High-quality photon-pair and heralded single-photon generation using periodically-poled thin-film lithium niobate

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Abstract: Photon-pair generation is shown using periodically-poled thin-film lithium niobate waveguides, with coincidences-to-accidentals ratio CAR>67,000 at 41kHz pairs rate, and heralded single-photon generation with g(2)(0)<0.05 at 860kHz herald rate.

1. Introduction. Periodically-poled lithium niobate (PPLN) waveguides are the most popular source used for efficient and high-quality photon-pair production, using the optically-pumped process of spontaneous parametric down conversion (SPDC). Traditional PPLN waveguides, which have a large waveguide cross-sectional area (typically, A_{eff}>20 μm^2), are a mature, commercially-available device technology when using relatively high pump powers (typically, P_{pump}>10 mW) and intended for use as fiber-coupled, stand-alone devices. To benefit future developments in on-chip integrated quantum photonics, it may be beneficial to achieve high pair-source brightness and quality while significantly reducing pump power requirements, e.g., to the sub-milliwatt level.

Recently, micron-scale waveguides (typically, A_{eff} <1 μm^2) using thin-film lithium niobate on insulator (LNOI) have been used to demonstrate record performance in integrated electro-optic modulators and second-harmonic generators. However, there are only a few results on SPDC in LNOI waveguides [1,2], currently showing a large performance gap compared to SPDC in traditional PPLN waveguides [3,4].

Quasi-phase matching (QPM) in single-mode waveguides is generally much more robust, stable and continuously tunable than modal phase matching in multi-mode waveguides. However, because of the significant waveguide dispersion of high-confinement nanophotonic waveguides, a relatively small poling period is required in LNOI (here, Λ = 2.8 μm). We have recently developed a high-quality poling recipe for x-cut LNOI, and demonstrated two useful diagnostic methods using in-situ poling monitoring, and a non-destructive nonlinear microscopy technique [5,6]. This allows us to improve the poling process, and identify suitable waveguides without destroying them e.g., by cross-sectioning, and etching using dilute acids, as is typically performed in traditional poling diagnostics.

2. Experimental details. The LNOI film consisted of 300 nm x-cut LN on 1.8 μm SiO_2 and Si handle wafer and was obtained from a commercial source (NANOLN). Waveguides of length 0.7 cm were etched to a ridge depth of 50 nm, without taper formation, with propagation loss <1 dB/cm. The quasi-TE-polarized fundamental modes had effective area 1.1 μm^2 at 1570 nm and 0.4 μm^2 at 785 nm. Type-0 quasi-phase matching was achieved by poling. Gold electrodes (with a Cr adhesion layer) were lithographically patterned and used for poling, with the calculated QPM period Λ = 2.8 μm. Poling, and diagnostics of the poled structures, were performed as described in Refs. [5] and [6]; the poling duty cycle was nearly ideal (50%) over the 0.5 cm poled length. The chip was simply diced for measurement, without polishing, and thus incurred high, un-optimized coupling losses to standard, telecommunications-wavelength, lensed, tapered fibers (Oz-Optics, no index-matching fluid) of 16 dB/facet at 785 nm, and 7 dB/facet at 1570 nm. The residual pump was filtered by a long-pass filter (insertion loss 2 dB), and a passband of width $\Delta\lambda$=0.8 nm was selected around the phase-matched wavelength of 1568.9 nm using a telecommunications-grade filter. For detecting single photons, SNSPD's with detection efficiency of 68% (Photon Spot) were used, and detected signals were processed using a time-to-digital converter instrument (quTAG), with coincidence window of 15 ns. We first performed a second harmonic generation (SHG) measurement, for an input cw pump around 1569 nm, generating second-harmonic light at 784.5 nm. We measured a SHG conversion efficiency of 1.76 x 10^3 %.W^{-1}.cm^{-2}, with a phase-matching (sinc-squared) full-width at half-maximum spectral bandwidth of 1.26 nm. Next, experiments on photon-pair generation through SPDC were performed.

3. SPDC Results.

3.1 Brightness: The brightness of the SPDC pair source (B, units: pairs.s^{-1}.mW^{-1}.nm^{-1}) is calculated using the formula $B = N_S N_I/(C\ P_{pump}\ \Delta\lambda)$ where N_S and N_I are the on-chip rates of signal and idler photons, scaled from the measured rates by the waveguide-fiber coupler losses, fiber and filter transmission loss, and detector efficiency at 1569 nm, C is the on-chip coincidences rate, P_{pump} is the pump power in the waveguide, on the chip, estimated from the measured pump power after the chip and the measured coupling loss at the pump wavelength, 784.5 nm, and $\Delta\lambda$

is the full-width at half-maximum of the filter (0.8 nm at 1569 nm) used before the single-photon detectors. The calculated value of B=5.5 x 10^7 pairs.s^{-1}.mW^{-1}.nm^{-1} (at a P_{pump} 0.21 mW), which is similar to Ref. [2] and four times higher than Ref. [4].

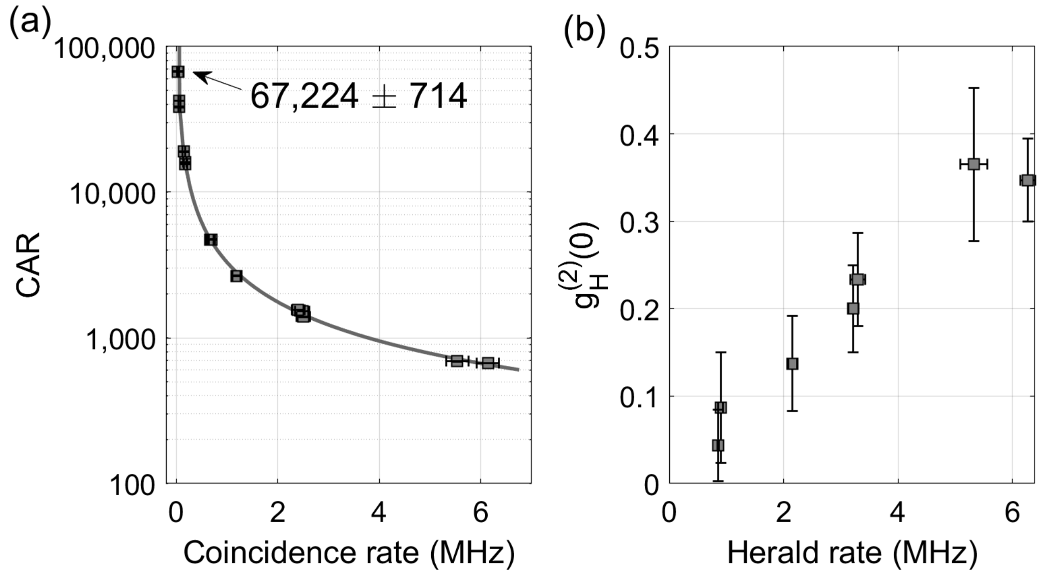

Figure 1: Non-classicality of the SPDC source. (a) coincidences-to-accidentals ratio (CAR) versus on-chip pair generation rate. (b) Heralded single-photon second-order self-correlation function versus on-chip singles rate. Errorbars are determined by one standard-deviation in the constituent terms in the respective calculations.

3.3 CAR: As shown in Fig. 1(a), we measured the second-order signal-idler correlations, resulting in a coincidences-to-accidentals ratio CAR=668 ± 1 (the errorbar is one standard deviation) at on-chip pair generation rate PGR=6.1 ± 0.2 MHz, and CAR=(6.7 ± 0.03)x10^4 at PGR=41 ± 1 kHz. As usual, the relationship between CAR and P_{pump} (or, equivalently, the singles rate, N_S or N_I) was inversely-proportional, with a good fit observed over the range of pump powers that was used in this experiment (0.16 μW to 0.21 mW, on chip), for which the on-chip singles rate, averaged over the signal and idler, varied between 7.6 MHz and 69 kHz. Previously, using LNOI waveguides, maximum CAR values of about 6-15 [1] and up to 600 (the latter at PGR=0.8 MHz) [2] were reported. For any type of PPLN waveguide, the record CAR is 8x10^5 measured at PGR of only 5 Hz [3]; thus, in comparison, our waveguide offers a large (7.5x – 700x) improvement in achieving high CAR at high PGR.

3.4 $g^{(2)}_H(0)$: Detecting one photon of the photon pair results in a heralded single-photon source, since the other photon is then expected to show non-classical anti-bunching behavior. The heralded (i.e., conditional) single-photon second-order self-correlation function is obtained by detecting one of the generated photon pair as a herald, and measuring the self-correlation of the other photon in the presence of the herald. Because our chip is not yet packaged [4], we did not measure heralding at the lowest pump powers used in Fig. 1(a). As shown in Fig. 1(b), $g^{(2)}_H(0)$ values were less than 0.5 (the classical limit) over the entire range of pump powers, and were as low as 0.044 ± 0.04 at an on-chip singles (herald) rate of 0.86 MHz (for which CAR is approximately 6,000).

4. Conclusion. To our knowledge, this is the first report of very high quality and bright photon-pair and heralded single-photon generation using periodically-poled thin-film lithium niobate on insulator (LNOI) waveguides.

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