

# Submicron axial resolution in an ultrabroadband two-photon interferometer using superconducting single-photon detectors

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**Abstract:** We generate ultrabroadband biphotons via the process of spontaneous parametric down-conversion in a quasi-phase-matched nonlinear grating that has a linearly chirped poling period. Using these biphotons in conjunction with superconducting single-photon detectors (SSPDs), we measure the narrowest Hong-Ou-Mandel dip to date in a two-photon interferometer, having a full width at half maximum (FWHM) of  $\approx 5.7$  fsec. This FWHM corresponds to a quantum optical coherence tomography (QOCT) axial resolution of  $0.85 \mu\text{m}$ . Our results indicate that a high flux of nonoverlapping biphotons may be generated, as required in many applications of nonclassical light.

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**OCIS codes:** (270.0270) Quantum optics; (270.5570) Quantum detectors; (040.5570) Quantum detectors.

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In 1987, Hong, Ou, and Mandel (HOM) introduced a new interferometric technique for measuring the subpicosecond temporal separation between two indistinguishable photons [1]. Their approach has since been employed in various applications; these include the generation of entangled states [2, 3], the measurement of the degree of indistinguishability between photons from a single-photon source [4, 5], and quantum optical coherence tomography (QOCT) [6, 7]. In the experimental arrangement used by HOM, the indistinguishable signal and idler photons (biphotons) are generated by the process of spontaneous parametric down-conversion (SPDC) [8, 9, 10] and each impinges on one of the input ports of a 50:50 beam splitter. The superposed beams interfere and single-photon detectors are placed at the output ports. The coincidence rate of the detector output pulses is recorded as a function of the temporal delay introduced between the two photons. The result is the celebrated HOM dip, in which the photon-coincidence rate vanishes at zero delay; the width of the dip is determined by the biphoton spectral density.

In a recent paper [11], the generation of ultrabroadband biphotons that span a bandwidth of  $\approx 300$  nm about the wavelength  $\lambda_0 = 812$  nm has been reported. Using these ultrabroadband biphotons in conjunction with semiconductor single-photon avalanche photodiodes (APDs), a narrow HOM dip with a FWHM of 7.1 fsec was measured. However, since the APDs used in their experiments had a limited bandwidth (particularly in the near infrared-region), the authors speculated that the bandwidth of the emitted biphotons could in fact be larger than that observed in their experiments, and that an even narrower HOM dip would emerge, were they to make use of single-photon detectors with a broader spectral response.

The measurement of an ultranarrow HOM dip reveals the possibility for engineering ultranarrow biphoton wavepackets, which in turn enables the generation of a high flux non-overlapping

biphotons [12]. This is essential for making practical use of SPDC light in nonclassical applications such as entangled-photon microscopy [13], spectroscopy [14], and photoemission [15].

In this paper, we discuss the generation of ultrabroadband biphotons following the prescription provided in Ref. [11], but we make use of superconducting single-photon detectors (SSPDs), which offer a broader spectral response than APDs [16]. This has enabled us, on the twentieth anniversary of the appearance of Ref. [1], to measure the narrowest HOM dip to date, with a FWHM of  $5.7 \pm 0.2$  fsec, corresponding to an axial resolution of  $\approx 0.85 \mu\text{m}$  in QOCT.

The method we use to generate ultrabroadband biphotons in this work makes use of a quasi-phase matched (QPM) nonlinear grating with a nonuniform poling period  $\Lambda$  [11, 17, 18]. The poling pattern  $\Lambda(z)$ , where  $z$  is the spatial coordinate along the direction of pump propagation, provides a collection of phase matching conditions over the length of the grating, which leads to broadband biphoton generation; at the same time, the poling pattern can be chosen to engender a special phase relation among the various spectral components, thereby allowing the biphoton wavepacket to be compressed using the techniques of ultrafast optics [19]. For example, in the absence of group-velocity dispersion (GVD), a linearly chirped spatial frequency,  $K_g(z) = 2\pi/\Lambda(z)$ , ensures an exact linear chirp of the biphoton wavepacket [18], which is readily compressed.

In particular, our biphoton source consists of a near-stoichiometric lithium tantalate (SLT) crystal onto which a grating of length  $L = 1.8$  cm has been poled with a linearly chirped spatial frequency,  $K_g(z) = K_0 - \alpha z$ , where  $K_0$  is the grating's spatial frequency at its entrance face ( $z = 0$ ), and  $\alpha = 9.7 \times 10^{-6} \mu\text{m}^{-2}$  is a parameter that represents the degree of linear chirp. We make use of third-order QPM for which  $K_g(z) = 3 \cdot 2\pi/\Lambda(z)$ , so that  $K_0 = 3 \cdot 2\pi/\Lambda_0$  where  $\Lambda_0 = 9.824 \mu\text{m}$  is the poling period at  $z = 0$ . Our SLT crystal was fabricated from congruently melting composition lithium tantalate using the vapor-transport-equilibration (VTE) method [20, 21]. A monochromatic  $\text{Kr}^+$ -ion laser operated at  $\lambda_p = 406$  nm pumps our chirped periodically poled SLT grating that was operated at a temperature of  $T = 52.6$  °C. The resulting down-converted signal and idler photons are each centered at the degenerate wavelength  $\lambda_0 = 812$  nm and emitted in a noncollinear direction that makes an angle  $\theta \approx 1.1^\circ$  with the pump. Using these entangled-photons in an HOM interferometer, we trace the HOM dip using two types of single-photon detectors: APDs and SSPDs.

The APDs used in our experiments were commercially available single-photon-counting modules (SPCM-AQR-15) from EG&G, whereas the SSPDs were our own devices, assembled following the method described in Ref. [22]. The active element of each SSPD was a meander-shaped narrow stripe of width 80-120 nm that covers a  $10 \mu\text{m} \times 10 \mu\text{m}$  area. The stripe was fabricated from a 4-nm-thick superconducting niobium nitride (NbN) film that has been sputtered on a double-sided polished sapphire substrate, using direct electron-beam lithography and reactive ion etching, following Ref. [23]. The devices were fitted at the bottom of a vacuum insert that was placed vertically in a standard 60-liter liquid-helium transport dewar. By reducing the He vapor pressure inside the vacuum insert, the operating temperature of the SSPDs could be reduced to 1.8 K. The optical input was fed to the active area of each SSPD via a single-mode fiber, and the electrical output was connected to a high-frequency coaxial cable through a gold coplanar transmission line that also served as the electrical contact to the NbN meander. The outputs of the coaxial cables were then connected to room-temperature high-frequency amplifiers (Phillips Scientific 6954 0.0001-1.5 GHz) to boost the electrical signals before they were fed to the discrimination and coincidence circuitry. Further information and illustrative figures are available in Ref. [22].

These single-photon detectors were used in a HOM interferometer and the coincidence rate  $N_c(\tau)$  of the detector output pulses were recorded as a function of the temporal delay  $\tau$  between the signal and idler photons. The results are presented in Fig. 1. The symbols represent the

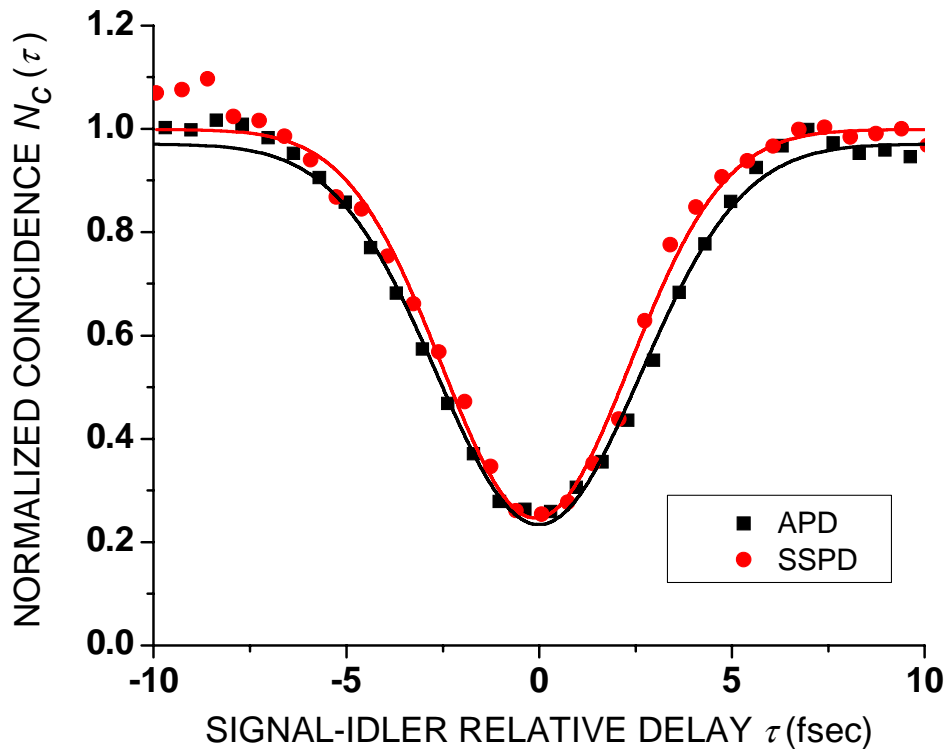


Fig. 1. (Color online). Normalized Hong-Ou-Mandel (HOM) coincidence interferograms (dips) that were obtained using a pair of semiconductor single-photon avalanche photodiodes (APDs) (squares), and using a pair of superconducting single-photon detectors (SSPDs) (circles). The symbols represent the measured data points and the curves are Gaussian fits to the data. The FWHM of the measured dips are  $6.2 \pm 0.1$ , and  $5.7 \pm 0.2$  fsec for the experiments conducted using APDs and SSPDs, respectively. These observed ultra narrow dips translate to ultra-high axial QOCT resolution of  $0.93$  and  $0.85 \mu\text{m}$ , respectively.

measured data points and the curves are Gaussian fits to the data. Although theoretical formulas are available for these curves [11], Gaussian fits serve our purposes well, as confirmed by the reduced  $\chi^2$  values, which were  $0.0005$  and  $0.0014$  for the HOM dips obtained with the APD and SSPD detectors, respectively.

The HOM dip obtained using the APD detectors (squares) has a FWHM of  $6.2 \pm 0.1$  fsec while that obtained using the SSPD detectors (circles) has a FWHM of  $5.7 \pm 0.2$  fsec. These ultra narrow dips translate to ultra-high axial QOCT resolutions of  $\approx 0.93$  and  $0.85 \mu\text{m}$ , respectively.

We have also computed the root-mean-square (RMS) width of these HOM dips directly from the data without fitting and confirmed that the use of SSPDs results in an  $\approx 9\%$  narrowing of the dip. The data in Fig. 1 indicate that the HOM dip obtained using SSPDs is slightly asymmetric and this was also confirmed by computing the third central moment for the data. This effect may be attributed to the shape of the spectral response of the SSPDs.

Simulations for an ideal experimental arrangement (with no spectral cutoffs) predict a biphoton bandwidth of  $\approx 550 \text{ nm}$  (see Fig. 4(a) of Ref. [11]), corresponding to a HOM dip of width

2.7-fsec (see simulation curves for  $\alpha = 9.7 \times 10^{-6} \mu\text{m}^{-2}$  in Figs. 3 and 4(c) of Ref. [11]). The limited bandwidths of the various optical components in the experimental arrangement, including the detectors and beamsplitter, increase the width of the measured dip, as expected. The reduced visibility of the observed dips arises from the spatial asymmetry of the HOM interferometer that was used in these experiments; one of the arms had an even number of mirrors while the other had an odd number. The symmetric HOM used in the experiments reported in Ref. [11] yields dips with higher visibility.

We conclude that the use of the SSPD detectors broadens the overall spectral response of the HOM interferometer, as evidenced by the narrowing of the HOM dip, thereby confirming that a higher density of nonoverlapping biphotons can, in fact, be obtained.

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