A telecom-band cavity-enhanced single-photon source with high Klyshko efficiencies

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Abstract: We develop an on-chip telecom-band single-photon source with Klyshko efficiencies up to 48%, the highest value for cavity-enhanced photon sources. For the first time, we relate Klyshko efficiency to high-order correlations and verify this relation experimentally.

Heralded single-photon sources are mainly based upon spontaneous parametric down conversion (SPDC) or spontaneous four-wave mixing (SFWM) in nonlinear bulk crystals, optical fibers, on-chip waveguides, or microcavities [1]. Heralding efficiency is an important parameter for applications including quantum teleportation [2] and quantum computing [3]. For photon sources based on bulk crystals, the raw heralding efficiency, i.e., the Klyshko efficiency [4], has been pushed above 82.8% at a wavelength of 810 nm [5], and 60% at a telecom wavelength [6]. Recently, microcavity-based photon sources have attracted significant interest due to their small footprints, below-milliwatt pump powers, and narrow photon spectra. However, the Klyshko efficiencies of the microcavity-based photon sources are typically limited below 10%. Moreover, no quantitative experiments have been conducted to study the heralding efficiency systematically in the photon sources with cavity enhancement.

High-Q silicon microresonator is a great photon-pair source with high spectral brightness, large coincidence to accidental ratios (CARs), and single-mode properties [7–9]. In this paper, we herald single photons out of the photon pairs generated by spontaneous four-wave mixing in a high-Q silicon microresonator. We investigate the heralding efficiency and demonstrate a Klyshko efficiency of 48%, the highest value for cavity-enhanced photon sources. Further, we find the relation between the Klyshko efficiency and high-order correlations for the first time.

Our tapered-fiber coupled photon source has the advantage of directly coupling photons from device into the single-mode fiber (Fig. 1(a)). To characterize the performance of photon sources, preparation efficiency [10] is defined as the heralding efficiency in the single-mode fiber, excluding the effects of optical components and detector efficiency. The preparation efficiency is determined by two factors, the photon coupling efficiency and the tapered-fiber efficiency. First, the photon lost inside the cavity can not be coupled out. This photon coupling efficiency η_c is related to the cavity transmissions as $\eta_c = (1 \pm \sqrt{T_c})/2$, where T_c stands for the transmissivity at the center wavelength of the cavity mode,

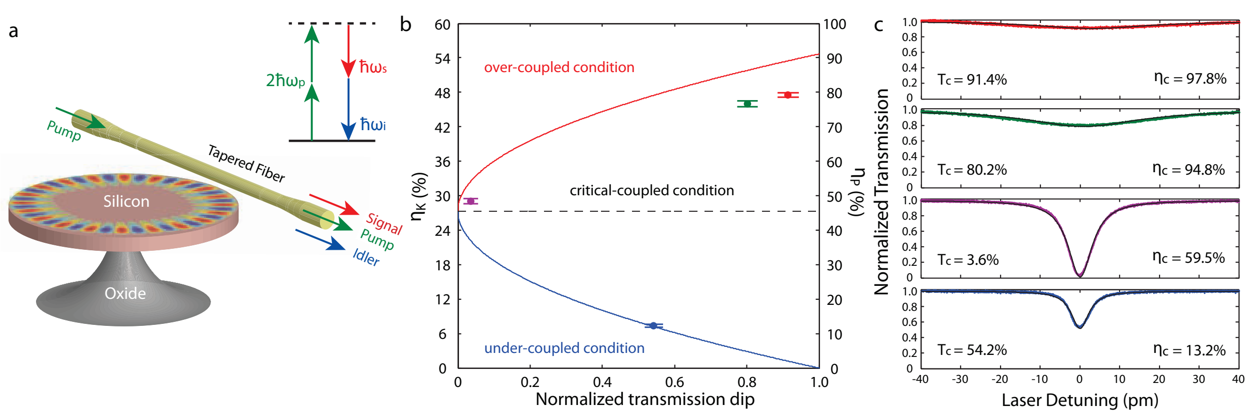

Fig. 1. (a) Schematic illustration of the silicon microresonator photon source based on spontaneous four-wave mixing, with the inset showing the energy diagram. The fiber-device distance can be tuned to change the photon coupling rate. (b) Theoretical predictions of η_K for over-coupled (red) and under-coupled (blue) conditions. Experimental data points are from various fiber-taper coupling conditions with transmission traces shown in (b). (c) The normalized cavity transmission traces with theoretical fitting in black. T_c represents the transmissivity at the center wavelength of the cavity resonance. η_c stands for the photon coupling efficiency.

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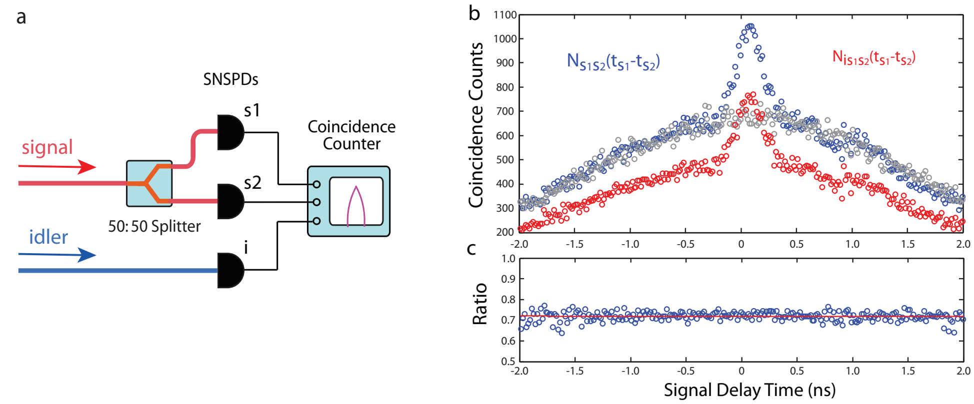

Fig. 2. (a) Scheme of the three-detector setup. (b) Coincidence counts of self correlation, background of self correlation, and triple coincidence shown in blue, grey, and red, respectively. (c) Ratio of triple-coincidence and self-correlation counts.

and the plus/minus signs correspond to the over-/under-coupled conditions, respectively (Fig. 1(c)). The red curve in Fig. 1(c) shows that the photon coupling efficiency is 97.8%, which means the photon loss inside the cavity is less than 3%. Second, the photons coupled out from the cavity can be lost in the tapered fiber. The loss of the tapered fiber before the cavity does not affect the heralding efficiency, because the photons are generated inside the cavity. Thus the efficiency related to tapered fiber is $\eta_{\rm tf} = \sqrt{\rm T_{tf}}$, where $\rm T_{tf}$ is the fiber taper transmittance. The fiber taper used in the experiment has a transmittance of 83.0%, which corresponds to a $\eta_{\rm tf}$ of 91.1%. The theoretical predictions of Klyshko/preparation efficiencies, $\eta_{\rm P} = \eta_{\rm c}\eta_{\rm tf}$, are plotted in Fig. 1(b). The experimental data points are 79%, 77%, 48%, and 12%, which largely agree with our theoretical predictions. Fig. 1(c) shows the normalized transmission traces of experimental data in Fig. 1(b), with colors labeling respective data points. The over-coupled condition in red leads to a preparation efficiency of 79% and a Klyshko efficiency of 48%, among the highest values for telecom-band photon sources. The preparation efficiency ($\eta_{\rm P}$) is related to the Klyshko efficiency ($\eta_{\rm K}$) by $\eta_{\rm P}/\eta_{\rm K} = 60\%$ in this experiment, which takes into account the detection efficiency (78%) and the transmittance in optical components (77.3%).

We characterize the heralded single photons in a three-detector setup (Fig. 2(a)), which can measure triple-coincidence counts ($\rm N_{is_1s_2}$) and self-correlation counts ($\rm N_{s_1s_2}$) at the same time. We find that Klyshko efficiency can be verified by the ratio of these counts ($\eta_{\rm R} \equiv \rm N_{is_1s_2}/N_{s_1s_2}$) as $1-\eta_{\rm R} = (1-\eta_{\rm K})^2$, because the only cases that no idler photons are heralded in triple coincidence are those in which both signal photons fail to herald the idler photons. To verify this relation, we compare the triple-coincidence and self-correlation counts in Fig. 2(b). The ratio of triple coincidence counts to self correlation counts ($\eta_{\rm R}$) is plotted in Fig. 2(c), which is a constant of 72% regarding signal delay time. The Klyshko efficiency is thus calculated to be 47%, which is very close to the experimental value of 46% (the green dot in Fig. 1(b)). This is the first time that high-order correlations are used to verify Klyshko efficiency.

In sum, we develop a telecom-band heralded single-photon source in a high-Q silicon microresonator. We investigate its Klyshko/preparation efficiency and demonstrate a Klyshko efficiency of 48%, the highest value for cavity-enhanced photon sources. We also demonstrate a method to verify Klyshko efficiency by high-order correlations.

1. B. Lounis and M. Orrit, *"Single-photon sources,"* Rep. Prog. Phys. **68,** 1129-1179 (2005).
2. B. J. Metcalf et al., *"Quantum teleportation on a photonic chip,"* Nature Photon. **8,** 770-774 (2014).
3. P. Kok et al., *"Linear optical quantum computing with photonic qubits,"* Rev. Mod. Phys. **79,** 135-174 (2007).
4. D. N. Klyshko, *"Use of two-photon light for absolute calibration of photoelectric detectors,"* Sov. J. Quantum Electron. **10,** 1112 (1980).
5. M. Giustina et al., *"Bell violation using entangled photons without the fair-sampling assumption,"* Nature **497,** 227-230 (2013).
6. S. Wollmann, M. Weston, H. Chrzanowski, and G. J. Pryde, *"High heralding efficiency single photon source at telecom wavelength,"* CLEO/Europe-EQEC, Paper EB-3.2-wed (2015).
7. W. C. Jiang, X. Lu, J. Zhang, O. Painter, and Q. Lin, *"Silicon-chip source of bright photon pairs,"* Opt. Express **23,** 20884-20904 (2015).
8. X. Lu, W. Jiang, J. Zhang, and Q. Lin, *"High-purity single-mode photon source for integrated quantum photonics,"* SPIE Sensing Technology and Applications, 950018-9, Baltimore, MD (2015).
9. S. Rogers, X. Lu, W. C. Jiang, and Q. Lin, *"Twin photon pairs in a high-Q silicon microresonator,"* Appl. Phys. Lett. **107,** 041102 (2015).
10. J. B. Spring et al., *"On-chip low loss heralded source of pure single photons,"* Opt. Express **21,** 13522-13532 (2013).