

# Single photon nonlinear optics on photonic crystal chips

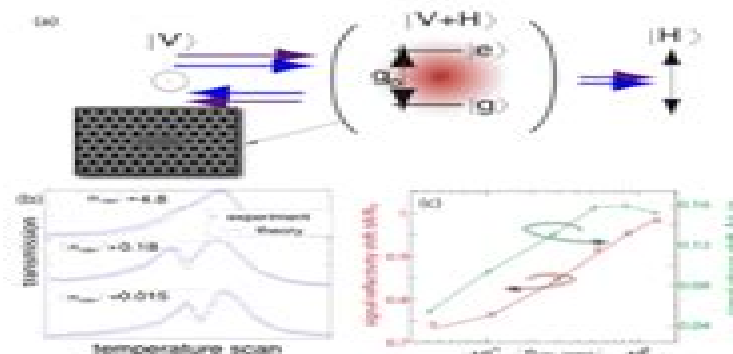
Dirk Englund, Andrei Faraon, Ilya Fushman, and Jelena Vučković

*A single semiconductor quantum dot that is strongly coupled to a photonic crystal nanocavity yields optical nonlinearities at the single photon level.*

The promise of quantum information processing is driving developments in several different physical implementations. Photons are attractive as carriers of quantum information because they can travel long distances without losing their information through interactions with their environment. However, their passive nature can be a problem in applications such as the construction of logic gates, where it is necessary for two or more photons to interact. This interaction requires a nonlinear optical medium. Particularly strong nonlinearities are achieved when photons drive an emitter near its resonance frequency, and this nonlinearity is even greater if the photon is confined near the emitter in an optical cavity.

We work with single semiconductor quantum dots (QDs) coupled to photonic crystal nanocavities. Recently, we showed that such a system enables an optical nonlinearity<sup>1</sup> at the single-photon level: the cavity transmission spectrum changes dramatically when the power nears one intracavity photon number ( $\langle n_{\text{cav}} \rangle$ ) per cavity lifetime (see Figure 1). The transmission spectrum obtained in the cross-polarized configuration shown in Figure 1(a) changes as plotted in Figure 1(b) when  $\langle n_{\text{cav}} \rangle$  increases from nearly zero to  $\langle n_{\text{cav}} \rangle \sim 5$ . This nonlinearity relies on saturation of the QD, which occurs when the photon flux reaches roughly one photon per emitter lifetime.

This single-photon-level nonlinearity has many promising applications. One application of particular interest in quantum information processing concerns the realization of large phase shifts on a signal beam conditioned on the intensity of a control beam. Using a homodyne setup, we measured the phase of the transmission through the cavity near the QD resonance frequency.<sup>2</sup> As the probe power increases to  $\langle n_{\text{cav}} \rangle \sim 3$  and the QD saturates, we found that the phase of the transmitted beam changes by up to  $0.24\pi$ . In applications such as quantum



**Figure 1. Resonant probing of the quantum dot (QD)-cavity system.** (a) The cavity is probed by a vertically (V) polarized laser beam. The transmission of the cavity is detected in the orthogonal polarization (H) in order to reduce direct scattering from the incident beam. We model the quantum dot as an excited ( $e$ ) and ground state ( $g$ ) which is coupled to the cavity mode by a rate  $g$ . (b) The transmission spectrum shows the vacuum Rabi splitting due to the strongly coupled QD. The splitting disappears as the QD is saturated at an intracavity photon number ( $\langle n_{\text{cav}} \rangle$ ) near unity. (c) The phase of the signal beam changes by up to  $0.16\pi$  when the control beam intensity is raised to an incident power of  $1\mu\text{W}$ , corresponding to  $\langle n_{\text{cav}} \rangle \approx 1$ .

non-demolition measurements, it is useful to spectrally separate the control and signal beams. Thus, for a detuning of  $0.03\text{nm}$ , we measured a  $0.16\pi$  phase change in the signal beam when the control beam intensity was raised to  $\langle n_{\text{cav}} \rangle \approx 1$ , as plotted in Figure 1(c).

A measurement of the photon statistics reveals the quantum nature of the interaction in the strongly coupled QD/cavity system.<sup>3</sup> One interesting phenomenon is the photon blockade effect, in which light couples to the cavity

*Continued on next page.*

# Selected Papers On Photon Statistics And Coherence In Nonlinear Optics

**Terry Yuan-Fang Chen**



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