Independent telecom-fiber sources of quantum indistinguishable single photons

Monika Patel\textsuperscript{1,3}, Joseph B Altepeter\textsuperscript{2}, Yu-Ping Huang\textsuperscript{1,2,4}, Neal N Oza\textsuperscript{2} and Prem Kumar\textsuperscript{1,2}

\textsuperscript{1} Center for Photonic Communication and Computing, Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, Illinois 60208, USA
\textsuperscript{2} Center for Photonic Communication and Computing, Department of Electrical Engineering and Computer Science, Northwestern University, 2145 Sheridan Road, Evanston, Illinois 60208, USA
E-mail: yuping-huang@northwestern.edu

Received 3 February 2014, revised 11 March 2014
Accepted for publication 21 March 2014
Published 23 April 2014

New Journal of Physics \textbf{16} (2014) 043019
doi:10.1088/1367-2630/16/4/043019

Abstract
Quantum-mechanically indistinguishable photons produced by independent (or equivalently, mutually phase incoherent) light sources are essential for distributed quantum information processing applications. We demonstrate heralded generation of such photons in two spatially separate telecom-fiber spools, each driven by pulsed pump waves that are measured to have no mutual phase coherence. Through Hong–Ou–Mandel experiments, we measure the quantum interference visibility of those photons to be 76.4 ± 4.2\%. Our experimental results are well predicted by a quantum multimode theory we developed for such systems without the need for any fitting parameter.

Keywords: indistinguishable single photons, independent photon source, Hong–Ou–Mandel measurement

\textsuperscript{3} Current address: Raytheon BBN Technologies, Cambridge, MA 02138, USA.
\textsuperscript{4} Author to whom any correspondence should be addressed.
1. Introduction

At the heart of many quantum information processing protocols, particularly those of quantum repeaters [1, 2] and teleportation [3], is the second-order interference of single photons that share no prior phase coherence [4, 5]. A prerequisite for such interference to occur is that those photons are quantum-mechanically indistinguishable. That is, when two single photons are mixed on a beamsplitter, one from each port, it is impossible—even in principle—to distinguish which photon came from which input port. For distributed quantum applications, this prerequisite calls for independent sources of indistinguishable single photons. Additionally, for applications utilizing the fiber-based optical infrastructure, one would require the capability of coupling such photons into and out of telecom fibers with little loss and quantum-state decoherence.

To date, significant laboratory progress has been made toward demonstrating generation of indistinguishable single photons in a variety of physical systems. Examples include observations of quantum interference between the outputs of a parametric downconverter and a weak coherent light source [6], between the emissions from a laser and a quantum dot [7], between single photons created during two passes of a pump pulse through a spontaneous parametric downconversion (SPDC) crystal [8, 9], and between single photons produced by two separate SPDC crystals pumped by the same laser beam [10]. There have also been experiments demonstrating quantum interference between photons produced in microstructured fiber, polarization-maintaining fiber, and dispersion-shifted fiber [11–15], as well as in silicon waveguides and periodically-poled lithium-niobate waveguides, with both sources powered by the same laser [16, 17]. In all the above experiments, however, it remains to be examined whether or not the photon-generation processes were independent because each experiment used either the same pump beam for the two sources of single photons or different pump beams derived from the same parent laser. To address this issue, indistinguishable photons from two nonlinear crystals pumped by two separate, synchronized lasers have been recently demonstrated [18–20].

In this paper, we demonstrate independent sources of indistinguishable photons in the telecom O-band (1310 nm) using an all-fiber setup, thus making such devices drop-in compatible with the existing fiber-based telecommunications infrastructure [21]. In our experiment, individual pairs of photons are created through spontaneous four-wave mixing (FWM) in two spatially separate fiber spools driven by pulsed pump waves that are measured to have no mutual phase coherence. By detecting the idler (anti-Stokes) photon in each photon pair, creation of the corresponding signal (Stokes) photon from each pair is heralded. The quantum indistinguishability of the heralded photons from the two fiber spools is measured through Hong–Ou–Mandel (HOM) interference experiments. A high interference visibility of nearly 80% is obtained. All of our experimental results are well predicted by a quantum multimode theory we developed for such fiber systems without the use of any fitting parameter [22–25]. We note that a major advantage with our sources is their drop-in compatibility with fiber-based quantum information networking, as the photons generated can be directly coupled into and out of telecom fibers with little loss. They are also relatively compact as the fibers are wound on spools only a few inches in diameter.
2. Experimental setup

Our entire experimental setup is sketched in figure 1 and is similar to that used in [25]. The pump is a 10 GHz hybrid mode-locked laser (U2T, model TMLL1310) whose output is pulse-picked at 50 MHz rate using an optical amplitude modulator (EOSPACE, model AK-OK5-10). This amplitude modulator is driven by the output of a 20 Gbps 2:1 selector (Inphi, model 20709SE), which is clocked at 50 MHz by an electrical signal source that also triggers the single-photon detectors (NuCrypt, model CPDS-4) used in the experiment. The picked pulses are then amplified and fed to a 50:50 fiber splitter. Each output branch of the splitter leads to a FWM fiber spool (500 m of standard single-mode fiber cooled to 77 K) in a Faraday-mirror configuration [21]. The Faraday mirror effectively doubles the length of fiber available for FWM while simultaneously compensating for any polarization changes which may occur in the spooled fiber. The signal and idler photons are created via spontaneous FWM and are filtered from the residual pump photons by two cascaded filtering stages (dense wavelength-division multiplexers, custom-made by AC Photonics) which provide $\approx 100$ dB of isolation. These filters have a single-stage transmission efficiency of approximately 80% and full-width at half-maximum of approximately 0.4 nm. The filtered signal and idler photons then pass through fiber polarization controllers (not shown in figure 1) and the signal photons are led to the two input ports of an in-fiber 50:50 coupler. Careful adjustment of the polarization controllers and precise temporal alignment using a variable delay stage in the path of one of the signal photons ensures that the signal photons arriving at the 50:50 coupler are identical in all degrees of freedom: polarization, spectral-temporal, and spatial. Note that even though these signal photons are identical, they may still be partially or completely distinguishable. This distinguishability may arise from the inherent spectral correlation of the signal photons with their paired idler photons (heralds) imposed by phase matching, or from the presence of background photons that originate in the FWM fiber owing to Raman scattering. Four InGaAs single-photon detectors

![Figure 1](image-url)
are used to count the photons, one each at the outputs of the idler arms and the 50:50 coupler. These detectors are gated at a 50 MHz repetition rate synchronous with the arrival of photons and have a dark-count probability of $1.6 \times 10^{-4}$ per pulse. Their quantum efficiencies are approximately 20%. The delay stage is used to vary the temporal overlap of the signal photons while the photon counts from all four detectors are recorded.

3. Results

We perform the HOM interference measurement between the heralded single photons by recording fourfold coincidence counts registered on the single-photon detectors A, B, C, and D shown in figure 1. Figure 2 shows such fourfold coincidence counts (i.e. the HOM interference pattern of the heralded single photons) recorded per 40 billion gates; that is, each datum point reflects the photon count accumulation for approximately 14 min using the 50 MHz detectors in our setup. The measured visibility of the HOM interference curve plotted in figure 2 is $76.4 \pm 4.2\%$. To quantitatively explain this result, we perform numerical simulations using a quantum multimode theory we have developed for such fiber-based systems. This theory accounts for all the relevant effects such as multi-pair production, spontaneous Raman scattering, fiber-line transmission loss, and detector dark counts. A description of this theory can be found in [22–25]. In order to estimate the photon-pair production rate, we first calculate the total detection efficiency of the signal photons, $\eta_s$, by multiplying together three relevant experimentally measured efficiencies: (i) the effective transmission efficiency through the fiber spool, determined by averaging over the birthplace of the photon pairs in the FWM fiber; (ii) the transmission efficiencies of the passive optical components such as the circulators, filters, waveplates, polarizers, and the 50:50 fiber splitter; and (iii) the quantum efficiency of the single photon detectors. We compute the total detection efficiency of the the idler photons, $\eta_i$, in a similar manner. The pair production rate is then estimated by dividing the measured twofold coincidence counts by $\eta_s \times \eta_i$. In our experiment, the total detection efficiencies of the signal and idler photons are determined to be in the range of 5 to 10%, and the pair production rate is estimated to be in the range of 1 to 2%. In comparison, the Klyshko detection efficiency [26] of the signal photons in our experiment (given by the ratio of the measured coincidence counts to
The measured idler photon counts is 4.9%, which is consistent with our measurements above. The simulation result obtained using these measured parameters and no other free parameter is plotted in Figure 2, where good agreement with the experimental data is shown.

In order to demonstrate the generation of indistinguishable single photons from independent sources, we next pump the two fiber spools with pulses that have no mutual phase coherence. To do so, we first measure the temporal coherence length of the pulses from the mode-locked laser (U2T, model TMLL1310) that serves as the pump laser in our experiment. An in-fiber Mach–Zehnder interferometer is built by connecting two 50:50 fiber couplers. Its two arms are initially balanced to yield identical optical-path lengths and the same amount of fiber polarization drift. Then, a sinusoidal phase shift between 0 and $\pi/2$ is applied in one arm through the use of a piezoelectric fiber stretcher. The resulting interference pattern is recorded by measuring the power from one output port using a slow detector (that measures the average power of the 10 GHz pulse train) and an oscilloscope. When the two arms of the Mach–Zehnder interferometer are balanced, a near-unity visibility is observed because the pulses that are mixed at the second coupler are split from a common pump pulse, and hence are phase coherent with each other. By inserting a fiber delay line into one arm, a relative time delay is created between pulses traveling in the two arms of the Mach–Zehnder interferometer. As a result, the recorded pattern becomes a measurement of the interference between the two temporally delayed pulses. A degradation of the interference visibility as the delay increases gives a measure of the temporal coherence length of the pulse-train emitted by the mode-locked laser. The experimental results of such measurements are shown in Figure 3, where one sees that the interference visibility starts to drop almost immediately with even a single-pulse delay (corresponding to about 2 cm of extra fiber in one arm of the Mach–Zehnder interferometer). It decreases to about 50% for a fiber-line delay equivalent to 17 pulses (corresponding to a temporal coherence length of the mode-locked pulse train of about 1.7 ns), and approaches zero.

Figure 3. Second-order interference visibility of pump pulses (the dashed red line is for eye guiding) and HOM interference visibility of heralded single photons from the two fiber spools (blue squares), both plotted as a function of the pump delay in units of pulse number. As shown, the pump interference visibility drops rapidly, approaching zero at a 90-pulse delay. In contrast, there is no measured degradation in the heralded two-photon interference visibility for any pump delay, even that by 1000 pulses.
for delays over 90 pulses. These results indicate clearly that there is no phase coherence between pulses separated by over 90 pulse periods (i.e. 9 ns).

In order to assert the mutual phase incoherence of the pump pulses, we insert an extra length of fiber into the lower path of the dual-arm setup, as shown in figure 1. As a result, the HOM interference measurement is now for single photons heralded in the individual fiber spools by different pump pulses from the mode-locked train with a relative delay between them. In our experiment, three delay settings are used: (i) 4 m of extra fiber, corresponding to 200-pulse delay or 20 ns; (ii) 8 m of extra fiber, corresponding to 400-pulse delay or 40 ns; (iii) 20 m of extra fiber, corresponding to 1000-pulse delay or 100 ns. In all these cases, the light pulses that pump the two fiber spools are completely phase incoherent with each other, as shown by the second order visibility measurement plotted in figure 3. The HOM interference patterns obtained for each delay setting are plotted in figure 4, where they are also shown to follow the same theory curve computed using our quantum multimode model. The measured HOM interference visibilities are $\pm 77.9 \pm 3.8\%$, $\pm 76 \pm 4.6\%$, and $\pm 77.5 \pm 4.4\%$, respectively, and are plotted in figure 3 using the right vertical scale. These values are within error limits of each other and coincide with the value obtained using phase-coherent pump pulses (cf figure 2), thus demonstrating unambiguously that the indistinguishable single photons in our experiment are indeed generated from independent fiber sources.

4. Effects of experimental imperfections

In this section, we numerically study the contributions of the various experimental imperfections that affect the current HOM visibility using our quantum multimode theory. Specifically, we simulate changes in the HOM visibility by manually turning off one of the following imperfections at a time: Raman scattering, multipair production, detector dark counts, and non-unity total detection efficiencies. The results are shown in figure 5. The solid curve shows the initial interference pattern with visibility of $\sim 77.3\%$. By either setting the detector dark counts to zero or assuming the total detection efficiencies to be unity, negligible change in the HOM interference pattern is observed, and hence these conditions are not shown in figure 5. In contrast, when the Raman scattering is turned off, the visibility increases to 82.2% (dashed curve in figure 5). When the multipair production is eliminated, the visibility becomes 90.1% (dash-dotted curve in figure 5). These results show that the HOM visibility in our current experiment can be significantly improved by operating at a lower photon-pair production rate.

![Figure 4](image-url). Measured fourfold coincidences (black squares) and the theoretical prediction (blue curves) of the fourfold coincidence pattern (i.e. HOM interference pattern of the heralded single photons) for (a) 200-pulse delay, (b) 400-pulse delay, and (c) 1000-pulse delay.
(assuming, of course, that the system would remain stable over the commensurately longer photon-counting intervals to accumulate statistically meaningful fourfold coincidences). In order to obtain a nearly 100% visibility, one may further need to use appropriately shaped signal and idler photon filters to ensure that the interfering photons are in identical spectral-temporal modes [24].

5. Conclusion

We have demonstrated heralded generation of indistinguishable single photons utilizing spontaneous FWM in separate telecom-fiber spools. When subjected to HOM interference measurements, these photons yield $76.4 \pm 4.2\%$ interference visibility. In addition, the HOM interference visibility does not experience any detectable degradation when the spools of fiber are pumped by laser pulses that have no measurable mutual phase coherence. All of our experimental results fit well with the predictions of our quantum multimode theory without the need for any fitting parameter. Our experiment is, therefore, the first unambiguous demonstration of the generation of heralded indistinguishable single photons from independent telecom-fiber sources, which points to the possibility of developing networked quantum applications utilizing the existing fiber-based telecommunications infrastructure. To increase the source brightness while keeping the multi-photon probability low, one can multiplex $N$ such fiber sources using low-loss $N$-to-1 [27] switches, e.g. constructed with low-loss fiber switches we recently demonstrated [28].

Acknowledgements

This research was supported in part by the Defense Advanced Research Projects Agency (DARPA) under the Zeno-based Opto-Electronics (ZOE) program (grant no. W31P4Q-09-1-0014) and the Quiness Program (grant no. W31P4Q-13-1-0004), by the United States Air Force Office of Scientific Research (USAFOSR) (grant no. FA9550-09-1-0593), and by the National Science Foundation Integrative Graduate Education and Research Traineeship (IGERT) (grant no. DGE-0801685).
References

[1] Briegel H J, Dür W, Cirac J I and Zoller P 1998 Phys. Rev. Lett. 81 5932–5
[2] Duan L M, Lukin M, Cirac J I and Zoller P 2001 Nature 414 413
[3] Bennett C H, Brassard G, Crepeau C, Jozsa R, Peres A and Wootters W K 1993 Phys. Rev. Lett. 70 1895
[4] Mandel L 1983 Phys. Rev. A 28 929–43
[5] Hong C K, Ou Z Y and Mandel L 1987 Phys. Rev. Lett. 50 2044
[6] Rarity J G, Tapster P R and Loudon R 2005 J. Opt. B: Quantum Semiclass. Opt. 7 S171
[7] Bennett A J, Patel R B, Nicoll C A, Ritchie D A and Shields A J 2009 Nat. Phys. 5 715–7
[8] Bouwmeester D, Pan J W, Mattle K, Eibl M, Weinfurter H and Zeilinger A 1997 Nature 390 575
[9] Jennewein T, Weihs G, Pan J-W and Zeilinger A 2001 Phys. Rev. Lett. 88 017903
[10] de Riedmatten H, Marcikic I, Tittel W, Zbinden H and Gisin N 2003 Phys. Rev. A 67 022301
[11] Fulconis J, Alibart O, Wadsworth W J and Rarity J G 2007 New J. Phys. 9 276
[12] Fulconis J, Alibart O, O’Brien J L, Wadsworth W J and Rarity J G 2007 Phys. Rev. Lett. 99 120501
[13] Soller C, Cohen O, Smith B J, Walmsley I A and Silberhorn C 2011 Phys. Rev. A 83 031806
[14] Li X, Yang L, Cui L, Ou Z Y and Yu D 2008 Opt. Exp. 16 12505
[15] Takesue H 2007 Appl. Phys. Lett. 90 204101
[16] Harada K, Takesue H, Fukuda H, Tsuchizawa T, Watanabe T, Yamada K, Tokura Y and Itabashi S 2011 New J. Phys. 13 065005
[17] Aboussouan P, Alibart O, Ostrowsky D B, Baldi P and Tanzilli S 2010 Phys. Rev. A 81 021801
[18] Kaltenbaek R, Blauensteiner B, Żukowski M, Aspelmeyer M and Zeilinger A 2006 Phys. Rev. Lett. 96 240502
[19] Kaltenbaek R, Prevedel R, Aspelmeyer M and Zeilinger A 2009 Phys. Rev. A 79 040302
[20] Yang T, Zhang Q, Chen T-Y, Lu S, Yin J, Pan J-W, Wei Z-Y, Tian J-R and Zhang J 2006 Phys. Rev. Lett. 96 110501
[21] Hall M A, Altepeter J B and Kumar P 2009 Opt. Exp. 17 14558
[22] Huang Y-P, Altepeter J B and Kumar P 2010 Phys. Rev. A 82 043826
[23] Huang Y-P, Altepeter J B and Kumar P 2011 Phys. Rev. A 84 033844
[24] Huang Y-P and Kumar P 2011 Phys. Rev. A 84 032315
[25] Patel M, Altepeter J B, Huang Y-P, Oza N N and Kumar P 2012 Phys. Rev. A 86 033809
[26] Klyshko D N and Sov J 1980 Quantum Electron. 10 1112
[27] Migdall A L, Branning D and Castelletto S 2002 Phys. Rev. A 66 053805
[28] Hall M A, Altepeter J B and Kumar P 2011 Phys. Rev. Lett. 106 053901