Fiber based source of photon pairs at telecom band with high temporal coherence and brightness for quantum information processing

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We experimentally demonstrate a bright pulsed source of correlated photon pairs at 1550 nm telecom band by pumping 300 m dispersion shifted fiber with a 4 ps pulse train. We investigate the coherence property of the source by measuring the second order intensity correlation function \( g^{(2)} \) of individual signal (idler) photons. A preliminary Hong-Ou-Mandel type two-photon interference experiment with two such sources confirms the high temporal and spatial coherence of the source. The source is suitable for multi-photon quantum interference of independent sources, required in quantum information processing. © 2008 Optical Society of America

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Quantum interference (QI) among independent sources of entangled photon pairs plays an important role in quantum information processing (QIP), such as entanglement swapping, quantum teleportation, generation of GHZ states, quantum repeater and linear optical quantum computing [1–4]. Because of the independent nature of the photons, in order to obtain high visibility in QI, photons must be in identical single mode so that they are indistinguishable. Nowadays, the most popular sources of photons are realized via spontaneous parametric down-conversion (SPDC) by pumping a \( \chi^{(2)} \) nonlinear crystal with ultrashort pulses. Although the SPDC parametric processes are independent, the timing provided by the ultrashort pump pulse can be used to realize synchronization of different sources of independent photons [5]. However, the dispersive nature of the \( \chi^{(2)} \) crystal completely messes up the temporal mode structure of the down-converted fields. To preserve the temporal indistinguishability, optical filtering is necessary so that the coherence time of the down converted signal (idler) photons is much longer than the pump pulse duration. This requirement, coupled with the low SPDC efficiency in \( \chi^{(2)} \) crystal, severely limits the brightness of the photon pairs. It should be mentioned that efforts are made recently to engineer the structure of the \( \chi^{(2)} \) materials to tailor their temporal mode structure [6].

Recently there are growing interests in generating photon pairs in optical fiber by means of four wave mixing (FWM) [7–11], because of its inherent compatibility with the transmission medium, the excellent single spatial-mode purity, and a better nonlinear vs. loss figure of merit over \( \chi^{(2)} \) nonlinear crystal. Because of the near degenerate nature of FWM in dispersion shifted fiber (DSF), when the pump wavelength is close to the zero dispersion wavelength \( \lambda_0 \), dispersion plays a relatively small role in phase matching in the sense that the band width of the signal and idler fields are exceptionally wide even for a fiber with a length of more than hundreds meters [12]. This leads to very simple spectral structure and relatively mild filtering is enough to achieve good temporal coherence. Indeed, recent Hong-Ou-Mandel (HOM) type experiments using two pairs of visible photons originated from independent MF-based sources [13] was reported with a visibility of 95%. However, for the photons at 1550nm telecom band produced by two independent DSF-based sources [14], a visibility of only about 20% and 50% was obtained in a two-fold and four-fold coincidence measurement, respectively. The result was far from the ideal situation achievable by using photons with a good spatial and temporal mode.

In this paper, we study the coherence property of light at telecom band generated in DSF by measuring the normalized intensity correlation function \( g^{(2)} \) under various conditions for individual signal (idler) field. According to Refs. [15] and [16], \( g^{(2)} \) of individual signal and idler fields is related directly to the coherence property of the field. We demonstrate that the source has high temporal coherence and brightness. Moreover, to illustrate its potential application for QIP, a two-photon HOM type interference experiment is performed with signal photons originated from two DSF-based independent sources. A visibility of 33% in the HOM interference dip is observed, consistent with the thermal nature of the individual signal (idler) field in single mode.

A schematic to characterize our fiber based source is shown in Fig. 1. The pump pulses with a pulse width of ~ 4 ps are spectrally carved out from a mode-locked femto-second fiber laser with a repetition rate of 40 MHz. To achieve the required power, the pump pulses are amplified by an erbium-doped fiber amplifier. The pump pulses are further cleaned up with a band-pass filter F1, which has various bandwidth by cascading a combination of tunable filters (TF) (Newport/TBF-1550-1.0, Santec/OTM-30M-03D) and one channel of an array-waveguide-grating (AWG). The pump is then passed through a fiber polarization controller (FPC1) and a po-
larization beam splitter (PBS1) to ensure its polarization and power adjustment. A 90/10 fiber coupler is used to split 10% of the pump for power monitor.

Signal and idler photons at $1546.9\,\text{nm}$ and $1530.9\,\text{nm}$ are produced by pumping 300 m DSF with laser pulses having a central wavelength $\lambda_p = 1538.9\,\text{nm}$. The DSF with $\lambda_0 = 1538 \pm 2\,\text{nm}$ is submerged in liquid nitrogen ($77\,\text{K}$) to reduce the Raman scattering (RS). Signal and idler photons co-polarized with the pump are selected by adjusting FPC2 placed in front of PBS2. To reliably detect the signal and idler photons, an isolation between the pump and signal/idler photons in excess of 100 dB is required, because of the low efficiency of spontaneous FWM in DSF. In addition, detecting signal (idler) photons with different bandwidth is also necessary to characterize the source. We achieve these by passing the photon pairs through a filter ensemble $F_2$ which is realized either by using double grating filters (DGFs) [7] or TF, or by cascading a DGF and one channel of AWG.

The signal (idler) photons are counted by single photon detectors (SPD, id200) operated in the gated Geiger mode. The 2.5 ns gate pulses arrive at a rate of about 600 KHz, which is $1/64$ of the repetition rate of the pump pulses, and the dead time of the gate is set to be $10\,\mu\text{s}$.

We first test the brightness of the source by directly sending the signal and idler to A and B channels, respectively. The full-width-half-maximum (FWHM) of pump is about $0.9\,\text{nm}$, set by $F_1$ with two cascading TFs. The filter ensemble $F_2$ consists of the AWG and DGF with a combined FWHM of about $0.33\,\text{nm}$. We measure the number of scattered photons in signal (idler) band per pump pulse, $N_{s(i)}$ as a function of the average pump power, $P_{\text{ave}}$ [Fig. 2(a)] and fit the measured data with $N_{s(i)} = s_1 P_{\text{ave}} + s_2 P_{\text{ave}}^2$, where $s_1$ and $s_2$ are the linear and quadratic coefficients, which respectively determine the strengths of RS and FWM in DSF. The fitting result [Fig. 2(a)] shows that the number of photons via RS is much less than that via FWM. To demonstrate that the background of our source is low enough to allow a multi-photon pair experiment, we measure the accidental coincidence between the signal and idler fields by put a delay between A and B so that A and B register photons from adjacent pulses. We plot the accidental coincidence rate $R_{\text{acc}}$ as a function of the average pump power [Fig. 2(b)] and fit the experimental data to a polynomial function $R_{\text{acc}} = a P_{\text{ave}}^2 + b P_{\text{ave}}^3 + c P_{\text{ave}}^4$, where the coefficients $a$, $b$ and $c$ are the weights of the coincidence contributed by the random overlap between Raman photons and Raman photons, Raman photons and FWM photons, and FWM photons and FWM photons, respectively. The result of the fit clearly shows that $R_{\text{acc}}$ is dominated by the event of multi-photon pairs originated from FWM. Therefore, the coincidence rate presented here is an indication of double pair or four-photon coincidence rate, which is rather high at only a pump power of $0.25\,\text{mW}$.

Next, we measure the photon bunching effect or $g^{(2)}$ of individual signal (idler) photons. The photon bunching effect in spontaneous parametric process was proven to be closely associated with the visibility of QI involving independent photon pairs [15, 17, 18] because of its connection to the coherence property of the fields [15, 16]. In the experiment, one output of our fiber source, i.e., signal (idler) photons, is fed to the port labeled ”C” and passes though a 50/50 beam splitter (BS) (see Fig. 1). The two outputs of the BS are detected by SPD1 and SPD2, respectively, and both the coincidence and accidental coincidence of the two SPDs are recorded. The second order correlation function $g^{(2)}$ is the ratio between the measured coincidence and accidental-coincidence rates. The result shows that when the bandwidth of the pump and the detected field are $0.9\,\text{nm}$ and $0.33\,\text{nm}$, respectively, the value of $g^{(2)}$ for the individual signal (idler) photons is $1.97 \pm 0.03$, which is very close to that of single mode field, $g^{(2)} = 2$, indicating the signal (idler) photons produced by the fiber source can be viewed as a single spatial and temporal mode [15].

Although setting the central wavelength of pump close to $\lambda_0$ of DSF makes phase matching a less important factor, filters are still necessary to clean up the temporal modes [12]. We next investigate the dependence of $g^{(2)}$ on the bandwidth of signal (idler) and pump photons. Using various filters ranging from $0.26\,\text{nm}$ to $1.3\,\text{nm}$ for the pump and signal (idler) fields, we measure $g^{(2)}$ when the peak power of the pump is about $1\,\text{W}$. As shown in Fig.3, the value of $g^{(2)}$ depends highly on the ratio between the optical bandwidths of photon pairs and that of pump pulses: $g^{(2)}$ depends highly on the ratio increases. This is consistent with a simple theory on the coherence of the individual signal and idler fields [19].

Finally, we perform a two-photon HOM interference experiment with signal photons originated from two independent DSFs (300 m) to demonstrate that our source has the potential application for QIP. With the experimental setup shown in Fig. 4(a), we measure two-fold coincidences in the outputs of the HOM interferometer versus the position of the translation stage for two settings of the signal and pump bandwidths, corresponding to $g^{(2)} = 2$ and $g^{(2)} = 1.54$ in Fig.3. Fig.4(b) shows the HOM interference result with visibility of $33\%$ and $20\%$, respectively. The result is consistent with the theory of fourth-order interference between two thermal field [15].

In conclusion, we have demonstrated a fiber source of photon pairs with high brightness at telecom band. The normalized intensity correlation function $g^{(2)} = 2$ for individual signal (idler) field is obtained, which indicates that the fields are in a single temporal and spatial mode. With this fiber source, the ideal visibility in two-photon HOM interference from independent sources is achieved.

Because of lack of detectors, we cannot perform the HOM interference with independent signal photons gated on the detection of the idler photons, which ideally will give $100\%$ visibility [13]. Work is underway. Nevertheless, our two-photon experiment leads the same conclusion about the coherence property of the source as the four-photon experiment [13]. Although the produc-
tion rate and detection rate of the photon pairs in current experiment is low, it can be dramatically increased by using state-of-the-art pulsed fiber lasers with a repetition rate over 10 GHz and by using the newly developed super-conducting single-photon detectors [20] with a higher detection efficiency.

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Fig. 3. (Color online) The second correlation function \( g^{(2)} \) versus the ratio between the bandwidth of the signal (idler) photons and that of the pump photons. The FWHM of signal and pump photons is denoted by \( \Delta \lambda_s \) and \( \Delta \lambda_p \), respectively.

Fig. 4. (Color online) (a) Two-photon Hong-Ou-Mandel interferometer with signal photons originated from two independent DSF-based sources. (b) Twofold coincidences measured as a function of the position of the translation stage. The error bar of the data is about the same as the size of the data points.