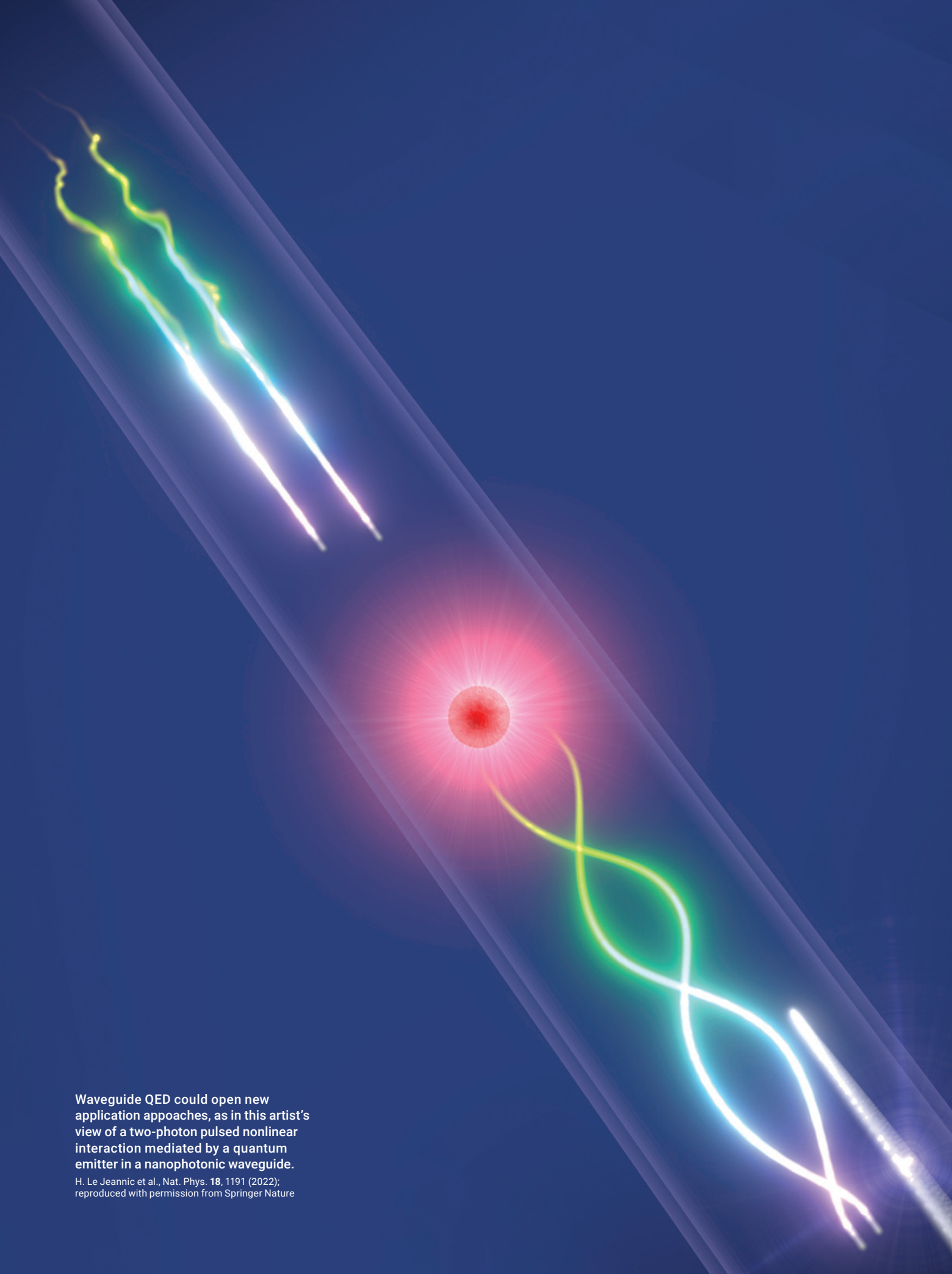


Waveguide QED could open new application appoaches, as in this artist's view of a two-photon pulsed nonlinear interaction mediated by a quantum emitter in a nanophotonic waveguide.

H. Le Jeannic et al., Nat. Phys. **18**, 1191 (2022); reproduced with permission from Springer Nature

Waveguide Quantum Electrodynamics

Francesco Ciccarello, Peter Lodahl and Dominik Schneble

Engineering photon–emitter interactions in 1D—using a suite of tools ranging from photonic-crystal waveguides to quantum dots to ultracold atoms in optical lattices—is opening intriguing experimental and practical opportunities in quantum information science and technology.

Many emergent applications in quantum information science and technology (QIST), especially in computing, communication and sensing, are enabled by engineered quantum states of light and matter. A major challenge for synthesizing quantum states of light is that photons on their own do not interact with each other.

Yet modern quantum optics research has developed ways to engineer such photon–photon interactions through deterministic photon–emitter couplings. These naturally arise when a single quantum emitter, such as an atom or a quantum dot, is deterministically coupled with light, since a quantum emitter can scatter only one photon at a time. And such strong photon–emitter coupling in turn allows for engineering quantum states of matter, through long-lived excitations of quantum emitters generated by coherent, photon-mediated couplings between them.

Achieving strong photon–emitter couplings has been a long-standing challenge in cavity quantum electrodynamics (QED), a field that studies interactions of emitters with a single, spatially localized mode. But a second, intriguing alternative has recently emerged: waveguide QED (wQED). In this scheme, the zero-dimensional (0D) cavity mode is replaced by 1D propagating modes with an engineered spectral structure, and deterministic coupling is achieved when emitter decay into unwanted modes external to the waveguide is strongly suppressed. Such a highly selective coupling to guided modes can be realized, for instance, in photonic-crystal waveguides, which are nanofabricated materials that feature an optical band structure.

Coupling a quantum emitter to a waveguide in this way has distinct advantages. In contrast to a high-finesse cavity, a waveguide is an inherently open environment, in which photon–emitter, photon–photon and emitter–emitter interactions can be tailored via waveguide dispersion engineering and optical pulse shaping.

As such, wQED constitutes a distinct, emerging paradigm of quantum optics that offers a wealth of new opportunities for photon-based quantum technologies. In this article, we introduce the fundamentals of wQED, illustrate some experimental implementations and applications using atomic, solid-state and synthetic quantum emitters, and outline some of the unique opportunities this emerging model creates for QIST. (Note: wQED can also be implemented in superconducting microwave circuits, a topic outside the scope of this article.)

Fundamentals of wQED

The basic differences in a quantum emitter's photonic environment in wQED, versus free-space and cavity QED, rest in two characteristics. One is the 1D geometric confinement of the modes in a waveguide, compared with 3D in free space and 0D in a cavity. The other is the additional ability in a waveguide to control the modes' photonic dispersion relation, which allows tailoring the group velocity of light. One way to achieve this at optical frequencies is by periodically modulating the refractive index along the waveguide, thereby creating a 1D photonic crystal in which the otherwise linear photon dispersion is modified to give rise to a photonic band structure (see "From free space to wQED," below).

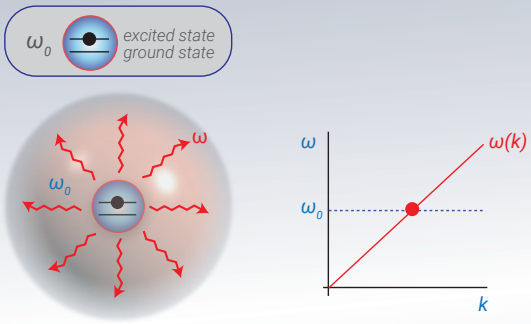
The magnitude of the bands and band gaps depends on the depth of the index modulation. For a deep modulation, the dispersion relation in a single band is sinusoidal, and the photonic-crystal waveguide can be visualized as an array of cavities weakly coupled to one another, in which a photon tunnels from cavity to cavity at a rate proportional to the width of the photonic band.

In general, photon–emitter interactions will be qualitatively different whether the emitter's excitation energy lies in a photonic band or in a band gap, and will also depend on the frequency separation from the nearest photonic band edge. We explore these differences in the next few sections (see infographic, p. 38).

wQED in a photonic band

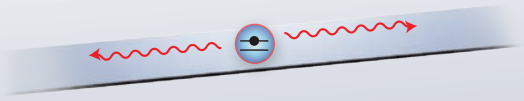
Let us first consider an emitter lying in a photonic band. Under weak coupling, the dynamics is equivalent to

From free space to wQED



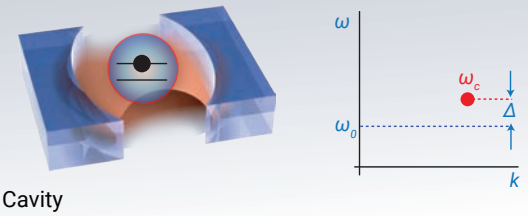
Free space

Emission by a two-level emitter (frequency ω_0) into 3D free space, which has a linear dispersion relation $\omega(k)$. There exists a resonant mode for any emitter frequency.



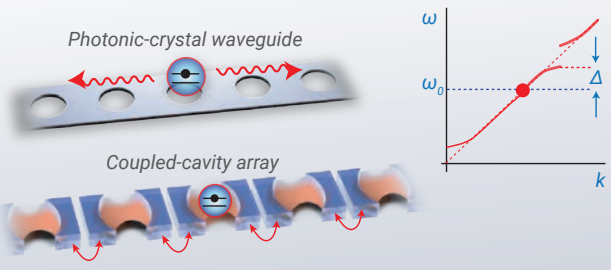
Continuous 1D waveguide

In a 1D waveguide, emission is restricted along one axis.



Cavity

In cavity QED, the continuum of modes is replaced by a single cavity mode with frequency ω_c. The atom and cavity frequencies need not be exactly the same (detuning, $\Delta = \omega_c - \omega_0$).



Structured waveguide

By periodically structuring the 1D waveguide, as in a photonic crystal, the dispersion relation acquires a band structure; the emission can occur in a band ($\Delta > 0$) or in a band gap ($\Delta < 0$). Considering the photonic crystal as a linear array of coupled cavities, a photon tunnels with a rate that is proportional to the band width.

Illustration by Phil Saunders

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wQED constitutes a distinct, emerging paradigm of quantum optics that offers a wealth of new opportunities for photon-based quantum technologies.

that in the 1D mode continuum of an unstructured waveguide. Unlike in cavity QED, where an excited quantum emitter undergoes coherent vacuum Rabi oscillations, the decay dynamics in wQED in a photonic band is exponential and thus resembles that of 3D free space—albeit with an emission rate that depends on the details of the mode structure (the Purcell effect).

However, photon–emitter interactions in a waveguide are qualitatively different from free space for at least two reasons. First, a photon launched in the waveguide is geometrically constrained to scatter off an embedded emitter that it impinges on. Second, the 1D geometry distills out interference mechanisms that are irrelevant in higher dimensions.

Mirror-like behavior. For instance, in a scattering event, the incoming and transmitted waves can interfere destructively, in such a way that a resonant photon will be reflected with 100% probability. The waveguide thus promotes significant photon–emitter interactions at the single-quantum level. In an experimental setting, the so-called β-factor—the fraction of photons emitted into the guided modes—is the relevant figure of merit determining how close the photon–emitter waveguide system is to a true 1D system.

Subradiance and superradiance. A pair of quantum emitters embedded in a waveguide can enable strong Fabry–Pérot-like interference effects. Depending on the distance between the emitters, the emission of a single photon shared between them can be enhanced or suppressed, as with a traditional Fabry–Pérot cavity trapping an optical mode between two mirrors. Unlike classical mirrors, however, the quantum emitters in a waveguide feature an internal quantum degree of freedom that crucially affects the phase picked up by the photon upon reflection from an emitter.

Therefore, the suppression of emission occurs only for a specific collective quantum state of the two emitters, known as a subradiant state. Conversely, there exists a superradiant state for which the Fabry–Pérot cavity resonance condition breaks down maximally. This state favors the photon traveling away from the emitters instead of getting trapped between them; it also yields an enhanced emission rate compared with that of a single emitter.

Such cooperative phenomena can readily be generalized to many-emitter arrays. One can even realize conditions such that only a single, superradiant state dissipatively couples to the guided modes. Since the intensity of a mode propagating in a 1D waveguide ideally does not decay with distance, such effects also extend to emitter separations that are large compared with the wavelength of the radiation, enabling long-range interactions between distant emitters. In contrast, superradiant emission in free space would require emitters to be packed together in regions much smaller than the wavelength—a challenging configuration to realize, and one that would not produce the high directionality obtainable in a waveguide.

Chiral and directional interactions. Such Fabry–Pérot-like effects implicitly rely on the photon's ability to propagate along the waveguide's two directions ("rightward" and "leftward"). It is possible, however, to engineer waveguides with unidirectional or "chiral" photon–emitter interactions, and this fundamentally changes the picture. For emitter pairs that can couple only to photons traveling rightward, for example, the emitter to the left can excite its neighbor on the right (upon photon emission), but the converse process is forbidden. Such nonreciprocal interactions have dramatic effects; the emitter to the left decays as if it were alone, while the one to the right will absorb the photon and re-emit it rightward (with no back-reflection), thereby changing the emitter dynamics. Remarkably, such cascaded interactions are independent of the distance between the emitters—only their arrangement matters.

All of the above phenomena in wQED occur in regimes where the time taken by the photon to travel between the emitters is negligible compared with the exponential decay time. However, it has recently become possible to break this condition in some setups—a largely unexplored regime of quantum optics that evades traditional theoretical approaches. Early investigations suggest that exciting new physics arises in this regime.

Two-photon wQED scattering with a single emitter has been used to induce strong dynamical quantum correlations and even nonlocal time–energy entanglement.

Nonlinear quantum responses. So far, we have considered single-photon wQED interactions. But since each quantum emitter is a quantized two-level system, it can scatter only a single photon at a time. When two or more photons in a pulse simultaneously impinge on a ground-state emitter, the emitter effectively shifts out of resonance, such that the condition for perfect reflection is no longer fulfilled. This constitutes a complex quantum nonlinear response with amplitude and phase characteristics that sensitively depend on the photon number and pulse duration and shape.

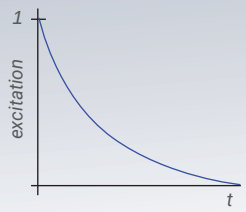
Two-photon wQED scattering with a single emitter has been used to induce strong dynamical quantum correlations and even nonlocal time–energy entanglement. When extended to multiple emitters, such photon–photon interactions make it possible to successively build up highly correlated states of many photons.

wQED near and in a band gap

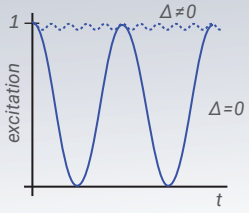
Emitter–photon bound states. When an excited emitter has its frequency close to the edge of a photonic band, the spontaneous emission can resemble a damped oscillation rather than being exponential. This so-called fractional decay process is rather remarkable—an emitted photon does not simply escape but can return to the emitter several times, and even then, never escapes completely. In a sense, this behavior lies between that of free-space and cavity QED, where an emitter periodically emits a photon into the cavity and reabsorbs it altogether in the form of a vacuum Rabi oscillation.

Such an incomplete decay is caused by the coupling to an emitter–photon bound state that is (energetically) located in the nearby band gap, where spontaneous emission cannot occur due to a lack of resonant modes. In the gap, a photon is emitted and immediately reabsorbed

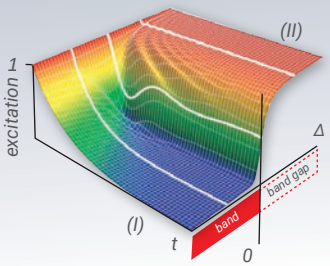
Dynamical regimes and effects in wQED



Free space
In free space, the decay is exponential and irreversible.



Cavity
In a cavity, the emitter undergoes oscillations in which the photon is periodically emitted and reabsorbed.



Photonic crystal
Near a band edge in wQED, the decay can be exponential (deep in a band – I), oscillatory toward a remaining population (fractional decay - near the edge), or not occur (in the band gap - II).

Phenomenology

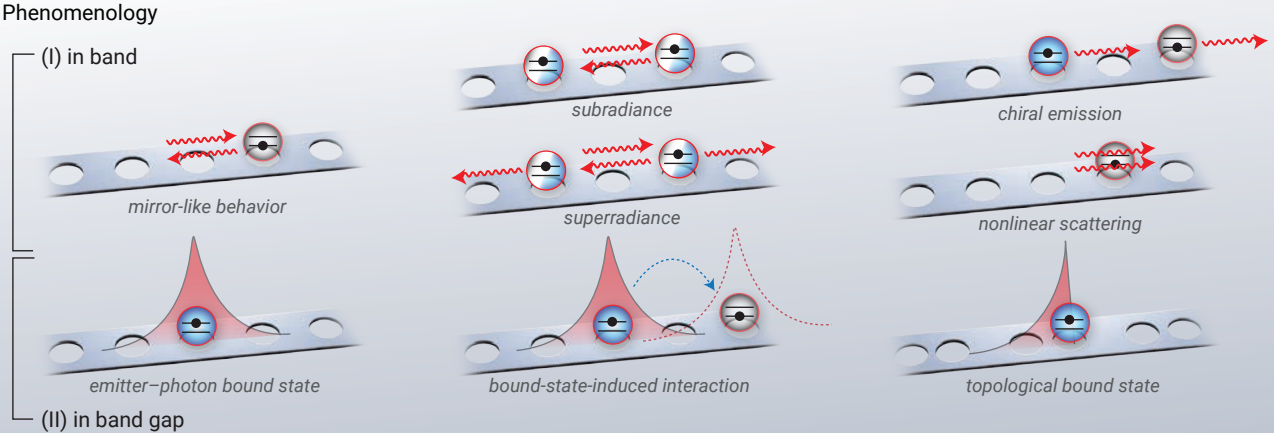


Illustration by Phil Saunders

over a finite spatial and spectral range in virtual second-order processes. These processes renormalize the emitter's frequency, by an amount known as the emitter's self-energy or Lamb shift that is modified by the photonic-crystal structure.

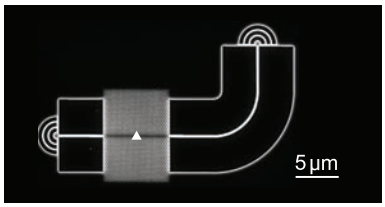
The bound state as such is a dressed state consisting of a partially excited emitter that is surrounded by an exponentially localized cloud of a photonic vacuum excitation. It particularly arises when the emitter is tuned to emit in the band gap, with a localization length (that is, a characteristic width) that depends sensitively on the detuning and diverges close to the band edge.

Remarkably, when a waveguide contains two or more identical emitters that are tuned to emit in the band gap, a virtual photon leaving an excited emitter can be immediately absorbed by another emitter initially in the ground state. This virtual-photon exchange between emitters, mediated by the aforementioned bound state, gives rise to effective dipole–dipole interactions between them. In the band gap, they are not accompanied by any energy dissipation, unlike near a band edge inside the band. As a result, a system of quantum emitters tuned to a photonic band gap can effectively form a many-body system of pseudospins with (typically) short-range interactions. Their range can be dynamically tuned, a property that can be advantageous, for instance, for the implementation of efficient quantum simulation protocols.

Bound-state-induced hopping. Close to the band edge, the photon admixture can become large, and a different picture arises in which the partial excitation and its accompanying photon cloud now form a composite quasiparticle (a so-called polariton) that hops from emitter to emitter. In large emitter arrays, the hopping leads to the formation of an extended polaritonic band structure, while at the same time the polaritons inherit the emitters' strong nonlinearities. It thus becomes possible to engineer versatile wQED systems that can quantum simulate strongly correlated transport behavior in solids.

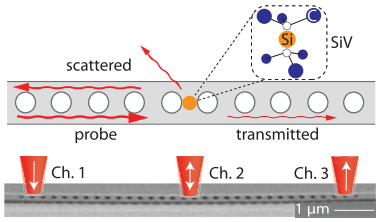
Topological band structures and chiral interactions. In condensed-matter physics, the band gaps of certain periodic materials—so-called topological insulators—can host electronic states localized at geometrical edges that are remarkably protected against disorder, making them appealing for applications. In wQED, topological band structures can be implemented by tailoring the waveguide. An emitter can then behave as a "quantum edge," with the photon–emitter bound state localized entirely on one side. This can result in chiral interactions between emitters in which the virtual-photon–mediated coupling between them strictly vanishes (or not) irrespective of distance, but depending only on whether one emitter sits on the side where the bound state seeded by the other one has a zero (or nonzero) amplitude.

Some wQED platforms



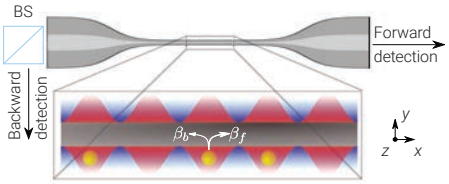
Quantum dot coupled to a photonic-crystal waveguide.

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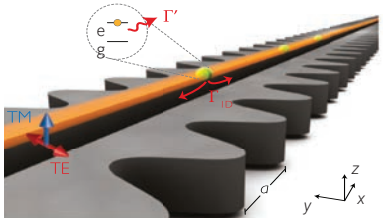
SiV center in a diamond photonic crystal.

A. Sipahigil et al., Science **354**, 847 (2023); reprinted with permission of AAAS



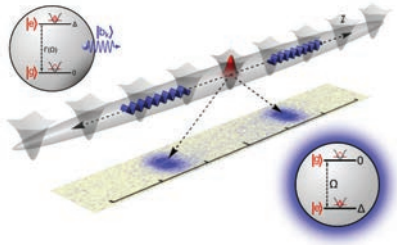
Atoms in a nanofiber-based dipole trap interfaced with a guided mode.

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Atoms in a cylindrical optical dipole trap on an alligator photonic-crystal waveguide.

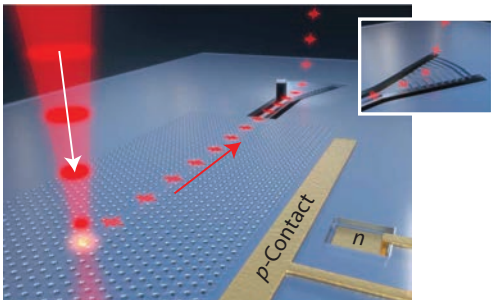
J.D. Hood et al., Proc. Natl. Acad. Sci. **113**, 10507 (2016); CC-BY NC ND 4.0



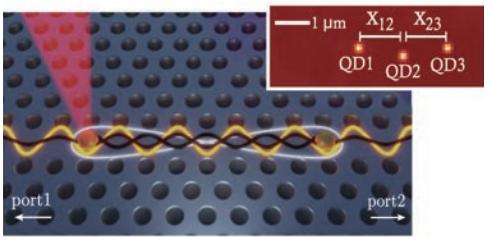
Ultracold atomic matter-wave emitters in an optical lattice.

L. Krinner et al., Nature **559**, 589 (2018); reproduced with permission from Springer Nature

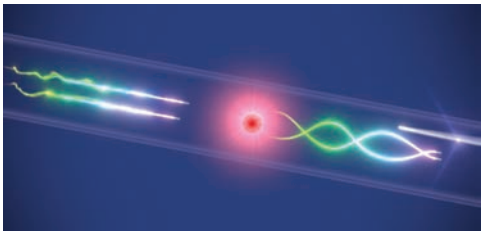
Some applications of wQED



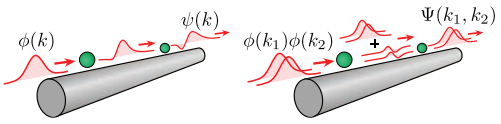
Deterministic source of indistinguishable photons.
R. Uppu et al., Sci. Adv. **6**, eabc8268 (2020); CC-BY NC 4.0



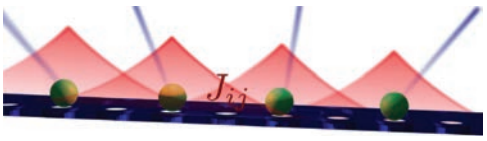
Entanglement between two quantum emitters mediated by the waveguide.
A. Tiranov et al., Science **379**, 389 (2023); reprinted with permission of AAAS



Two-photon nonlinear optics in wQED.
H. Le Jeannic et al., Nat. Phys. **18**, 1191 (2022); reproduced with permission from Springer Nature



Deterministic photon sorting in wQED.
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Variational analog quantum simulator based on wQED.
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Implementing wQED

wQED has been implemented in a number of physical systems. In the optical domain, the most important ones include solid-state and atomic quantum emitters. In general, the solid-state platform features very efficient coupling to the waveguide but is challenging to scale up to many emitters, while the opposite is the case for atomic emitters. For this reason, the physics and applications of the two systems are largely complementary. Remarkably, wQED has also been studied in the completely different context of an ultracold atomic system in an optical lattice, in which synthetic quantum emitters exchange spontaneously emitted atoms rather than photons. As a platform that captures wQED physics with matter waves, it unites the two aspects of efficient coupling with scalability.

Semiconductor quantum dots (QDs) and vacancy centers in diamond constitute the two leading solid-state experimental platforms in wQED. QDs are nanometer-sized semiconductor particles featuring discrete electronic energy levels, while single-ion vacancy centers—for example, nitrogen–vacancy (NV) or silicon–vacancy (SiV) centers—are optically active color centers found in diamond solids.

QDs either are grown with UHV molecular epitaxy or can be synthesized chemically (using techniques honored by the 2023 Nobel Prize in Chemistry). III–V QDs, such as InAs embedded in GaAs, have been the most promising for wQED, and the high refractive index of GaAs (about 3.5 in the near-infrared) implies that high-confinement waveguides can be realized. The highest β-factor is realized in photonic-crystal waveguide membranes obtained by nanostructuring, where coupling efficiencies exceeding 98.4% have been obtained near the band edge due to a slow-light-enhanced Purcell effect.

Laser-cooled neutral atoms trapped near optical nanofibers provide a naturally scalable wQED platform where collective emitter effects can be studied. To achieve coupling of the atoms to the guided modes, the atoms are placed into the evanescent tail of the guided modes outside the fiber core. Because the laser-cooled atoms are delivered and optically trapped at some distance from the waveguide, β-factors are typically restricted to the 1%–10% level, albeit with significant enhancements up to values of 50% when alligator photonic-crystal waveguides with a band edge near an atomic resonance are used.

Creating deterministic emitter systems with individually addressable atoms coupled to a waveguide, and more generally to optical nanostructures, is a challenge and a subject of ongoing efforts. Yet the possibility of bringing thousands of laser-cooled atoms into the close vicinity of an optical waveguide gives access to wQED systems that feature large optical depths for guided modes and that display strong collective effects.

Ultracold atoms in optical lattices constitute an exotic platform for studies of wQED physics. In this analog platform,

wQED has been implemented in a number of physical systems, including solid-state and atomic quantum emitters, as well as in the context of an ultracold atomic system in an optical lattice.

the sites of an optical lattice act as an array of quantum emitters, with "excitations" in the form of single stored atoms; atomic de Broglie waves take the role of the emitted photons. Upon coherently inducing an atom stored in a site to flip its spin, the converted atom is released, with a β-factor of unity, into a 1D continuum of motional states with a quadratic dispersion relation.

This mechanism is fundamentally equivalent to spontaneous emission from an electromagnetic quantum emitter near a band edge. Importantly, the matter-wave emitter's effective frequency and vacuum coupling can be independently and even dynamically controlled. Moreover, it's possible to realize a full, and fully tunable, band structure for the emitted radiation, in analogy to that of a photonic crystal. While there are important fundamental differences between this approach and photonic systems—after all, matter waves, while having wavelengths comparable to optical photons, move at millimeters per second rather than at the speed of light—much of the fundamental wQED physics is the same.

Applications of wQED

Single quantum emitters efficiently coupled to a waveguide constitute a deterministic source of single photons that has been widely explored with single QDs and vacancy centers, but also with a range of different emitters such as single atoms or molecules. The field is very mature; deterministic QD sources are even offered as a commercial product. The deterministic photon–emitter interface has a range of additional applications and is being researched for the generation of deterministic multiphoton entanglement, photonic quantum gates or even quantum transduction between microwave qubits and photons.

Scaling up to coupling multiple emitters has also begun. Here, in solid-state implementations, local tuning of each individual emitter is required to compensate for intrinsic inhomogeneities. With these capabilities, wQED-mediated dipole–dipole coupling has been demonstrated as a means to remotely entangle two QDs in the same waveguide. Another direction has been to operate multiple QD waveguides on the same chip and implement independent local electric-field tuning of each QD to demonstrate Hong-Ou-Mandel interference between two separate sources. These are key capabilities required for scaling up the approach. Excitingly, just two deterministic sources suffice for creating universal photonic resource states for photonic quantum information processing and computing.

Systems of atoms coupled to nanofibers and other nanostructures offer a plethora of additional applications due to their inherent scalability. They range from fundamental studies of collective radiative effects, the generation of slow light and coherent photon storage, to the realization of nanophotonic optical isolators and photon routers based on chiral effects. On the other hand, they may also be used for simulations of many-body systems with effective spin–spin interactions.

In contrast, the applications of matter waves mostly lie in the exploration of basic wQED physics. Recent experiments have observed phenomena such as oscillatory fractional decay, bound-state formation, band-structure-induced and cooperative effects including super- and subradiance, and the formation of strongly correlated polaritonic phases. This approach to wQED has opened a wide road for studies of exotic processes, ranging from the detailed effects of retardation to the domain of quantum optics with fermions. OPN

Francesco Ciccarello is with the Università degli Studi di Palermo, Italy. Peter Lodahl is with the Niels Bohr Institute, University of Copenhagen, Denmark. Dominik Schneble (Dominik.Schneble@stonybrook.edu) is with Stony Brook University, NY, USA.

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