Integrated photonic crystal networks with coupled quantum dots

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ABSTRACT

Single InAs quantum dots can be used to control the transmission function of photonic crystal cavities, as we have already shown for systems that operate both in strong and weak coupling regime. Here we present our most recent work on devices where the cavity is connected in a micron-scale optical network via multiple photonic crystal waveguides terminated with input and output optical couplers. This architecture allows for multiple signal and control beams to be coupled simultaneously in the cavity via distinct ports. The devices are equipped with two input ports where the waveguides are terminated with input grating-couplers that allow for coupling into the waveguide from an out-of-plane direction. A third waveguide coupled to the cavity is terminated with a different kind of grating out-coupler that allows for improved directional scattering of the light transmitted through the cavity. We have already shown in previous experiments with a single cavity with coupled quantum dots, that this system acts as a highly nonlinear medium that enables all optical switching at powers down to the single photon level. In our most recent experiments we take significant steps towards demonstrating that this switching can be done in integrated structures, as needed for optical signal processing devices for both classical and quantum information science.

Keywords: quantum information, photonic crystal, quantum dot, quantum networks

1. INTRODUCTION

Quantum dots in photonic crystals have recently emerged as one of the most promising quantum technologies for on chip optical signal processing. Recent developments on this platform include the demonstration of weakly[1] and strongly[2–4] coupled system, and the development of tuning[2,5] and coherent probing techniques.[6] These techniques enabled experiments on optical[7,8] and electrical[9] switching based on single coupled quantum dots. In the next two sections of this paper we discuss about how these quantum light switches can be integrated into a on-chip photonic network.

2. ALL OPTICAL INTEGRATED DEVICE

In our recent experiments we have shown that a coupled cavity-quantum dot system has a ultra-high optical nonlinearity[6] that can be used to implement optical switching[7] as needed for all optical signal processing. In that work we have used a photonic crystal cavity that was probed via external laser beams in a cross-polarized reflectivity measurement.[6] However, to take full advantage of the photonic crystal technology, it is necessary to integrate these strongly nonlinear systems in optical networks. Towards this goal, we were able to demonstrate dipole-induced transparency[10] in a cavity connected to a phootnic crystal waveguide that was terminated with a grating outcoupler for efficient scattering of the transmitted light (Fig.1(a)). The device was equipped with a metal-coated heating pad that allowed for local control of the device temperature using an external laser beam.[2] The transmission of the system is measured by focusing a laser beam into the cavity from the top, and then collecting the light scattered through the grating. Both the collection and the excitation is done through the same microscope objective. A laser beam with fixed frequency was coupled into the cavity and then the cavity and quantum dot frequency were scanned via local temperature tuning. The transmission spectrum in Fig.1(b) shows a typical Lorentzian cavity shape with a drop in transmission that is due to the coherent interaction between the probe laser, cavity field and the quantum dot.

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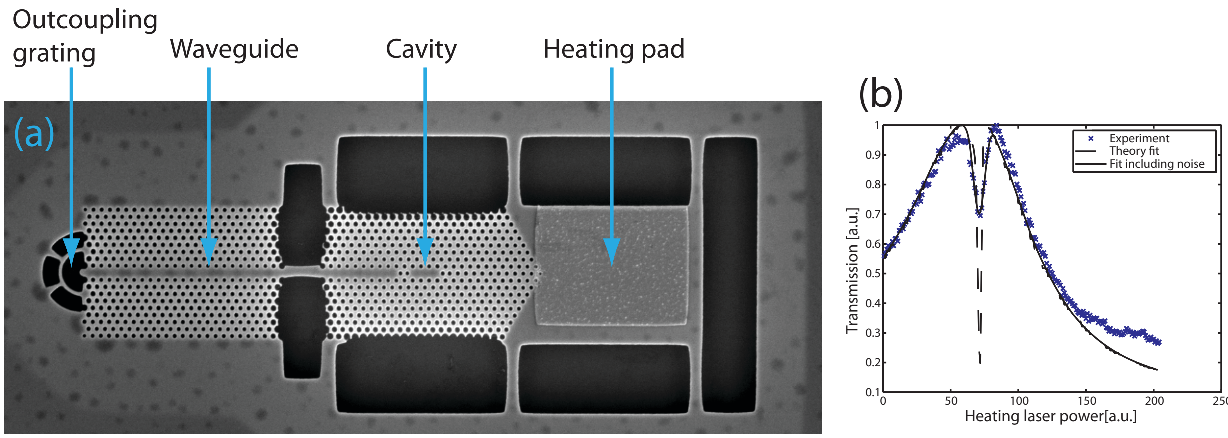

Figure 1. (a) Photonic crystal device composed of a suspended photonic crystal cavity butt-coupled to a waveguide that is terminated with a grating outcoupler. The heating pad next to the cavity is used to control the temperature of the device using an external laser beam. (b) Transmission function of the waveguide-coupled cavity.

This proof of concept experiment demonstrates some basic level of integration between of cavities with quantum dots, and waveguides that can rout optical signals on the chip. The next step is to couple the cavity to multiple waveguides for input, output and control optical signals. A concept device of this type is shown in Fig.2. It consists of a linear three hole defect cavity connected to three butt-coupled photonic crystal waveguides. The input waveguides are coupled to the cavity in an angled configuration while the output waveguide is aligned with the cavity axis. These coupling configurations were studied in Ref.,[11] where we demonstrated high coupling efficiencies between cavities and waveguides in the photonic crystal architecture.

The device is designed to couple to laser beams incident from a direction perpendicular to the plane of the device. For this reason, the waveguides are terminated with photonic crystal gratings that allow for good coupling efficiency of light in to and out of the waveguides. Currently we are able to map the transmission function of cavities with weakly coupled quantum dots from one of the input waveguides to the output port. However, the demonstration of all optical switching in this structure is still work in progress. We are currently investigating multiple systems to find a system that operates in the strong coupling regime. At the same time we are experimenting with other photonic crystal designs that should allow for better coupling efficiency.

3. INTEGRATED DEVICES WITH ELECTRICAL CONTROL

Beside all optical switching, another topic of high interest in the opto-electronic community is the design and fabrication of electro-optic swithches that operate at GHz speed and have very low power consumption. Devices based on the cavity quantum electrodynamics of single emitters coupled to cavities are attractive candidates because they operate in the desired speed range and have ultra-small effective volumes which should enable ultra-low energies of operation.

Recently we demonstrated an electro-optic modulator based on a strongly coupled quantum dot that was electrically controlled using an electrode fabricated in the very close proximity of the cavity ($\sim 750nm$).[9] The electrode was in Schottky contact with the GaAs substrate. A depletion region, and thus a bias electric field, is created around the electrode when a bias voltage is applied on it. The electric field shifts the quantum dot frequency via the quantum confined Stark effect thus enabling electrical control of the cavity quantum dot system. Using this system, we demonstrated electro-optic switching of a coupled laser beam up to speeds as high as 150MHz,[9] limited by the RC time constant of the driving electronics. The active medium that is responsible for the switching action has a volume smaller than a cubic micron, which translates into energies per switching operation smaller that 1fJ.

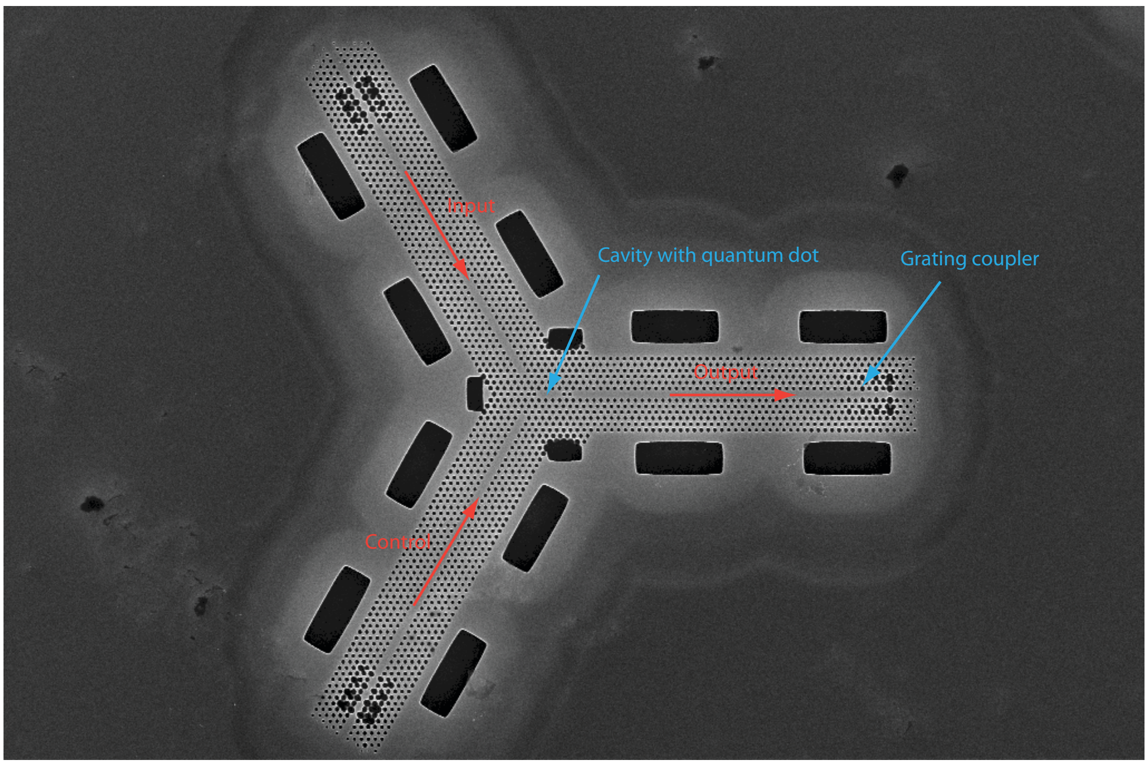

Figure 2. Integrated device with cavity and three coupled waveguides terminated with photonic crystal grating for in/out coupling of light from an out-of-plane direction.

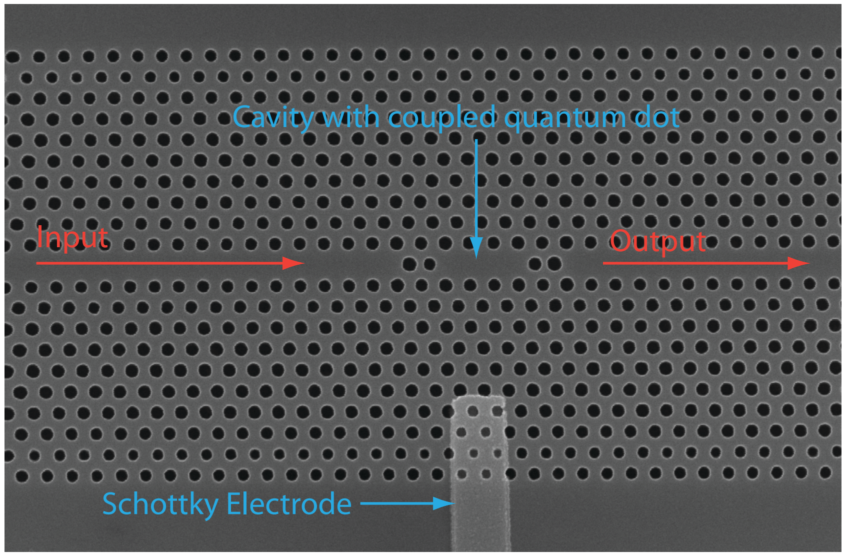

Figure 3. Integrated electro-optic modulator based on a quantum dot it a photonic crystal cavity that is connected to two waveguides for efficient signal routing directly on the chip.

Currently we are investigating devices where the cavity is integrated with photonic crystal waveguides for on-chip routing of the input and output signal. A prototype device of this kind is shown in Fig.3. It consists of a linear three hole defect photonic crystal cavity that butt-coupled to two photonic crystal waveguides with two hole separation. We expect to push the performance of these devices up to speeds as high at 10GHz and operating intensities up to a few nanowatts.

4. CONCLUSION

In conclusion, we demonstrated optical and electrical switching using quantum systems composed of a single quantum dot coupled to a photonic crystal cavity. Our current effort concentrates in integrating these quantum photonic devices into photonic networks that should enable the next generation of all optical and electro-optical signal processing devices.

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