Nonclassical Interference and Entanglement Generation Using a Photonic Crystal Fiber Pair Photon Source

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We demonstrate two key components for optical quantum information processing: a bright source of heralded single photons; and a bright source of entangled photon pairs. A pair of pump photons produces a correlated pair of photons at widely spaced wavelengths (583 nm and 900 nm), via a $\chi^{(3)}$ four-wave mixing process. We demonstrate nonclassical interference between heralded photons from independent sources with a visibility of 95% (after correction for background), and an entangled photon pair source, with a fidelity of 89% with a Bell state.

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Photons are ideal for quantum technologies, including quantum communication [1] and quantum metrology [2], due to an increasingly low decoherence and easy one-qubit rotations. However, realizing two-qubit logic gates for quantum computation requires a massive optical nonlinearity. Measurement-induced nonlinearities can be realized using linear optical networks combined with single photon sources and detectors [3]. The scaling of linear optical networks to many qubits is currently limited by the lack of bright single photon sources. We describe a possible solution based on photonic crystal fibers [4]. We demonstrate the suitability of this source for photonic quantum information processing with two key experiments. We show high visibility (95% after correction) nonclassical interference between photons from separate sources and configure the source to produce high fidelity (89%) entangled photon pairs. The photons are created within a single fiber mode which can be efficiently coupled into linear optics circuits and on to detectors. This source promises much higher rates of multiphoton generation than conventional sources.

Since the original proposal [3] there have been a number of important theoretical improvements [5–7] and experimental proof-of-principal demonstrations [8–14], which combined, make optical quantum computing promising. Experiments have typically relied on producing photons via spontaneous parametric down-conversion. However, the practical limit of standard down-conversion is five [12,15] or six [16,17] photons. This is highlighted when we consider the counting rates in multiphoton experiments where N pairs are selected to create a $2N$ multiphoton state. The $2N$ fold counting rate is of order

$$\bar{C}_{2N} = R\mu^N \eta^{2N}, \tag{1}$$

where R is the pump laser repetition rate, μ the probability of creating a pair of photons in a single temporal and spatial mode, and η the product of all efficiencies between source and detector or *lumped efficiency*. As the statistics of creation of multiple pairs follows a thermal distribution the probability of creating $N + 1$ photon pairs in any pulse $P(N + 1)$ is of order μ times the probability of creating N pairs. This creates a background which reduces the visibility of the required interference effects and normally we are restricted to $\mu \leq 0.1$. The ideal operating regime for a bright source is therefore to reach $\mu \sim 0.1$ with reasonable pump power. To achieve high coincidence counting rates we also need to couple the photons to detectors with high efficiency. Standard sources do not reach $\mu \sim 0.1$ until very high pumping powers (of order the maximum power of a Ti:sapphire laser $\sim$1 W), making high rates of multiphoton generation very difficult. Measured lumped efficiencies (in multiphoton interference experiments) are of order 12% (e.g., Ref. [16]).

Here we approach the problem by developing a photonic crystal fiber (PCF) based source where the photon pairs are created from a four-wave mixing process, in the single mode of a microstructured fiber. PCFs with very small solid cores can have zero dispersion wavelength (ZDW) in the visible and near infrared region of the spectrum. It has been shown recently that by pumping slightly blueshifted into the normal dispersion region (at 708 nm) one can generate correlated pair of photons at widely spaced wavelengths (583 nm and 900 nm). The confined geometry enhances the nonlinear interaction and the required $\mu \sim 0.1$ pairs per pulse is reached at mW pump powers [18–20], and high collection efficiencies into standard optical fibers are possible.

At the quantum level the four-wave mixing process can be regarded as the virtual absorbtion of two pump (p) photons and subsequent creation of a signal (s) and idler (i) photon pair. The process then has to satisfy energy conservation

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$$2\omega_p = \omega_s + \omega_i \tag{2}$$

and a significant build up of amplitude in a length of fiber requires phase matching

$$2k_p - 2\gamma P_p = k_s + k_i, \tag{3}$$

where P_p is the peak pump power, and γ is the nonlinear coefficient of the fiber

$$\gamma = 2\pi n_2/\lambda_p A_{\mathrm{eff}}, \tag{4}$$

where $n_2 = 2 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$ is the nonlinear refractive index of silica, and A_{eff} is the effective cross-sectional area of the fiber mode.

In the anomalous dispersion regime the single photon pairs are close to the pump wavelength. This makes it difficult to separate photon pairs from spontaneous Raman scattering which is also guided in the fiber [21–23]. In contrast, pump wavelengths in the normal dispersion regime generate photon pairs widely spaced in wavelength [18], making their separation from the pump, Raman background, and each other relatively straightforward [18,19]. The exact wavelengths of the photon pair can be tuned by engineering the PCF core size (and hence ZDW), and for a given PCF can be fine-tuned by adjusting the pump wavelength [20].

Since photon pair creation requires annihilation of two pump photons the pair generation rate is proportional to the square of the incident intensity. A PCF source thus operates best under pulsed pumping conditions: the pair creation rate is enhanced while reducing the relative contribution from the Raman background, which is linear in pump intensity. We have previously demonstrated a PCF source operating in this regime with a detected coincident photon rate of $\sim 3.2 \times 10^5$ per second with a pump power as low as 0.5 mW [9]. PCFs therefore satisfy the brightness requirement, providing wavelength-tunable, polarized, and single spatial mode photon pairs in a naturally narrow bandwidth [we measure $\sim$5 nm and $\sim$10 nm full width at half maximum (FWHM) bandwidths for the signal and idler, respectively].

In our first experiment, we demonstrate high visibility interference between single photons from different sources. When two photons are incident on separate ports of a 50:50 beam splitter, nonclassical interference suppresses coincident detections across the output ports [24]. For high visibility, we require that the two photons be indistinguishable in every degree of freedom (wavelength, bandwidth, polarization, spatial and temporal mode, etc.). Figure 1(a) is a schematic of our experiment. We demonstrate nonclassical interference of heralded photons in two regimes: a low pump power regime ($P_p = 1$ mW per fiber) where a high nonclassical raw visibility of 88% is observed [Fig. 1(b)]; and a higher pump power regime ($P_p = 8$ mW per fiber) where a net visibility of 95% is seen after subtraction of the accidental coincidence events [Fig. 1(c)]. In the latter result a high background fourfold coincidence rate arises from the emission of two pairs from one fiber and one pair from the second fiber. We measure this constant background by blocking one input port of the beam splitter (and subsequently the other one) and looking at the fourfold coincidence rate revealing the rate of multi-

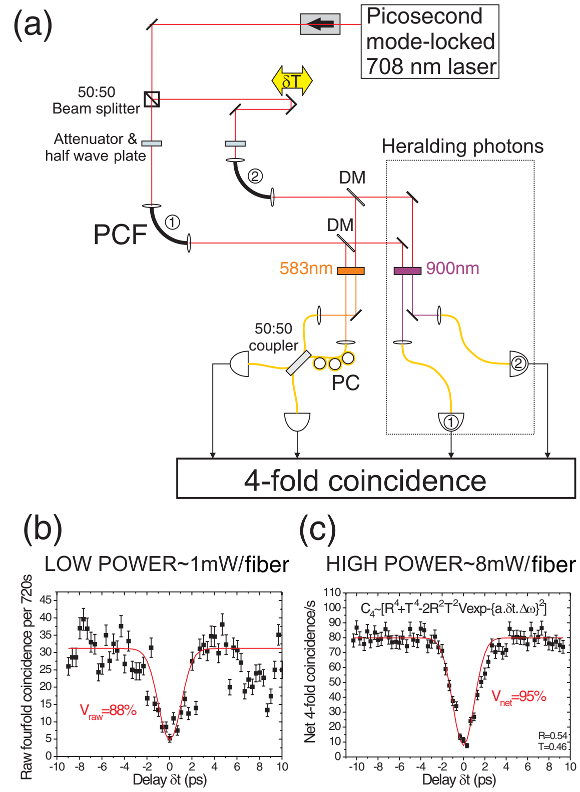

FIG. 1 (color online). Interference experiment involving two heralded single photons from separate sources. (a) A picosecond Ti:sapphire laser emitting 1.5 ps pulses with a repetition rate of 82 Mhz is split in a 50:50 beam splitter and then pumps two fibers (PCF 1 and 2, each 12 cm long) with variable delay δt. The pair photon outputs are collimated using aspheric lenses and then separated into signal and idler arms using dichroic mirrors (DM) centered at 700 nm. The signal beams are then launched into single mode fibers to guarantee optimal spatial mode overlap on the 50:50 fiber beam splitter. A polarization controller (PC) and 0.28 nm FWHM bandpass filter (583 nm center wavelength) further ensured the indistinguishability of the signal photons. A slightly wider (2 nm FWHM) filter is used on the long wavelength (900 nm) idler beams mainly to minimize losses. These beams are also collected in single mode fiber and idler detections are used to herald signal detections in a fourfold coincidence circuit. (b) Fourfold coincidences measured as a function of delay time between the heralded photons δt clearly showing the expected dip around zero delay with a width corresponding to the coherence length of the filtered photons ($l_c \approx 1.2$ mm for 0.28 nm bandwidth at 583 nm). Using 1 mW of pump power per fiber, we obtain 1700 pair coincidences/s per fiber and 0.04 fourfold coincidences/s. (c) Increasing the pump power to 8 mW per fiber we see a net 80 fourfold coincidences per second and a high visibility dip after correction for background. Note that in both experiments there is no contribution from any other process such as Raman scattering or fluorescence.

photon events. We find it contributes about 60% of our fourfolds at 8 mW. However, raw visibility was still 40%, greater than the 33% classical limit for thermal sources [25]. A similar correction improves the raw 88% to ~95% in the low power case. A simple theory of multiphoton background effects in the low power regime also appears in [25]. Our visibilities are close to the theoretical maximum of 97% based on the interference filter bandwidths. In the higher power case, we observe 80 net fourfold coincidences per second, comparable to the best coincidence rate reported in previous experiments [16]. Optimization of the experimental setup will increase this rate and reduce the background. Note that the great difference in fourfold coincidences between the low and high powers is due to the fact that the rate is proportional to P_p^4.

For most quantum information processing applications, entangled photon pairs are an essential resource. Here we create the polarization entangled state which is a coherent superposition of $|HH\rangle$ and $|VV\rangle$, where $|HH\rangle$ and $|VV\rangle$ represent horizontally and vertically polarized photon pairs, respectively. To do this, we use the fiber in a Sagnac interferometer with a polarizing beam splitter (PBS) as shown in Fig. 2. The key advantage of the Sagnac loop is that the counterpropagating pairs remain in a coherent superposition without any phase or path adjustments [22]. The pump beam polarization is rotated to 45° so that equal intensities pump the clockwise and counterclockwise pairs. As the fiber is slightly birefringent there are different phase matching conditions along orthogonal axes. Thus we choose to pump the fiber along only one axis (axis 1 shown on Fig. 2) and twist the fiber to align this axis on the respective pump polarizations coming out of the output ports of the PBS (the PBS reflects the V polarization). Therefore, we pump the fiber in both directions and in the clockwise direction the H polarization of the pump is used to create W polarized pairs at the output, whereas in the counterclockwise direction V polarized pump photons create HH polarized pairs. When the pairs recombine on the PBS we end up with a superposition of the two states created $|HH\rangle$ and $|VV\rangle$ in the same mode. A consequence is that the pairs exit the PBS in the same arm as the input pump beam and we separate them using a notch mirror. A dichroic mirror then separates the short wavelength (583 nm) photon from the longer wavelength (900 nm). We couple both photons into single mode fibers to ensure that we only collect the fundamental modes emitted from the source.

We use quantum state tomography and maximum likelihood techniques [26] to characterize the output from our entangled photon source. The resulting density matrix is shown in Fig. 2(b). This density matrix has a fidelity of $F_{\Phi+} = 0.89$ with the maximally entangled Bell state $|\Phi^+\rangle = |HH\rangle + |VV\rangle$, indicating that this is indeed a source of highly entangled photons. The main reason for the nonunit fidelity with $|\Phi^+\rangle$ is that the coherences between the $|HH\rangle$ and $|VV\rangle$ populations are smaller than for

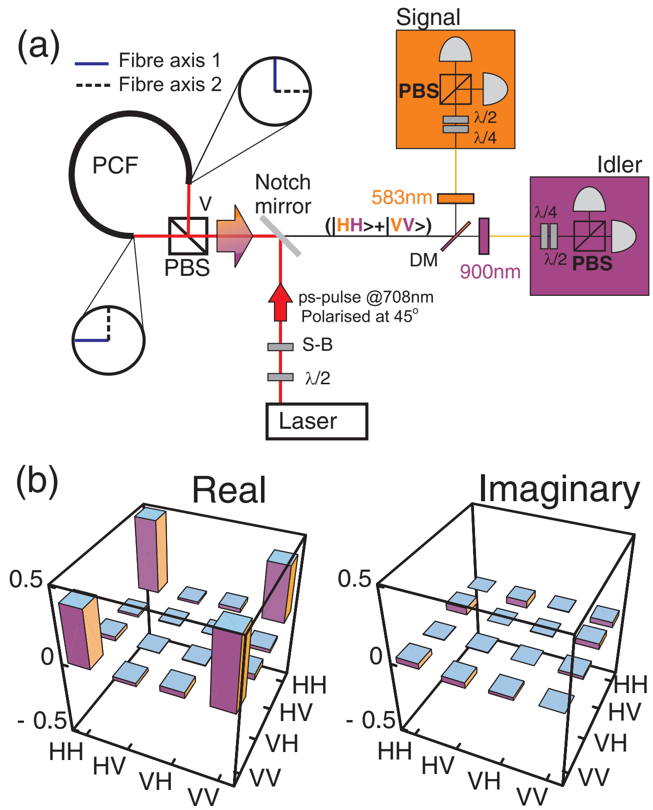

FIG. 2 (color online). (a) Schematic of the entangled photon pair source. The same pump laser as in the previous interference experiment is used in this setup. The laser pulse polarization is here rotated to 45° in a half-wave plate. The pump pulses are then split in the PBS and launched into each end of the PCF. The fiber is twisted so that both pump directions are polarized along the same axis and identical phase matching conditions hold. The photon pairs thus exit from the PBS in the same port as the pumping beam and a notch mirror is used to separate them from the input pump beam. The entangled photons are launched into single mode fiber and narrow-band filtered (0.28 and 2 nm in the signal and idler arms, respectively) to ensure indistinguishability between the $|HH\rangle$ and $|VV\rangle$ components and the small static phase shift between them is compensated in the pump beam by adjusting the Soleil-Babinet compensator (S-B). We use a quarter- and half-wave plate followed by a PBS to analyze the various polarization correlations needed to reconstruct the state [26]. (b) Tomographic reconstruction of the real and imaginary parts of the density matrix of the generated state. This clearly shows that what we produce is very close to the maximally entangled state $|HH\rangle + |VV\rangle$.

a pure, maximally entangled state. The degree of mixture of the state can be characterized by the linear entropy $S_L = 0.25$, consistent with these coherences. Finally, the degree of entanglement can be quantified by the tangle $T = 0.63$. These results show that we have a highly entangled source of photon pairs. We suspect that the small amount of mixture observed arises from group velocity walk-off. Since we are pumping the fiber close to its ZDW, the signal and idler photons have similar group velocities. However, the group velocity difference between the photons of a pair and the pump photons is significant and walk-off becomes comparable to the pulse width for fibers longer than approximately 12 cm. This walk-off issue could thus be reduced by using a shorter PCF than the 20 cm one used in this experiment. Here, with less than 6 mW of pump power, the source produces 6×10^3 coincidences per second. This figure could be improved by reducing losses in the PBS and notch mirror and we expect to reach several tens of thousands of detected entangled pairs per second with less than 20 mW pump power.

In summary, we have described a photonic crystal fiber source of single photons for quantum information processing applications; we demonstrated that heralded single photons from independent sources undergo nonclassical interference with high visibility, and demonstrated the production of highly entangled photon pairs. The key achievement is that we have 0.1 single mode pair photons per pulse with $\sim$3 mW of pump power. This compares to $\sim$1 W pump power for standard sources (e.g., Ref. [16]). Two routes to high rate multiphoton ($\geq$6) generation are thus open. First, we can increase the repetition rate of our laser while keeping the number of pair photons per pulse constant. Second, the lumped detection efficiency could be increased. In previous experiments we have achieved $\sim$22% lumped efficiency in the short wavelength (signal) and $\sim$12% in the long wavelength (idler) channel [19]. The long wavelength efficiency is primarily reduced due to falloff in detector efficiency (to $\sim$35%). We lose further efficiency due to the narrow-band filters where averaged transmission is $\sim$25%, resulting in $\sim$5% lumped efficiencies. By improving our filters, optimizing detection wavelengths, and reducing coupling losses we expect to be able to increase lumped efficiencies to at least 12% in the near future. For $\eta = 0.12$, $\mu = 0.1$, and $R = 80$ MHz, Eq. (1) predicts a 6-photon rate of $\sim$0.24 Hz, comparable to that in recent 6-photon experiments [16]. However, by increasing the laser repetition rate by an order of magnitude, we use 30 mW of pump and achieve a 6-photon rate of $\sim$2.4 Hz. Ultimately, we aim for $\eta \geq 0.2$ (via all-fiber implementations of our source) which will open the way for $\geq$8-photon experiments. Of course, at this efficiency and 800 MHz repetition rate we will be detecting photons at $\geq$16 MHz which will require improved detectors. However, we can alternatively operate at $\mu > 0.1$ with background correction as we do at present and, in the future, photon number resolving detectors could be used to suppress the contribution from higher order terms. Thus, PCF sources will open the way to a variety of novel experiments including cascaded linear gates, building large entangled cluster states, testing error correcting protocols, and directly measuring fault tolerance thresholds.

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