Opinionated article

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High-*Q* nanophotonics: sculpting wavefronts with slow light

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Abstract: Densely interconnected, nonlinear, and reconfigurable optical networks represent a route to high-performance optical computing, communications, and sensing technologies. Dielectric nanoantennas are promising building blocks for such architectures since they can precisely control optical diffraction. However, they are traditionally limited in their nonlinear and reconfigurable responses owing to their relatively low-quality factor (*Q*-factor). Here, we highlight new and emerging design strategies to increase the *Q*-factor while maintaining control of optical diffraction, enabling unprecedented spatial and temporal control of light. We describe how multipolar modes and bound states in the continuum increase *Q* and show how these high-*Q* nanoantennas can be cascaded to create almost limitless resonant optical transfer functions. With high-*Q* nanoantennas, new paradigms in reconfigurable wavefront-shaping, low-noise, multiplexed biosensors and quantum transduction are possible.

Keywords: high-*Q*; slow light; wavefront manipulation.

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1 Introduction

Networks lie at the heart of both natural and engineered systems. The useful information density of a network scales with both the number of elements and, importantly, the number of connections. For optimal optical communications networks, considerable effort has been devoted to miniaturizing photonic components, in order to increase the number of *elements* in the network. Such progress is akin to the semiconductor industry's strides in miniaturizing transistors to increase the power of digital computers. However, unlike electronic chip design, optical engineering is bound by the diffraction limit; plasmonic components have promised to overcome this limit [1–9] but generally suffer from strong absorption. Here, we describe an alternate strategy for scaling photonic networks: increasing the number of *connections* between wavelength-scale components (i.e., components at the diffraction limit), thereby performing highly sophisticated operations. Though the diffraction limit sets a bound on the number of optical elements that can be included in the network, there is no limit on the number of diffracted channels. With this in mind, can we construct highly efficient compound optical devices with nanoantennas? And more importantly, can we dynamically modify their operation in time with electro-optic or nonlinear effects? We believe such photonic networks are possible with high-quality-factor (high-*Q*) nanoantennas and metasurfaces.

Dielectric nanoantennas, or multipolar Mie resonators, represent ideal diffraction-limited optical elements for generating, manipulating, and modulating light waves (Figure 1i). These nanoantennas act as quasi-point sources whose scattering can be understood, much like atoms and molecules, as a superposition of electric and magnetic multipolar modes [10]. The electric and magnetic modes of nanoantennas present a library of available scattering or radiation patterns that can be combined spatially to perform nearly arbitrary transformations to the incident light [11–17]. One drawback of Mie resonators is that light typically only interacts with them over a few hundred femtoseconds. Combined with the usually very weak

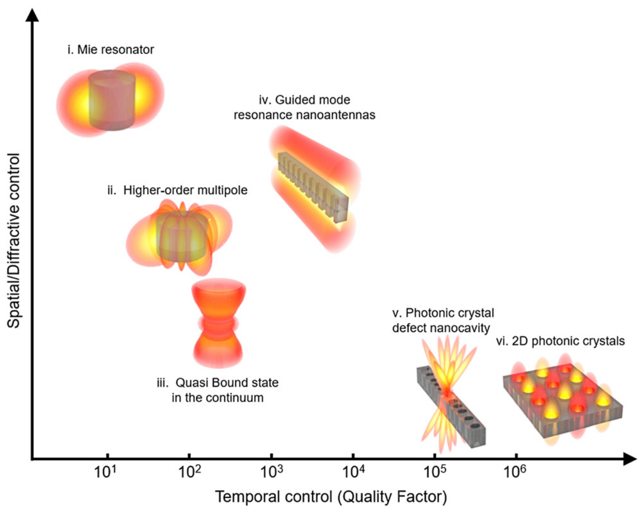

Figure 1: Landscape of dielectric nanophotonic structures for temporal and spatial control of light. From left to right: Conventional Mie resonator used for wavefront shaping in metasurfaces. Higher order multipoles increase the quality factor, at the expense of more complex radiation patterns. Interfering Mie-like and Fabry-Perot–like resonances increases the quality factor compared to dipole resonances, forming a quasi-bound state in the continuum (Q value from the study by Koshelev et al. [31]). Utilizing one translational degree of freedom, coupling to guided mode resonances within a nanoantenna can generate high-Q dipolar-like resonances for wavefront shaping, with a quality factor tuned independently of the metasurface transfer function (Q value taken from the study by Lawrence et al. [30]). Photonic crystal defect nanocavities increase the Q to 10^6 using photonic mirrors but lose the ability to controllably shape far-field radiation (Q from the study by Quan and Loncar [49]). Photonic crystals with two spatial degrees of freedom generate ultrahigh-quality factors whose resonant diffraction is geometrically set (Q from the study by Jin et al. [50]).

light-matter coupling strengths at the material level, this fleeting interaction often limits such devices to passive applications; consequently, generating efficient and active nanoantennas is an active area of research [18–20].

Optical modes appear spectrally as resonances, whose full width at half maximum is inversely proportional to the average lifetime of light within the antenna and local electric field enhancement, important attributes for sensing [21] and nonlinear optics [22, 23]. This lifetime is quantified by the quality factor Q and is composed of various limiting loss mechanisms like radiation loss, material absorption, and fabrication imperfections. The increased lifetime and reduced spectral bandwidth of high-Q resonances are critical to the operation of on-chip photonics. In ring resonators and photonic crystal defect cavities, for example, high-Q modes reduce the required optical or electrical budget for nonlinear optical transformations [24, 25] required for communications technologies. In many ways, these on-chip cavities are the antithesis of Mie scatterers, critically relying on input/output channels being confined to single- or few-mode coupling through a small number of waveguides. By limiting the configurations to 2 or 4 ports and evanescent weak coupling, generating high-quality factors is comparatively easier than in structures that communicate with the entire radiation continuum, such as optical nanoantennas. Therefore, the density of node connections in existing on-chip high-Q cavity designs is extremely limited.

Mie modes are designed with radiation in mind, so their interaction and coupling to free space can be tailored to increase the Q; in parallel, coupling to other antenna modes can be engineered to be as dense as desired. In simple nanophotonic systems, resonant lifetimes tend to increase with multipole order, consistent with a decrease in the angular density of radiation channels and an increased field contribution from large Fourier components (see Figure 1ii). Consequently, the lower order dipolar modes that are commonly used in diffractive metasurface designs necessarily have relatively low quality (Q) factors, of the order ~10. However, there is no physical limitation preventing much higher quality factors. That is to say, highly resonant dipole-like emitters can exist with proper design. After all, nanoantenna modes consist of both radiative (low momentum) and nonradiative (high momentum) waves. Traditionally, these components are highly correlated, but by carefully addressing their relative contributions, the entire parameter space of optical state variables can potentially be manipulated in both space and time, independently. Previous work has already shown that the superposition of two or more multipoles within a subwavelength object can have profound effects on far-field scattering. For example, tailoring a nanoantenna so as to adjust the relative strength and spectral overlap of its electric and magnetic dipole modes produces highly directional scattering, including zero-backscattering and zero-forward scattering conditions [26–28]. Generalizing this notion to device designs composed of point-like sources that can controllably release a very small amount of leakage into interesting spatial distributions will allow for simultaneous control of far-field optics, required for high-density integration, and near-field light localization useful for reconfigurability and sensitive signal readouts. This opportunity requires sculpting the three-dimensional (3D) Fourier map of a nanoantenna in order to fully decouple the directionality and strength of radiation loss.

2 Design methodologies for sculpting free-space light with resonant nanoantennas

Achieving resonant, or high Q, scattering in multipolar nanoantennas is an active area of research [29–31]. Overlapping two or more multipoles (Figure 1iii) whose radiation patterns spatially overlap can lead to strong destructive interference that suppresses far-field scattering and increases the resonance quality factor [31–33]. The moderate enhancement in lifetime over subwavelength volumes may be useful in nonlinear integrated optics. However, current demonstrations of localized quasi-BICs have relied on the combination of distinct spatial modes. The incomplete cancelation of the multipoles not only places bounds on the achievable Q factor, tied to the intrinsic properties of the uncoupled modes, but it will also be very difficult to engineer the corresponding far-field pattern without affecting the Q factor. Additionally, constraining systems to single antennas may reduce the degrees of freedom available for far-field manipulation. The radiation profiles available to multipolar nanoantennas are intrinsically limited by the destructively interfering modes, requiring particular illumination strategies to couple into and out of the modes of interest. Future metasurface-based devices, for example, will rely on judicious design methodologies that allow spatially varying transfer functions composed of many nanoantennas that operate at the same frequency but with variable phase or amplitude.

Rather than relying on the overlap of multiple modes within a single nanoantenna, the resonant lifetime can be increased by capitalizing on the additional degrees of freedom afforded by periodic structures [34, 35]. Periodic systems composed of subwavelength objects provide opportunities for high-quality-factor transmission or diffraction. Two-dimensionally periodic nanostructures whose band structure contains a flat region can induce light localization [36–38], although their stability to structural perturbations is limited. Using degrees of freedom like mode polarization, mode type (electric vs. magnetic) [39], spatial symmetry [40, 41], and others, coupling to radiation can be significantly reduced [42]. Otherwise fully bound modes can leak out to their environment, forming a quasi-bound state. Perhaps the most robust method to date in reducing free-space radiation is in photonic crystal membranes (Figure 1vi), where bound states can be created and destroyed in a deterministic manner and ultrahigh-quality factors have been observed [43]. Here, the interplay between multiple spatial degrees of freedom is required to generate the modes of interest. Accordingly, bound modes such as these exist at particular points in k-space that are not easily moved; their utility in the far field is therefore limited. While these designs can generate ultrahigh-quality factors, they are at the expense of limited momentum-space tunability.

Recent results using bound modes with lower dimensionality or nonlocality have begun to combine resonant optical cavities with wavefront shaping [30, 44]. Here, light trapping can occur along one direction, while the scattering in an orthogonal plane can mimic a dipole requisite for phase-gradient metasurfaces (Figure 1iv). Resonant optical responses within the diffraction plane can be decoupled (that is, separately designed) from the light trapping in this configuration. Exciting avenues of exploration exist with this scheme, spanning tunable beam steering, lensing [45], and nonlinear nanophotonics [46]. However, to date, the design principles exploited require one semi-infinite (or at least multimicron) dimensions for resonant mode coupling [30, 47, 48]. This property intrinsically limits the optical transfer functions to also act one-dimensionally. An open challenge is achieving resonant scattering of point-like sources with complete control over existing wavefronts; quasi-bound or guided states with long lifetimes embedded within a structure capable of arbitrary wavefront shaping in two dimensions would be a transformative development amenable to efficient reconfigurable and tunable devices and will surely be a focus of future research.

Even with new design methodologies, achieving theoretically predicted quality factors can present challenges. Intrinsic material absorption and fabrication-induced scattering losses will naturally reduce the achievable Q. In periodic structures, long-range order, illumination coherence, and device size all contribute to the achievable Q factors. As these modes exist with particular radiation patterns and mode locations in k-space, the careful design of illumination and collection configurations is critical to observe these quasi-bound states. Furthermore, recently developed designs in infinitely two-dimensionally periodic structures such as biperiodic unit cells [51] or other perturbations that couple otherwise dark modes to the radiation continuum all depend on small, perturbative, differences between metasurface elements. The previously derived scaling relations, where the quality factor has an inverse square relationship with the perturbation size [52], require uniformity that is substantially smaller than the perturbation of interest. At optical frequencies, this presents some practical limitations on the devices that can be made. Notions of topologically robust high-Q modes investigated in photonic crystals have shown promise [50], but their translation to lower dimensionality remains an open question. Further developments in robust design strategies will be important for the implementation of these ultrahigh-Q designs in deployable devices.

3 Summary and outlook

The strong resonant interaction and low loss of high-Q nanoantennas make them particularly well suited for application in tunable and nonlinear photonic devices [53, 54]. Individual Mie-resonant structures, for example, can be employed as light sources in a footprint several times smaller than the wavelength of the light being emitted, making them attractive for integration in dense photonic networks and system-on-a-chip sensors [55]. When arranged the form of a metasurface, such resonators may also assist in structuring coherent light, forming "metasurface lasers" [56] that are capable of producing new forms of chiral laser light [57] and accessing subwavelength lasing modes at low pump powers [38, 58]. Access to optical nonlinearities has also been used to form optical switches [59], achieve asymmetric transmission [60], dynamic reciprocity [61], and break Lorentz reciprocity for application in optical isolators and circulators. These Mie-resonant structures can also enhance the nonlinear response of materials with which they are interfaced when the material of interest is placed sufficiently within the near field of the Mie resonance; this property has been especially useful in studying the nonlinear properties of novel two-dimensional materials [62]. It is also possible to interface these structures with a host of other media to lend a strong resonant interaction at any wavelength desirable, from the IR through the UV [63].

In addition to nonlinear wavefront shaping, these resonant antennas can also form the basis of active and reactive optical devices [45, 64, 65]. For example, resonant nanophotonic antennas have allowed for wavelength conversion and modulation [66], quantum state transduction [67], and myriad other technologies for on-chip optical communication and computation. These technologies rely on the additional light-matter interaction and the resonant linewidth to make practical devices. Embedding these antennas into phase-gradient metasurfaces could enable wholly new device designs with complete and tunable control over *free-space* optical wavefronts with an optical or electric field. Furthermore, access to diffraction in a resonant manner could allow for multiplexed sensing modalities, in which an external change in the refractive index or other parameter can impact the diffraction. Optical biosensors relying on high-quality factors have already been demonstrated in transmissive and reflective devices [68], so extending the radiation channels available for sensing promises to increase sensitivity and multiplexing abilities. The local electromagnetic field can also be designed to be sensitive to particular properties of liquid analytes. For example, chiral light-matter interactions can be engineered to have enhanced near-field interactions with observables in the far field [69]. In addition, enhanced sensitivity to vibrational modes of molecules can be used for molecular identification [70]. Resonant nanophotonics that can be arbitrarily multiplexed in energy and momentum will provide increased degrees of freedom for sensitive detection and sensing of materials both in the near field and far field.

Integrated photonics researchers are currently focused on scaling up planar, waveguide-based chips, striving to revolutionize applications spanning light speed matrix multiplication to point-of-care multipathogen medical tests. But, foreshadowed by emerging 3D electronic circuit designs and by progress in artificial neural networks, photonic systems could soon also benefit from less intuitive and highly interconnected network architectures. High-Q nanoscale wavefront shaping structures will undoubtedly play a cornerstone role in bringing this vision to fruition. Developments in device design, material synthesis, nanofabrication, and characterization will need to be combined if the energy scaling requirements for real-world applications are to be met. We envision the intersection of these efforts transforming applications from optical sensing to quantum and classical computing with free-space optical devices.

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