A Chiral One-dimensional Atom Using a Quantum Dot in an Open Microcavity

A. Javadi¹, N. O. Antoniadis¹, N. Tomm¹, T. Jakubczyk¹, R. Schott², S. R. Valentin², A. D. Wieck², A. Ludwig², R. J. Warburton¹

¹Department of Physics, University of Basel, Klingelbergstrasse 82, Switzerland
²Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Germany

Abstract: We realize an optical equivalent of a diode that simultaneously shows nonlinear and non-reciprocal behavior. Using a quantum dot in a microcavity, we show that photon transmission is one order of magnitude larger in the forward direction compared to the backward direction. The system shows a strong nonlinearity with an onset at 100pW.

Linearity and reciprocity are the most fundamental properties of optical photons. While a broad range of non-reciprocal devices, such as diodes and circulators, already exist for electrons, quantum photonics still lack a fully functioning counterpart to these elements. Cavity quantum electrodynamics provides the key tools for breaking linearity and reciprocity simultaneously. A quantum emitter coupled efficiently to an optical mode can significantly modify the mode’s properties; for instance, it can inhibit or enhance the transmission through the optical mode. On the other hand, reciprocity can be broken through chiral interaction between photons and quantum emitters [1]. An optical mode with spin-momentum locking, i.e., the dependence of the handedness of light on the direction of the propagation, provides the grounds for breaking the reciprocity. A circularly polarized quantum emitter will naturally interact with spin-momentum-locked photons in one direction only, inducing non-reciprocal behavior in the system [2,3].

Here, we demonstrate highly non-reciprocal and nonlinear transmission at the single-photon level using a chirally coupled semiconductor quantum dot-microcavity system [4]. Figure 1(a) shows the design of our microcavity. It is composed of a semiconductor distributed Bragg reflector (DBR) at the bottom and a concave DBR at the top [5].

![Fig. 1 (a) Schematic of the device: A circular dipole is embedded in a tunable microcavity. (b) Transmission through the system for the two directions. (c) The autocorrelation function of the photons in the backward direction for three different powers. The bunching vanishes for increasing powers.](image-url)
The concave shape of the top DBR ensures a Gaussian mode profile and guarantees ideal mode matching between the cavity and a single-mode fiber. A layer of InAs quantum dots is grown on the bottom DBR. The optical part of the setup consists of two ports, Port 1 and Port 2. A combination of a polarizing beam-splitter and a quarter wave-plate implements the spin-momentum locking for photons such that photons propagating from Port 1 to Port 2 are right-hand polarized at the position of the quantum dot while photons propagating in the reverse direction are left-hand polarized.

The level structure of the quantum dot is shown in the insert of Fig. 1a. A magnetic field of 2 T splits the excited states of the quantum dot while ensuring that the transitions are circularly polarized. The dynamic nature of the microcavity allows us to move the quantum dots with respect to the center of the cavity and hence to tune the coupling strength between the cavity and the quantum dot. For this work, we tune the coupling strength to the critical coupling regime, that is 50% probability of interaction between photons and the quantum dot ($\beta=0.5$). In this regime, photons interacting with the quantum dot will be scattered outside the cavity [2,3].

We use a narrow-linewidth laser on resonance with the higher energy transition to demonstrate the operation of our system. Figure 1(b) shows the transmission of our diode in the two directions. In the forward direction (from Port 1 to Port 2), the transmission is nearly flat, around ~82%, and independent of frequency, while in the backward direction, the transmission is strongly suppressed (~7%) due to interaction between photons and the critically-coupled quantum dot transition. By comparing the two transmission curves, we extract an isolation of 10.7 dB for our diode, the highest non-reciprocal response recorded with a single quantum emitter.

The nonlinearity in the system arises due to the efficient coupling between a single quantum dot and the cavity mode. The quantum dot interacts coherently with single-photon states, while two-photon and larger number states tend to saturate the quantum dot and transmit through the system. We investigate the nonlinearity of the transmission in the backward direction by measuring the transmission, which shows a saturation curve with a critical power of around 100 pW. Further, we investigate the nonlinearity by measuring the auto-correlation of the transmitted photons, see Fig. 1(c). In the low power regime, we observe a photon bunching by a factor of 100 compared to a laser field. This bunching arises as the single-photon components of the laser field are scattered out of the system by the quantum dot, while the higher-photon states have a higher probability of transmission.

References

[1] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, “Chiral quantum optics”, Nature 541, 473-480 (2017).

[2] I. Söllner, S. Mahmoodian, S. L. Hansen, L. Midolo, A. Javadi, G. Kiršanskė, T. Pregnolato, H. El-Ella, E. H. Lee, J. D. Song, S. Stobbe, and P. Lodahl, “Deterministic photon–emitter coupling in chiral photonic circuits”, Nat. Nanotechnol. 10, 775 (2015).

[3] D. L. Hurst, D. M. Price, C. Bentham, M. N. Makhonin, B. Royall, E. Clarke, P. Kok, L. R. Wilson, M. S. Skolnick, and A. M. Fox, “Non-reciprocal Transmission and Reflection of a Chirally Coupled Quantum Dot”, Nano Lett. 18, 5475 (2018).

[4] N. O. Antoniadis, N. Tomm, T. Jakubczyk, R. Schott, S. R. Valentin, A. D. Wieck, A. Ludwig, R. J. Warburton, A. Javadi, “A chiral one-dimensional atom using a quantum dot in an open microcavity”, npj Quantum Inf 8, 27 (2022).

[5] N. Tomm, A. Javadi, N. O. Antoniadis, D. Najer, M. C. Löbl, A. R. Korsch, R. Schott, S. R. Valentin, A. D. Wieck, A. Ludwig, R. J. Warburton, “A bright and fast source of coherent single photons”, Nat. Nanotechnol. 16, 399 (2021).