

Two-photon quantum interference in the 1.5 μm telecommunication band

Seok-Beom Cho and Tae-Gon Noh

IT Convergence Technology Research Division, Electronics and Telecommunications Research Institute, Daejeon 305-350, Korea

tgnoh@etri.re.kr

Abstract: We report on two-photon quantum interference experiments in the standard telecommunication band. Two identical photons in the 1.5 μm wavelength band were generated in spatially separated modes by a type-I spontaneous parametric down-conversion process, and injected into a fiber-optic Hong-Ou-Mandel interferometer. Two-photon interference patterns of dip and spatial beating in the coincidence counting rate were observed by varying the difference in optical path lengths. The visibilities obtained in the net coincidences were close to the theoretical value of 100%. The raw visibilities were also well above the classical limit.

© 2007 Optical Society of America

OCIS codes: (270.0270) Quantum optics; (190.4410) Nonlinear optics, parametric processes; (270.5290) Photon statistics.

References and links

1. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge University Press, Cambridge, UK, 1995).
2. L. Mandel, "Quantum effects in one-photon and two-photon interference," *Rev. Mod. Phys.* **71**, S274–S282 (1999).
3. A. Zeilinger, "Experiment and the foundations of quantum physics," *Rev. Mod. Phys.* **71**, S288–S297 (1999).
4. C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," *Phys. Rev. Lett.* **59**, 2044–2046 (1987).
5. D. Bouwmeester, A. Ekert, and A. Zeilinger, eds., *The Physics of Quantum Information* (Springer-Verlag, Berlin, 2000).
6. N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum cryptography," *Rev. Mod. Phys.* **74**, 145–195 (2002).
7. E. Knill, R. Laflamme, and G. J. Milburn, "A scheme for efficient quantum computation with linear optics," *Nature* **409**, 46–52 (2001).
8. P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, "Linear optical quantum computing with photonic qubits," *Rev. Mod. Phys.* **79**, 135–174 (2007).
9. O. Landry, J. A. W. van Houwelingen, A. Beveratos, H. Zbinden, and N. Gisin, "Quantum teleportation over the Swisscom telecommunication network," *J. Opt. Soc. Am. B*, **24**, 398–403 (2007).
10. H. de Riedmatten, I. Marcikic, J. A. W. van Houwelingen, W. Tittel, H. Zbinden, and N. Gisin, "Long-distance entanglement swapping with photons from separated sources," *Phys. Rev. A*, **71**, 050302(R) (2005).
11. M. Halder, S. Tanzilli, H. de Riedmatten, A. Beveratos, H. Zbinden, and N. Gisin, "Photon-bunching measurement after two 25-km-long optical fibers," *Phys. Rev. A* **71**, 042335 (2005).
12. H. de Riedmatten, I. Marcikic, W. Tittel, H. Zbinden, D. Collins, and N. Gisin, "Long distance quantum teleportation in a quantum relay configuration," *Phys. Rev. Lett.*, **92**, 047904 (2004).
13. I. Marcikic, H. de Riedmatten, W. Tittel, H. Zbinden, and N. Gisin, "Long-distance teleportation of qubits at telecommunication wavelengths," *Nature* **421**, 509–513 (2003).
14. Z. Y. Ou and L. Mandel, "Observation of spatial quantum beating with separated photodetectors," *Phys. Rev. Lett.* **61**, 54–57 (1988).
15. T.-G. Noh, H. Kim, C. J. Youn, S.-B. Cho, J. Hong, T. Zyung, and J. Kim, "Noncollinear correlated photon pair source in the 1550 nm telecommunication band," *Opt. Express* **14**, 2805–2810 (2006), <http://www.opticsinfobase.org/abstract.cfm?URI=oe-14-7-2805>.

16. Note that the effects of accidental coincidences can be reduced by decreasing the pump power (Ref. [15]).
 17. J. Chen, K. F. Lee, and P. Kumar, "Generation of telecom-band indistinguishable photon pairs in dispersion-shifted fiber," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies 2007 Technical Digest* (Optical Society of America, Washington, DC, 2007), paper QTu4; H. Takesue, "1.5- μm band Hong-Ou-Mandel experiment using photon pairs generated in two independent optical fibers," *ibid.*, paper JTUA5.
-

1. Introduction

Quantum interference effects that cannot be described by classical wave theory have been a central issue in modern optics research [1, 2, 3]. The null-coincidence counting rate in the two output modes of a beam splitter, when two indistinguishable photons are injected simultaneously into the two different input ports, is the most typical example of such nonclassical interference effects [4]. This well-known Hong-Ou-Mandel (HOM) effect has recently found various applications in the rapidly growing field of quantum information processing, including linear optical quantum computing (LOQC) and scalable quantum networks [5, 6, 7, 8].

Although the HOM effect has already been used in the demonstration of various quantum information protocols, most experiments to date have been performed at visible or near-infrared wavelengths. For the construction of distributed LOQC and long-distance scalable quantum networks, it is important to develop the HOM interference technique in the standard telecom wavelength by using fiber-optic technology.

In a few recent experiments, the HOM effect with telecom-wavelength photons has been used for quantum communication applications over optical fibers [9, 10, 11, 12, 13]. However, the full quantum features of the HOM interference effect were not observed in those experiments. For instance, the observed interference visibilities were less than the classical limit of 50%, or visibilities greater than 50% were achieved by postselecting only some fraction of the photons in the two output modes of the beam splitter. The observation of a genuine HOM effect at telecom wavelengths remains a technical challenge. The spatial quantum beating effect [14], which is an important variation of the HOM effect, has also not been observed in this wavelength range. Thus, to enhance future applicability, further developments of the HOM technique at telecom wavelengths are desirable.

In this paper we present fiber-optic HOM quantum interference experiments in the standard telecom band that do not rely on postselection. To observe the HOM effect perfectly, it is crucial to generate two identical photons in spatially separated modes. We prepared such photons in the 1.5 μm telecom band using a noncollinear spontaneous parametric down-conversion process [15]. We observed nonclassical two-photon interference patterns of dip and spatial beating in the coincidence counting rate with high visibilities close to the theoretical value of 100%.

2. Experimental setup

Figure 1 shows the experimental setup. Laser pulses from a mode-locked Ti-Sapphire laser at a wavelength of 775 nm, with a pulse duration of 150 fs and a repetition rate of 75 MHz, were used to pump an 8 mm thick beta barium borate (BBO) nonlinear crystal. Signal and idler photons with the same polarization were created in well-defined spatiotemporal modes because of type-I noncollinear phase matching. The positions of the fiber-optic collimators were carefully aligned to ensure optimum collection of the down-converted light in the 1.5 μm wavelength band. The range of the collected bandwidth was estimated to be several hundred nanometers in this configuration. Details of the two-photon creation and collection procedure are similar to those of Ref. [15].

The signal and idler photons coupled into the standard single-mode fibers were directed to a 50/50 fiber-optic beam splitter. The beam splitter erases the spatial distinguishability by mixing

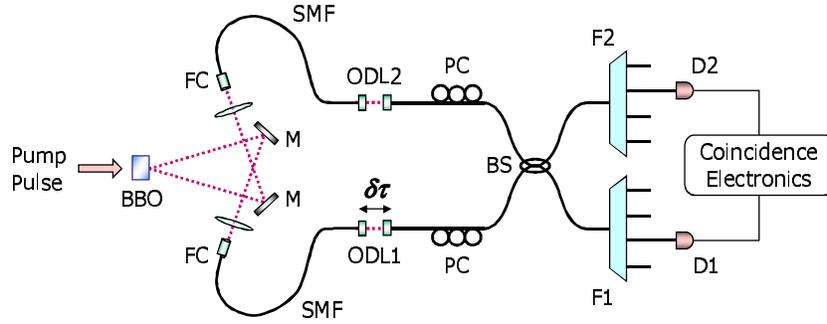


Fig. 1. Schematic of the experimental setup. M, mirror; FC, fiber-optic collimator; SMF, single-mode fiber; ODL1 and ODL2, optical delay lines; PC, fiber-optic polarization controller; BS, 50/50 fiber-optic beam splitter; F1 and F2, wavelength-division multiplexing (WDM) filter sets; D1 and D2, InGaAs/InP avalanche photodiode modules.

the signal and idler beams. The temporal and polarization modes must also be adjusted to ensure complete indistinguishability between the two photons entering the beam splitter. We used the optical delay lines to vary the optical path length from the crystal to the beam splitter, and the fiber-optic polarization controllers to match the polarization modes of the two photons.

The filter sets F1 and F2 are composed of a 1310/1550 nm WDM filter and a four-channel coarse WDM (CWDM) filter. The 1310/1550 nm WDM filter was used to reduce noise photons outside the 1.5 μm band. The cascaded CWDM filter divides the signal into four channels centered at 1510, 1530, 1550, and 1570 nm, with 18 nm passband width at 3 dB. Thus, the filter sets allow easy choice of the operating frequencies without affecting the remaining parts of the setup. After passing through the WDM filter set, each signal or idler photon was detected by the InGaAs/InP avalanche photodiode (APD) module. The APD modules operated in a gated Geiger mode with the trigger signals derived from the pump laser after lowering the signal rate from 75 MHz to 3.95 MHz. The output signals from the two APD modules and their coincidences within a 5 ns timing window were counted simultaneously.

3. Experimental results and analysis

Figure 2 shows the measured coincidence counts as a function of the optical delay line (ODL1) position. The position of the other optical delay line (ODL2) was fixed. When equal passbands of the 1550 nm channel were chosen in both CWDM filters, the usual HOM dip pattern was observed, as seen in Fig. 2(a). The spatial quantum beating pattern of Fig. 2(b) was obtained when the passbands were centered at the different conjugate wavelengths of 1530 and 1570 nm.

Following Ref. [14], the measured coincidence detection probability was approximated as

$$P \simeq A [1 - V e^{-\sigma^2 \delta\tau^2 / 2} \cos\{(\omega_1 - \omega_2) \delta\tau\}], \quad (1)$$

where A is a constant, V is the visibility, and $\delta\tau$ is the optical time delay between the two paths from the crystal to the beam splitter. ω_1 and ω_2 are the center frequencies of the passbands of the two CWDM filters. They should be conjugates satisfying the phase matching condition $\omega_1 + \omega_2 = \omega_p$, where ω_p is the pump laser frequency. The passband frequency responses of the CWDM filters are assumed to be Gaussian with rms widths σ .

The measured coincidence counts were fitted to Eq. (1). In Fig. 2(a), the visibility obtained was nearly 100% with a standard error of 1.1%, and the raw visibility without subtracting the accidental coincidences was $66.7 \pm 0.7\%$. The FWHM of the dip was $104.5 \pm 1.4 \mu\text{m}$. The theoretical value estimated from the 18 nm passband of the CWDM filters is 118 μm . The

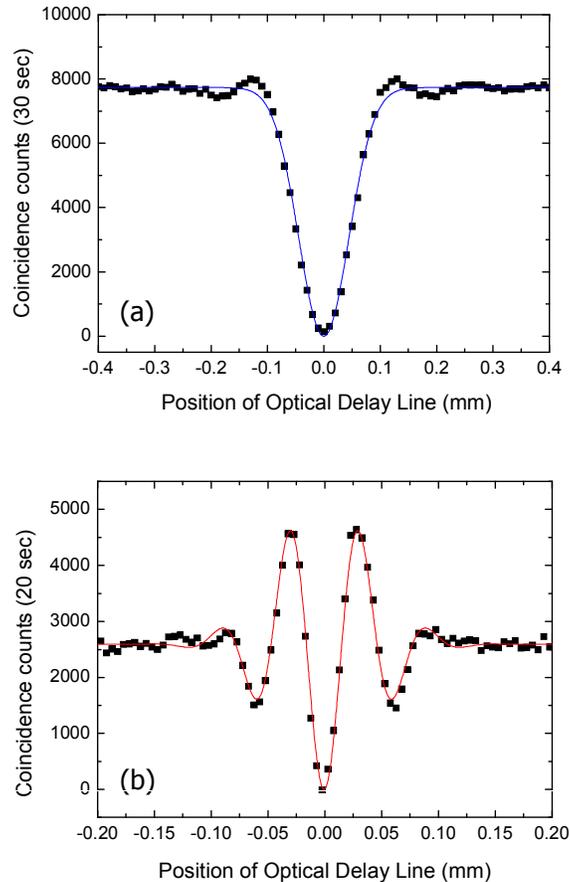


Fig. 2. Two-photon quantum interference patterns measured as a function of the optical delay line position or the optical time delay $\delta\tau$. The best-fit curves are based on Eq. (1). (a) $\omega_1 = \omega_2$. (b) ω_1 and ω_2 do not overlap.

observed dip showed a slight deviation from the usual Gaussian shape. This is because the spectral shapes of the CWDM filters are not well approximated by Gaussian functions. Note that if the CWDM filters had rectangular frequency responses, the dip shape would be a sinc function. In our experiment, however, the spectral shapes were very complex and not well approximated by either of these simple functions.

In Fig. 2(b), the visibility obtained was close to the theoretical value of 100% with a standard error of 1.8%. The raw visibility was $61.3 \pm 1.1\%$. The period of the cosine modulation was $62.3 \pm 0.3 \mu\text{m}$, which is in agreement with the theoretically estimated value of $60 \mu\text{m}$ considering the wavelength difference of 40 nm. The FWHM of the Gaussian envelope was $102.6 \pm 2.1 \mu\text{m}$. This can be compared with the dip width 104.5 nm in Fig. 2(a).

4. Conclusion

In conclusion, we have developed fiber-optic HOM interference techniques in the standard telecom wavelength range. Two identical photons in the $1.5 \mu\text{m}$ band were prepared with spatially separated modes using a type-I spontaneous parametric down-conversion process, and then injected into the two input ports of a fiber-optic beam splitter. The mode-matching difficulties

in the beam splitter, which are usually encountered in free-space HOM experiments, could be easily overcome by using fiber-optic techniques. Hence, we could obtain almost perfect non-classical two-photon interference patterns of dip and spatial beating in the coincidence counting rate. The visibilities obtained were near the theoretical value of 100%. It is worth noting that the raw visibilities can also be further improved by decreasing the pump power [16].

Acknowledgments

After submission of the present paper, two related experiments were presented in the conference CLEO/QELS 2007 [17]. This work was supported in part by the IT R&D program of MIC/IITA (2005-Y-001-04, Development of Next Generation Security Technology).