High Brightness Broadband Photon-Pairs at 2 μm in Lithium Niobate Nanophotonics

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Abstract:
We present a photon-pair source at 2 μm with more than 45 THz bandwidth and a generation rate of 122 GHz/mW in lithium niobate nanophotonics, opening up many opportunities in mid-infrared quantum information processing.

Photon-pair sources are crucial to the development of photonic quantum technologies, offering significant advantages in communication, computation, sensing, and metrology. The majority of sources have been demonstrated at 1550 nm or shorter wavelengths [1,2]; however, there remains a need for mid-infrared (MIR) sources. This region of the spectrum offers unique applications in free-space quantum key distribution (QKD) protocols, owing to its reduced solar irradiance and lower scattering losses near 2 μm [3]. Recent work on photonic bandgap fibers has produced hollow-core fibers working near 2 μm with lower losses and two-photon absorption compared to traditional silica fibers at 1550 nm [4]. Silicon photonics platforms have similar benefits at 2 μm [5]. Moreover, high-quality MIR sources will unlock numerous opportunities in quantum-enhanced gas sensing and spectroscopy.

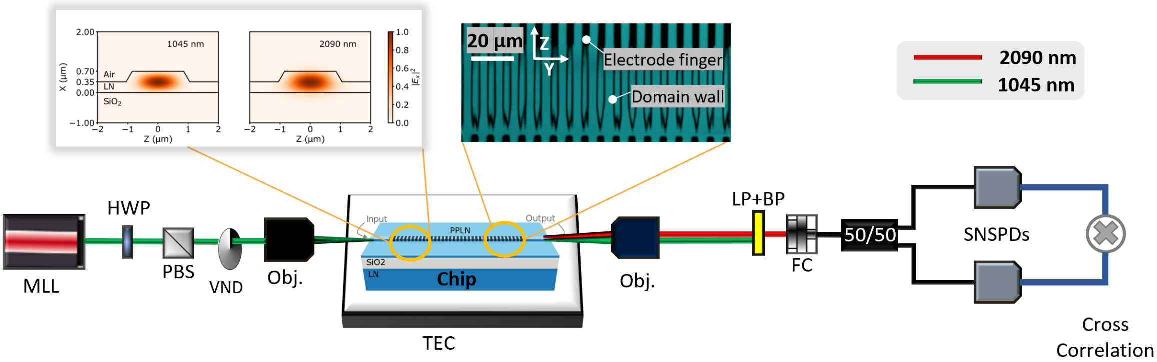

Fig. 1. Schematic of the experimental setup. A mode-locked 75-fs 250-MHz laser (MLL) centered at 1045 nm pumps a periodically-polled lithium niobate (PPLN) waveguide. Output light is long-pass and band-pass filtered. Photon pairs are fiber coupled and sent to two SNSPDs (see text for details). HWP: half-wave plate; PBS: polarising beam-splitter; VND: variable neutral density wheel; Obj:reflective objective; TEC: thermoelectric cooler; LP+BP: long pass and band-pass filter; FC: fiber collimator; 50/50: 50/50 fiber splitter at 2 μm ± 100 nm; SNSPDs: superconducting nanowire single-photon detectors; Insets show the simulated mode profiles [6] of the signal and the pump fields and a second harmonic microscope image of the poled region. Chip inset taken from [6].

We present an integrated source of ultra-broadband photon-pairs centered at 2.09 μm with high brightness. Our device is shown in Fig. 1 labeled as "Chip". A 5-mm-long region is periodically poled on an x-cut 700-nm-thick lithium niobate on silica platform, and a waveguide is defined using electron beam lithography and argon ion milling. Waveguide dimensions and poling period are optimized for photon-pair generation via spontaneous parametric down-conversion (SPDC) of a 75-fs pump 250-MHz mode-locked laser centered at 1045 nm.

We characterize these devices using the experimental setup shown in Fig. 1. The pump laser is sent through a motorized half-wave plate (HWP) and polarizing beam-splitter (PBS) to vary the input power. The pump beam is collected and focused onto the input faced via a reflective objective. The chip itself sits atop a thermoelectric cooler (TEC) to allow for temperature tuning of the phase matching. Light from the output facet is collected via a second reflective objective and passed through a series of long-pass and band-pass filters to reject the pump and carve a 48-nm wide portion of the SPDC spectrum before being collected by a fiber collimator (FC). All measurements are performed through this 48 nm filter to improve the coincidence to accidentals ratio (CAR). Once in fiber, the SPDC photons are split at a 50/50 fiber splitter and sent to two superconducting-nanowire-single-photon (SNSPD) detectors to perform a standard Hanbury Brown–Twiss experiment. Our SNSPDs have 13% and 12% estimated efficiency, respectively, and dark count rates of 3.6 kHz and 2.8 kHz. Efficiencies for the signal and idler channel are found to be 1e-4 and 9e-5 respectively from fitting the signal, idler, and coincidence data from the SNSPDs.

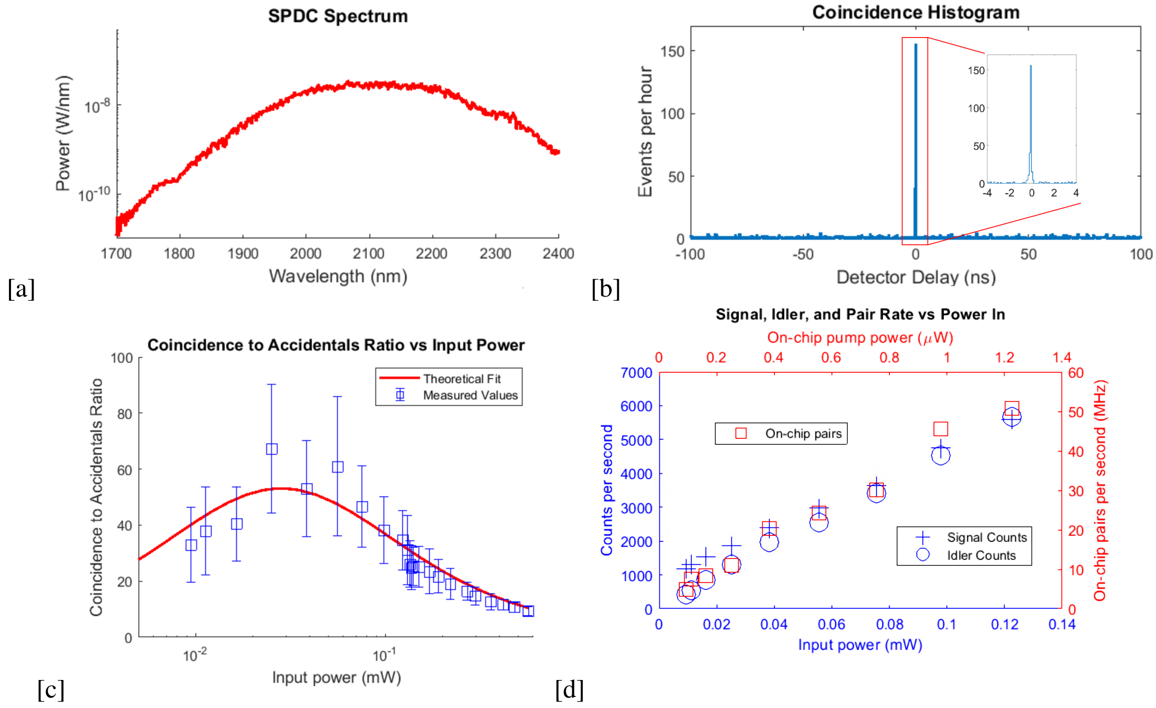

Fig. 2. (a) Spontaneous Parametric Down-Conversion (SPDC) spectrum measured at the output of our waveguide (46THz of bandwidth measured -20dB from peak) (b) The coincidence histogram generated by our SNSPDs. (c) Coincidence-to-accidentals (CAR) ratio of the source as a function of input power. (d) Signal and idler rates as a function of input power, and on-chip pair generation rates as a function of on-chip power.

These agree well with the chip facet to the fiber loss of 27 dB measured by fitting the SPDC power vs pump power curve with hyperbolic sine squared. Input coupling loss is estimated to be 20dB by measuring pump throughput at low power.

Figure 2 shows the measurement results for our device. In Fig. 2a, the measured spectrum of our SPDC emission is displayed, confirming a bandwidth of more than 45 THz. The signal-idler coincidence histogram as a function of delay is shown in Fig. 2b. The peak at zero delay corresponds to true coincidences. The CAR (Fig. 2c) is measured by varying the injected pump power and monitoring the coincidence histogram computed between the two SNSPDs. Every histogram uses a 100-ps bin and a 300-ps coincidence window. A coincidence peak seen at zero delay represents the arrival of photon pairs, while accidental peaks spaced at the laser repetition rate represent an "accidentally" heralded photon. The raw data is fitted with the model used in [7]. Mean and variance are computed using the accidental peaks at different delays. We measure a maximum CAR of 67 ± 22 at 800 nW of on-chip power. Signal and idler count rates are shown as a function of input power in Fig. 2c, along with the computed coincidence rate vs of on-chip power. We extract a slope of 20.7 GHz/mW of on-chip pair generation over a 48 nm bandwidth centered at 2.09 μm, a record-breaking rate for integrated photon pair sources. Extrapolating this rate to the entire spectrum gives us a rate of 122 GHz/mW and 6.2 MHz/mW/GHz within the filter bandwidth. We achieve an order of magnitude of brightness improvement over similar devices [1, 8] via the broad-bandwidth of our input pump as this improves the utilization of the available phase-matching bandwidth provided by the dispersion-engineered PPLN. The pair generation rate and source purity may be improved by increasing the overlap between the spectrum of the pump and the phase matching through dispersion and poling engineering and/or using a broader pump.

In conclusion, we have shown a broadband source of photon pairs at 2 μm with high brightness, paving the way for a wide range of quantum applications in the MIR region. When combined with other resources in lithium niobate nanophotonics such as electro-optic modulators, filters, and tapered edge-couplers, this source can serve as the heart of a fully-integrated chip-scale platform for quantum metrology and information processing. Device performance is currently limited by the lack of deterministic signal-idler separation, chip-coupling efficiencies, and insufficient mode-selectivity. Integrating our device with on-chip tunable filters and inverse tapers would enable the exploitation of our wide bandwidth and high brightness via spectral multiplexing to create many tunable pair sources from one device.

References

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