



Optical-field information manipulation based on nonlocal metasurfaces: From passive to active systems

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Abstract

Metasurfaces, as a key platform for flat optics, enable advanced manipulation of light by harnessing rich local and nonlocal resonant modes at subwavelength-structured interfaces. Distinct from conventional local metasurfaces that primarily modulate optical wavefronts over broad spectral ranges, nonlocal metasurfaces based on collective resonances provide enhanced spectral and momentum selectivity together with strengthened light-matter interaction. This review surveys recent advances in optical-field information manipulation enabled by nonlocal metasurfaces, where “information manipulation” denotes the high-dimensional control of amplitude, phase, and polarization across spectral, temporal, spatial, and momentum domains, with a particular focus on integrating local and nonlocal resonances to enhance device performance and functionality. We first introduce the fundamental characteristics of nonlocal resonances and summarize representative progress in real- and momentum-space light control within passive nonlocal metasurfaces. We also discuss recent advances in active nonlocal metasurfaces, including applications in nonlinear harmonic generation, quantum-state control, and spatial information lasers. Finally, we highlight emerging trends in on-chip and tunable nonlocal metasurfaces and outline key challenges and future research directions for this rapidly evolving field.

Keywords: Nonlocal metasurfaces, bound states in the continuum, guided mode resonances, light-matter interaction, optical field manipulation

1. Introduction

Light intrinsically carries rich spectral, temporal, spatial, and momentum information, offering unprecedented opportunities to engineer structured optical fields in modern nanophotonics. Traditional optical systems typically operate as bulky components that rely on light propagation and refraction to control electromagnetic waves, thereby limiting their modulation capabilities and restricting the miniaturization and integration of optical devices. Over the past few decades, advances in micro- and nanofabrication technologies have enabled metamaterials and metasurfaces to localize light at subwavelength scales, significantly enhancing light-matter interactions and accelerating the development of flat optics^[1-8]. By designing meta-atoms with tailored materials, geometries, and sizes, metasurface arrays can be engineered to exhibit a wide range of optical functionalities. Generally, metasurfaces can be broadly categorized into local metasurfaces, which operate through individual subwavelength scatterers, and nonlocal metasurfaces, which rely on the coupling of spatially extended modes over many unit cells^[9]. Local metasurfaces typically exploit local resonant phases (e.g., arising from surface plasmon resonances in metals and Mie resonances in dielectric structures),



geometric phases governed by unit-cell rotation, and propagation phases tuned via the effective refractive index to achieve broadband wavefront manipulation^[10], thereby enabling advanced optical functionalities such as full-Stokes polarization imaging^[11,12], broadband achromatic metalenses^[13–17], and complex-amplitude holography^[18–20]. In contrast, nonlocal metasurfaces based on collective interactions support high-quality (Q) resonances, in which the response of individual elements is inherently coupled. While this coupling constrains the generation of arbitrary wavefronts, it provides an opportunity for highly selective spectral engineering and precise tailoring of optical responses^[9,21–24].

As shown in [Figure 1a](#), unlike local resonances that exhibit deep subwavelength in-plane mode confinement and flat-band dispersion, typical nonlocal resonances feature near-field distributions that extend across multiple unit cells and therefore correspond to dispersive band structures. The band dispersion of nonlocal metasurfaces, corresponding to a wavevector-dependent optical response (spatial dispersion), extends the functional capabilities beyond those of local metasurfaces and enables new optical functionalities. For example, by engineering the angle-dependent reflection or transmission amplitude distribution from a nonlocal design perspective, various spatial-frequency filters can be implemented to perform analogue optical computing tasks such as spatial differentiation^[25–27], edge detection^[28–30], and solving integral equations^[31]. This analog optical computing platform enabled by nonlocal metasurfaces is flat and ultracompact, eliminating the need for lenses to perform Fourier transformations in traditional Fourier optical systems. On the other hand, by engineering angle-dependent transmission phases while maintaining nearly constant transmission amplitudes, various nonlocal spaceplates can effectively compress the optical propagation distance, thereby reducing the thickness of optical devices^[32,33]. Another notable feature of nonlocal metasurfaces is their ability to support multiple high- Q resonances with ultranarrow spectral linewidths^[34], thereby enabling important applications in optical modulators^[35,36], biosensing^[37,38], and nonlinear signal enhancement^[39,40]. These applications have been extensively developed in traditional nonlocal metasurface systems, such as photonic crystal slabs^[41] and guided-mode-resonance (GMR) gratings^[42,43]. Bloch modes in these structures represent a typical type of nonlocal mode arising from the coherent coupling of electromagnetic waves in periodically modulated dielectrics, enabling strong light confinement through their spatially extended and momentum-selective characteristics. In parallel to these dielectric platforms, the principles of collective electromagnetic responses have been widely explored in metamaterial arrays of discrete resonators, tracing from foundational macroscopic models of spatially dispersive media^[44] and fundamental lattice scattering framework^[45] to the development of resonant metalenses^[46] and electromagnetically induced transparency^[47]. Furthermore, strong cooperative interactions in these resonator arrays can induce sharp transparency resonances^[48] and support macroscopically extended, many-body subradiant states^[49]. Driven by these cumulative advances in collective scattering and subradiant mode engineering, emerging nonlocal metasurfaces now incorporate novel coupling mechanisms to reach the ultimate limit of light confinement. Most notably, bound states in the continuum (BICs)^[50,51], which can be viewed as extreme cases of perfectly confined subradiant states, not only further enhance optical field confinement but also enable versatile and flexible wavefront control. First theorized by von Neumann and Wigner in 1929 within quantum mechanics, BICs represent perfectly localized states that coexist with a continuous spectrum^[50]. Physically, BICs arise from perfect destructive interference among multiple radiation channels, which completely decouples the mode from the external environment to yield a theoretically infinite Q factor. Consequently, as shown in [Figure 1b,c](#), by integrating nonlocal resonances such as BICs with the multidimensional optical-field manipulation capabilities of local resonances, nonlocal metasurfaces offer a pathway to maximizing the complementary advantages of both photonic crystals and local metasurfaces^[52]. Recently, the control of light fields and information encoding based on nonlocal metasurfaces has expanded from passive to active systems^[53]. Such rapid progress highlights the unique capabilities of nonlocal metasurfaces in realizing integrated, miniaturized platforms for information lasing and modulation, paving the way for novel photonic functionalities beyond the reach of conventional optics and local metasurfaces.

In this review, we summarize recent advances in the rapidly developing field of nonlocal metasurfaces for controlling optical-field information, encompassing both linear passive and active systems, as shown in [Figure 1d](#). Previous reviews on nonlocal metamaterials and metasurfaces have mainly provided comprehensive overviews of the fundamental mechanisms of nonlocal effects and their applications in optics^[9,21,24] and other wave systems^[23]. Some works have further focused on specific aspects such as the manipulation of nonlinear optics processes^[54] and diffraction fields^[22], as well as particular classes of nonlocal resonant modes, including leaky modes in all-dielectric metasystems^[55], optical BICs^[53], and topological GMRs^[56]. In contrast, this review emphasizes the role of nonlocal metasurfaces in encoding complex optical information across different passive and active systems, enabling flexible reconstruction and manipulation of optical fields. The structure of this article is as follows. [Section 2](#) introduces the manipulation of optical-field information in linear passive nonlocal metasurfaces from the perspectives of real space and momentum space. We focus on how nonlocal resonances provide spectral and wavevector degrees of freedom for manipulating real-space optical information, as well as how nonlocal momentum-space polarization singularities, such as BICs, enable the construction of complex light fields in momentum space. [Section 3](#) discusses recent advances of nonlocal metasurfaces in active systems, including the generation and control of nonlinear harmonic sources and quantum states, along with spatial information lasing featuring controllable wavefronts. Finally, [Section 4](#) outlines the key challenges in optical-field information manipulation based on nonlocal metasurfaces and highlights promising research directions that are likely to attract future attention.

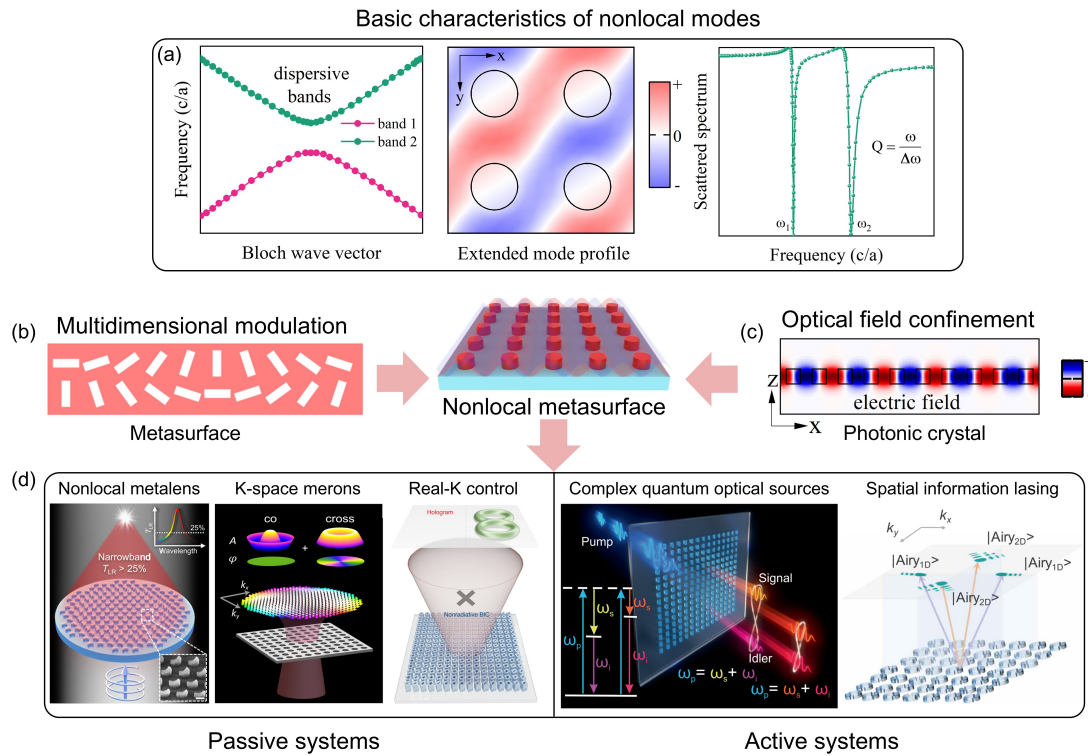


Figure 1. Schematic diagram of optical-field information manipulation based on nonlocal metasurfaces. (a) Nonlocal resonant modes in metasurfaces typically exhibit dispersive energy-band characteristics, spatially extended near-field distributions, and narrow resonance linewidths in their scattering spectra, corresponding to high Q factors. By combining (b) local multidimensional optical-field modulation mechanisms (middle left. Reproduced from reference^[60]. CC BY 4.0.) with (c) the enhanced optical-field confinement (middle right) provided by nonlocal resonances, (d) various novel applications have been demonstrated in passive nonlocal-metasurface systems (bottom left, such as nonlocal metalenses (Reproduced from reference^[82]. CC BY 4.0.), k -space merons (Reproduced with permission from reference^[93]. Copyright © 2025 American Physical Society.) and real- k space multifunctional control (Reproduced from reference^[103]. CC BY 4.0.) and in active nonlocal-metasurface platforms (bottom right, such as complex quantum light sources (Reproduced with permission from reference^[108]. Copyright © 2022 American Association for the Advancement of Science.) and spatial information lasers (Reproduced from reference^[153]. CC BY 4.0.)).

2. Manipulation of Optical-Field Information Based Nonlocal Metasurfaces in Passive Systems

Due to the negligible near-field coupling between meta-atoms in the local metasurfaces, the optical response at a given position on the output surface is determined solely by the design at the corresponding position on the input surface^[24]. Consequently, such systems can flexibly manipulate multiple degrees of freedom of the light field, including amplitude, phase, and polarization across a broad spectral range^[57-59]. In contrast, nonlocal resonances are characterized by spatial dispersion, narrow spectral linewidths, and extended leakage modes, which introduce additional degrees of design freedom such as the spectrum and wavevectors. However, these collective interactions couple individual unit cells, preventing independent phase control across the surface^[60]. Emerging nonlocal metasurfaces can mitigate or eliminate phase drift between structural arrays induced by inter-element coupling through new physical mechanisms and design strategies, thereby enabling multidimensional control of optical information fields in the real and momentum spaces while preserving high- Q resonances.

2.1 Optical manipulation in real space

One significant advantage of nonlocal metasurfaces is their strong spectral selectivity, arising from the presence of rich high- Q resonances, which enables broad applicability in filtering^[43,61], sensing^[37,38,62], and modulating^[35,36]. A representative example is dye-free structural coloration, which relies on well-defined resonances in the visible spectrum and enables high-resolution, fade-resistant color printing^[63]. Previous dielectric metasurfaces relied on localized Mie resonances in multilayer dielectric structures to achieve highly saturated structural colors^[64]; however, they still faced challenges in producing deeply saturated red hues, which are inherently rare in nature. By designing a silicon monolayer nanoantenna that supports the partial spectral overlap of two quasi-BIC modes at wavelengths above 600 nm, and by leveraging diffraction and absorption to suppress higher-order modes at shorter wavelengths, Dong *et al.* realized Schrödinger red pixels with both high saturation and high brightness^[65]. Due to the nonlocal characteristic of quasi-BIC resonance, it is highly sensitive to the incident angle and polarization, enabling its use in information encryption^[66,67]. Therefore, by integrating multiple degrees of freedom such as spectrum, polarization, and wavevector, nonlocal metasurfaces can achieve more diverse control of the optical-field information.

As shown in Figure 2a, by engineering the collective interference of nonlocal plasmonic GMRs in metal–insulator–metal diatomic metasurfaces, Cheng *et al.* achieved spectral- and spin-encoded information encryption^[68]. By varying the relative spacing d between the two umbrella-shaped nanostructures A and B, the coupling between the metasurface and left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) light can be precisely controlled, enabling continuous tuning of the system's circular dichroism at the resonant wavelength of GMRs and the realization of counterintuitive chirality reversal. By tailoring the spacing d and arc lengths of the nanostructures, the reflection amplitude at the resonant wavelengths of the local resonance and nonlocal GMRs can be independently controlled, thereby enabling the formation of coding elements for chiral optical encryption. Complete near-field grayscale imaging is achieved exclusively under LCP light excitation at a wavelength of 1,530 nm, providing an effective strategy for information encryption. In addition to regulating the amplitude and polarization at the resonant wavelength, nonlocal metasurfaces can simultaneously achieve spectral and angular control of the optical response^[69–72]. As shown in Figure 2b, the researchers proposed a bilayer misaligned dielectric metagrating capable of supporting optically asymmetric radiation modes, which can be utilized to tailor the transmission and reflection characteristics of the structure^[72]. Figure 2c presents the reflectance of the investigated mode as a function of wavelength and incident angle. It can be observed that high reflectance is achieved only within a limited range of resonant wavelengths and incident angles, thereby breaking the intrinsic dispersion locking associated with the continuous band structure of conventional nonlocal periodic systems. Figure 2d demonstrates the spatial–spectral selective imaging performance of the metagrating. The image transmission is suppressed within the range of $\pm 4^\circ$ and $1,342 \pm 5$ nm, whereas clear image transmission is realized outside this wavelength–angle window, enabling high-contrast wavelength–angle selective imaging. The spectral and angular selectivity of nonlocal resonances can be further extended to enable independent control of optical functionalities in different wavelength regions. For example, by utilizing superwavelength unit cells to suppress higher-order modes in the visible regime, broadband zeroth-order transparency can be achieved, while infrared light can be diffracted into the +1st order through nonlocal GMRs. Based on this mechanism, a high-performance wearable eye-tracking system has been successfully demonstrated^[71]. A similar strategy can be applied to achieve high- Q beam deflection and focusing by introducing nanonotch defects into the perturbative metagrating^[73,74]. However, because the periodicity along the grating-finger direction remains subwavelength and the defect sizes must be tightly controlled, this approach is still restricted to one-dimensional wavefront control and imposes more stringent requirements on nanofabrication.

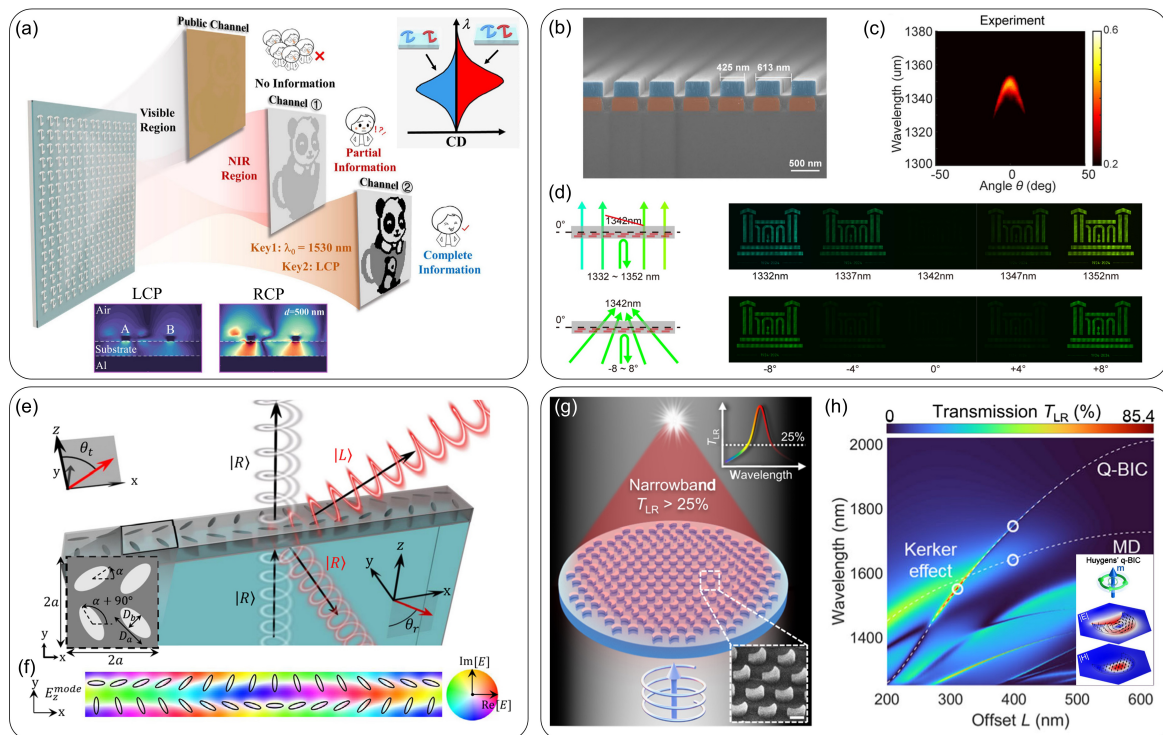


Figure 2. Real-space manipulation of optical-field information based on passive nonlocal metasurfaces. (a) Spin- and wavelength-selective optical encryption enabled by nonlocal plasmonic GMRs. The inset in the upper-right corner illustrates how the spacing d between the A and B nanostructures in the diatomic metasurface unit cell enables the reversal of CD. The lower inset presents the near-field $|E_z|$ distributions of the chiral nonlocal GMRs when $d = 500$ nm under excitation with LCP and RCP, respectively. Reproduced with permission from reference^[68]. Copyright © 2025 John Wiley & Sons; (b)–(d) Spatial–spectral selective light manipulation with bilayer misaligned metagratings; (b) SEM image of the fabricated metagrating sample; (c) Experimentally measured reflectance distribution under different incident angles and wavelengths; (d) Experimental transmission images obtained under normal incidence at different wavelengths (top panel) and under different incident angles at 1,342 nm (bottom panel). Reproduced from reference^[72]. CC BY 4.0; (e)–(f) Narrow-band beam deflection leveraging a quasi-BIC resonance; (e) Schematic diagram of nonlocal phase gradient

metasurface; (f) E_z field distribution of the nonlocal supermode in the simulated $16 \times 2p$ supercell at the quasi-BIC resonant wavelength, showing a continuous gradient phase evolution induced by the rotation of the elliptical hole nanostructures. Reproduced with permission from reference^[75]. Copyright © 2020 American Physical Society; (g)-(h) single-layer, high-efficiency nonlocal metalens based on Huygens' quasi-BICs; (g) Schematic of a narrowband nonlocal metalens that surpasses the 25% efficiency limit of conventional nonlocal metalenses. The inset presents an SEM image of the fabricated sample composed of crescent-shaped meta-atoms; (h) Calculated circularly polarized transmission conversion efficiency T_{LR} as a function of the structural parameter L . The two white dashed lines indicate the dispersions of the quasi-BIC and the MD resonance; their intersection corresponds to the generalized Kerker condition. The lower-right inset shows the simulated electromagnetic field distributions of the hybrid Huygens quasi-BIC mode. Reproduced from reference^[82]. CC BY 4.0. GMRs: guided-mode-resonances; CD: circular dichroism; LCP: left-handed circularly polarized; RCP: right-handed circularly polarized; SEM: scanning electron microscopy; BIC: bound state in the continuum; MD: magnetic dipole.

Combining the tunable high- Q factors of quasi-BIC metasurfaces with local geometric-phase engineering provides a more flexible strategy for narrowband wavefront manipulation^[60,66,75]. As shown in Figure 2e,f, Overvig *et al.* proposed a nonlocal phase-gradient metasurface based on quasi-BIC resonances that selectively deflects circularly co-polarized reflected light and circularly cross-polarized transmitted light at the resonant wavelength, while leaving off-resonant wavelengths largely unaffected^[75]. The unit cell with $p2$ space group symmetry consists of 250-nm-thick silicon elliptical holes patterned on a quartz substrate. The hole dimensions, denoted by D_a and D_b , govern the resonant wavelength and Q factor of quasi-BICs, while the rotation angle α introduces a geometric phase of $\varphi = 2\alpha$. Arranging unit cells with different rotation angles and sizes into a nonperiodic metasurface that satisfies a prescribed phase distribution has enabled the experimental demonstration of a variety of nonlocal wavefront-shaping devices, including multispectral and multifunctional nonlocal metalenses and beam deflectors. However, this type of nonlocal device based on the local phase manipulation has a theoretical efficiency limit of 25%^[66]. Employing few-layer chiral designs and exploiting the Huygens' surfaces to suppress backscattering can substantially enhance the efficiency of narrowband wavefront control^[76-78]. Huygens' surfaces can support spectrally overlapping and orthogonal electric and magnetic dipole resonances with equal strength. The resulting multipolar interference can completely suppress backward scattering, thereby enabling near-unity forward transmission efficiency together with a full 2π phase coverage, a phenomenon also known as the Kerker effect^[79-81]. The extension of multipolar interference to higher-order multipoles has allowed the generalized Kerker effect to be widely applied in high-efficiency wavefront manipulation with metasurfaces^[77,78]. As shown in Figure 2g, Yao *et al.* proposed a single-layer high-efficiency nonlocal metalens based on Huygens-type quasi-BIC resonances^[82]. Tuning the size L of crescent-shaped amorphous silicon nanoblocks spectrally aligns the Mie-type magnetic dipole resonance with quasi-BIC modes, establishing a Huygens scattering regime governed by the generalized Kerker condition. This leads to enhanced forward radiation, thereby enabling efficient circular polarization conversion and high- Q resonance behavior (Figure 2h). Furthermore, the introduction of geometric phase through structural rotation experimentally demonstrated wavelength-selective focusing and imaging, achieving a transmission polarization-conversion efficiency of 55% and a Q factor of 104, surpassing the conventional performance limit of nonlocal metalenses. In addition, harnessing the interference effect of nonlocal leaky modes enables the realization of functionalities that are difficult to achieve with conventional local metasurfaces, such as perfect anomalous reflection and refraction at large angles^[83-86]. Overall, nonlocal metasurfaces not only provide additional degrees of freedom, including spectral and angular control, for manipulating optical-field information, but also enable further performance enhancement of conventional metadevices.

2.2 Optical manipulation in momentum space

In addition to enabling control of light fields in real space, BICs in nonlocal metasurfaces give rise to polarization singularities in momentum space, facilitating the generation of novel structured light fields^[50,87]. For a C_{4v} -symmetric photonic crystal slab, a symmetry-protected BIC located at the Γ point exhibits a non-zero topological charge, and evolves into linearly polarized GMRs distributed along finite in-plane wavevectors $\mathbf{k}_{\parallel}$ ^[88]. Therefore, the GMR states at frequencies near the Γ -point BIC under different $\mathbf{k}_{\parallel}$ can be regarded as an effective wave plate with an azimuth angle θ . When circularly polarized light with a certain $\mathbf{k}_{\parallel}$ is incident, the transmitted cross-polarized circular component acquires a geometric phase of $\pm 2\theta$, which corresponds to the solid angle enclosed by the polarization-state trajectory on the Poincaré sphere^[89]. Owing to the presence of polarization vortices formed by the polarization states of GMRs at different k points on the isofrequency contour near the BIC, a slightly convergent laser beam containing multiple k components can be used to excite resonances at different $\mathbf{k}_{\parallel}$ values in the photonic crystal slab. As a result, the transmitted cross-polarized circular component acquires a helical phase wavefront with a topological charge of $l = \pm 2q$. Based on the above mechanism, Shi and co-workers experimentally realized momentum-space BIC-associated vortex beams, which correspond to a high-order quasi-Bessel beam with diffraction-resistant characteristics^[88]. Furthermore, because this vortex light generator relies on nonlocal effects in momentum space, its structure is spatially uniform and does not require precise alignment with the center of the incident beam. Similar to narrowband wavefront manipulation in real space, the efficiency of nonlocal vortex beam generators based on the geometric phase of circularly polarized light conversion is inherently limited. Nevertheless, recent studies demonstrate that employing a reflective mirror approach or dual-resonance design strategies can substantially enhance the conversion efficiency of nonlocal vortex beam generation^[90-92]. As shown in Figure 3a, through the engineering of the relative magnitudes of the intrinsic material absorption loss γ_0 and the scattering loss γ_s of the nonlocal GMRs in a hybrid metal-dielectric reflective nonlocal metasurface, the radiative loss rate can be effectively tailored. As illustrated in Figure 3b, coupled-mode theory calculations indicate that the reflected light can achieve a higher cross-polarization conversion efficiency when the scattering loss

γ_s is much larger than γ_0 . This theoretical prediction was further verified by experimental results. Figure 3c presents the measured doughnut-shaped far-field intensity profiles of the cross-polarized light under LCP and RCP excitation, together with the corresponding interference patterns formed with a reference beam, each exhibiting two spiral arms. These observations confirm the generation of vortex beams with topological charges of $l = \pm 2$, for which the maximum conversion efficiency can reach up to 86%. The same design strategy can be further extended to generate more complex topological spin textures in momentum space, such as skyrmions and merons. As shown in Figure 3d,e, an operational wavelength of 782 nm was selected, corresponding to the isofrequency contour of the GMR states near the Γ -point BIC^[93]. Under RCP illumination ($|R\rangle$), the simulated momentum-space amplitude and phase distributions indicate that the cross-polarized LCP component ($|L\rangle$) exhibits a phase vortex with a topological charge of $-2(|-2\rangle)$, whereas the co-polarized RCP component ($|R\rangle$) carries zero topological charge ($|0\rangle$). Therefore, the total transmitted light can be expressed as $|E_{\text{out}}\rangle = A_1|0\rangle|R\rangle + A_2|-2\rangle|L\rangle$, which conforms to the formal representation of Stokes-type skyrmionic spin textures. As shown in Figure 3f, the experimentally obtained momentum-space S_3 spin texture under RCP illumination exhibits a second-order meron with a skyrmion number close to 0.5, whose projection onto the Poincaré sphere covers the upper hemisphere. Under LCP illumination, the opposite spin texture is observed, thereby realizing a polarity-switchable meron spin texture in momentum space. Furthermore, through the engineering of momentum-space phase modulation, large lateral beam shifts^[94,95] induced under normal-incidence excitation and ultrathin reciprocal lenses^[96] have been successfully demonstrated.

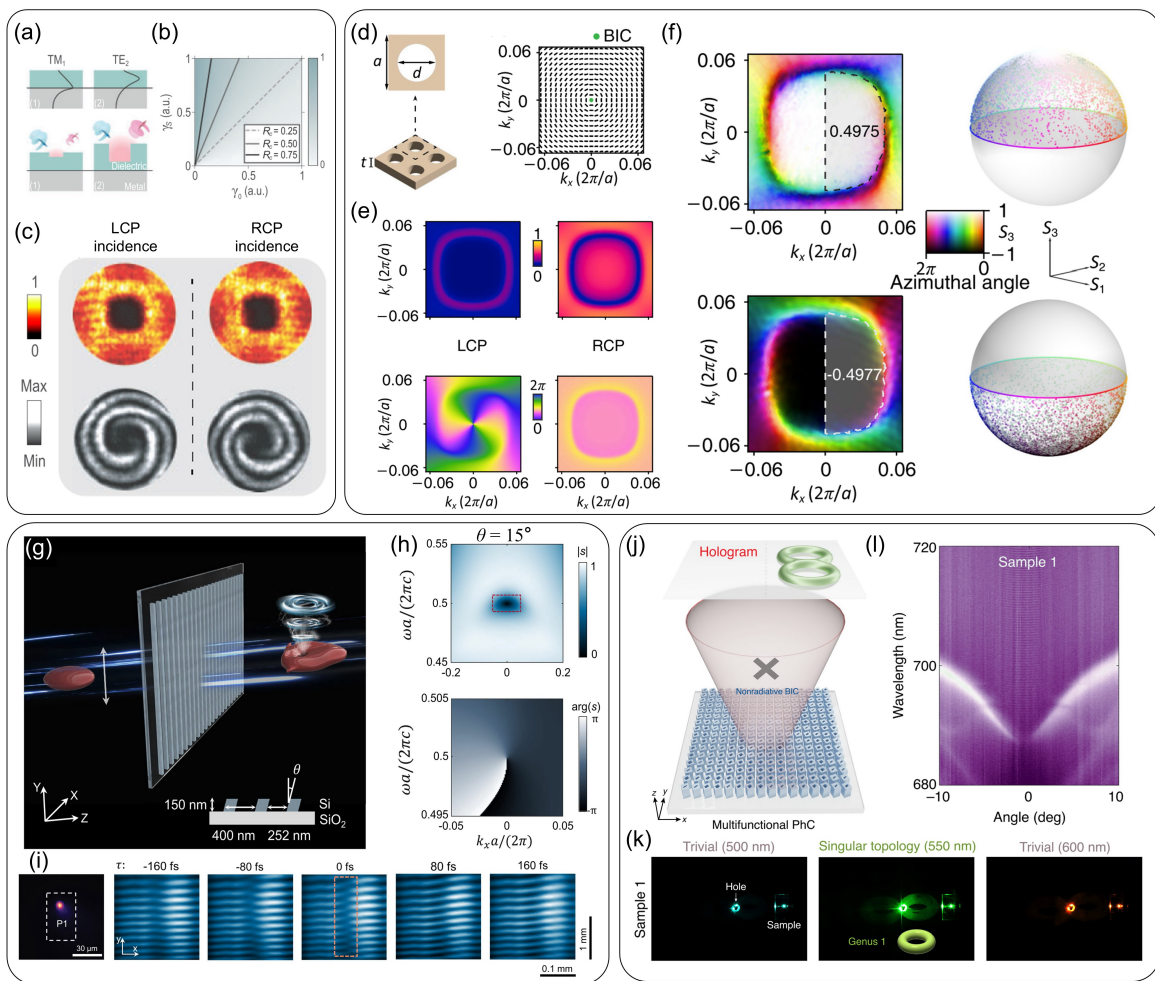


Figure 3. Momentum-space manipulation of optical-field information based on passive nonlocal metasurfaces. (a)–(c) Generation of high-efficiency nonlocal vortex beam via momentum-space polarization vortices; (a) Schematic of electric field distributions (top panel) and out-of-plane scattering rates (bottom panel) of the TM₁ and TE₂ bands in a hybrid metal–dielectric reflection-type metasurface; (b) Cross-polarization conversion efficiency map obtained from coupled-mode theory under different normalized intrinsic loss (γ_0) and scattering loss (γ_s); (c) Experimentally measured intensity profiles and interference fringes of the reflected cross-polarized light under LCP (left panel) and RCP (right panel) illumination. Reproduced from reference^[91]. CC BY 4.0; (d)–(f) Generation of momentum-space meron spin textures by anisotropic GMRs near a BIC in a photonic-crystal slab; (d) Structural schematic of the designed photonic crystal slab (left) and the polarization distribution in k -space near the BIC (right); (e) Simulated amplitude (upper panel) and phase distributions (lower panel) in momentum space for the transmitted cross-polarized (left) and co-polarized (right) components under RCP illumination; (f) Experimentally measured spin texture (left) under RCP (upper panel) and LCP (lower panel) illumination, along with the corresponding meron projections onto

the Poincaré sphere (right). Reproduced with permission from reference^[93]. Copyright © 2025 American Physical Society; (g) A schematic diagram illustrating the generation of spatiotemporal optical vortices based on zero-transmission singularities in the momentum–frequency space. The inset represents the designed symmetry-breaking slanted silicon nanograting; (h) Simulated amplitude distribution (upper panel) of the transmission coefficient s and the corresponding phase distribution (lower panel) within the red rectangular region when $\theta = 15^\circ$; (i) Time-resolved interference fringe evolution at the P1 position under femtosecond pulse pumping (80 fs time interval). The orange dashed box highlights a phase singularity. Reproduced from reference^[101]. CC BY 4.0; (j) A schematic diagram of a slotted metasurface that simultaneously supports nonlocal BIC in momentum space and local singularity-assisted topological phase for arbitrary meta-hologram generation in the real space; (k) The measured real-space holograms at wavelengths of 500 nm, 550 nm, and 600 nm, clear images are observed only around 550 nm, enabled by the singular topological phase. (l) Angle-dependent band structure measurement that confirms stable non-radiative BICs. Reproduced from reference^[103]. CC BY 4.0. TM: transverse-magnetic; TE: transverse-electric; LCP: left-handed circularly polarized; RCP: right-handed circularly polarized; GMRs: guided-mode-resonances; BIC: bound state in the continuum.

Beyond spatial light-field control enabled by momentum-space polarization singularities, the deliberate construction of optical singularities in joint frequency–momentum space provides a powerful route to tailoring and reshaping light fields in the spatiotemporal domain, exemplified by spatiotemporal optical vortices (STOVs)^[97–101]. Specifically, upon excitation by an incident pulse, the optical field $g(\omega, k_x)$ in the frequency-momentum space can be transformed into the spatiotemporal pulse $G(\tau, x)$ via a Fourier transform, expressed as $G(\tau, x) = \mathcal{F}\{g(\omega, k_x)\}$. Consequently, the prerequisite for generating a STOV is equivalent to locating zero-valued phase singularities within the (ω, k_x) space. According to the two-resonance temporal coupled-mode theory, symmetry-protected BICs in metasurfaces with in-plane C_2 rotational symmetry and out-of-plane σ_z mirror symmetry manifest as nodal lines, rather than isolated points, in the transmission spectrum of the (ω, k_x) space. As a result, additional symmetries must be broken to successfully construct STOVs. As shown in Figure 3g, Huo *et al.* experimentally observed the space-time evolution of a STOV with transverse orbital angular momentum (OAM) carried by femtosecond pulses using a slanted silicon nanograting^[101]. This grating structure simultaneously breaks both the in-plane and out-of-plane symmetries, thereby obtaining isolated zero-value transmission singularities in the ω – k_x space, accompanied by a spiral phase distribution around it (Figure 3h). They further pumped the system with 80 fs ultrashort pulses and used a time-resolved interference setup to observe and characterize the generation of STOVs. As shown in Figure 3i, when the temporal delay approaches zero, the left and right interference fringes gradually bend in opposite directions, eventually forming a series of fork-like patterns along the central axis, indicating the presence of spatiotemporal phase vortices. By constructing phase vortices in the frequency-momentum domain, STOVs have been successively realized in reflective nonlocal metasurfaces and liquid surface wave platforms^[98,99]. Recent progress in nonlocal metasurfaces has enabled the simultaneous manipulation of optical-field information in both real and momentum spaces^[102,103]. As shown in Figure 3j, Lv *et al.* proposed a nonlocal metasurface that simultaneously supports the real-space local singularity-assisted topological phase for spatial information encoding and momentum-space nonlocal BICs^[103]. The perturbed titanium dioxide (TiO₂) slotted metasurface architecture enables the generation of a spectral-zero-assisted topological phase, providing efficient 2π phase coverage by tuning the width of the notch, while leaving the momentum-space topological properties of the underlying BIC resonance unchanged. Therefore, as shown in Figure 3k,l, the experiments reveal clear holographic images only near a wavelength of 550 nm, while the measured momentum-space band structure confirms the robust existence of a non-radiative BIC. This synergistic strategy can be further leveraged to simultaneously and independently exploit the real-space Pancharatnam–Berry phase for broadband wavefront shaping and momentum-space polarization vortices for vortex beam generation^[102]. The flexible integration of real-space and momentum-space degrees of freedom in nonlocal metasurfaces enables enhanced information capacity and tunability in optical-field manipulation, thereby further advancing the development of flat optics.

3. Manipulation of Optical-Field Information Based on Nonlocal Metasurfaces in Active Systems

Nonlocal resonances such as quasi-BICs, GMRs, and surface lattice resonances^[104] with high Q factors and strong optical-field confinement enable efficient enhancement of light–matter interactions. When combined with material gain and optical nonlinearities, nonlocal metasurfaces have enabled a range of active photonic applications, including nonlinear harmonic generation^[39,40,105,106], quantum light sources^[107,108], and nanolasers^[109–111]. By integrating real-space and momentum-space optical field control enabled by nonlocal metasurfaces into micro- and nanoscale light-source generation, active optical information manipulation such as nonlinear optical-field scanning and spatial information lasing can be effectively achieved. These capabilities offer promising prospects for the development of miniaturized optical systems that integrate light sources with information transmission and modulation.

3.1 Manipulation of nonlinear sources

As shown in Figure 4a, the periodic gold split-ring resonators (SRRs) act as a perturbation that couples the guided modes in the lower TiO₂ dielectric waveguide to free space, thereby forming narrowband radiative GMRs while preserving strong modal confinement in the waveguide layer^[112]. Owing to the pronounced near-field enhancement in the vicinity of the waveguide layer and the increased nonlinear effective polarizability induced by the collective scattering of SRRs, an eightfold enhancement of second-harmonic generation (SHG) was experimentally achieved. As shown in Figure 4b, the colormap of the normalized SHG conversion efficiency under TE-polarized excitation at different incident angles and wavelengths is consistent with the dispersion of the TE GMRs,

indicating that the nonlinear enhancement originates from the collective interaction of nonlocal GMRs. It is worth noting that, because SHG arises from the second-order nonlinear response at the gold surface, the maximum enhancement occurs at an incident angle of 22° , where optimal spectral and spatial overlap is achieved between the local surface plasmon resonance of SRRs and the waveguide mode. In addition to enabling efficient harmonic generation, nonlinear metasurfaces based on the local and nonlocal resonances can flexibly control the optical-field information of harmonic sources by tailoring nonlinear optical interactions. Through the exploitation of nonlinear selection rules to tailor the local phase and amplitude of the nonlinear coefficients^[113], a variety of beam-shaping functionalities, including nonlinear holography^[114,115], diffraction control^[116,117], vortex beam generation^[118,119], and nondiffracting beams^[120], have been experimentally demonstrated. Very recently, the enhanced field confinement and abundant mode coupling provided by nonlocal metasurfaces have enabled the simultaneous improvement of harmonic generation efficiency and the encoding of richer information into the harmonic sources^[121]. As shown in Figure 4c, a 125-nm-thick rectangular anisotropic silicon nanoarray on insulator is employed to achieve efficient third-harmonic generation (THG), owing to its large third-order susceptibility and negligible absorption loss at telecommunication wavelengths^[122]. At an excitation wavelength of 1,554 nm, the local Mie resonance and the nonlocal quasi-BIC mode spectrally overlap, giving rise to a hybrid mode characterized by a redistribution of the electric field within the silicon nanoarray. Therefore, as shown in Figure 4d, when the incident angle of the collimated pump femtosecond pulse was changed from 0° to 22° experimentally, the generated THG diffraction switched from the $(\pm 1, 0)$ order to the $(0, \pm 1)$ order. Moreover, owing to the local field enhancement induced by the nonlocal high-Q resonance under oblique incidence, a two-orders-of-magnitude enhancement of the THG intensity relative to normal incidence was experimentally achieved.

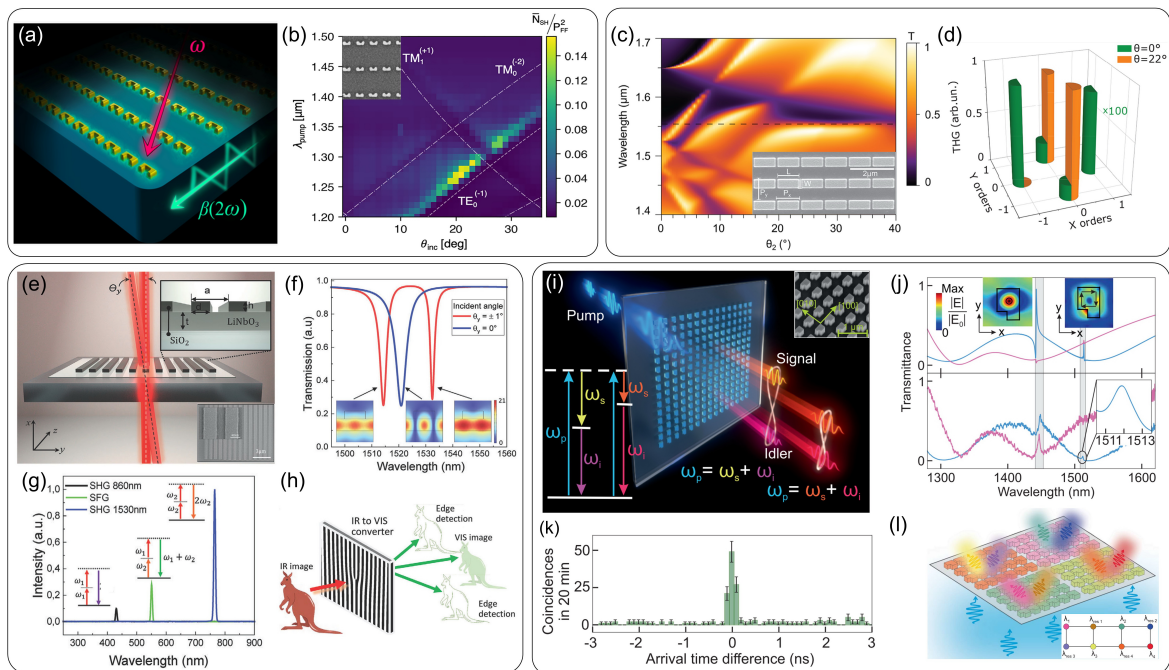


Figure 4. Generation and manipulation of nonlinear harmonic and quantum light sources based on active nonlocal metasurfaces. (a) Schematic illustration of collective-resonance-enhanced SHG in a gold-TiO₂ hybrid waveguide nonlocal metasurface; (b) Measured forward normalized SHG efficiency as a function of pump incident angle and wavelength. The white dashed lines mark the dispersion of the GMRs. Reproduced from reference^[112]. CC BY 4.0; (c) The calculated transmission spectra of a high-Q silicon nonlocal metasurface under TE-polarized illumination at different incident angles and wavelengths. The inset in the lower-right corner shows the SEM image of the fabricated metasurface. The dashed lines denote the excitation wavelength of 1,554 nm; (d) Experimentally measured power distribution of THG at different diffraction orders for incident angles of 0° and 22° . Reproduced with permission from reference^[122]. Copyright © 2021 American Chemical Society; (e) Schematic diagram of an SiO₂-LN nonlocal metasurface; (f) Calculated transmission spectra of the metasurface under normal and oblique incidences. The normalized electric-field distributions at the resonant wavelengths in the bottom insets exhibit nonlocal, spatially extended mode characteristics; (g) Measured nonlinear signal intensities of SHG and SFG under simultaneous excitation by two incident beams: an 860 nm pump beam and a 1,530 nm signal beam; (h) Schematic diagram of a spatially-variant nonlocal metasurface that simultaneously performs zero-order upconversion imaging of sum-frequency light and ± 1 -order diffraction edge detection. Reproduced from reference^[127]. CC BY 4.0; (i) Schematic diagram of multiplexed entangled-photon generation in a multi-resonant quasi-BIC GaAs metasurface; (j) Simulated (top) and measured (bottom) linear transmission spectra of the multi-resonant metasurface under x- and y-polarized excitation. The inset shows the normalized electric-field distributions at the two quasi-BIC wavelengths; (k) Measured distribution of the photon arrival-time differences for two superconducting nanowire single-photon detectors, demonstrating photon-pair generation. Error bars represent the statistical uncertainties of all measured quantum metasurfaces; (l) Spatial multiplexing of four high-Q nonlocal metasurfaces to generate a complex, scalable quantum cluster state (inset in the lower-right corner) with a single multifrequency pump beam. Reproduced with permission from reference^[108]. Copyright © 2022 American Association for the Advancement of Science. SHG: second-harmonic generation; GMRs: guided-mode-resonances; TE: transverse-electric; SEM: scanning electron microscopy; THG: third harmonic generation; LN: lithium niobate; SFG: sum-frequency generation; BIC: bound state in the continuum; GaAs: gallium arsenide.

In addition to efficient harmonic generation and wavefront shaping, nonlocal metasurfaces enable a broad range of complex nonlinear optical responses, including nonlinear imaging based on sum-frequency generation (SFG)^[123], four-wave mixing^[124,125], and high-harmonic generation^[126], as well as generation of quantum light sources^[107,108]. As shown in Figure 4e, a one-dimensional SiO₂ grating deposited on a lithium niobate (LN) layer forms a nonlocal metasurface that is used to enhance infrared vision via nonlinear upconversion^[127]. Figure 4f illustrates simulated transmitted spectra under normal and oblique incidences, which present the resonant splitting induced by the strong nonlocal properties of GMRs. Moreover, because the extended resonant modes are predominantly confined within the LN waveguide layer, the large second-order nonlinear susceptibility of LN can be effectively exploited to enhance the nonlinear conversion efficiency. As shown in Figure 4g, the high-Q nonlocal metasurface was simultaneously excited by an 860 nm pump beam and a 1,530 nm signal beam, corresponding to the resonant wavelengths that yield maximum SHG enhancement. As a result, SFG emission at 550 nm was experimentally obtained, exhibiting a record 458-fold enhancement compared with that from a bare LN film. Owing to the linear transfer function of the SFG process, the authors further achieved infrared imaging with record-high upconversion efficiency and image quality by employing appropriate Fourier imaging techniques in their experiments. By further designing spatially varying nonlocal metasurfaces, simultaneous upconversion imaging and image processing can be realized. As shown in Figure 4h, a topologically dislocated one-dimensional nonlocal metagrating enables upconversion imaging of the zeroth-order SFG signal, while simultaneously performing edge detection on the input infrared image in the first diffraction order. Based on the conjugate relationship between SFG and spontaneous parametric down-conversion, high-Q nonlocal metasurfaces can generate entangled photon pairs or more complex quantum states in the spatial or angular domains^[107]. As shown in Figure 4i, the authors designed a gallium arsenide (GaAs) semiconductor metasurface supporting multiple symmetry-protected quasi-BIC resonances, enabling the generation of multiplexed entangled photon pairs under optical pumping^[108]. Specifically, the quantum metasurface supports two high-Q quasi-BIC resonances in the near-infrared region, whose resonant wavelengths can be independently engineered, enabling the generation of two distinct types of entangled photon pairs with comparable efficiencies (Figure 4j). Figure 4k shows the coincidence counts measured by two single-photon detectors, thereby confirming the generation of photon pairs. Beyond entangled photon pairs, more complex quantum graph states can be generated by exciting the designed nonlocal metasurface with multiple coherent pump beams at different wavelengths, such as frequency combs and spectrally filtered supercontinuum sources. Analogous to the segmented design strategy employed in local multiplexed metasurfaces^[58,59], spatially multiplexed quantum states under single-pump excitation can be realized by integrating multiple nonlocal metasurfaces within a single optical platform. As illustrated in Figure 4l, each metasurface supports nonlocal resonances at distinct wavelengths, enabling the simultaneous generation of multiple entangled photon pairs across separate wavelengths under excitation by a single multifrequency pump beam^[108]. Overall, the presence of abundant high-Q resonances in nonlocal metasurfaces enables complex quantum state engineering from a single nanoscale quantum light source, offering promising prospects for the miniaturization of photonic quantum information processing. A paramount manifestation of this concept has been experimentally demonstrated in atom-array-based quantum metasurfaces. Specifically, a single monolayer of trapped atoms in an optical lattice can function as a cooperative subradiant mirror governed by long-range, nonlocal dipole-dipole interactions^[128]. Crucially, the optical response of such atomically thin metasurfaces can be coherently switched and spatially controlled at the single-quantum level by manipulating a single Rydberg ancilla atom^[129], unlocking new paradigms for deterministic light-matter entanglement.

3.2 Manipulation of information lasers

While nonlinear metasurfaces primarily address the frequency conversion of external excitation, the realization of miniaturized, multidimensional coherent light sources, referred to as information lasers, requires the integration of gain media with cavities that offer both high Q factors and precise modal control. Nonlocal metasurfaces emerge as ideal candidates for such cavity designs. In contrast to their local counterparts, these systems account for the coupling between individual structures, forming photonic bands analogous to energy band structures in solid-state physics. Through judicious lattice engineering and structural design, nonlocal metasurfaces realize on-demand band dispersion, yielding a high density of states at specific high-symmetry points in the Brillouin zone^[130-132]. The inter-band coupling and interaction with the radiation continuum underpin emerging phenomena such as BICs^[50,51,133-135], parity-time (PT) symmetry^[136], and exceptional points (EPs)^[137], establishing nonlocal metasurfaces as a premier platform for momentum-space engineering.

Leveraging flexible band engineering and improved fabrication capabilities, various high-Q resonant modes realized in nonlocal metasurfaces, such as BICs^[109,138-140] and photonic topological insulators^[141-144], have been applied to lasing. By combining these with extensive wavefront manipulation methods, multi-dimensional control of spatial information lasing has been achieved^[145-148]. As shown in Figure 5a, Spägle *et al.* overcame the limitation that transmission and reflection amplitudes of local metasurfaces cannot locally exceed 1 by considering the coupling between supercell elements^[149]. They demonstrated multiple independent optical functions (a Gaussian, a focused helical beam with OAM of 1 and a Bessel beam on separate diffraction orders) at different and large deflection angles with high efficiency. Compared to independent scatterers carrying phase and polarization information in a local metasurface unit cell, the larger supercell acts locally as a grating; thus, a supercell library satisfying the phase and amplitude of all local diffraction orders was compiled. This nonlocal supercell metasurface can be further integrated with a laser diode to realize a compact, wavelength-tunable external-cavity laser with arbitrary beam-shaping capabilities. As shown in Figure 5b, one diffraction order of the reflection from the supercell metasurface provides cavity feedback to achieve lasing, while other diffraction orders can

be designed for collimated light output or a holographic output beam. Beyond utilizing the high reflectivity of a specific diffraction order for optical feedback, a more direct and compact approach involves using the gain medium as the material for the nonlocal metasurface itself. For example, based on the BIC-enabled optical field confinement mechanism, low-threshold vortex lasers with controllable topological charges have been demonstrated^[109,150]. However, their topological features are strictly dictated by the intrinsic lattice symmetry of the real-space unit cell, imposing fundamental constraints on the deterministic tailoring of lasing topological charges. To break this symmetry-induced constraint, recent strategies have evolved towards local symmetry breaking in quasi-BICs^[151]. As shown in Figure 5c, by reducing the symmetry of a triangular photonic crystal slab from C_6 to C_2 , a Möbius-like correspondence between the geometric orientation of the structural perturbation and the intrinsic linear polarization of the quasi-BICs was unveiled^[151]. By repeating photonic crystal slabs with three different azimuthal angles θ n times in real space, the emitted topological laser can carry a topological charge of $q = \pm n$, where the sign depends on whether the angular arrangement is repeated in a clockwise or counterclockwise direction. As shown in Figure 5d, leveraging this unique topological mapping, compound cavities constructed by spatially splicing distinct quasi-BIC sectors enable the generation of designable vectorial topological lasing with highly flexible integer orders (for example, from -5 to +5).

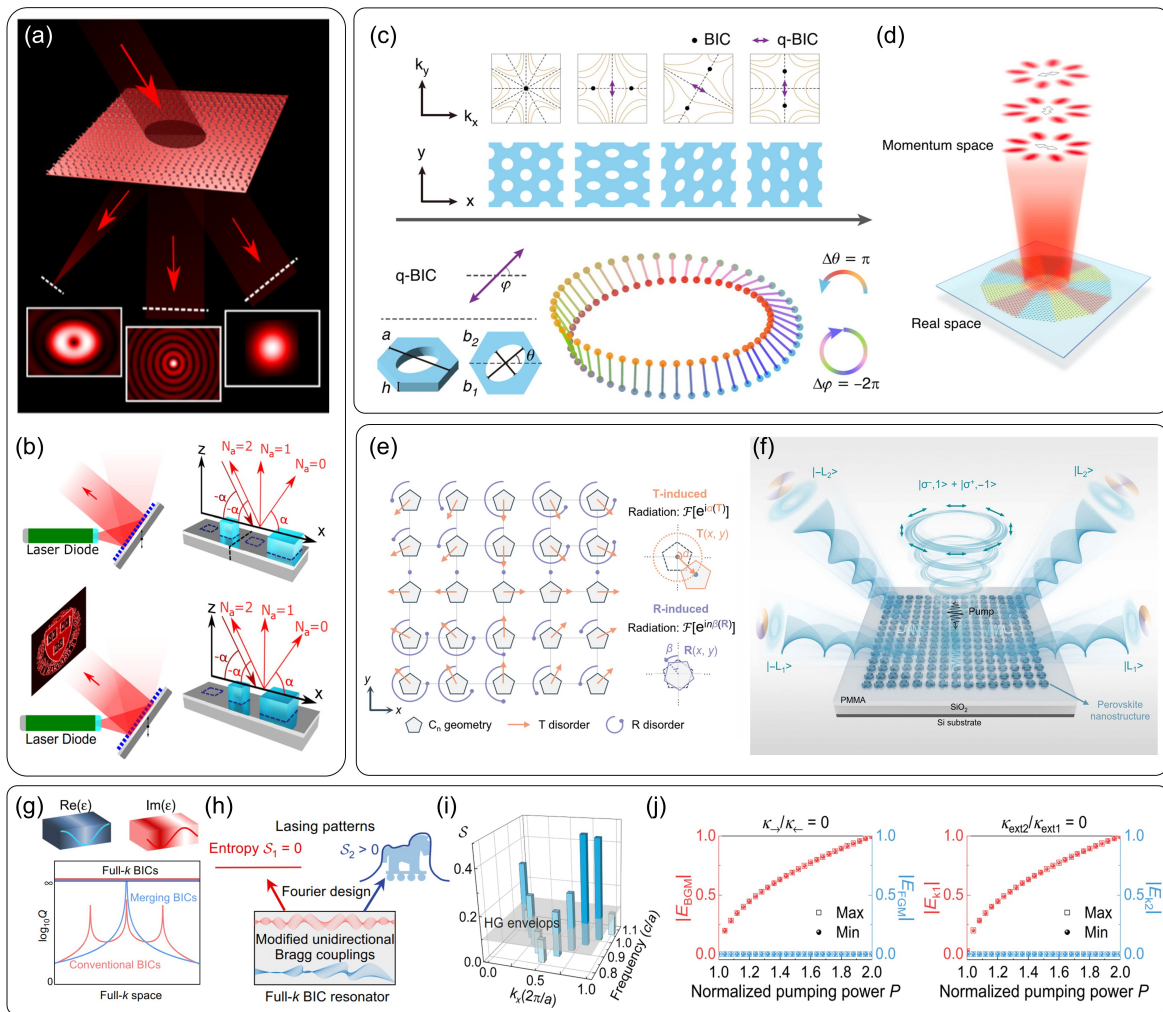


Figure 5. Spatial information lasing based on active nonlocal metasurfaces. (a)-(b) Real-space supercell engineering for multifunctional wavefront shaping; (a) Schematic of a supercell metasurface splitting an incident beam into multiple independent structured beams at distinct deflection angles; (b) Operational principle of the metasurface-based external cavity laser. One diffraction order (red arrow pointing back) provides optical feedback to the laser diode, while other orders (red arrows pointing out) generate independent output beams, such as collimated (top) or holographic (bottom) light. Reproduced from reference^[149]. CC BY 4.0; (c)-(d) Vectorial topological lasing enabled by quasi-BIC compound cavities; (c) The Möbius-like correspondence between real-space symmetry breaking and eigen-polarizations of quasi-BICs from the triangular PhC slab induced by local symmetry breaking of the lattice from C_6 down to C_2 ; (d) The generation of a vectorial lasing with -4 topological charge via the spatial splicing of distinct quasi-BIC PhC sectors. Reproduced from reference^[151]. CC BY 4.0; (e)-(f) Multidimensional control of structured light via a "DoD" meta-cavity; (e) Spatially decoupled symmetry-breaking mechanisms induced by translational (T) and rotational (R) disorders; (f) Schematic illustration of the multichannel structured lasing emission from a shared aperture. Reproduced from reference^[153]. CC BY 4.0; (g)-(j) Spatial information lasing enabled by full-k-space BICs; (g) Profiles of the real and imaginary parts of the permittivity (top) and the resulting full-k-space BICs showing diverging Q factors across a continuous band (bottom); (h) Schematic illustration of spatial information lasing

enabled by full- k -space BICs in a PTMM. The lasing information entropy (S) is controlled by engineering the complex Fourier components of the PTMMs; (i) Calculated lasing information entropy S of the considered energy band; (j) Bifurcation diagrams depicting the steady-state maximum and minimum of the amplitude $|E|$ versus the normalized pumping power ($P = 1$ at the threshold), in the case of band mode competitions (left) and k -mode competitions. $\kappa_{\rightarrow}/\kappa_{\leftarrow}$ ($\kappa_{\text{ext } 2}/\kappa_{\text{ext } 1}$) is the asymmetric mode (external) coupling factor in the laser rate equations. Reproduced with permission from reference^[159]. Copyright © 2024 American Physical Society. BIC: bound state in the continuum; PhC: photonic crystal; DoD: disorder-on-disorder; PT: parity-time; PTMM: PT-modulated metasurface.

This quasi-BIC-based Möbius-like correspondence approach enables arbitrary control over the orbital angular momentum of nanolasers, while manipulation of individual degrees of freedom of lasing emission, such as polarization and directionality, has also been successfully demonstrated. Nevertheless, achieving arbitrary manipulation of the laser wavefront remains challenging because tailoring the wavefront while preserving the nanolaser cavity mode is difficult. Recently, Zeng *et al.* suggested and realized a new type of laser, a metalaser, by using the interplay between local and nonlocal responses of dielectric resonant metasurfaces, providing a viable solution to the problem^[152]. They identified a special quasi-BIC mode in which the geometric phase induced by rotational disorder can be locally applied to each pixelated meta-unit without destroying the high- Q nonlocality. As a result, the laser emission can exhibit an arbitrarily shaped wavefront, enabling unprecedented capabilities, such as speckle-free laser holographic displays. Beyond approaches that rely on geometric phases induced by isolated rotational disorder, the paradigm for generating structured light from a single aperture has evolved toward the intricate fusion of diverse perturbations, enabling spatially structured lasing with highly multiplexed channels and expanded physical degrees of freedom. As shown in Figure 5e, the advent of the “disorder-on-disorder” (DoD) meta-cavity exemplifies this paradigm by exploiting the spatially decoupled symmetry-breaking mechanisms of translational (T) and rotational (R) disorders^[153]. By superimposing these geometrically decoupled disorders onto C_3 -symmetric perovskite nanostructures that exhibit robust wavelength stability against geometric perturbations, precise and independent phase modulation across multiple radiation channels is achieved without compromising the intrinsically high Q factors or low lasing thresholds. Consequently, this monolithic DoD platform enables the simultaneous generation of phase and polarization vortices, one-dimensional and two-dimensional Airy beams, as well as tailored Hermite–Gaussian and Laguerre–Gaussian modes from a shared aperture (Figure 5f), fundamentally transcending the symmetry constraints of conventional periodic lattices.

Beyond modulating the laser wavefront in real space via perturbations to robust modes (e.g., BICs), nonlocal metasurfaces offer extensive capabilities for achieving informational nanolasers by utilizing momentum-space design. Specifically, by exploiting degrees of freedom such as lattice symmetries^[154,155], disorder^[156], radiative couplings^[157], and active gain–loss engineering^[158], these strategies allow for the precise tailoring of emission characteristics. As shown in Figure 5h, Chai *et al.* proposed the concept of spatial information lasing enabled by precise control of each lasing Fourier component, demonstrating a paradigm of intracavity informational lasing where information modulations are realized inside the laser cavity^[159]. Distinct from conventional BICs limited to zero-dimensional singularities, this work utilizes PT-modulated metasurfaces (PTMMs) to realize full- k -space BICs. By precisely balancing gain and loss, a continuous energy band possessing theoretically infinite Q factors is formed (Figure 5g). On this basis, by configuring the complex Fourier components of the permittivity, the researchers directly engineered the Bragg couplings. This configuration determines the energy distribution among different diffraction orders and achieves continuous control over the spatial information entropy (Figure 5i). To overcome potential instability from mode competition, the scheme exploits the intrinsic unidirectional scattering of non-Hermitian systems near EPs. Combined with external seeding, this mechanism locks a specific momentum mode, ensuring stable single-mode lasing (Figure 5j). In contrast to local phase modulation, this strategy allows the system to convey rich spatial information through global momentum-space control, offering a new physical framework for informational coherent amplification.

4. Conclusions and Outlook

In this review article, we have presented an overview of light-field information manipulation enabled by emerging nonlocal metasurfaces. While the progression from passive to active systems, and from real space to momentum space, serves as a logical framework for categorizing these advancements, the unifying perspective of this rapidly evolving field lies in the intentional, synergistic integration of local and nonlocal degrees of freedom. Conventional metasurface designs often force a choice between high spatial resolution (relying on localized, low Q resonances) and strong light-matter interaction (relying on delocalized, high Q resonances). Nonlocal metasurfaces bridge this divide. By combining tight optical-field confinement with the strong spatial dispersion and high Q factors inherent to collective scattering, they offer a transformative route to breaking fundamental performance trade-offs in optical information manipulation. Within this framework, we have reviewed how spectral and momentum degrees of freedom enable narrowband beam steering and spectrally decoupled diffraction, how topological singularities like BICs structure optical fields in momentum space, and how introducing nonlinearity and gain allows for spatial information lasing. Moving forward, to transition from phenomenological demonstrations to practical and scalable photonic technologies, several critical bottlenecks and controversies must be addressed. We envision the following strategic directions:

Tunable and on-chip applications based on nonlocal metasurfaces. Nonlocal resonances induced by symmetry and other global effects can significantly enhance light-matter interactions while exhibiting high sensitivity to parameters such as polarization and

resonant wavelength, thereby enabling a wide range of tunable applications. For instance, inversion-symmetry-broken photonic cavities have been exploited to realize spin-controlled coherent emission at room temperature without external magnetic fields^[160], while symmetry breaking in nonlinear polarization mediated by resonant metasurfaces has been demonstrated as a route to generating tunable quantum entanglement, allowing for the continuous transition from partially entangled states to a Bell state simply by adjusting the pump wavelength^[161]. Crucially, these novel mechanisms can be seamlessly integrated into guided-wave photonic systems^[162,163]. Harnessing high- Q collective resonances, on-chip nonlocal metasurfaces enable the spectrally selective extraction of guided waves. This capability is exemplified by an on-chip color router based on symmetry-broken quasi-BICs, which yields a significant improvement in energy utilization efficiency through spectral cascade multiplexing^[164]. Looking forward, transferring the flexible wavefront shaping capabilities and high- Q characteristics of free-space nonlocal metasurfaces into guided-wave architectures remains a critical frontier. We anticipate that combining the multidimensional optical field manipulation capabilities of nonlocal metasurfaces with diverse dynamic tuning mechanisms, such as liquid crystals^[165], phase-change materials^[166,167], and LN^[168], will pave the way for on-chip and tunable information lasers and information modulation in both classical and quantum systems.

Resolving fundamental trade-offs in device performance. While the combination of local and nonlocal effects enables wavefront manipulation with high Q factors, the resulting metadevices often face limitations in efficiency, bandwidth, numerical aperture, and information crosstalk. Specifically, although mode coupling and breaking of out-of-plane symmetry can enhance the efficiency of narrowband optical information manipulation, their experimentally achieved efficiencies remain inferior to those of conventional local devices^[169-171]. Consequently, the experimental realization of more efficient nonlocal metalenses, momentum-space vector optical fields, and information lasers would be highly significant^[172,173]. The limited operational angular bandwidth of nonlocal metadevices primarily arises from the spatial dispersion of their resonant modes. Leveraging diverse resonance-coupling mechanisms and twisted moiré structures to simultaneously realize high Q factors, flat-band dispersion, and controllable multidimensional optical field manipulation constitutes a promising strategy^[174-179]. On the other hand, nonlinear harmonic sources based on nonlocal resonances can achieve high conversion efficiencies but still face challenges in controlling their nonlinear wavefront. Therefore, nonlinear light sources that simultaneously offer high efficiency and tailorable functionality are highly desirable. Additionally, for high- Q nonlocal metasurfaces, random disorder introduced during practical fabrication heavily degrades the coherence of long-range interactions, severely limiting experimentally achievable Q factors^[34]. Overcoming this requires not just improved fabrication precision, but disorder-immune design strategies, such as integrating topological protection mechanisms^[133] or the etching of low-refractive-index materials^[180,181]. Encouragingly, recognizing this sensitivity has also led to new metrology applications, where phase-transition modulation based on nonlocal BICs and quasi-BICs can be utilized to improve nanoscale alignment accuracy in semiconductor lithography^[182].

Reevaluating design paradigms through artificial intelligence (AI). A major theoretical bottleneck in the field is that conventional local-scattering models based on isolated meta-atoms cannot adequately describe the strong collective interactions inherent to nonlocal metasurfaces. AI-empowered inverse design represents a necessary paradigm shift rather than just an optimization tool. By exploiting a vastly expanded set of geometric and physical degrees of freedom, AI provides an effective route to engineer these long-range multipolar resonances directly, allowing for the realization of ordered phase distributions even within large-area, freeform metasurfaces^[183-188]. For example, integrating coupled-mode theory with adjoint optimization critically reduces the computationally prohibitive costs of large-area full-wave simulations^[189]. Recently, freeform topology optimization has enabled the precise decoupling and arbitrary control of near-field mode profiles, wavevectors, and complex amplitudes^[190]. We anticipate that transitioning from purely data-driven models to physics-informed networks will resolve the current computational bottlenecks in simulating and designing complex nonlocal interactions.

Expanding nonlocal responses in emerging physical systems. Finally, advances in nanofabrication techniques have made it possible to control light localization and delocalization at the nanoscale in a wide range of emerging material platforms. By engineering strong light-matter coupling with anisotropic van der Waals materials, semiconductor excitons, and zero-index materials, it is possible not only to generate polaritons with exotic properties arising from diverse forms of spatial dispersion, but also to realize exciton-polariton condensates and polariton lasers^[191-193]. For example, the nontrivial topological properties of BICs in photonic crystal waveguides can be exploited to construct a supersolid phase in exciton-polariton condensates^[194]. Moreover, studies of nonlocal and local resonant states in non-Hermitian, nonreciprocal, and time-varying systems are expected to uncover new physical phenomena^[24]. For instance, strong resonances in metasurfaces can be exploited to broaden the momentum bandgaps of photonic time crystals and to enhance spontaneous emission and lasing^[195,196].

Overall, the true value of nonlocal metasurfaces lies not in replacing local designs, but in providing an expanded, multidimensional parameter space for the flexible tailoring of optical field confinement and spatial dispersion. By directly confronting the current limitations in efficiency, bandwidth, and computational design models, future research will undoubtedly drive the evolution of planar metadevices from passive wave-shapers to highly active, intelligent platforms for classical and quantum information processing.

Declarations

Authors contribution

Yu S, Ma J: Conceptualization, methodology, formal analysis, investigation, writing-original draft, writing-review & editing.

Liu W, Liu H: Investigation, writing-review & editing.

Li Z, Cheng H, Chen S: Conceptualization, supervision, writing-original draft, writing-review & editing.

Conflicts of interest

Shuqi Chen is an Editorial Board Member of *Light Manipulation and Applications*. The other authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

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