Progress towards interaction-free all-optical devices

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We present an all-optical control device in which coupling a weak control optical field into a high-Q lithium niobate whispering-gallery-mode microcavity decouples it from a signal field due to nonlinear optical interactions. This results in switching and modulation of the signal with low-power control pulses. In the quantum limit, the underlying nonlinear-optical process corresponds to the quantum Zeno blockade. Its "interaction-free" nature effectively alleviates loss and decoherence for the signal waves. This work therefore presents experimental progress towards acquiring large phase shifts with few photons or even at the single-photon level.

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Strong interactions between optical fields enable a variety of applications in physics and engineering. Among these applications, switching, routing, and modulating optical signal pulses by optical control pulses while preserving the pulse energy and coherence are some of the most desirable. Achieving this with classical low-power pulses would greatly enhance the field of optical communications and optical computing; with single-photon pulses this would provide the basis for quantum logic operations and quantum computing [1,2]. Such interactions have to be mediated by a matter with a strong nonlinear-optical response, e.g., an ensemble of atoms or semiconductor quantum dots. Isolated atoms or ions have also been shown to provide resonant nonlinearities sufficiently strong to realize interactions at single-photon energies [3,4]. These systems, however, typically require very low temperatures.

At room temperature a transparent nonresonant optically nonlinear medium can be used, but at the cost of requiring large optical control powers. This presents a virtually prohibitive difficulty for achieving efficient interaction between single photons, such as necessary for implementation of quantum logic gates [1]. It also presents a serious problem in switching a quantum-level signal with even moderately strong control pulses, since any such direct interaction can lead to adding noise to the former and to its decoherence. For the operations where such degradation is not acceptable, a different type of interaction is necessitated. To that effect, the quantum Zeno blockade (QZB) effect [5–7] can be utilized to realize an "interaction-free" coupling of the optical fields.

The quantum Zeno effect is a phenomenon where frequent or continuous measurements performed on a quantum state inhibit its evolution. This effect can be used to realize a blockade, analogous to the Rydberg or Coulomb blockade, wherein the occupation of a quantum state suppresses additional population of the same mode [5]. In all-optical systems, the "measurement" can be facilitated by nonlinear interaction with a control pulse. Such ancillary coupling can also impart large phase shifts to a signal wave without generating phase noise—an important step towards all-optical quantum-logical operations [8].

Achieving sufficiently strong ancillary coupling of optical low-energy (ultimately single-photon) pulses presents a serious challenge. Fortunately, the burgeoning field of optical whispering-gallery-mode (WGM) microcavities [9] has resulted in the development of extremely high-Q resonators that greatly enhance the nonlinear interaction of photons. For example, the crystalline resonators possessing a $\chi^{(2)}$ (quadratic) susceptibility provide an attractive platform for realizing low-light-level optical nonlinear interactions. Such interactions have been realized in second harmonic generation [10–12], parametric down conversion [13–16], and recently in sum-frequency generation (SFG) [17].

The theoretical proposals [18–20] for single-photon-level quantum logic utilizing the interaction-free QZB place exacting criteria on the resonators, requiring a high-quality factor, small mode volume, and strong overlap between the interacting modes. Here we report our progress towards this goal by observing all-optical amplitude modulation and pulse switching in the picojoule power range.

Nonlinear optical interaction in our system is mediated by naturally phase-matched SFG in a triply resonant, dual-pumped, high-Q lithium niobate microresonator. A signal pulse couples to the resonator with coupling rate κ_s. When it is phase matched for SFG with the control pulse, strong ancillary coupling arises and the resonance shift ensues at the signal wavelength, decoupling it from the cavity. Therefore, the presence or absence of the control pulse determines whether the signal pulse enters the cavity or is reflected, which implements an all-optical switch. At a single-photon level, this would correspond to the quantum Zeno effect utilizing a driven transition for the ancillary coupling, similar to the original demonstration of the quantum Zeno effect for Be ions [21].

The ancillary nonlinear interaction can be realized as either sum-frequency or difference-frequency generation. However, for quantum logic gates, where background noise photons are extremely detrimental, higher frequency control is undesirable as it can lead to emission of noise photons into the frequency bands of interest. Therefore, we chose to implement the SFG and utilize this process as a coherent level-splitting mechanism [18] for the control pulse to prevent the signal pulse from entering the resonator. We further prove the intrinsically "interaction-free" character of this mechanism, which in our system means the suppressed SFG, and study its temporal dynamics.

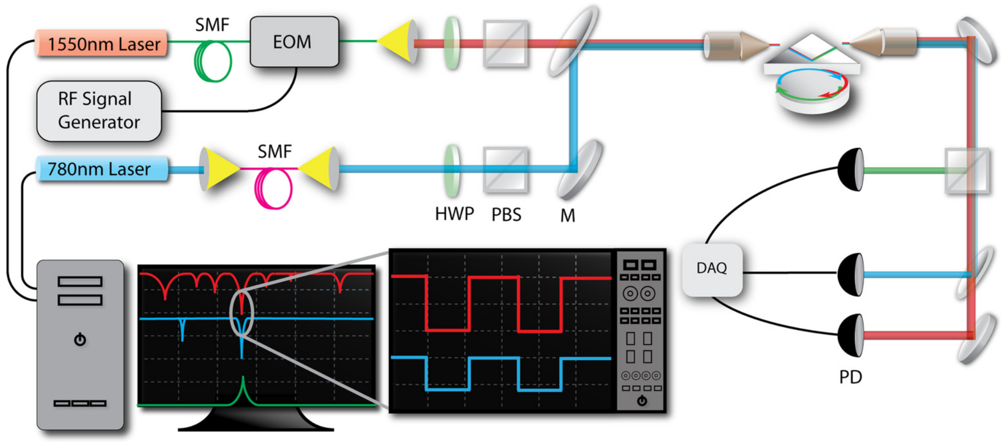

FIG. 1. (Color online) Experimental setup. PD, photodetector, M, mirror; DM, dichroic mirror; PBS, polarization beam splitter; HWP, half-wave plate; DAQ, data acquisition unit; and EOM, electro-optical modulator producing pulses. Objective lenses (10×) were used to focus the lasers onto the prism-resonator interface and to collect the output light.

Leveraging our understanding of SFG channels in the triply resonant microcavity [17], we now proceed to demonstrate optical QZB and its applications for all-optical switching and modulation. Our experimental setup is shown in Fig. 1. This is an upgraded version of the experimental setup we have used for demonstration of the SFG in lithium niobate WGM resonator [17]. Retaining the same resonator, lasers, and the WGM tracking and stabilization infrastructure, we have incorporated in our system an electro-optical amplitude modulator capable of producing square pulses in the control channel. The pulses extinction ratio is very high (of the order 1:1000) and their repetition rate greatly exceeds the laser sweep rate across the WGMs. The mode-tracking electronics has been supplied with low-pass filters so as not to be disturbed by the pulses. The high-speed data acquisition electronics, on the other hand, can be configured to capture a sufficient number of pulses while the signal and control lasers are either on resonance or have desired detuning from their WGM resonances.

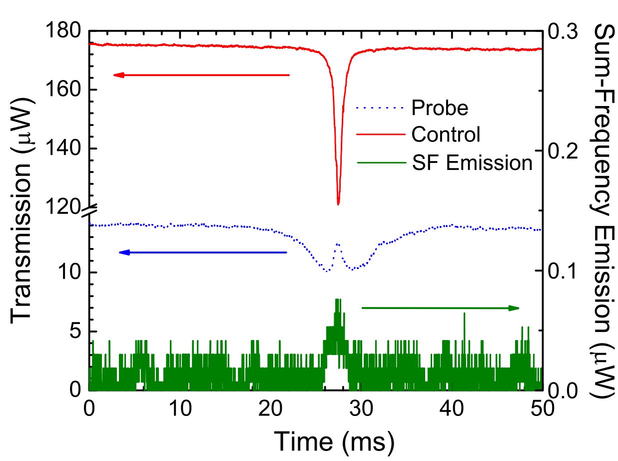

FIG. 2. (Color online) Line splitting in a quasi-CW regime: provided the phase matching, the control field coupling into the resonator suppressed the the signal field coupling; a small amount of the sum frequency is generated.

First, we demonstrated the classical limit of a quasistatic coherent quantum Zeno effect in which the signal (long) and control (short) pulses were produced by simultaneously sweeping the lasers across the WGM resonances. In this measurement the control was slightly over-coupled to the resonator and the signal was critically coupled. The in-coupled control power was approximately 180 μW, while the in-coupled signal power was 20 μW. It is the coupling and power difference that make the system asymmetric and assign the "control" and "signal" roles to the optical fields. Upon achieving phase matching in the microdisk [17], the signal was decoupled from the resonator with up to 80% extinction ratio, as shown in Fig. 2, and the sum-frequency light was detected. Outside the phase-matching temperature window, the signal coupling was unperturbed and no SFG was observed.

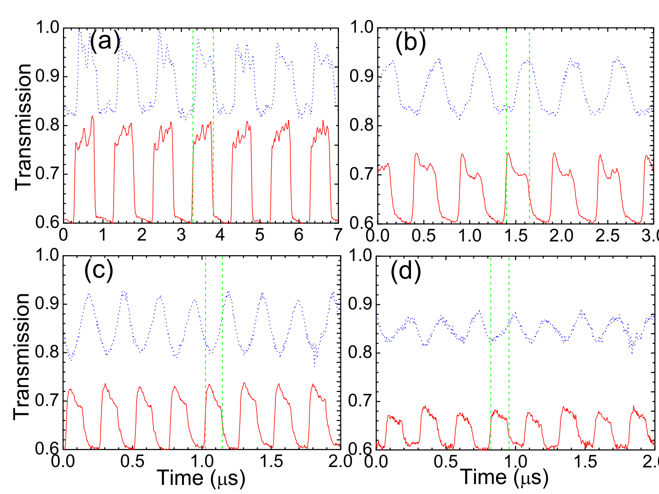

FIG. 3. (Color online) The nearly "interaction-free" modulation is imprinted on the signal (dashed line) by the control (solid line) pulse train for (a) 405-pJ control with a 89-pJ signal operating at 1 MHz, (b) 67-pJ control with a 46-pJ signal operating at 2 MHz, (c) 34-pJ control with a 23-pJ signal operating at 4 MHz, and (d) 8.3-pJ control with a 22-pJ signal operating at 4 MHz. The phase lag, highlighted via dotted vertical lines, is determined by the detuning from resonance for each of the control and signal waves.

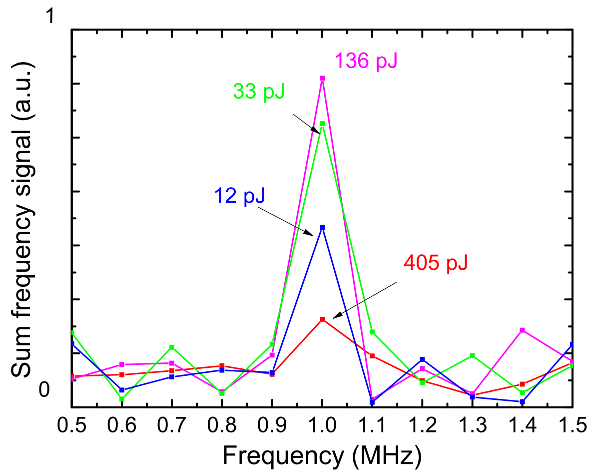

FIG. 4. (Color online) Under the coupling conditions for the interaction-free modulator, a decrease in SF efficiency was observed as the control power increased.

Next, we have shown that the "interaction-free" system can be used as a high-speed all-optical switch or modulator. Due to the high-Q cavity, the control pulse width was limited to $\Delta\tau \gtrsim 125$ ns. We employed the electro-optic modulator and the rf waveform generator to produce square control pulses for studying the dynamics. The WGM coupling alignment was also changed to favor the control field. In Fig. 3 we see that the control pulses have imprinted themselves onto the out-coupled signal waveform. When the control pulses are long, such as in Fig. 3(a), the signal faithfully reproduces the square control pulses. The pulses are in phase, so the maximum control power corresponds to minimum signal coupling, consistent with Fig. 2. As the control pulses become shorter, the WGM bandwidth limitation comes into play and the output signal modulation becomes more sine-shaped due to the low-pass filtering. It also starts to lag in phase, as in Fig. 3(b), and then gets out of phase completely, as in Fig. 3(c).

Various other behaviors have been observed when the control and/or signal were detuned from their respective WGM resonances, when the sum frequency was detuned from its WGM (i.e., the phase matching was imperfect), or when the signal was overcoupled rather than undercoupled. In the latter case, for example, the nonlinear "loss" due to the SFG tunes the resonator closer to (rather than further from) the critical coupling for the signal, and the control pulse increases its coupling contrast. This coupling-enhancing modulation does not have as high amplitude contrast as the coupling-reducing modulation, but it can provide the physical foundation for the QZB-enabled *phase* switch [19].

We did not show the SFG signal in Fig. 3 because as a time series, it is well below the detector noise. However, the SFG can be detected by performing Fourier analysis of a sufficiently long time series. These data are shown in Fig. 4. Again, we see that for higher control power the SFG is suppressed.

In summary, we have observed the all-optical modulation and pulse switching in an optical whispering-gallery-mode resonator, which at quantum level corresponds to the Zeno blockade. We studied the temporal dynamics of this process under different regimes of operation. Though the employed control energies were of the picojoule scale, which is still far from single-photon regime, smaller resonators will decrease the mode volume, as well as improve the coupled WGMs overlap. Both these factors will significantly increase the SFG efficiency. Projecting our experimental results onto attainable microresonators less than 100 microns in diameter, we expect that the nonlinear interaction of few- or single-photon pulses can be observable. Furthermore, with a more suitable morphology and a single-mode resonator, an all-optical Fredkin gate [19] could be realized with a strongly overcoupled control and a critically coupled signal. Our present design precludes this possibility due to the high spectral density of the modes. Alternatively, a more exotic application for the optical Zeno blockade is the simulation of quantum random walks in photosynthetic energy transfer. In particular, our experiment can be altered to serve as a site of tunable decoherence for the signal. In the case of multiple such resonators [22], a photonic simulation of environment-assisted quantum transport processes may be realized.

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[1] M. Nielsen and I. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, UK, 2000).

[2] B. Brecht, A. Eckstein, A. Christ, H. Suche, and C. Silberhorn, New J. Phys. **13**, 065029 (2011).

[3] J. M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73**, 565 (2001).

[4] H. Mabuchi and A. C. Doherty, Science **298**, 1372 (2002).

[5] Y.-P. Huang and P. Kumar, Phys. Rev. Lett. **108**, 030502 (2012).

[6] J. D. Franson, B. C. Jacobs, and T. B. Pittman, Phys. Rev. A **70**, 062302 (2004).

[7] J. D. Franson, T. B. Pittman, and B. C. Jacobs, J. Opt. Soc. Am. B **24**, 209 (2007).

[8] J. H. Shapiro, Phys. Rev. A **73**, 062305 (2006).

[9] K. Vahala, *Optical Microcavities* (World Scientific, Singapore, 2004).

[10] V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, Phys. Rev. Lett. **92**, 043903 (2004).

[11] J. U. Fürst, D. V. Strekalov, D. Elser, M. Lassen, U. L. Andersen, C. Marquardt, and G. Leuchs, Phys. Rev. Lett. **104**, 153901 (2010).

[12] P. S. Kuo and G. S. Solomon, Opt. Express **19**, 16898 (2011).

[13] A. A. Savchenkov, A. B. Matsko, M. Mohageg, D. V. Strekalov, and L. Maleki, Opt. Lett. **32**, 157 (2007).
[14] J. U. Fürst, D. V. Strekalov, D. Elser, A. Aiello, U. L. Andersen, Ch. Marquardt, and G. Leuchs, Phys. Rev. Lett. **105**, 263904 (2010).
[15] T. Beckmann, H. Linnenbank, H. Steigerwald, B. Sturman, D. Haertle, K. Buse, and I. Breunig, Phys. Rev. Lett. **106**, 143903 (2011).
[16] C. S. Werner, T. Beckmann, K. Buse, and I. Breunig, Opt. Lett. **37**, 4224 (2012).
[17] D. V. Strekalov, A. S. Kowligy, Y.-P. Huang, and P. Kumar, New J. Phys. **16**, 053025 (2014).
[18] Y.-P. Huang and P. Kumar, Opt. Lett. **35**, 2376 (2010).
[19] Y.-P. Huang and P. Kumar, IEEE J. Sel. Top. Quantum Electron. **18**, 600 (2012).
[20] Y.-Z. Sun, Y.-P. Huang, and P. Kumar, Phys. Rev. Lett. **110**, 223901 (2013).
[21] W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A **41**, 2295 (1990).
[22] F. Caruso, N. Spagnolo, C. Vitelli, F. Sciarrino, and M. B. Plenio, Phys. Rev. A **83**, 013811 (2011).