Electrically tunable metasurfaces: from direct to indirect mechanisms

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Abstract

Intensive development of nanofabrication processes has opened a new window to control electromagnetic waves using subwavelength nanostructures array, named metasurfaces. Although the metasurfaces have succeeded in achieving unprecedented functionality by arranging various shapes of nanostructures to modulate the properties of the incident light, inherent passive characteristics make it impossible to alter the engraved functions after it is fabricated. To give tunability to metasurfaces, various methods have been proposed by using a thermal, chemical, optical and physical stimulus. In particular, electrically tunable metasurfaces are attractive in that they are easy to control precisely and could be integrated into electronic devices. In this review, we categorize the representative electrical tuning mechanisms and research into three; voltage-operated modulation, electrochemical-driven modulation, and externally mediated modulation. Voltage-operated modulation uses materials that could be directly reorganized by an electric field, including liquid crystals and Drude materials. Electrochemical-driven modulation adjusts the optical properties of metasurfaces through electrochemical responses such as electrochromism and electrodeposition. Lastly, externally mediated modulation causes a change in the geometric parameters of metasurfaces or in the phase of the constituent materials by converting electrical energy into thermal or mechanical stimulation. This paper concludes after explaining the pros and cons of each mechanism and the new possibilities which electrically-responsive metasurfaces could bring about.

1. Introduction

Light-modulating properties of metasurfaces and their applications have been thoroughly studied over the last decades. Interactions between subwavelength structures and lights at certain states are used to utilize metalenses [1–3], metaholograms [4–8], perfect absorbers [9, 10], color filters [11–14], and so on. The working principles of the devices are mainly based on the architectural configurations [15], so that appropriate designs are needed to achieve the desired optical attributes. Ongoing studies of metasurfaces have been focused on placing for two or more functionalities in a device, involving reflection and transmission metasurface [16], dual-band meta holograms [7, 17], orbital angular momentum mode-based holography [8], and more. However, such rigid metasurfaces could not change their optical responses after fabrication. For the design of dynamically operating metadevices, metasurfaces that display diverse responses with external stimuli, so-called tunable metasurfaces, have been introduced. This aspect of tunable metasurfaces was used to demonstrate applications such as beam steering [18, 19], switchable structural color presentations [20–22], and multiple holographic images [20] with different types of stimulations. Electricity can trigger various working mechanisms of tunable metasurfaces, enabling
possibilities of integrations with other electrical devices. For this reason, the latest articles of electrically tunable metasurfaces have been collected in this review, especially those operating on visible and infrared (IR) regions. There are various methods to drive internal/external changes in the active metasurfaces [23, 24]. In this review, we have sorted electrically tunable metasurfaces into three principal sections.

The first section is the voltage-operated modulation of metasurfaces. They consist of substances that can rearrange their molecules or charges depending on the direction of the electromagnetic field. Liquid crystal (LC) is one example of such. An appropriate electric field applied to LC could change its physical alignments, making them sensitive to the polarization of incident light. Drude materials with metasurfaces are also responsive to electric variations, in which charge carriers’ movements are invoked. The change causes shifts in its plasma frequency, leading to changes in both refractive index and absorption coefficient. This unique property is compatible with epsilon-near-zero effect, inducing strong electromagnetic confinements.

Two electrochemical phenomena form another class of electrically tunable metasurfaces. Electrochromic materials encounter changes in its refractive index when electrochemical measures such as ion intercalations and redox reactions happen. The alternations dedicate for resonance shifts in metasurfaces to display multi-colorations or switching abilities. Reversible electrodeposition is the other category of electrochemical-driven metasurfaces. Metal ions dispersed within the electrolyte are deposited/dissolved onto the electrode with redox reactions.

Lastly, mechanical transitions triggered by electric field modulation for tuning metasurfaces have been introduced. Joule heat induced by electric current have been used for phase-change materials (PCMs) applied metasurfaces. The transitions between individual states of PCMs show huge optical contrasts in near- and mid-IR (NIR and MIR). Metasurfaces employing micro/nano actuators are called electromechanical systems and are another branch of electric transitions. The physical deviations in the electromechanical systems are triggered by external gap control and internal deformation system.

Each of the sections will thoroughly discuss the working mechanisms, values of stimuli, and the performances of the representative research.

2. Voltage-operated modulation

2.1. Liquid crystals

Modulating the refractive index of the local environment around the metasurface via LCs is one of the widely used methods to realize tunable metasurfaces [25]. The polarization of the wave in respect of the long dimension of the rod-shaped LC molecule affects the interaction between LC molecules and electromagnetic waves. Conventionally, the LC was used as an independent element to control the polarization of light. Recent studies of metasurfaces however, have been integrating LC to modulate the background index of metaatoms.

Driencourt et al experimentally demonstrated an electrically tunable multicolored filter (figure 1(a)(i)) by combining birefringent plasmonic resonators and LC to overcome the color vibrancy limitation of plasmonic resonators [26]. The silver nanowire resonators support a localized plasmon resonance for the transverse magnetic (TM) wave. The voltages applied to the LC not only rotated the polarization analyzer (figure 1(a)(ii)) to modulate the range of transmitted color but also resulted additional chromaticity due to the LC’s birefringence. As the applied voltage increases from 2 to 4.2 V, major contribution of transmitted spectrum is shifted from the excited plasmon resonance to LC. By combining the nanostructure possessing a cyan transmission spectrum to the birefringence-induced colors of the LC, the full width at half maximum of the transmission peaks was reduced at high voltages. All additive and subtractive primary colors which are highly saturated as well as diverse tons of white were generated. By applying a voltage to the LC ranging from 2 to 6.5 V, a single filter can cover over 70% of the color gamut of sRGB area. The measured maximum switching time was about 75 ms at the highest voltage.

LC can also be integrated with metasurfaces for an additional degree of information encryption to hide certain messages [27]. Li et al proposed an electrically switchable, polarization-sensitive optical encryption based on metasurfaces combined with polymer-dispersed LCs. The designed arrangement of nanoapertures enables encryption of the optical image because polarization responses of the plasmonic resonance are different depending on the symmetry of the nanoapertures. An opaque polymer-dispersed LC layer [28–30], overlayed onto the backside of the metasurface (figure 1(b)(i)), becomes completely transparent when the index of the realigned LC matches that of the polymer by applied voltages. Consequently, the systems behave optically as bare nanoaperture arrays. While the LC with a different refractive index from the polymer causes strong scattering illustrating an opaque state, with no transmission. A different transmission was exhibited upon the applied voltages (figure 1(b)(ii)), and the measured response time was 38 ms at 17 V with the 90% normalized transmission.

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In a similar way, refractive index matching was used for an electrically controllable digital metasurface device demonstrated by Li et al but LC was not used in the traditional way [31]. The alternating columns of rectangular gold nanorods forming an angle of $\pi/2$ are covered by high-birefringence LCs and polymethyl methacrylate (PMMA) eliminating the influence on the LC alignment. (Figure 1(c)(i)) without bias, the refractive index of LC is 1.92 and the phase factor satisfying $2\pi$ leads to the ‘1’ state of the metasurface pixel. While the refractive index of LC decreases to 1.53 which is almost equal to that of PMMA when the voltage is applied and the reflection vanishes perfectly satisfying the phase factor of $\pi$ which gives rise to switching to the ‘0’ state. Through the device, a high-intensity modulation as 105:1 with a fast modulation speed of millisecond time scale was experimentally achieved at 633 nm (figure 1(c)(ii)).

Li et al integrated the nanoantennas into an LC-spatial light modulator device enabling abrupt phase change and pixel-size miniaturization [32]. Below 670 nm, phase varies hugely with spectral shifts of the nanoantenna resonances caused by the refractive index change of the LC. Especially in around 665 nm, phase variations corresponding to LC director orientations of 0°, 45°, and 90° spaced at around $2\pi/3$ to each other with high transmission. In the unit cell for three LC director orientations, the incident plane wavefronts remain almost similar when propagating through the LC layer while the transmitted wavefronts tilt due to different phase retardations from interaction with the nanoantennas (figure 1(d)(i)). The optimized number of antennas per pixel was three (figure 1(d)(ii)) for accommodating the fringing electric field and phase-broadening effects with sufficient electrode width [33]. The metasurface comprises

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**Figure 1.** LC-based electrically driven tunable metasurfaces. (a) Multicolored filter using birefringent plasmonic resonators and LCs [26]. (i) Elements of filtering system: polarizer, plasmonic nanostructure, and a voltage-controlled polarization analyzer. (ii) Model of polarization rotation of the analyzer as a function of the voltage applied to the LC cell. (b) Digital metasurface device using a dynamic spatial frequency modulation [31] (i) schematic of the device. (ii) Intensity of the anomalously reflected light as a function of the applied voltage. (c) Metasurface integrated with PDLCs [27]. (i) Schematic of electrically switchable transmission. (ii) Transmission spectra at different applied voltages for the device. (d) Dielectric metasurfaces for phase only transmissive spatial light modulator [32]. (i) E field distribution in the unit cell for three LC director orientations at 665 nm. (ii) Transmission spectra of the three diffraction orders ($T_{-1}$, $T_0$, and $T_{+1}$) of a wave passing through the beam-deflecting configuration.
periodically repeated supercells consisting of three pixels with different LC rotations. The diffraction angles were tuned by different configurations of the addressed electrode with a device comprising individually addressable electrodes and a maximum deflection angle was 11° at 660 nm. The reversal of the deflection direction was also achieved through the designed device that two of three adjacent bottom electrodes were connected to the two terminals of a voltage source. The measured beam deflection efficiency was 36% at 660 nm.

2.2. Drude materials

Drude materials, which follow the Drude’s model, have abundant charge carriers enough to provide electrical conductivity. Such conductive materials could modulate the refractive index by accumulating (or decumulating) their charge carrier concentration according to Drude’s model. Capacitor structure is widely used to control the carrier density, which consist of electrodes and Drude material separated by an insulating material [34–36]. As the voltage between the two electrodes increases, a charge accumulation (or decumulation) layer is formed at the side of active materials facing to the insulator. Because the plasma frequency is directly related to the charge carrier density, the plasma frequency shifts in the same direction as the change of carrier concentration [37]. The transition of plasma frequency causes a change in permittivity, and this difference in permittivity is significantly strengthened for epsilon-near-zero materials where the real value of permittivity is almost zero. Since the movement of electrons occurs very directly and quickly, the fact that they can get high speeds to MHz makes this mechanism attractive [38]. However, there is a fundamental drawback that the charge accumulation (or decumulation) layer is extremely thin (≤2 nm). Although a metal–insulator–metal (MIM) structure and high permittivity ultrathin insulation layer are widely adopted to amplify the optical response and boost up the ratio between active layer and the passive layer, low modulation depth is a remained problem to be solved.

Recently, indium tin oxide has been noted as an attractive candidate for transparent conductive oxides because of its epsilon-near-zero behavior in IR. In order to effectively control the reflectance and phase shift according to the applied voltage of ITO and counter electrode, a complex unit cell which is composed of an Au back-reflector, an Al2O3 dielectric layer, an ITO layer, and a HfO2/Al2O3 laminated (HAOL) gate dielectric, and Au fishbone antenna was proposed [39] (figure 2(a)). This research shows the possibility of electrically reconfigurable device by allowing the phase manipulation of 96 antennas up to ~270° according to external signals. Multifunctionality such as beam steering and dynamic focusing mirror is realized by applying a voltage that matches the desired phase profile to the device. For example, a meta-device with a focal length of 2 μm can change its focus from 1.5 to 3 μm according to electrical signals. Despite their dynamic multifunctionality, a single resonator has a limitation to modulate the light precisely because the amplitude and phase shift of reflected light are strongly coupled. The top and bottom of the ITO layer could be independently controlled to achieve two degrees of freedom for the reflectance and phase shift (figure 2(b)) [38]. The full phase modulation at fixed reflectivity is attained by the controllable carrier concentration profile in the ITO layer with the distinct electrodes. Ideal wavefront shaping without undesirable noise come from uneven amplitudes allows high side mode suppression ratio of +2.7 dB in the beam steering process. This high-precision beam-steering is essential for high accuracy detection such as light detection and ranging (LiDAR) sensor. The authors show the possibility of LiDAR-on-chip by accurately scanning 4.7 m of space using the time-of-flight method.

The change of charge carrier concentration can be also carried out in the conductive polymers. The change movement occurring in the backbone chain of poly(3,4-ethylenedioxythiophene) (PEDOT), a representative transparent conductive polymer, works as polaronic charge carriers and can cause a change in permittivity, same as electrons. This phenomenon is observed in both PEDOT:poly(styrenesulfonate) (PEDOT:PSS) [40] and PEDOT:sulf [41, 42], which have a high electrical conductivity. PEDOT:PSS switches the metallic mode and insulating mode with 30 Hz depending on the applied voltage, and shows a different optical response in IR (figure 2(c)). Like other metasurfaces, this material can be shaped into a rectangular nanoantenna that can exploit the plasmonic switching effect via top-down fabrication. This metadevice has succeeded in realizing beam steering with a low operation voltage (±1 V).

3. Electrochemical-driven modulation

3.1. Electrochromic materials

Electrochromic materials display different colors depending on the amount of charges in the material [43]. The change in colors is due to refractive index variations of the materials, which is caused by insertion/extraction of charges. As shown in figure 3(a), the refractive index and the absorption coefficient differ with varying amount of Li⁺ ions inserted in WO3 film [44]. Such switchable materials opened up prospects for light modulating devices [45, 46] involving smart windows [47, 48], fast switching displays
Figure 2. Electrically tunable metasurfaces achieved by Drude materials. (a) Metasurface using a change of carrier density in ITO layer [39]. (i) Schematic of the metasurface. (ii) Phase shift of the reflection as a function of applied voltage for different wavelengths. (iii) Measured intensity profile of the reflected beam from the focusing meta-mirror (focal length = 2 μm).
(b) Metasurface which independently controls two different electrodes at the top and bottom side of ITO [38]. (i) Schematic of the metasurface. (ii) Measured phase shift of reflected light with fixed reflectivity according to applied voltage combination. (iii) Intensity distribution of beam steering. (c) Metasurface using PEDOT:PSS as a transparent conductive polymer [40]. (i) Real value of permittivity at insulating and metallic states. (ii) Transmittance of rectangular nanoantenna of the ON and OFF states. Electric field polarized parallel to the nanoantenna long axis. (iii) Camera images and intensity profiles in the ON and OFF states.

[49, 50], and more. Recently, metasurfaces employing electrochromic materials have been introduced, combining the color-switching property of electrochromic materials and the versatile wave modulating property of metasurfaces.

Li et al devised a tunable color device with a MIM structure composed of an Al layer, WO3 layer, and rectangular shaped Al nanostructures in order (figure 3(b)(i)) [51]. With Li⁺ ions from LiFePO4 electrolyte intercalated into the WO3 (delithiated: +1 V from lithiated: −1.4 V), the refractive index of the film shifts from 2.1 to 1.9, altering a resonance shift. The Al nanobrick with different width and length caused the resonance to be dependent on the polarization state of the incident light. For longitudinal polarization, the structure appeared blue and showed a resonance shifting of 58 nm whereas for perpendicular polarization, the color and the shift were each orange and 36 nm (figure 3(b)(ii)). The device posed significant color changes with the both of incident polarization and the lithiated/delithiated states of the WO3 layer. A cyclic voltammetry sweep of 3 mV s⁻¹ was carried out to show continuous changes in the resonance peak and a switching time of 20 s was measured from the device. Another study by Marika et al, has been aimed to develop a WO3 Fabry–Pérot structure with both high chromaticity and brightness [52]. The electrochromic device was ordered so that the light passing through the device was not blocked by the counter electrode (reversed structure). A complementary form where the counter electrode blocks the transmitting light (conventional structure) was devised for comparison. The reversed structure was composed of a WO3 film.
sandwiched by an Au metal film and a porous Pt film to create Fabry–Pérot cavity. Since the counter electrode in the reverse structure was positioned away from the light path, the reflectivity of the structure increased up to 20% compared with the conventional structure. Also, with varying thickness of the WO3 film, assorted colors ranging from light blue to dark yellow were expressed. However, tunable metasurfaces made of WO3 suffer from the intrinsic problems of the inorganic material. Such problems include limited range of tunable colors and slow switching speed reaching up to seconds [53].

Conductive polymers could present both insulating and metallic features depending on the doping states of the material [54]. With more than five different color states, stability, and ease in fabrication [55], polyaniline (PANI) has been a favored material for electrochromic researchers. Xu et al demonstrated an Au nanoslit absorber deposited with PANI that showed both high chromatic contrast and fast switching speed [56]. The nanoslit was built orthogonal to the glass substrate and was immersed in electrolyte as depicted in figure 3(c)(i). As the charge-state of PANI switched from oxidized to reduced (switching voltage from 0.3 to \(-0.2\) V), the metal-dielectric structure changed from an absorber to a transmitter at 632.8 nm TM-polarized input. To fully compare the effectiveness of the slit-structure with parallelly layer structure, the researchers stated the figure of merits (FOM) as the ratio of switching contrast ($\gamma$) and switching time ($\tau$). As depicted in figure 3(c)(ii), the FOM of the nanoslit ($\gamma = 70\%$, $\tau = 14$ ms) is more than six times higher than the FOM of its counterpart ($\gamma = 10\%$, $\tau = 9$ ms).
In addition, full-color switching Au nanoslit was demonstrated using another electrochromic material, poly(3,4-(2,2-dimethylproplylenedioxy)thiophene) (PProDOT-Me2) instead of PANI. Another PANI using electrochromic device was presented by Peng et al, and they reported gold nano core-shells coated with PANI to construct multi-color nanopixels [23]. The idea of PANI coating on colloidal Au nanostructures has been ongoing and was dealt by similar studies [57, 58]. The coated core-shells were drop casted on to an Au film and both metals generated localized cavity resonance at the gap (figure 3(d)(i)). The gap enabled not only the resonance but also ensured enough spacing between each metaatoms to prevent unwanted coupling. Testing on different gapped PANI shells, researchers discovered that the achievable spectrum of diffracted lights showed dependency on the size of the gap; bigger gap led to bigger color range. With the largest achievable gap size of 20 nm, voltages were swept from −0.2 to 0.6 V and showed scattering light ranging from green to red (figure 3(d)(ii)). The meta atoms showed high stability, reproducibility, and were also capable of managing video-speed switching (20 Hz). In addition, centimeter-scale metasurface pixels were generated, offering possibilities for scalability of the idea. However, the demonstrated nanopixels were suffering low switching contrast (~20%) at 20 Hz, revealing a flaw in the metasurface. Nevertheless, the idea of PANI-coated metasurface has been ongoing and finally, Kaisner et al demonstrated a PANI-electrochromic metasurface that enables high contrast switching up to 860:1 with appropriate application of Pancharatnam–Berry (PB) phase [59]. The device of interest is consisted of rows of Au rectangular nanorods with odd rows (static pixels) coated with PMMA and even rows (active pixels) with PANI (figure 3(e)(i)). When PANI changes from reduced state (‘OFF’ state, −0.2 V) to oxidized state (‘ON’ state, 0.6 V), the refractive index of PANI deviates from \( n_{\text{OFF}} = 1.5 + 0i \) to \( n_{\text{ON}} = 1.13 + 0.26i \) (figure 3(e)(ii)) at 633 nm. Using the fact that the refractive index of PMMA equals to that of PANI at ‘OFF’ state, the static and active pixel’s nanorods were deliberately placed orthogonal to each other so that PB phase of \( \pi \) is achieved on the metasurface. Thus, with circularly polarized incident light, the transmission of metasurface at ‘OFF’ state reaches zero. On the ‘ON’ state, since refractive indexes do not match, transmission suppression becomes ineffective and light transmits through the metasurface. The geometrical modulation was proven as the key factor for high contrast switching since the normalized intensity contrast between ‘ON’ and ‘OFF’ state was up to 860:1, and only 10:1 in a control experiment with PB phase dismissed. Other electrochromic materials have also been studied for displaying color-tunable features [60, 61]. One is PProDOT-Me2, and researchers have worked on the material to demonstrate a video speed switching (20 ms) metasurface [60]. The material’s superior switching contrast on the visible region [62] was used to turn on and off the reflection from the device. The metasurface is composed of colloidal covered metallic layers coated with gold (figure 3(f)(i)) and the switchable colored surfaces displaced a near 50% contrast with potential deviation from −1.0 to 0.5 V. The bumpy shape of the surface enlarged the ion transfer and the switching time reduced to a quarter compared to a planar shaped surface (figure 3(f)(ii)), enabling video speed switching (20 Hz). Further analyses were carried out to find appropriate ionic liquid type for another display-applicable property, i.e. long lifetime. The usage of 1-butyl-3-methyl imidazolium/\text{BF}_4^- showed profound intensity consistency after 10 million switches.

3.2. Electrically deposited metals

Electrodeposition is the traditional method of depositing metals using electrochemistry. Metal ions dissolved in the electrolyte are reduced by the current of the electrode and adhere to the surface of the electrode. This technology, which has been actively used industrially, can be effectively applied to various metals in micro/nanostructures [63]. This technique is generally irreversible process and therefore unsuitable for tunable devices, however, some researches show that the metal could be deposited and stripped reversibly. Compared to other tunable mechanisms, this process has the advantage of being able to selectively deposit a metal at a desired location and control the thickness of the deposited metal at the nanoscale level. It is attractive that it can be combined with plasmonic nanostructures that exhibit unique optical properties, however, relatively slow response times, unavoidable surface non-uniformities are pointed out as limitations.

Lithium (Li) can be electrically deposited in electrolyte, and be stripped when reverse voltage is applied (figure 4(a)) [64]. A structure composed of relatively stable Ag and SiO₂ is used as an electrode and as a metaatom, and the applied voltage is delicately controlled within a range that does not damage the nanostructure. A 50 nm SiO₂ and Ag thin layers are stratified on a 100 nm Ag reflector to form a MIM structure. The magnetic dipole moment induced from the both metal layers generate strong magnetic field confinement in the grating structure named magnetic plasmon resonance (MPR). When an electrical deposition current is applied, Li ions of the electrolyte are selectively deposited on the sidewall of the MIM pattern and creates Li bridge connecting the top and bottom metal layers. Because these metal bridges change the MIM to be continuous metal structure and allow the plasmon to move freely, the dominant
optical response is switch from MPR to surface plasmon polariton (SPP). Two different resonances are identified in the reflection spectra.

Dissolution with a chemical agent allows the Ag to be deposited reversibly. A chemically well-cocktailed electrolyte, i.e. a mixed solution of Cu$^{2+}$ and Br$^-$ in an appropriate ratio, can dissolve Ag spontaneously [65]. The deposition process proceeds only when the deposition speed is higher than the dissolution speed, otherwise Ag slowly dissolves into the electrolyte. Since the deposition rate of Ag is proportional to the applied current, the deposition rate can be easily altered by controlling the voltage. Spherical Au cores positioned in a hexagonal hole based on an anodized aluminum oxide template is used as an electrode (figure 4(b)) [66]. Ag ions are gradually deposited on the surface of the Au core to form nanodome structure, and then a nanostructure grows as the deposition time increases. As the effective radius of the nanodome grows, the plasmonic resonance blueshifts and exhibits a significant color change. This metadevice is attractive in that it can express most of the colors of visible light in a single device by manipulating the deposition time.

4. Externally mediated modulation

4.1. Phase-change material

PCM is a solid that converts its optical characteristics depending upon its atomic structure. This unconventional physical property is caused by the bonding mechanism changes. The electrical controllability of a PCM-based tunable metasurface for devices with complex functionalities can be achieved via Joule heating. For instance, a longer current pulse with low voltage or current is used to crystallize by heating it above its crystallization temperature. A short pulse with high voltage or current is applied to amorphize by a melt-quench process. Its reversible change on the nanosecond time scale makes PCMs attractive candidates for active metasurfaces.

Vanadium dioxide (VO$_2$), one of the representative PCMs, exhibits an insulator-to-metal transition under a characteristic temperature with the lattice structure change from monoclinic to tetragonal. From NIR to MIR, the monoclinic phase has low loss, while the tetragonal phase is very absorbing [67]. Low
Figure 5. Electrically controlled metasurfaces using PCMs. (a) Metasurface in which a VO2 layer integrated into the dielectric gap of antennas [70]. (i) Simulated magnetic field magnitude in the unit cell, with VO2 in the insulating and metallic phase. (ii) Continuously tunable phase shift of the metasurface as a function of applied voltage. (b) Dispersion-free metasurface combining VO2 [71]. (i) Schematic of tunable broadband polarization states. (ii) Optical images of 60 nm-thick VO2 film subjected to different currents. (iii) Measured reflectivity of the sample as a function of the current under x-pol incidence. The sample can work as a half or quarter-wave plate when the current is lower than the transition point (dotted line). (c) Metasurface devices based on GST [73]. (i) Schematics of the metasurface. (ii) Measured spectra of the scattered light from the antenna after ten cycles of reset and set pulses, under dark-field illumination. (iii) Simulated spectra of the scattered light from the antenna with different crystallinities of GST. (d) GST-based metasurfaces [75]. (i) Schematic of device configuration. (ii) Simulated steady-state temperature profiles within of an optimized heater with curved boundaries. (iii) Reflectance spectra of the multi-state switching device after crystallization pulses with different voltages.

phase transition temperature ($T_c$) of around 68 °C quite close to room temperature makes VO2 a more fascinating material [68]. Due to its volatile property, however, continuous heating is needed to sustain the metallic state of VO2 [69].

To actively control wide phase shift in the NIR range, Kim et al integrated a VO2 active layer directly into the dielectric gap of metaatoms in a reflect array metasurface for the strong light–matter interaction in the resonance cavity (figure 5(a)(i)) [70]. When the VO2 layer is in the metallic (insulating) state, the magnetic field is mainly concentrated in the Al2O3 layer (between the top metallic stripe and back reflector) (figure 5(a)(ii)). Such change enables the reflected light modulation in the amplitude and the phase. The applied bias voltage ($V_a$) to locally heat the top Au stripe induced the phase transition in VO2. The phase of the reflected light was continuously shifted from 0° to 180° at 1550 nm in-between values of 9 V $\leqslant V_a \leqslant 11$ V upon the effective thickness of the dielectric layer (figure 5(a)(iii)). The maximal phase shift of 250° at 1520 nm and the modulation speed of a millisecond level were achieved through the device.

In addition to using VO2 as antenna elements, it is also feasible to add a VO2 layer above [71] or underneath [76] antennas. Shu et al added a VO2 film above the whole waveplate for electrically tunable broadband polarization (figure 5(b)(i)). The thickness-dependent dispersion of the SiO2 spacing layer
which can compensate for the dispersion of the resonant modes of the ‘L’ nanoantennas results in a dispersion-free response [72]. The two ends of a silver electrode were connected to external circuitry for electrical control of the Joule heat-induced phase transition of VO₂. When VO₂ is an insulator, the device acts as a broadband half- or quarter-wave plate upon the geometric parameters of the MIM structure, while it functions as a broadband mirror when VO₂ is a metal. Under x-polarized incidence at 4.7 μm, the polarization conversion efficiency of a half-wave plate was achieved a maximum of about 85% at lower than 0.328 A (figure 5(b)(iii)). In the case of a quarter-wave plate under x-polarized incidence at 4.4 μm, the operation efficiency reached up to 86% at 0.35 A (figure 5(b)(iv)). The polarization state was modulated continuously and reversibly within the millisecond time scale.

The germanium-antimony-telluride (GST) is one of the widely used phase change chalcogenides for tunable metasurfaces. When the amorphous phase is crystallized, covalent bonding reconfigures into resonance bonding which gives higher optical matrix elements and smaller average bandgaps than electron pair bonding [73]. No rupture of strong covalent bonds during the phase transition makes the process rapid and stable [74]. Especially, its non-volatile property makes the GST-based devices consume less power than those made with VO₂ for infrequent switching. A relatively higher TC of GST (160 °C) offers higher temperature resistance, and two stable phases, the amorphous phase and the metastable crystalline (rock salt-type), coexist in GST at room temperature.

Wang et al stacked a GST nanobeam on top of a silver strip that serves as a plasmonic antenna and nano hot plate for electrically tunable phase change metasurfaces (figure 5(c)(i)) [73]. Heat can be excellently dissipated to the substrate via a wider silver strip heater than the GST beam. In simulations, SPPs were operating speed of 10 kHz range (figure 5(c)).

Electrically binary switchable and quasi-continuous tunable non-volatile metasurface using recently developed Ge₂Sb₂Se₄Te₁ (GSST) was reported by Zhang et al [75]. GSST breaks traditional coupling; trade-off between index contrast and absorption loss [77]. The meta-atoms patterned in a GSST film arranged in a square lattice and rested on a metal heater acting simultaneously as a reflector (figure 5(d)(i)). The heater geometrically optimized with curved boundaries improved the uniform transition throughout the meta-atoms (figure 5(d)(ii)). GSST offers broadband transparency mitigating optical losses and the larger switching volume enhancing light-matter interaction, which underlies ultra-broadband resonance tuning [77,78]. Single 20 V, 5 μs and 10 V, 500 ms pulses were applied for amorphization and crystallization, respectively. The outstandingly large resonance tuning range covering half-octave, from 1190 to 1680 nm, and the large reflectance modulation up to 400% at 1.43 μm were achieved via the device.

### 4.2. MEMS and NEMS

In this section, studies of micro/nano electromechanical systems (MEMS/NEMS) merged with metasurface [79–82] will be discussed. The mechanical movements of metasurfaces differ the gap between each optical element, or physically deform one to display various light interactions.

Arbabi et al demonstrated a varifocal metalens by coaxially placing two metasurfaces and tuning their gap using MEMS-optical metasurface (OMS) [83]. As shown in figure 6(a)(i), a metalens with a glass substrate is fixed, and the other metalens with a SiNx membrane moves toward/away from its counterpart, increasing/decreasing the effective focal length (EFL). The SU-8 spacing layer attached onto the static metalens provided initial spacing of 15 μm and Au layers surrounding each metasurfaces were used as capacitors for gap control. By electrically controlling the gap between two metasurfaces from 15 to 12 μm (from 0 to 8 V), the MEMS-OMS displayed an EFL change from 565 μm to 629 μm (figure 6(a)(ii), device 2). A similar study of MEMS-OMS with gap surface plasmon control was introduced by Meng et al showing both anomalous reflection and reflective focusing capabilities (figure 6(b)(i)) [84]. While the previous research altered the mutual interaction between the metalenses, the optical resonance shift induced within an OMS was studied. The supercell of the OMS is configured with an Au metasurface positioned on top of an Au mirror with its Au nanosquares facing the metallic mirror. The gap surface plasmon of the tunable structure varied greatly with the separation between the metasurface and the mirror. Figure 6(b)(ii) depicts simulation results of diffraction efficiencies with varying air gap (tₐ). As tₐ increases, diffraction efficiency at m = 0 increases whereas diffraction efficiency at m = +1 decreases. Due to the symmetry of the nanosquares, the efficiency is independent of polarization mode (TM/TE). At a small air gap (tₐ = 20 nm, V = 0 V), the phase modulated waves were reflected from the Au mirror to achieve anomalous reflection (15.5°), while with big air gap (tₐ = 350 nm, V = 3.75 V) the waves were attenuated and resulted
Figure 6. Electromechanical system integrated metasurfaces. (a) Varifocal MEMS [83]. (i) Schematics of varifocal MEMS composed of a static metasurface and a movable metasurface. (ii) Effective focal lengths (EFLs) of varifocal MEMS with distance between lenses. Dashed line: simulation results of EFL, dots: experimental EFL of 8 devices under different voltage. (b) Dynamic piezoelectric MEMS-metasurface [84]. (i) Schematics. (ii) Diffraction efficiencies of $-1^{\text{st}}, 0^{\text{th}}, +1^{\text{st}}$ modes depending on the air gap and input polarization. (c) NEMS-chiral metasurface [85]. (i) Schematics of two chiral metasurfaces. (ii) CD changes with respect to electric potential shifts. (d) Reconfigurable NEMS-kirigami [86]. (i) Schematics of a 2D pinwheel array switching to 3D. (ii) Left: reflection spectrum of the pinwheel array. Right: modulation contrast ($\Delta R/R$) of spiral array. Both are depicted with varying electric potentials.

A specular reflection. The diffraction efficiency calculated at $+1^{\text{st}}/0^{\text{th}}$ order changed from 77/0% to 0/96%. Using these results, a MEMS metalens displaying tunable focusing efficiencies and polarization-independent 2D focusing was realized.

Alongside with MEMS, research on nanoscale actuation of metasurface has also been carried out [85]. Kwon et al showed NEMS-tunable dielectric chiral metasurfaces which was composed of two teeth-shaped silicon metasurfaces (figure 6(c)(i)). The chunks of each metasurface were intentionally built to break the $n$-fold symmetry ($n > 2$) so that strong chiroptical reflection properties were achieved. When electric potentials were given to the gold electrodes, the neighboring structures from different metasurface received different potentials from its counterpart, forming a pair of capacitors. This induced electrostatic forces between the sets of silicon structures, altering the gaps ($g_1, g_2$) so that the chirality of the nano structures was broken. To validate, reflective circular dichroism (CD) of the NEMS metasurface defined as $|R_{L,L} - R_{R,R}|$ ($R_{L,L(R,R)} = L(R)\text{CP reflection}; L(R)\text{CP input}$) was investigated with varying electric potential. Experimental results confirmed continuous tuning of reflective CD from 0.45 to 0.01 (from 0 to 2.8 V) (figure 6(c)(ii)). Another study by Chen et al demonstrated reconfigurable NEMS-kirigami displaying multiple functionalities [86]. As depicted in figure 6(d)(i), the metasurface is composed of an etched Au film supported by SiO$_2$ pillars and Si substrate fabricated with delicate processes involving wet and dry etching. When an appropriate electric potential is given, the sliced parts of the gold film are pulled down by the electrostatic force between the Au film and the Si film, forming a 3D-Au structure deformed from its
| Category                              | Mechanism                          | Materials           | Operating wavelength | Response time | Advantages                                      | Disadvantages                  | References |
|--------------------------------------|------------------------------------|---------------------|----------------------|---------------|------------------------------------------------|--------------------------------|------------|
| Voltage-operated modulation          | Molecular orientation              | LC                  | Visible              | £ 1 kHz       | - High efficiency                               | - Bulkiness                    | [31, 32]   |
| Carrier concentration modulation      | Drude materials                    | NIR                 | £ 5 MHz              | £ 5 MHz       | - High modulation speed                         | - Technical maturity           | [38, 39]   |
| Conductive polymers                  |                                    | NIR                 | £ 30 Hz              | £ 30 Hz       | - Low price                                     | - Low energy consumption       | [40–42]    |
| Electrochemical-driven modulation     | Electrochromism                     | WO$_3$, electrochromic polymers | Visible, NIR      | £ 30 Hz       | - Low price                                     | - Slow modulation speed        | [23, 52]   |
| Electrodeposition                    | Ag, Li                             | Visible, NIR       | £ 1 Hz               | £ 1 Hz        | - Low price                                     | - Slow modulation speed        | [64, 66]   |
| Externally mediated modulation        | Phase transitions                  | GST, GSST, VO$_2$   | NIR, MIR             | £ 10 kHz      | - High modulation speed                         | - Low energy efficiency        | [74, 76]   |
| Mechanical modulations               | Mechanical actuator (MEMS/NEMS)     | NIR                 |                       | £ 1 kHz       | - High compatibility with IC                    | - Complex fabrication          | [83, 84, 86] |
initial 2D film. This is a reversible process within the film’s elastic deformation range. A pinwheel-curved structure (0 V/31 V) and a spiral-curved structure (0 to 60 V) were introduced, each displaying reflection contrast with electric potential variations (figure 6(d)(ii)).

5. Conclusion

This review has shown the recent advances of electrically-controllable nanophotonic devices and their mechanisms. The means for engraving tunable properties on the systems tie up the aspects of the devices, such as composing material, target wavelength, and others. The various mechanisms introduced in this paper are summarized for the reader’s clear understanding and simple comparison (table 1). PCMs can modulate their lattice structures very quickly, however, structural limitations and relatively high energy loss due to the microheater are issues to be solved for the practical designs of metasurfaces. LCs not only can change the effective refractive index and polarization in visible region but also have wide candidate materials due to their technical maturity, however, the required bulky volume could be an obstacle for compact nanophotonic device. For electrochromic materials, slow modulation speed of up to a minute is a major problem. Metasurfaces that rely on electrodeposition/dissolution process can utilize plasmonic phenomenon which is difficult to exploit in other methods, but slow reaction rate drags their responses. Inorganic conductive materials such as ITO show an extremely fast response time due to the speedy movement of electrons, but their low modulation efficiency and fabrication difficulty have remained as nagging issues. Although electrical tuning process using a conductive polymer based on a similar phenomenon has been recently introduced, it still shows a slower speed than inorganic-based carrier modulation. Finally, mechanical modulation-driven tuning methods can directly change their geometric parameters and can be easily integrated with the integrated circuit (IC) chip, but the complex fabrication and high cost have to be solved. In addition to the various technologies introduced so far, some notable progresses have been developed. Especially, linear modulation of refractive index by Pockels effect displayed prominent results [87–90], which could lead to SLM, free space applications and more. The phenomena induce optical birefringence on electrically polarized materials such as ferroelectrics and electrically poled polymers.

By comparing the above electrical tunable approaches, we were able to get some important insights related to the intrinsic features of the mechanisms. At first, the methods based on electrochemistry, e.g. electrochromism, electrodeposition process, and other mechanisms using polymers, show distinctly slower operating speed compared to other methods. This is because of the unavoidable slow movement of the ions at the electrolyte that necessarily accompanies the chemical reaction. Second, the properties of mechanisms via a thermal or mechanical process are constrained by the behavior of the intermediator. For example, an electrically-driven phase transition process suffers from disadvantages such as high energy loss, structural design constraints, and limited operating speed due to the existence of microheater. Similarly, in MEMS/NEMS, the speed and design of the metasurface are defined by the mechanical driving part. Therefore, most of the aforementioned shortcomings could be improved by optimizing the intermediate system.

The various mechanisms introduced so far anticipate to pave the way for developments of new science and practical applications. The development of spatiotemporal metasurfaces based on novel materials and dynamic optical devices would lead to physical phenomena such as non-Hermitian systems [91–93] and topological photonic systems [94–100] and arguably derive fascinating ideas for further advanced electro-optical devices [98, 101–103]. Additionally, electrically operated nanophotonic devices can be easily extended to industrial uses. Several pioneering studies have already implemented active hologram displays [20, 104–112], varifocal metalens [39, 113–117], and LiDAR [18,38,118] as experimental applications, and are expected to be a great inspiration for smart windows, next-generation communication systems, and photonics ICs.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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