Non-classical interference between two telecom photons converted by difference-frequency generation

Rikizo Ikuta[1] * Toshiki Kobayashi[1] Hiroshi Kato[1] Shigehito Miki[2] Taro Yamashita[2] Hirotaka Terai[2] Mikio Fujiwara[3] Takashi Yamamoto[1] Masato Koashi[4] Masahide Sasaki[3] Zhen Wang[2] Nobuyuki Imoto[1]

[1] *Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan*
[2] *Advanced ICT Research Institute, National Institute of Information and Communications Technology (NICT), Kobe 651-2492, Japan*
[3] *Advanced ICT Research Institute, National Institute of Information and Communications Technology (NICT), Koganei, Tokyo 184-8795, Japan*
[4] *Photon Science Center, The University of Tokyo, Bunkyo-ku, 113-8656, Japan*

Abstract. We demonstrated the Hong-Ou-Mandel (HOM) interference between two photons after visible-to-telecommunication wavelength conversion. In the experiment, we prepared a heralded single photon by using spontaneous parametric down-conversion and the other photon from a weak laser source at 780 nm. We converted the wavelength of both photons to the telecommunication wavelength of 1522 nm by using difference-frequency generation, and then observed the HOM interference between the photons. The observed visibility is 0.76 ± 0.12 which clearly shows the non-classical interference of the two photons.

Keywords: quantum communication, frequency down-conversion, HOM interference

Introduction – A quantum interface for wavelength conversion of photons [1] is an integral part for building quantum information networks among different kinds of physical systems, and it has been actively studied [2, 3]. Especially, for optical-fiber-based quantum communication over a long distance with quantum repeaters [4], wavelength conversion of photons entangled with quantum memories to telecommunication bands is required. So far many of quantum memories entangled with visible photons have been demonstrated [5], which necessitates a quantum interface for visible-to-telecommunication wavelength conversion without destroying entanglement. Furthermore, in order to establish an entanglement between the remote quantum memories through two-photon interference, two down-converted telecom photons must be indistinguishable in the Bell measurement at the relay node. Entanglement-preserving visible-to-telecommunication wavelength conversions with high fidelities have been demonstrated in Ref. [7]. However, non-classical interference, i.e. the Hong-Ou-Mandel (HOM) interference [6] between two down-converted telecom photons has never been demonstrated. Related experiments have been restricted to the HOM interference between up-converted visible photons [3].

In this work, we present the first demonstration of the HOM interference between two light pulses at the telecommunication band after frequency down-conversion, which matches up with fiber-based quantum communication with quantum repeaters. We initially prepared two light pulses at 780 nm, one being a heralded single photon generated from spontaneous parametric down-conversion (SPDC) and the other being a coherent light pulse directly from the laser. Their wavelengths were converted to 1522 nm by difference-frequency generation (DFG) using a periodically-poled $LiNbO_3$ (PPLN) waveguide. We then observed the HOM interference between the converted light pulses. The interference visibility was 0.76 ± 0.12, which clearly exceeds the maximum value of 0.5 in the classical wave theory [8].

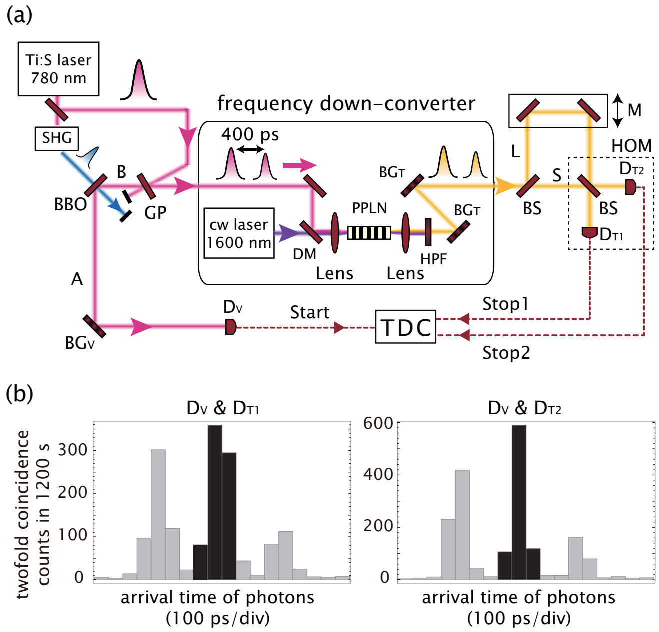

Figure 1: (a) The experimental setup. (b) Two-fold coincidence counts between D_V and D_{T1}, and between D_V and D_{T2}.

Experiments – The experimental setup for the HOM interference is shown in Fig. 1 (a). A pico-second light pulse from a mode-locked Ti:sapphire (Ti:S) laser (wave-

*ikuta@mp.es.osaka-u.ac.jp

length: 780 nm; pulse width: 1.2 ps; repetition rate: 82 MHz) is divided into two beams. One beam is frequency doubled by second harmonic generation (SHG), and then pumps a Type-I phase-matched 1.5mm-thick β-barium borate (BBO) crystal to generate a vertically(V)-polarized photon pair in modes A and B through SPDC. The photon in mode A is measured by a superconducting single photon detector (SSPD) [10] denoted by D_V after the spectral filtering by a Bragg grating (BG_V) with a bandwidth of 0.2 nm, and then a heralded single photon in mode B is prepared. The other beam with an average photon number of ~ 0.2 is sent along the same light path as the photon B. Time difference between the photon B and the subsequent coherent light pulse is set to ~ 400 ps. The two light pulses in the visible range are then sent to the frequency down-converter.

In the frequency down-converter, a V-polarized cw pump laser at 1600 nm with a power of 500 mW is combined with the signal beams at 780 nm by a dichroic mirror (DM). They are focused on the Type-0 quasi-phase matched PPLN waveguide [9]. The length of the PPLN crystal is 20 mm and the acceptable bandwidth is calculated to be 0.3 nm. After passing through the PPLN waveguide, the strong pump light is reduced by a high-pass filter (HPF), and the light converted to the wavelength of 1522 nm is extracted by two BGs (BG_T) with a bandwidth of 1 nm.

The light pulses from the frequency down-converter are split into a short path (S) and a long path (L) by a BS. Time difference between S and L is changed by mirror M on a motorized stage. The pulses passing through S and L are mixed by a second BS for the HOM interference. The two output beams from the BS are coupled to single-mode fibers followed by two SSPDs D_{T1} and D_{T2}.

An electric signal from D_V is connected to a time-to-digital converter (TDC) as a start signal, and electric signals from D_{T1} and D_{T2} are connected to the TDC as stop signals. Fig. 1 (b) shows the histograms of the coincidence counts of D_V&D_{T1} and D_V&D_{T2}. The central peak among the observed three peaks in each histogram includes the events where two photons from the heralded single photon and the coherent light pulse simultaneously arrived at the BS. Therefore, in order to see the HOM interference, we collect the coincidence events within 300-ps time windows of the two central peaks, which corresponds to the threefold coincidence events among D_V, D_{T1} and D_{T2}.

The experimental result of the dependency of the threefold coincidence counts on the optical delay is shown in Fig. 2, which clearly indicates the HOM dip. The observed visibility of 0.76 ± 0.12 at the zero delay point was obtained by the best fit to the experimental data with a Gaussian. The full width at half maximum was approximately 2.9 mm which corresponds to ~ 10 ps of a delay time. The high visibility clearly shows the non-classical interference of the two light pulses converted to the telecommunication band.

Conclusion – We have demonstrated the HOM interference of the two light pulses which are frequency down-converted to the telecommunication wavelength of 1522 nm from the visible wavelength of 780 nm. We observed a visibility of 0.76 ± 0.12, which clearly shows the non-classical interference of the two light pulses. We believe that the high-visibility wavelength conversion will be one of the key devices for many applications of quantum communication over long distance such as quantum repeaters.

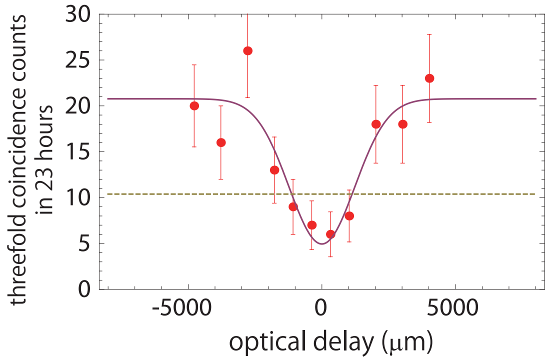

Figure 2: Observed HOM interference between two light pulses. The threefold coincidence counts have been observed in the 300-ps time windows. Solid curves are Gaussian fitted to the experimental counts. Dashed horizontal lines describe the minimum values of the dips in the classical wave theory.

This work was supported by the Funding Program for World-Leading Innovative R & D on Science and Technology (FIRST), MEXT Grant-in-Aid for Scientific Research on Innovative Areas 20104003 and 21102008, the MEXT Global COE Program, and MEXT Grant-in-Aid for Young scientists(A) 23684035.

References

[1] P. Kumar, Opt. Lett. **15**, 1476 (1990).

[2] S. Tanzilli *et al.*, Nature (London) **437**, 116 (2005); M. T. Rakher *et al.*, Nature Photonics **4**, 786 (2010); R. Ikuta *et al.*, Nature Commun. **2**, 537 (2011); S. Zaske *et al.*, Phys. Rev. Lett.**109**, 147404 (2012).

[3] H. Takesue, Phys. Rev. Lett.**101**, 173901 (2008); S. Ates *et al.*, Phys. Rev. Lett.**109**, 147405 (2012).

[4] N. Sangouard *et al.*, Rev. Mod. Phys **83**, 33 (2011).

[5] W. Rosenfeld *et al.*, Phys. Rev. Lett.**101**, 260403 (2008); S. Olmschenk *et al.*, Science **323**, 486 (2009); E. Togan *et al.*, Nature (London) **466**, 730 (2010); S. Ritter *et al.*, Nature (London) **484**, 195 (2012); J. Hofmann *et al.*, Science **337**, 72 (2012).

[6] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett.**59**, 2044 (1987).

[7] Y. O. Dudin *et al.* Phys. Rev. Lett.**105**, 260502 (2010); R. Ikuta *et al.*, Phys. Rev. A**87**, 010301(R) (2013).

[8] Z. -Y. J. Ou, *Multi-photon Quantum Interference* (Springer, New York, 2007).

[9] T. Nishikawa *et al.*, Opt. Express **17**, 17792 (2009).

[10] S. Miki *et al.*, Opt. Express **17**, 23557 (2009); S. Miki *et al.*, Opt. Lett. **35**, 2133 (2010).