lett.* **2019**, *19*, 8964.

[141] Y. Hu, X. Luo, Y. Chen, Q. Liu, X. Li, Y. Wang, N. Liu, H. Duan, *Light: Science & Applications* **2019**, *8*, 86.

This article is protected by copyright. All rights reserved.
[142] Y. Bao, Y. Yu, H. Xu, C. Guo, J. Li, S. Sun, Z.-K. Zhou, C.-W. Qiu, X.-H. Wang, *Light: Science & Applications* **2019**, *8*, 95.
[143] F. Zhang, M. Pu, P. Gao, J. Jin, X. Li, Y. Guo, X. Ma, J. Luo, H. Yu, X. Luo, *Advanced Science* **2020**, *7*, 1903156.
[144] K. T. P. Lim, H. Liu, Y. Liu, J. K. W. Yang, *Nature Communications* **2019**, *10*, 25.
[145] S.-Y. Ding, J. Yi, J.-F. Li, B. Ren, D.-Y. Wu, R. Pannierselvam, Z.-Q. Tian, *Nature Reviews Materials* **2016**, *1*, 16021.
[146] A. M. Shaltout, V. M. Shalaev, M. L. Brongersma, *Science* **2019**, *364*, eaat3100.
[147] C. V. Poulton, M. J. Byrd, P. Russo, E. Timurdogan, M. Khandaker, D. Vermeulen, M. Watts, *IEEE Journal of Selected Topics in Quantum Electronics* **2019**, *25*, 1.
[148] N. Li, C. P. Ho, I.-T. Wang, P. Pitchappa, Y. H. Fu, Y. Zhu, L. Y. T. Lee, *Nanophotonics* **2021**, *10*, 1437.
[149] X. Li, L. Chen, Y. Li, X. Zhang, M. Pu, Z. Zhao, X. Ma, Y. Wang, M. Hong, X. Luo, *Sci. Adv.* **2016**, *2*, e1601102.
[150] H. Gao, Y. Wang, X. Fan, B. Jiao, T. Li, C. Shang, C. Zeng, L. Deng, W. Xiong, J. Xia, M. Hong, *Sci Adv* **2020**, *6*, eaba8595.
[151] E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, M. Faraji-Dana, A. Faraon, *Nat. Commun.* **2018**, *9*, 812.
[152] N. I. Zheludev, E. Plum, *Nat. Nanotechnol.* **2016**, *11*, 16.
[153] S. Colburn, A. Zhan, A. Majumdar, *Optica* **2018**, *5*, 825.
[154] S. C. Malek, H.-S. Ee, R. Agarwal, *Nano Lett.* **2017**, *17*, 3641.
[155] S. M. Kamali, E. Arbabi, A. Arbabi, Y. Horie, A. Faraon, *Laser Photonics Rev.* **2016**, *10*, 1002.
[156] P. Gutruf, C. Zou, W. Withayachumnankul, M. Bhaskaran, S. Sriram, C. Fumeaux, *ACS Nano* **2016**, *10*, 133.
[157] L. Zhang, X. Q. Chen, S. Liu, Q. Zhang, J. Zhao, J. Y. Dai, G. D. Bai, X. Wan, Q. Cheng, G. Castaldi, V. Galdi, T. J. Cui, *Nature Communications* **2018**, *9*, 4334.
[158] X. G. Zhang, W. X. Jiang, H. L. Jiang, Q. Wang, H. W. Tian, L. Bai, Z. J. Luo, S. Sun, Y. Luo, C.-W. Qiu, T. J. Cui, *Nat. Electron.* **2020**, *3*, 165.
[159] A. Pirilakis, O. Tsilipakos, F. Liu, K. M. Kossifos, A. C. Tasolamprou, D. -H. Kwon, M. S. Mirmoosa, D. Manessis, N. V. Kantartzis, C. Liaskos, M. A. Antoniades, J. Georgiou, C. M. Soukoulis, M. Kafesaki, S. A. Tretyakov, *IEEE Transactions on Antennas and Propagation* **2021**, *69*, 1440.
[160] S.-Q. Li, X. Xu, R. Maruthiyodan Veetil, V. Valuckas, R. Paniagua-Dominguez, A. I. Kuznetsov, *Science* **2019**, *364*, 1087.
[161] A. Liningier, A. Y. Zhu, J.-S. Park, G. Palermo, S. Chatterjee, J. Boyd, F. Capasso, G. Strangi, *Proc Natl Acad Sci USA* **2020**, *117*, 20390.
[162] J. Tian, H. Luo, Y. Yang, F. Ding, Y. Qu, D. Zhao, M. Qiu, S. I. Bozhevolnyi, *Nat. Commun.* **2019**, *10*, 396.
[163] C. R. de Galarreta, A. M. Alexeev, Y.-Y. Au, M. Lopez-Garcia, M. Klemm, M. Cryan, J. Bertolotti, C. D. Wright, *Adv. Fun. Mater.* **2018**, *28*, 1704993.
[164] M. Zhang, M. Pu, F. Zhang, Y. Guo, Q. He, X. Ma, Y. Huang, X. Li, H. Yu, X. Luo, *Adv. Sci.* **2018**, *5*, 1800835.
[165] J. Li, S. Kamin, G. Zheng, F. Neubrecht, S. Zhang, N. Liu, *Sci Adv* **2018**, *4*, eaar6768.
[166] J. Park, B. G. Jeong, S. I. Kim, D. Lee, J. Kim, C. Shin, C. B. Lee, T. Otsuka, J. Kyoung, S. Kim, K.-Y. Yang, Y.-Y. Park, J. Lee, I. Hwang, J. Jang, S. H. Song, M. L. Brongersma, K. Ha, S.-W. Huang, H. Choo, B. L. Choi, *Nat. Nanotechnol.* **2021**, *16*, 69.
[167] Z.-Y. Li, L.-L. Lin, *Phys. Rev. E* **2003**, *67*, 046607.
[168] Y. Shen, D. Ye, I. Celanovic, S. G. Johnson, J. D. Joannopoulos, M. Soljačić, *Science* **2014**, *343*, 1499.

This article is protected by copyright. All rights reserved.
[169] H. E. Bussey, J. H. Richmond, Antennas and Propagation, IEEE Transactions on 1975, 23, 723.
[170] Y. Huang, J. Luo, M. Pu, Y. Guo, Z. Zhao, X. Ma, X. Li, X. Luo, Adv. Sci. 2019, 6, 1801691.
[171] Y. Guo, Z. Zhang, M. Pu, Y. Huang, X. Li, X. Ma, M. Xu, X. Luo, iScience 2019, 21, 145.
[172] X. Xie, M. Pu, Y. Huang, X. Ma, X. Li, Y. Guo, X. Luo, Adv. Mater. Technol. 2019, 4, 1800612.
[173] X. Luo, M. Pu, Y. Guo, X. Li, F. Zhang, X. Ma, Advanced Optical Materials 2020, n/a, 2001194.
[174] M. G. Moharam, T. K. Gaylord, Journal of the Optical Society of America A 1981, 71, 811.
[175] S. Divitt, W. Zhu, C. Zhang, H. J. Lezec, A. Agrawal, Science 2019, 364, 890.
[176] S. Colburn, A. Zhan, A. Majumdar, Sci. Adv. 2018, 4, eaa1114.
[177] D. Costantini, A. Lefebvre, A.-L. Coutrot, I. Moldovan-Doyen, J.-P. Hugonin, S. Boutami, F. Marquier, H. Benisty, J.-J. Greffet, Physical Review Applied 2015, 4, 014023.
[178] S. M. Kamali, E. Arbabi, A. Arbabi, Y. Horie, M. Faraji-Dana, A. Faraon, Phys. Rev. X 2017, 7, 041056.
[179] Balamati Choudhury, Metamaterial Inspired Electromagnetic Applications, Springer, 2017.
[180] Kenneth Diest, Numerical Methods for Metamaterial Design, Springer Science & Business Media, 2013.
[181] W. Ma, F. Cheng, Y. Liu, ACS Nano 2018, 12, 6326.
[182] Y. Li, Y. Xu, M. Jiang, B. Li, T. Han, C. Chi, F. Lin, B. Shen, X. Zhu, L. Lai, Z. Fang, Phys. Rev. Lett. 2019, 123, 213902.
[183] C. Qian, B. Zheng, Y. Shen, L. Jing, E. Li, L. Shen, H. Chen, Nature Photonics 2020, 14, 383.
[184] S. An, C. Fowler, B. Zheng, M. Y. Shalaginov, H. Tang, H. Li, L. Zhou, J. Ding, A. M. Agarwal, C. Rivero-Baleine, K. A. Richardson, T. Gu, J. Hu, H. Zhang, ACS Photonics 2019, 6, 3196.
[185] Z. Liu, D. Zhu, K.-T. Lee, A. S. Kim, L. Raju, W. Cai, Advanced Materials 2020, 32, 1904790.
[186] M. H. Tahersima, K. Kojima, T. Koike-Akino, D. Jha, B. Wang, C. Lin, K. Parsons, Scientific Reports 2019, 9, 1368.
[187] W. Ma, Z. Liu, Z. A. Kudyshev, A. Boltasseva, W. Cai, Y. Liu, Nature Photonics 2020, DOI 10.1038/s41566-020-0685-y.
[188] J. Jiang, M. Chen, J. A. Fan, Nature Reviews Materials 2020, DOI 10.1038/s41578-020-00260-1.
[189] Y. Shen, N. C. Harris, S. Skirlo, M. Prabhu, T. Baehr-Jones, M. Hochberg, X. Sun, S. Zhao, H. Laroche, D. Englund, M. Soljačić, Nat. Photonics 2017, 11, 441.
[190] X. Lin, Y. Rivenson, N. T. Yardimci, M. Veli, Y. Luo, M. Jarrahi, A. Ozcan, Science 2018, 361, 1004.
[191] M. Mansource, H. Kwon, E. Arbabi, A. McClung, A. Faraon, A. Arbabi, Optica 2020, 7, 77.
[192] D. Sell, J. Yang, S. Doshay, R. Yang, J. A. Fan, Nano Lett. 2017, 17, 3752.
[193] Z. Shi, A. Y. Zhu, Z. Li, Y.-W. Huang, W. T. Chen, C.-W. Qiu, F. Capasso, Sci. Adv. 2020, 6, eaba3367.
[194] J. S. Jensen, O. Sigmund, Applied Physics Letters 2004, 84, 2022.
[195] Z. Lin, A. Pick, M. Lonar, A. W. Rodriguez, Phys. Rev. Lett. 2016, 117, 107402.
[196] D. Vercruysse, N. V. Sapra, K. Y. Yang, J. Vuksović, arXiv preprint arXiv:2102.00681 2021.

This article is protected by copyright. All rights reserved
[197] X. Liang, S. G. Johnson, Optics express 2013, 21, 30812.
[198] Z. Lin, X. Liang, M. Lonář, S. G. Johnson, A. W. Rodriguez, Optica 2016, 3, 233.
[199] L. Yang, A. V. Lavrinenko, J. M. Hvam, O. Sigmund, Applied Physics Letters 2009, 95, 261101.
[200] Z. Lin, B. Groever, F. Capasso, A. W. Rodriguez, M. Lonář, Phys. Rev. Applied 2018, 9, 044030.
[201] W. Xue, O. D. Miller, arXiv preprint arXiv:2101.03160 2021.
[202] A. Y. Piggott, J. Lu, K. G. Lagoudakis, J. Petykiewicz, T. M. Babinec, J. Vučković Nat Photon 2015, 9, 374.
[203] N. V. Sapra, D. Vercruysse, L. Su, K. Y. Yang, J. Skarda, A. Y. Piggott, J. Vučković IEEE Journal of Selected Topics in Quantum Electronics 2019, 25, 1.
[204] N. V. Sapra, K. Y. Yang, D. Vercruysse, K. J. Leedle, D. S. Black, R. J. England, L. Su, R. Trivedi, Y. Miao, O. Solgaard, Science 2020, 367, 79.
[205] K. Y. Yang, J. Skarda, M. Cotrufo, A. Dutt, G. H. Ahn, M. Sawaby, D. Vercruysse, A. Arbabian, S. Fan, A. Alù, J. Vučković Nature Photonics 2020, 14, 369.
[206] C. Sitawarin, W. Jin, Z. Lin, A. W. Rodriguez, Photonics Research 2018, 6, B82.
[207] A. S. Backer, Opt. Express 2019, 27, 30308.
[208] Z. Lin, V. Liu, R. Pestourie, S. G. Johnson, Opt. Express 2019, 27, 15765.
[209] E. Bayati, R. Pestourie, S. Colburn, Z. Lin, S. G. Johnson, A. Majumdar, ACS Photonics 2020, 7, 873.
[210] D. C. Kim, A. Hermerschmidt, P. Dyachenko, T. Scharf, Optics Express 2020, 28, 22321.
[211] H. Chung, O. D. Miller, Opt. Express 2020, 28, 6945.
[212] Z. Lin, C. Roques-Carmes, R. E. Christiansen, M. Soljačić S. G. Johnson, Applied Physics Letters 2021, 118, 041104.
[213] R. E. Christiansen, F. Wang, O. Sigmund, Physical review letters 2019, 122, 234502.
[214] C. Dory, D. Vercruysse, K. Y. Yang, N. V. Sapra, A. E. Rugar, S. Sun, D. M. Lukin, A. Y. Piggott, J. L. Zhang, M. Radulaski, K. G. Lagoudakis, L. Su, J. Vučković Nat. Commun. 2019, 10, 3309.
[215] Y. Chen, Y. Hu, J. Zhao, Y. Deng, Z. Wang, X. Cheng, D. Lei, Y. Deng, H. Duan, Adv. Funct. Mater. 2020, 30, 2000642.
[216] Y. Pan, R. E. Christiansen, J. Michon, J. Hu, S. G. Johnson, arXiv preprint arXiv:2101.13382 2021.
[217] R. A. Wambold, Z. Yu, Y. Xiao, B. Bachman, G. Jaffe, S. Kolkowitz, J. T. Choy, M. A. Eriksson, R. J. Hamers, M. A. Kats, Nanophotonics 2020, 10, 393.
[218] M. M. R. Elsawy, S. Lanteri, R. Duvigneau, J. A. Fan, P. Genevet, Laser & Photonics Reviews 2020, n/a, 1900445.
[219] S. Molesky, Z. Lin, A. Y. Piggott, W. Jin, J. Vucković A. W. Rodriguez, Nature Photonics 2018, 12, 659.
[220] J. S. Jensen, O. Sigmund, Laser & Photonics Reviews 2011, 5, 308.
[221] R. E. Christiansen, O. Sigmund, JOSA B 2021, 38, 496.
[222] C. M. Lalau-Keraly, S. Bhargava, O. D. Miller, E. Yablonovitch, Opt. Express 2013, 21, 21693.
[223] B. S. Lazarov, F. Wang, O. Sigmund, Archive of Applied Mechanics 2016, 86, 189.
[224] E. W. Wang, D. Sell, T. Phan, J. A. Fan, Opt. Mater. Express 2019, 9, 469.
[225] M. Zhou, B. S. Lazarov, F. Wang, O. Sigmund, Computer Methods in Applied Mechanics and Engineering 2015, 293, 266.

This article is protected by copyright. All rights reserved
Figure 1. (a) Lycurgus Cup and (b) Chinese Magic Mirror. (a) Reproduced from [4] with permission. Copyright 2007, Elsevier Ltd.

Figure 2. Classification of spatial-temporal shaping of electromagnetic waves with subwavelength structures. According to the manipulation object of the electromagnetic field, spatial-temporal modulations are classified into six categories. High frequency wavevector excited in the subwavelength structures and high-index waveguide can be utilized for super-resolution imaging and subwavelength integrated optics; With local phase modulation ability, various flat optical devices and microwave antennas can be constructed for imaging, beam shaping, as well as holographic display. Through on-demand dispersion engineering of the phase and group velocity, achromatic metalens can be realized; Thanks to the strong anisotropy of subwavelength structures, ultra-thin polarizers and polarization converters can be developed. The electromagnetic amplitude can be adjusted by artificial absorbers, subwavelength patterns enhanced emitters. The local field enhancement help boost the nonlinear optical effect, such as harmonic generation and four-wave mixing frequency.
Figure 3. The analogy between mechanical architecture and Electromagnetic Architectures. (a) Schematic of crossroads and cross waveguides. (b) The gateway arch and catenary-shaped nanoaperture perforated in a metallic film.\textsuperscript{[42]} (b) Reproduced with permission from Wikipedia.\textsuperscript{[39]}

Figure 4. Typical unit structure. (a) Representative isotropic elements. The first and the second rows indicate solid and hollow structures, respectively. (b) Typical anisotropic elements. The first and the second rows indicate solid and hollow structures, respectively. (c) Typical planar chiral elements with different responses for opposite circular polarizations. (d) Examples of metagrating elements with dimensions larger than the operational wavelength.
Figure 5. (a)(b) Two kinds of lattice forms and evanescent wave coupling between (c) metallic and (d) dielectric elements.

Figure 6. Schematic of three kinds of local phase modulation. (a) Propagation phase, (b) geometric phase, and (c) Resonant phase. (b) Reproduced with permission. Copyright 2015 Science China Press and Springer-Verlag Berlin Heidelberg. (c) Reproduced with permission. Copyright 2013 The authors.
Figure 7. Structures for reconfigurable functions. (a) Tunable structural color by stretching the PDMS substrate. (b) Schematic of the solid-state spatial light modulator with independent phase and amplitude control. (c) Experimental demonstration of multistate switchable PSOIs at different crystallization levels under RCP and LCP illumination. Reproduced with permission.[135] Copyright 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced with permission.[166] Copyright 2021 The authors. (c) Reproduced with permission.[126] Copyright 2020 Wiley-VCH GmbH.

Figure 8. (a) Deep neural network (DNN)-assisted all-dielectric meta-devices design, through which amplitude and phase responses of all-dielectric meta-atoms are simultaneously derived in millisecond-timescale and meta-device inverse design models can be constructed.
Reproduced with permission.\textsuperscript{[184]} Copyright 2019, American Chemical Society. (b) GAN-assisted design of diatomic metamolecules for polarization manipulation. Left: designed and fabricated meta-atoms that can convert left-circularly polarized light to its cross-polarization. Right: measured polarization states. Reproduced with permission.\textsuperscript{[185]} Copyright 2019, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) DNN-assisted silicon-on-insulator-based 1×2 power splitters design. Reproduced with permission.\textsuperscript{[186]} Copyright 2019, The authors.

\textbf{Figure 9.} (a) Multiwavelength metalens design using the adjoint technique. Left panel: the forward and adjoint simulations in the adjoint optimization technique. Right panel: Color-coded plots of the surface electric current densities that are used as excitation sources in the adjoint simulation at the two wavelengths. Reproduced with permission.\textsuperscript{[191]} Copyright 2020, Optical Society of America. (b) Simulated averaged deflection efficiencies over both TE- and TM- polarizations of various transmission grating types as a function of deflection angle. These include the classical echelle grating, three types of established metagrating designs, and the topology-optimized metagrating. Reproduced with permission.\textsuperscript{[192]} Copyright 2017, American Chemical Society. (c) Topologically optimized continuous angle-tunable birefringence with freeform metasurfaces for arbitrary polarization conversion. Reproduced with permission.\textsuperscript{[193]} Copyright 2020, American Association for the Advancement of Science.
In this article, the relationship between the structures and functionalities of artificial optical/electromagnetic materials and devices is reviewed, including the characteristics of various typical subwavelength structures and typical methods for the study of optical/electromagnetic structural-functional relationships. Based on the analogy of mechanics and optics/electromagnetism, the concept of "Electromagnetic Architectures" is proposed and illustrated.
Mingbo Pu received the B.S. degree in physics from Nankai University, Tianjin, China, and the Ph.D. degree in optical engineering from the University of Chinese Academy of Sciences, Beijing, China. He is currently an associate professor in the State Key Laboratory of Optical Technologies on Nano-Fabrication and MicroEngineering, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, China. His research interests include plasmonic metamaterials, subwavelength optics/electromagnetics, catenary optics/electromagnetics, and their practical applications.

Xiaoliang Ma received the B.E. degree from the University of Science and Technology of China, Hefei, China, and the Ph.D. degree in optical engineering from the University of Chinese Academy of Sciences, Beijing, China. He is currently an associate professor with the
State Key Laboratory of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, China. His research interests include metamaterials and their practical applications.

Xiong Li received the B.E. degree in electronic science and technology from Chongqing University, Chongqing, China, and the Ph.D. degree in optical engineering from the Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, China. He is currently an associate professor with the State Key Laboratory of Optical Technologies on Nano-Fabrication and MicroEngineering, Institute of Optics and Electronics, Chinese Academy of Science. His research interests include nanophotonics, metasurfaces, and plasmonics.