tion of thermodynamic equilibrium still limits what is achievable. Greater sharpness can be achieved by expending energy to maintain the system away from equilibrium (*11*). Furthermore, formation of phase-separated superenhancers by cooperative interactions has been implicated in transcriptional regulation (*12*). The ordered assembly of these components and the contribution of cooperativity to gene expression characteristics remain unclear.

Cells harness cooperativity in a variety of contexts that extend beyond transcriptional control. One example is T cell activation, which depends on the cooperative clustering of the T cell receptor with costimulatory molecules in an ordered immunological synapse (*13*). T cells can also be synthetically activated with chimeric antigen receptors (CARs), which are fusions of motifs from the T cell receptor and costimulatory molecules. CARs have demonstrated therapeutic success, but they do not form an ordered immunological synapse (*14*). It is therefore possible that re-engineering a CAR to include multisubunit cooperativity could enhance its function and further its application in engineered cell therapy (*15*). A modular framework for constructing synthetic cooperative responses could be a major advance for the field of synthetic biology, boosting the ability to dissect the requirements, constraints, principles, and properties of cooperative processes. ■

> ***"...synthetic cooperative responses could be a major advance for the field of synthetic biology..."***

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QUANTUM INFORMATION

Overcoming quantum decoherence with plasmonics

The use of nanoscale plasmonic metamaterials can optimize photon-matter interactions

By **Simeon I. Bogdanov, Alexandra Boltasseva,** *and* **Vladimir M. Shalaev**

Photons occupy a special place as carriers of quantum information because they propagate information at the speed of light, with almost zero cross-talk, and interact relatively weakly with matter. They are primary candidates for implementing quantum networks (*1*), which are essential for both secure communication and transmission of quantum information. Nonclassical states of light (such as squeezed states) are also used in quantum simulation and emerging quantum sensing approaches. However, the robustness of photons as carriers of quantum information is a double-edged sword. In order to produce single photons or make them interact with each other, light must couple with matter. Photonic technologies, especially those implemented with nanoscale plasmonic metamaterials, can enable these interactions and help realize the full potential of photons in quantum information technology.

Unlike the strong interactions of electrons in solids, the weak interactions of photons with matter cause substantial difficulties in generating single photons and performing quantum operations at practical rates, exacerbating the effect of propagation losses. For example, in satellite-based quantum communication experiments (*2*), the demonstrated secure data transfer rates are in the kilohertz range or less. The probabilistic nature of linear optical quantum gates and heralded single-photon sources (pairs of correlated photons) (*3*) reduces the rate of successful multiphoton operations that are needed for most quantum information applications. Deterministic sources of indistinguishable single photons can be realized with quantum emitters (*4*), but they usually operate at low temperatures and their intrinsic operation speed is dictated by the spontaneous emission rate, which is typically less than 1 GHz.

Most photonic quantum technologies used so far face these issues of slow operation and require a targeted and strong enhancement of light-matter interactions. Optical resonators achieve such an enhancement, proportionally to the ratio of the resonator's quality factor Q (a measure of the photon storage time in the cavity) to the volume V in which the light is confined. In traditional dielectric photonic cavities (see the figure, left), Q can be very large, but the degree to which V can be reduced is restricted by the diffraction-limited volume V_0. Moreover, additional efforts to increase Q ultimately hinder high-speed performance (*5*).

In contrast, relatively low-Q plasmonic metamaterials enhance light-matter coupling by using highly localized electromagnetic modes of metallic nanostructures (see the figure, right). The performance improvement comes mainly from the nanoscale confinement of light, which decreases V by many orders of magnitude compared to dielectric cavities. Relatively high radiative losses of these low-Q plasmonic cavities enable broadband operation at much faster speeds (*6*) than can be achieved with high-Q dielectric resonators. Also, light-matter interaction in such broadband and ultrafast plasmonic cavities can be sped up so that it outpaces fast quantum decoherence rates in matter.

This plasmonic speed-up approach strongly contrasts with the conventional pursuit of longer matter coherence time through the use of low temperatures, low pressures, and other ways of increasing and protecting the coherence. The plasmonics-based strategy could enable, for example, a room-temperature on-demand source of indistinguishable photons operating at terahertz rates (*7*). Producing single indistinguishable photons at such high rates and at room temperature would strongly expedite long-distance quantum communication with portable chip-scale devices. Despite a relatively low Q, the light-confinement properties of plasmonic cavities can drive them into the strong coupling regime with single quantum emitters (*8*, *9*). This achievement is one of the important steps needed for ultrafast and deterministic multiphoton operations. Plas-

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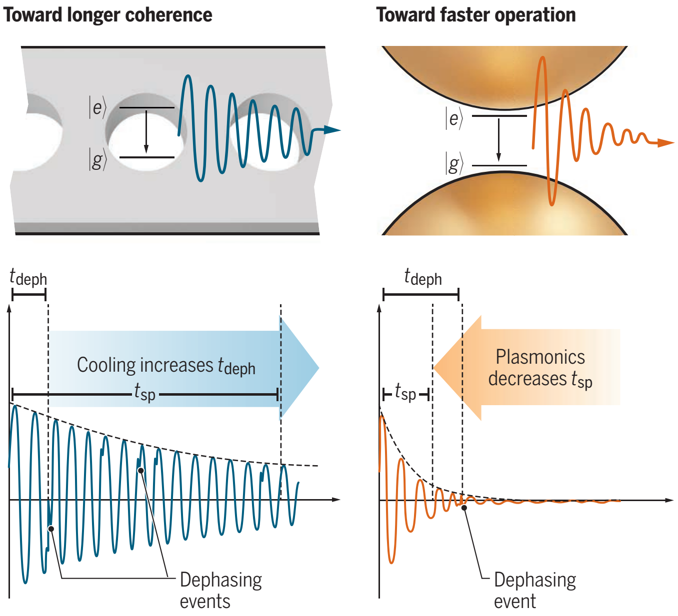
monic speed-up could also enable a single-shot readout of the electron spin in single diamond color centers, which are viable candidates for implementing both quantum memories for photons and quantum registers for spin-based quantum logic.

Quantum networks require not only the generation and manipulation of single photons but also their detection with high temporal resolution and efficiency. Most currently used integrated single-photon detectors are based on superconducting nanowires that require cryogenic cooling. However, as already shown in the mid-infrared range, confinement of light at scales much smaller than its wavelength can markedly shrink electrical detector volumes, suppress dark current, and increase operation speed (*10*). The same principle can also be applied to conventional semiconductor single-photon detectors (which operate near room temperature) to reduce device noise, timing uncertainty, and the dead time between detection events.

Plasmonic speed-up

Indistinguishable or "coherent" photons can be created with quantum emitters as their electrons spontaneously transition from an excited state |e⟩ to a ground state |g⟩. Coherence requires that the spontaneous emission time t_{sp} is shorter than t_{deph}, the dephasing time after which smooth oscillations are disrupted.



Quantum photonics with dielectrics
Coherence requires cooling the material so that $t_{deph} > t_{sp}$ for a given light-matter interaction strength, typically limited to gigahertz rates.

Quantum plasmonics
The enhancement of the light-matter interaction can shorten t_{sp} to beat t_{deph} and achieve coherence even for dephasing rates in the terahertz range.

Use of plasmonic components often leads to ohmic losses that limit device efficiency. However, losses in plasmonic devices can be minimized through several strategies. For example, the continuous development of new growth techniques yields materials with much lower losses relative to those typical of the earlier implementations of plasmonics. For example, recently developed epitaxial silver films featured record-low optical loss, with the imaginary part of the permittivity $\epsilon'' < 0.1$ in the visible range (*11*).

Device losses can also be substantially reduced by a careful geometric design, in which the needed coupling from and into the far-field modes occurs faster than the plasmon decay. In plasmonic resonators, this condition corresponds to a bound on $Q \ll \omega/\gamma$, where ω is the operation frequency and γ is the electron damping rate, typically in the terahertz range. If the same plasmonic resonator is used for both strong light confinement and plasmon outcoupling to the far field, then the confinement is intrinsically bound by the radiative limit through $V/V_0 \gg \gamma/\omega$. This condition precludes the use of particularly small V and limits the achievable light-matter coupling. Thus, it is beneficial to complement an ultrasmall plasmonic cavity needed for strong light confinement with a larger nanoantenna that enables the ultrafast coupling to far-field modes (*12*). A nanoantenna coupled to a plasmonic resonator can help match the impedance of small-wavelength plasmonic resonator modes to that of the far-field modes, thereby speeding up the outcoupling rate and reducing detrimental ohmic losses.

The so-called nanoparticle-on-metal systems (*13*) are a promising example of such an arrangement, in which the nanoparticle performs as an efficient antenna for the much smaller resonator formed in the plasmonic gap between the nanoparticle and the plasmonic film. These loss minimization strategies do not compromise the achievable light-matter interaction, as can occur with materials that have a reduced free carrier concentration (and thus a smaller plasma frequency) so that the smaller real part of the permittivity leads to a weaker mode confinement. Recent realizations of efficient devices that use plasmonic speed-up include optical modulators that have high bandwidth as well as low loss (*14*) and ultrabright room-temperature single-photon sources (*15*).

The incorporation of plasmonic nanostructures into quantum photonic platforms may confer several advantages over all-dielectric photonic approaches. Among these is the operation at terahertz speeds and at room temperature. Faster operation can also alleviate frequency mismatches between components that degrade performance. This property is particularly attractive for component scalability, which may otherwise be hindered by quantum emitter inhomogeneity or fabrication uncertainties with such nanostructures. Plasmonic materials can simultaneously carry optical and electrical signals. Thus, another important opportunity is the seamless incorporation of electronic controls for carrier injection, electrical modulation, and tuning in compact devices with length scales much shorter than the wavelength of light.

In a more distant future, one may expect a fully functional high-speed integrated platform for quantum information processing. Such a platform may feature deterministic quantum logic, with all components operating at room temperature. It remains to be shown, however, whether integrated electronic components can support terahertz clock rates in devices or whether all-optical operation is possible. The progress in component miniaturization and photonic integrated circuits may yield an answer to this question in the years to come. ■

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