Ultra-Broadband Entangled Photons on a Nanophotonic Chip

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Primary CNF Tools Used: JEOL 9500, AJA ion mill, CVC SC4500 odd-hour evaporator

Abstract:

Integrated photonic devices have shown great promise in scalable implementation of quantum technologies for applications in information processing, communication, computing, metrology, and sensing. Particularly, for applications in metrology and sensing, a broadband source of quantum entanglement is desired. To that end, we demonstrate an integrated source of entangled photon pairs with record-high bandwidth and efficiency not seen on chip-scale platforms before. This source is fabricated on thin-film lithium niobate-on insulator wafer at the Cornell NanoScale Facility.

Summary of Research:

One of the most widely used methods to generate quantum entanglement in light is by using a nonlinear optical process called spontaneous parametric down conversion (SPDC). In this process, a laser photon spontaneously breaks into two daughter photons inside a nonlinear optical material, which are entangled in time and energy [1]. The efficiency of this process and its bandwidth is determined by the dispersion of the material used in the interaction. Efforts to generate this entanglement over a broad spectral region is primarily confined to bulk materials where the control over material dispersion is severely limited. Due to this, the only feasible method of increasing the bandwidth is to create inhomogeneity in the medium [2,3]. This severely reduces the generated spectral brightness of the photons creating a tradeoff between brightness and bandwidth of the source [2,4]. Nanophotonics, on the other hand, does not have any such limitation since the wavelength-scale geometry of thin-film devices can be exploited for precise control of the refractive index. Here, we are reporting on fabrication of a nanophotonic waveguide on thin-film lithium niobate-on-insulator wafer (LNOI), which has been engineered to produce an entanglement bandwidth exceeding 100 terahertz (THz).

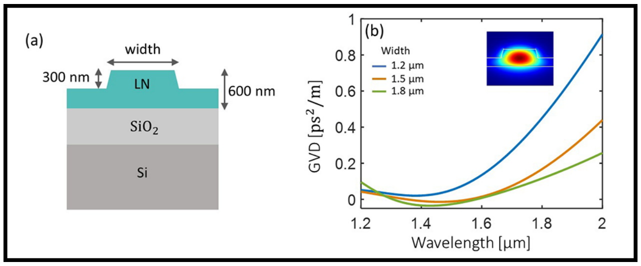

Figure 1: (a) Geometry of the lithium niobate waveguide on a 600 nm LNOI wafer. (b) Group velocity dispersion (GVD) of the waveguide at different widths with the inset showing the fundamental quasi-TE mode of the waveguide at a 1550 nm wavelength.

The waveguide is designed for 600 nm thick lithium niobate film with X-cut orientation of the crystal axis. In order to produce a broad parametric down-conversion spectrum, the dimensions of the waveguide are engineered to have zero group velocity dispersion (as shown in Figure 1) at an optical wavelength of 1550 nm, which will form the center of the generated spectrum. The resulting waveguide has a width of 1.5 μm and an etch depth of 300 nm. The waveguide is subsequently patterned on the wafer using electron-beam lithography on the JEOL 9500 using ZEP520A as the resist mask for the waveguide.

After development, the waveguide is etched using argon ion milling on the AJA ion mill achieving a 50% (300 nm) etching depth. The resist is then stripped using standard resist remover chemistry and the chip is prepared for a second electron-beam exposure. This is to pattern electrodes on both sides of the waveguide so that the material can be poled by applying high voltage electrical pulses that permanently alter the material's optic axis. This is done to bridge the refractive index gap between the pump laser photons, which are at a wavelength of 775 nm to the generated photon pairs which are centered at 1550 nm. The material is coated with PMMA resist and exposed again with electron-beam lithography to pattern the electrodes. After development, the chip is deposited with a 400 nm layer of gold using an evaporator (CVC SC4500). The electrode pattern is subsequently created by a resist liftoff process.

Figure 2 shows scanning electron microscope images of a fabricated device.

After fabrication, the waveguide is pumped by a laser with a tunable wavelength. The laser wavelength is scanned, and the generated photon pairs are detected using superconducting single-photon detectors. At 770.4 nm, we observe a parametric down-conversion spectrum spanning from the central wavelength of 1540.8 nm all the way to 1100 nm as shown in Figure 3(a), giving a half spectral-width at half maximum of 50 THz (300 nm).

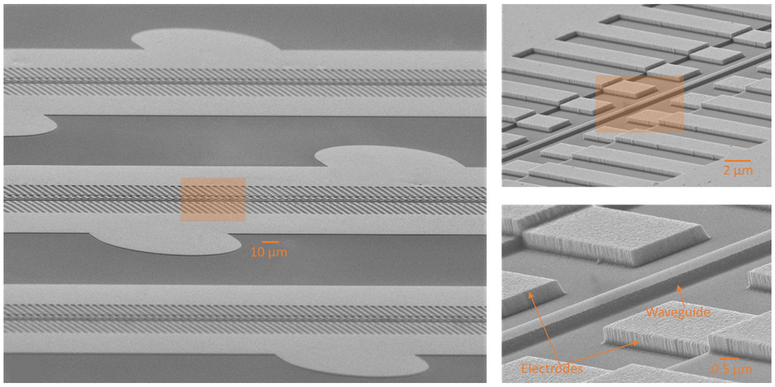

Figure 2: SEM images of a fabricated device at different magnifications.

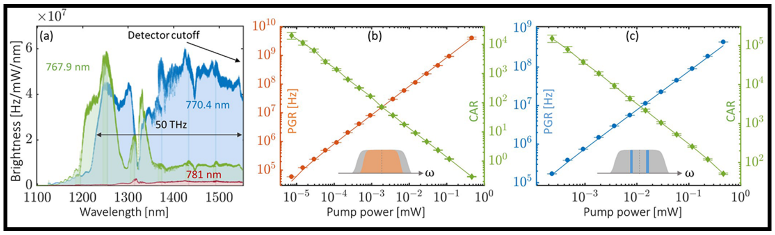

Figure 3: (a) Measured spectrum of the generated photon pairs at different pump wavelength with the blue curve plotting the highest (100 THz) bandwidth. The pair generation rate (PGR) and coincidence-to-accidental ratio (CAR) are plotted for the full spectrum in (b) and a 20 nm filtered section in (c).

The full spectrum is then expected to span up to 2000 nm, given the symmetry of the interaction, giving a total bandwidth of 100 THz. This is more than an order of magnitude larger than a typical chip-scale SPDC source. The device also shows a high efficiency of 13 GHz/mW of pump power, owing to such a large bandwidth and strong confinement of light as expected of a wavelength-scale device.

Another important metric of an entangled photon source is its signal-to-noise ratio, also known as coincidence-to-accidental ratio (CAR), which determines its performance in communication and computing applications. Figure 3(c) plots this measurement for a 20 nm filtered section of the spectrum. This is done to counter dispersive effects in the experimental setup to get the true noise characteristics. We observe a highest CAR of 152,000 the highest achieved for any chip-scale photon-pair source to date [5,6], indicating excellent noise performance, even at high pair generation rates. Additional measurements to verify quantum entanglement in the generated light are also done (not shown here) to verify our claims.

Conclusions:

To conclude, we have designed and fabricated an efficient waveguide source of ultra-broadband entangled photons. The large bandwidth of entanglement produced from this device along with its record efficiency and noise performance make such nanophotonic sources ideal for applications in quantum communication and computing.

Furthermore, we envision that this demonstration will motivate experiments in chip-scale metrology and spectroscopy with non-classical light.

References:

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