PHOTONIC DEVICES

Quantum underpinnings of an all-photonic switch

All-optical devices hold promise as a platform for ultralow-power, sub-nanosecond photonic classical and quantum information processing. Measurements of the dynamics of a single photon switch unveil the quantum correlations at the root of its operation.

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Single- or few-photon states have long been pursued as the information carriers necessary to implement distributed quantum information networks. To avoid the performance impacts of converting photons into electronic signals, a practical quantum optical network requires a coherent photonic switch. However, photons travelling in free space do not interact with each other, posing a fundamental challenge to developing this functionality. To circumvent this issue, researchers have been carefully crafting quantum and nonlinear optical platforms, often using photonic crystals to localize light and enhance its interaction with matter. The steady progress in nanofabrication techniques over the past couple of decades has enabled photonic devices to probe new regimes of photon–photon interactions. Now, as they report in *Nature Physics*, Hanna Le Jeannic and colleagues have incorporated a quantum dot into a photonic crystal waveguide to create an ultralow-power, single-photon switch, and experimentally observed the quantum correlations that arise among the particles of light[1].

Photonic crystals, first proposed in 1987[2,3], have become a cornerstone of solid-state optics. They are formed by perforating a material periodically across its surface to produce a highly reflecting optical structure that is analogous to the regular array of atoms that electrons pass through in a crystal. If a small section of the perforation is removed, light is confined and resonated in that region, forming a cavity. Removing entire rows of perforation allows light to propagate through, thus forming what is known as the photonic crystal waveguide. Photonic crystal structures have been integrated with light emitters for a variety of applications, including the vertical-cavity surface-emitting laser, now commonly used in technologies such as smartphone facial recognition.

The first developments towards a photonic switch[4] in 2008 used the optical nonlinearity generated by an emitter strongly coupled to light in a photonic crystal cavity. This nonlinearity meant a photon could be transmitted through the device only when accompanied by another photon. The ultrafast control of this process[5,6] was achieved in 2012, bringing the optical switching to picosecond timescales, thus nearing electronic transistor speeds with far lower energy dissipation.

These findings demonstrated immense potential for high-speed low-power information processing in the face of the rising data centre and computational needs. However, a number of challenges obstruct the path to scalable and efficient nanocavity-emitter systems. These include, but are not limited to, the optimization of the emitter positioning for maximal electromagnetic interactions, as well as cavity engineering for minimizing loss and cavity size and maximizing output coupling.

The specific design and fabrication difficulties faced in nanocavity systems are relaxed for photonic crystal waveguides. The translational symmetry of a waveguide provides multiple options for optimal emitter positions, while the output mode is often the propagation mode itself, removing the challenge of coupling. This, however, comes at a price of fewer light and matter interactions, which means that achieving reliable emission of light into the waveguide mode is paramount to reaching the desired photon–photon interactions. It has taken a decade to develop the techniques needed to fully realize schemes such as interfacing single photons[7], creating nonlinear dynamics, and accessing lifetime-limited transition timing[8].

On the heels of these developments, Le Jeannic et al. have now explored the phenomenology of a single-photon switch in the time domain. The authors first confirmed that single-photon switching is achievable in their system of a quantum dot in a nanophotonic waveguide by performing a two-photon pump–probe experiment (Fig. 1). A single particle of light interacting with the emitter produced an AC Stark effect that was sufficient to shift the resonance frequency by a full linewidth. Shifting the emitter resonance meant the second photon, which would normally be absorbed by the quantum dot, could freely propagate through the device.

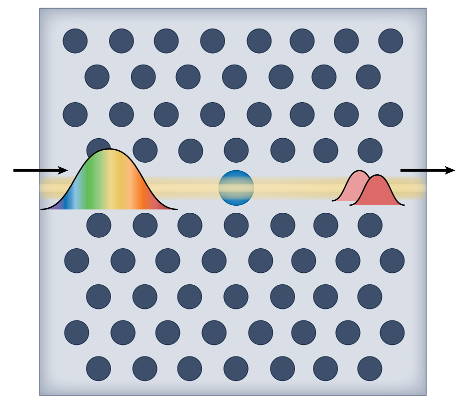

Fig. 1 | Photon–photon correlations in an all-optical switch. Interactions between photons in an incoming optical pulse are mediated by a quantum dot (blue circle) in a photonic crystal waveguide (light path bounded by periodic holes from top and bottom) resulting in measurable quantum correlations among transmitted photons.

The team went on to investigate the quantum nature of the underlying phenomena. Two photons were sent into the device and their transmission was measured and correlated in the time domain. The researchers performed two types of experiment to investigate the response to pulsed optical signals. The first experiment included individual photon pulses that encounter the quantum dot with a delay longer than its coherence time. This experiment set up a baseline of effects that arise from a single photon interacting with the emitter, later used to interpret the correlations in the experiment with a two-photon pulse. Then, by using pulses with shorter time separations they could observe the effects of two-photon interactions and found evidence of photon entanglement mediated by the quantum dot coupled to the waveguide.

The scalability of all-optical devices will be a key driver of their future applications.

In addition to quantum dots, nanophotonic systems that utilize emitters with higher spectral homogeneity, such as atoms or colour-centre defects in crystals, should be looked at as potential alternative platforms. Moving to large-scale industrial applications such as data centres and neural networks is likely to require implementations using materials that are compatible with the major semiconductor foundry processes, such as silicon. However, realizing the full potential of these platforms will require continued fundamental insights of the kind provided by Le Jeannic and co-workers. With improvements in our understanding of nonlinear photon–photon interactions in solid-state devices, engineering feats in controlling the flow of light, photon sorting, generation of entanglement and quantum simulation will follow. ❐

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Competing interests

The authors declare no competing interests.