Controlling the interference of single photons emitted by independent atomic sources

Alessandro Cerè[a], Victor Leong[a,b], Sandoko Kosen[a], Bharath Srivathsan[a], Gurpreet Kaur Gulati[a], and Christian Kurtsiefer[a,b]

[a]Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543

[b]Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542

ABSTRACT

Hong-Ou-Mandel interference between independent sources is a fundamental primitive of many quantum communication and computation protocols. We present a study of the Hong-Ou-Mandel interference of single photons generated via two different physical processes by two independent atomic systems: scattering by a single atom, and parametric generation via four-wave mixing in a cloud of cold atoms. By controlling the coherence time and central frequency of the heralded single photons generated by four-wave mixing we observe quantum beat and a varying degree of interference.

Keywords: quantum optics, cold atoms, hong ou mandel interference, four wave mixing, single atom

1. INTRODUCTION

Quantum networks promise to provide the infrastructure for distributed quantum computing and secure quantum communication.[1] Any network is based on nodes and the connections between them and, in a quantum network, both the nodes and the connections must be sufficiently resilient to the decohering effects of the environment. and show quantum properties. Many protocols propose nodes composed of single or an ensemble of neutral atoms, and single photons connecting them.[2] Hong-Ou-Mandel (HOM) interference[3] takes place when two indistinguishable photons arrive simultaneously at the two inputs of a 50:50 beam splitter, making them leave together from the same output port.[4] It provides a fundamental primitive for the coherent interfacing of separate quantum systems via their emitted photons[5] as an alternative to their direct interaction.[6,7] It is the basis of quantum teleportation[8–10] and entanglement swapping.[11,12] In a previous work[13] we demonstrated how the heralded single photons generated by four-wave mixing in a cloud of ^{87}Rb can interfere with photons scattered by a single ^{87}Rb atom in a Hong-Ou-Mandel configuration. We now present how adjusting the coherence time and central frequency of the heralded single photon leads to changes in the observed visibility and the rise of quantum beat.

2. SOURCES OF SINGLE PHOTONS

2.1 Photon Pairs From Four-wave Mixing In Cold ^{87}Rb Atoms

Four-wave mixing (FWM) is a parametric process that, as the name implies, mixes four different wavelengths. In Figure 1 we find the energy level scheme that provides the necessary third-order non linearity $\chi^{(3)}$. Two pumps of wavelength 780 nm (pump$_1$) and 776 nm (pump$_2$) excite the atoms from $5S_{1/2}, F = 2$ to $5D_{3/2}$, $F = 3$ via a two-photon transition. The 780 nm pump beam is red detuned by 60 MHz from the intermediate $5P_{3/2}$, $F = 3$ level to reduce the rate of incoherent scattering. From the excited $5D_{3/2}, F = 3$ level there are many possible decay paths. We select photons generated from the cascade decay to $5S_{1/2}, F = 2$ via $5P_{1/2}, F = 2$ using narrowband filters. The time correlation of the generated photons is ensured by the momentum conservation of the four participant modes, enforced by the choice of pumping and collection modes via single mode fibers. Using all four modes in a collinear geometry makes the alignment simpler and allows for an efficient coupling of

Further author information: (Send correspondence to A.C. and C.K.)
A.C. e-mail: cqtac@nus.edu.sg, C.K. e-mail: christian.kurtsiefer@gmail.com

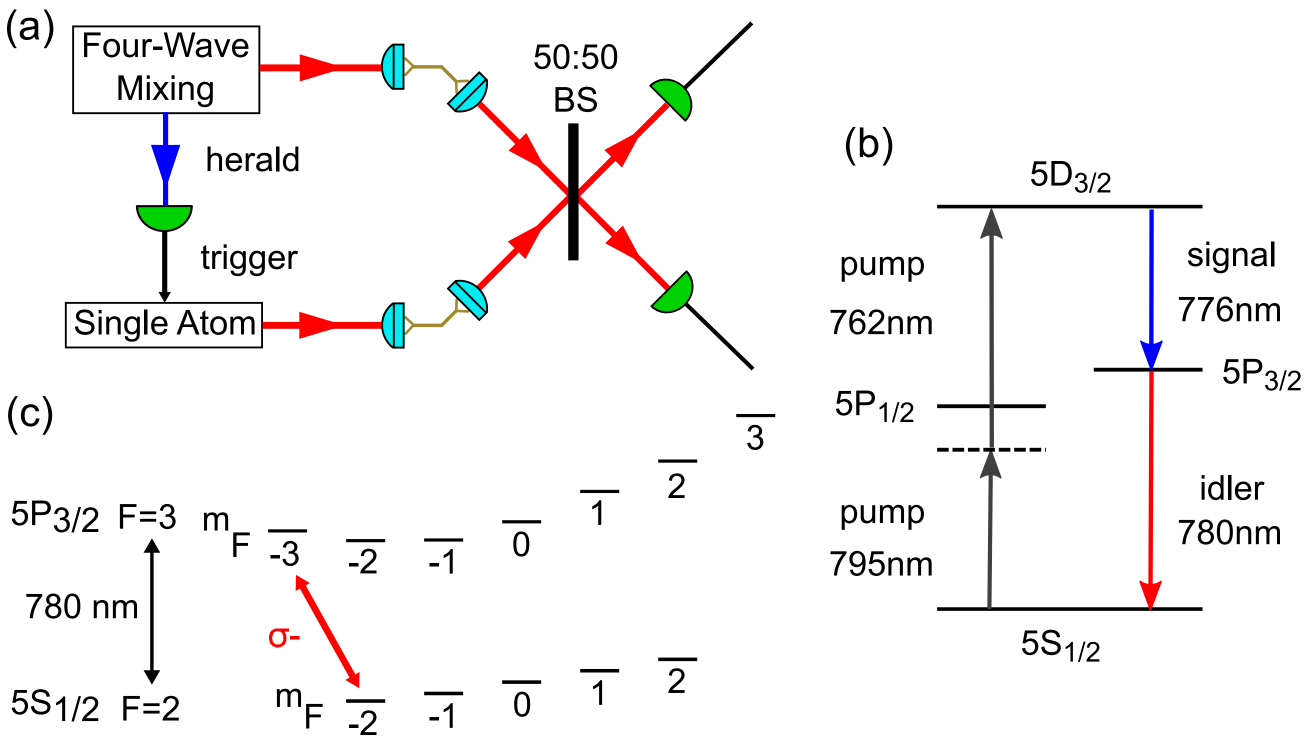

Figure 1. (a) Schematic representation of the Hong-Ou-Mandel experiment. Heralded photons from pairs generated by four-wave mixing in an atomic ensemble interfere with single photons generated by a single atom after heralding on a 50:50 beam splitter, and are detected by avalanche photodetectors at the outputs. (b) Simplified level scheme of the FWM process. (c) Level scheme for the single atom in the dipole trap and electronic transition used for exciting the single atom.

the generated photons into a single mode fiber. A schematic of the setup is shown in Figure 2. Using this setup we have already demonstrated the generation of correlated photon pairs,[14] the temporal shape of the emitted photons[15] and its manipulation,[16] and polarization entanglement.[17]

2.2 Single Photons Scattered By A Single Atom In Free Space

The single atom (SA) source generates single photons by optically exciting the electronic transition of interest and collecting the consequent photon emitted by spontaneous decay.[18] A single atom is trapped at the focus of a far-off-resonant optical dipole trap (FORT) obtained by focusing a Gaussian beam ($\lambda = 980\,$nm) to a waist of $1\,\mu$m using an aspheric lens (numerical aperture 0.55). Further details of the trapping are described in our previous works.[19,20] The trapped atom undergoes molasses cooling and is optically pumped to the $5S_{1/2}$, F=2, m_F=-2 state. To ensure a sufficiently long coherence time of the prepared state, we apply a bias magnetic field of 2 gauss along the optical axis. After the atom is prepared in the initial state, it can be excited to $5P_{3/2}$, F=3, m_F=-3 [see Fig. 1(c)] by a short resonant optical pulse generated using a fast electro-optic modulator (EOM). The beams used for optical pumping and excitation are collinear with the dipole trap, and are focused onto the atom by the same aspheric lens. The excitation pulse duration $\tau_e = 3\,$ns is much shorter than the excited state lifetime $\tau_s = 26\,$ns, and its amplitude is set to maximize the excitation probability.

The aspheric lens is also used to collect the spontaneously emitted single photons. The collection mode is separated from the excitation mode using a 99:1 beam splitter and is then coupled into a single mode fiber. The overall generation, collection and detection efficiency is $\approx 0.5\%$. We periodically check for the presence of the atom in the FORT by monitoring fluorescence with detector D_f; if the atom is lost, a new atom is loaded from a MOT.

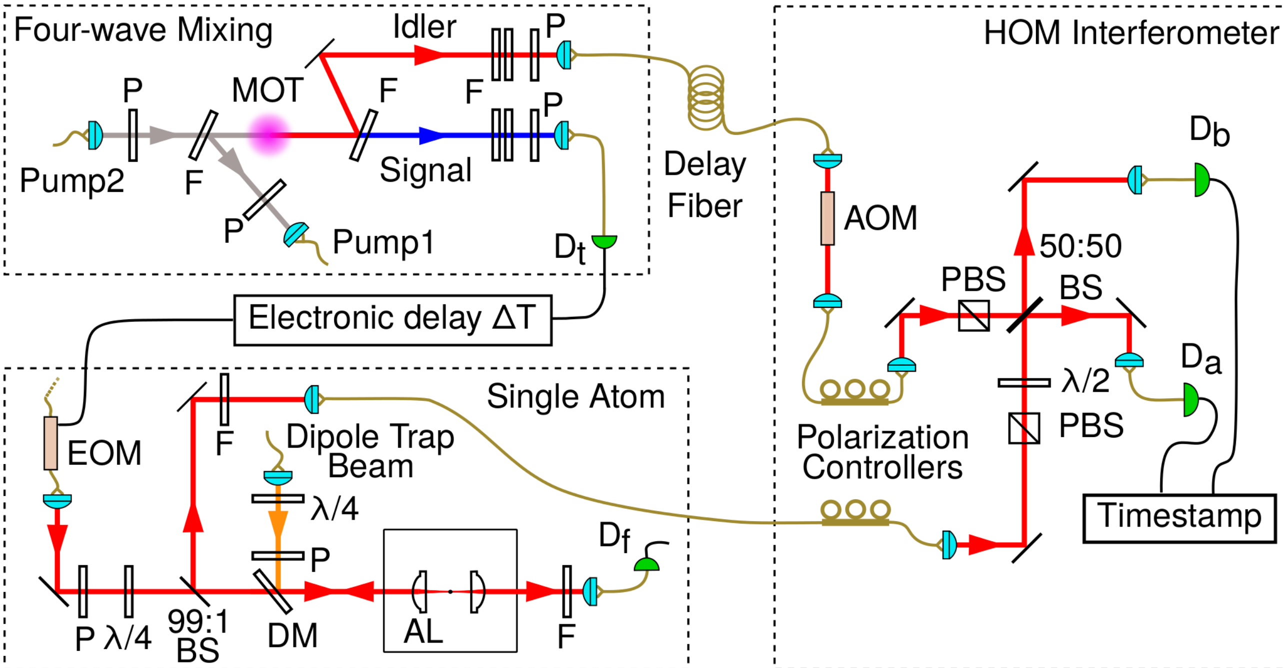

Figure 2. (Top left) Four-wave mixing setup: Pump 1 (795 nm) and Pump 2 (762 nm) are overlapped in a copropagating geometry inside the cold cloud of ^{87}Rb atoms in a Magneto-Optical Trap (MOT), generating signal (776 nm) and idler (780 nm) photon pairs. The detection of a signal photon heralds the presence of a single photon in idler mode, and is used to trigger the excitation of the single atom. (Bottom left) Single atom setup: A ^{87}Rb atom is trapped in free space between two confocal aspheric lenses (AL; numerical aperture 0.55) with a far-off-resonant optical dipole trap ($\lambda = 980$ nm). After an adjustable delay time ΔT from the trigger, an electro-optic modulator (EOM) generates an optical pulse to efficiently excite the single atom. The presence of an atom in the trap is periodically checked using APD D_f. (Right) HOM interferometer: single photons from both sources interfere at a 50:50 beam splitter (BS). An acousto-optic modulator (AOM) matches the central frequencies of both photons. P: polarizer, F: interference filters, $\lambda/2$, $\lambda/4$: half- and quarter-wave plates, PBS: polarizing beam splitter, BS: non-polarizing beam splitter, D_a, D_b, D_f, D_t: avalanche photodetectors.

3. HOM INTERFERENCE

The timing characteristics of the two sources are determined by the generation processes. The FWM process generates photon pairs with Poissonian statistics, and we obtain a heralded single photon by detecting one photon of the pair,[21–23] while the emission of a single photon from the single atom is triggered by an excitation pulse. The detection of the heralding photons from the FWM also serves as the trigger for the excitation pulse of the single atom source, effectively synchronizing the whole experiment.

Both sources generate single photons with a decaying exponential temporal envelope:

$$\psi_i(t) = \sqrt{\frac{1}{\tau_i}}\, e^{-\frac{t-t_i}{2\tau_i}}\, \Theta(t-t_i) \text{ with } i = f, s\,, \tag{1}$$

where $\tau_{f,s}$ are the coherence times from FWM and SA sources respectively, t_s is the single atom excitation time after a heralding event at t_f, and $\Theta(t)$ is the Heaviside step function. For the SA source, the time constant is given by the natural linewidth of the transition:[19] $\tau_s = 26.18 \pm 0.11$ ns, while for the FWM source it is determined by the optical density of the atomic ensemble.[14,24]

The HOM interference can be observed by comparing the probability of coincidence P between detectors D_a and D_b for interfering ($P_{||}$) and non-interfering ($P_{\perp}$) photons. Experimentally we estimate probabilities P by counting the number of coincidences. All detection events are timestamped with a temporal resolution of 125 ps. We offset the detection times of all detectors to account for the delays introduced by the electrical and optical

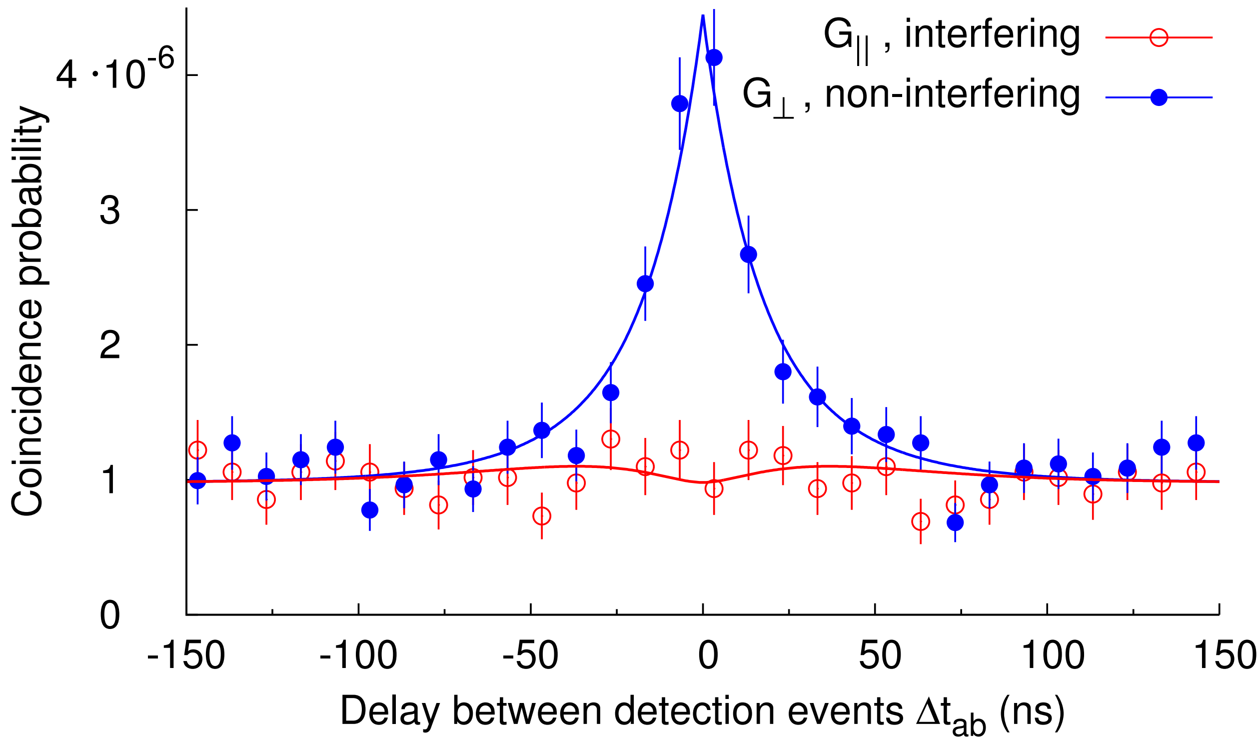

Figure 3. Coincidence probability between D_a and D_b. The filled and open circles represent the cases where photons have perpendicular (non-interfering) and parallel (interfering) polarizations, respectively. The data is sorted into 10 ns wide time bins and normalized to the total number of trigger events N_t. The upper solid line represents $G_{\rm acc} + A \cdot G_{\perp}(\Delta t_{ab})$ [see Eq. (2)], and the lower solid line represents $G_{\rm acc} + A \cdot G_{||}(\Delta t_{ab})$ [see Eq. (3)]. $G_{\rm acc}$ is a constant offset, while A is a scaling factor.

delay lines, and we only consider a detection sequence valid if either D_a or D_b clicks within 85 ns of a trigger from D_t. In Figure 3 we show the distribution of the probability of a coincidence G as a function of the delay of Δt_{ab} for the interfering and non-interfering cases. We sort the time delay between detection events Δt_{ab} into time bins of width 10 ns and normalize the distribution by dividing by the total number of trigger events N_t over the measurement time. Apart from a constant offset due to accidental coincidences, the two probability distributions are well described by:

$$G_{\perp}(\Delta t_{ab}) \;=\; \frac{1}{4}\int\limits_{-\infty}^{\infty} |\psi_f(t)\,\psi_s(t+\Delta t_{ab})|^2 + |\psi_f(t+\Delta t_{ab})\,\psi_s(t)|^2\,dt\,, \tag{2}$$

and

$$G_{||}(\Delta t_{ab}) \;=\; \frac{1}{4}\int\limits_{-\infty}^{\infty} |\psi_f(t)\psi_s(t+\Delta t_{ab}) -\; \psi_f(t+\Delta t_{ab})\psi_s(t)|^2\,dt\,. \tag{3}$$

4. QUANTUM BEAT OF INTERFERING SINGLE PHOTONS

The single atom experiences an AC Stark shift from the dipole trap and a Zeeman shift from a bias magnetic field, resulting in a detuning of δ_s from the natural transition frequency for the emitted photon. We measured δ_s by observing the extinction of light caused by the SA as a function of the probe frequency,[20] obtaining $\delta_s = 76{\pm}1$ MHz. In order to obtain a high visibility in the HOM interference, as seen in Figure 3, we compensated

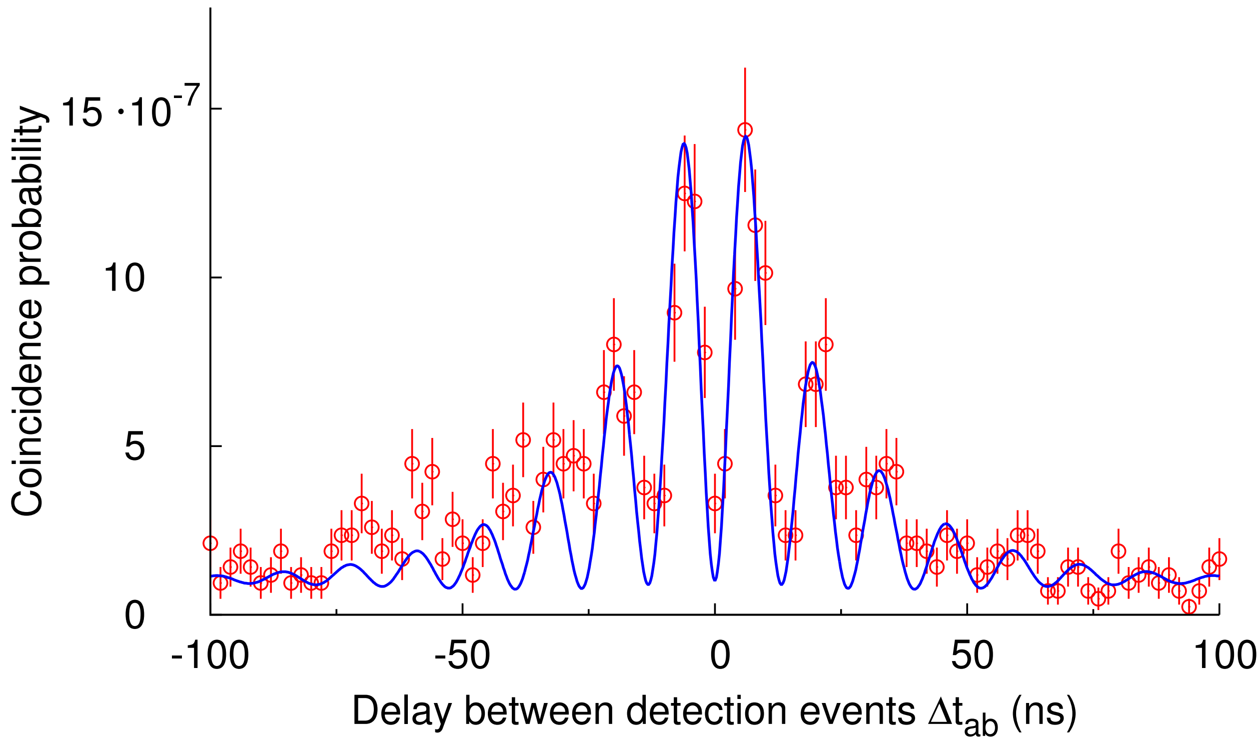

Figure 4. Quantum beat between single photons. Coincidence probability between D_a and D_b The data is sorted into 2 ns wide time bins and normalized to the total number of trigger events N_t. The finer time binning has been chosen to being able to resolve the temporal structure of the quantum beat. The solid line is a fit obtained from Equation (4).

this frequency shift in the central frequency of the heralded photon coming from FWM using an acousto-optic modulator (AOM). Without this compensation, it is possible to observe the HOM interference for single photons of different frequency generated by independent sources, an effect first reported by Legero *et al.*[25] Adapting their derivation[25] to the temporal waveform of Equation (1) we obtain:

$$G_{\text{beat}}(\Delta t_{ab}) = \frac{1}{4}\int_{-\infty}^{\infty} |\psi_f(t)\,\psi_s(t+\Delta t_{ab})|^2 + |\psi_f(t+\Delta t_{ab})\,\psi_s(t)|^2\; dt$$
$$-\frac{\cos(\delta_s \Delta t_{ab})}{2}\int_{-\infty}^{\infty} |\psi_f(t)\,\psi_s(t+\Delta t_{ab})\psi_f(t+\Delta t_{ab})\,\psi_s(t)|\; dt\,. \tag{4}$$

In Figure 4 we report the experimental data and a fit obtained using Equation (4) using as free parameters a scaling factor, the accidental count rate, and the detuning δ_s. We obtain a $\delta_s = 75.7 \pm 0.66\,\text{MHz}$, compatible with the value measured independently.

5. HOM INTERFERENCE AND PHOTON COHERENCE TIME

We also studied how the HOM interference changes for different coherence times of the FWM photons. A signature of the HOM is the change of probability of two photons being detected at the same output of the beam-splitter.[3,4] In order to estimate this probability, we replaced detector D_b with a 50:50 fiber beam-splitter and two similar APD, D_{b1} and D_{b2}. We can now compare the probability of a coincidence between D_a and

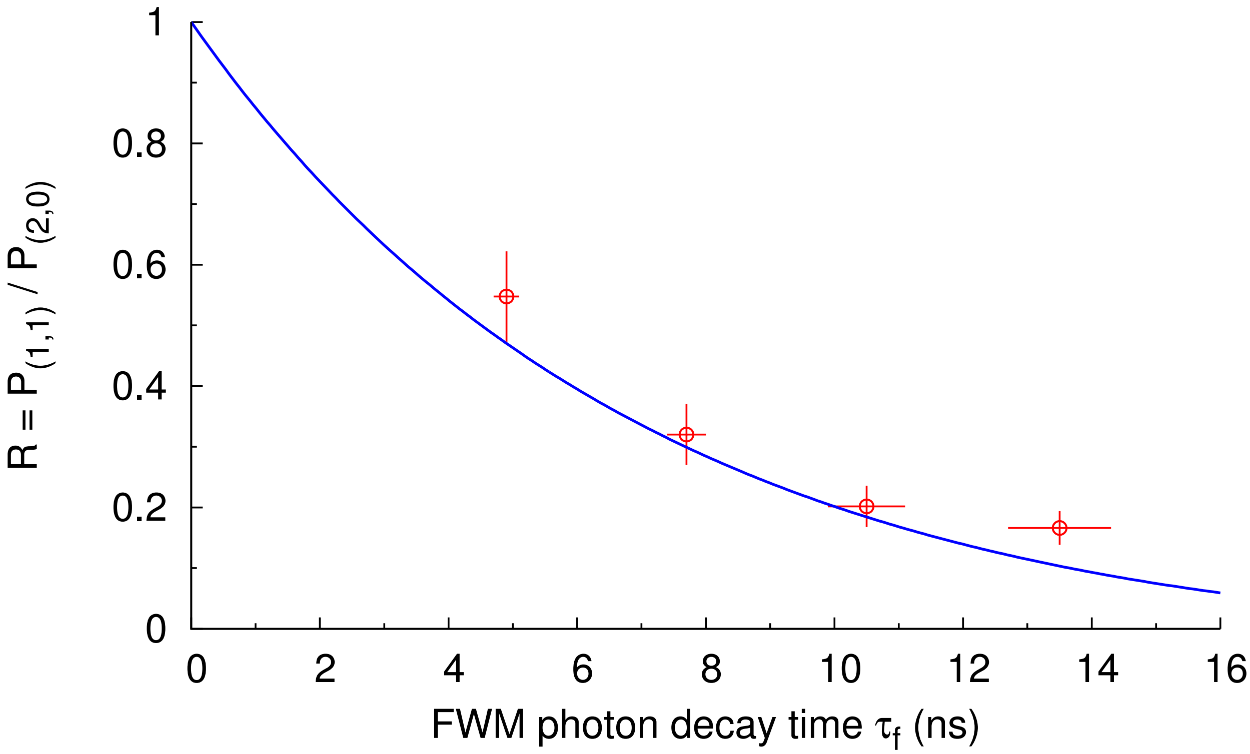

Figure 5. HOM interference as a function of the coherence time of the FWM photon. The interference is characterized by the ratio $R = P_{(1,1)}/P_{(2,0)}$. The continuous line represents Equation (5) with $\tau_s = 26.18\,\mathrm{ns}$. The coherence time τ_f is determined by the optical density of the atomic cloud.

either D_{b1} or D_{b2}, $P_{(1,1)}$, with the probability of coincidences between D_{b1} and D_{b2}, $P_{(2,0)}$. We define the ratio $R = P_{(1,1)}/P_{(2,0)}$. We obtain the expected behavior of R by integrating Equation (3):

$$R(\tau_f, \tau_s) = \left(\frac{\tau_f - \tau_s}{\tau_s + \tau_f}\right)^2 . \tag{5}$$

Experimentally, we can choose the coherence time of the FWM photons τ_f by adjusting the optical density of the atomic cloud.[14] In Figure 5 we can observe the probability ratio R as a function of τ_f. We compare it with the expected behavior, predicted by Equation (5), represented by the continuous line.

6. CONCLUSION

We have presented a study of the amplitude interference of two single photons generated by two independent atomic sources. We have shown how the difference of central frequency of the two photons gives rise to quantum beat, and how the control of the temporal shape of the photon generated by FWM can be used to modulate the visibility of the interference.

ACKNOWLEDGMENTS

We acknowledge the support of this work by the National Research Foundation (partly under grant No. NRF-CRP12-2013-03) & Ministry of Education in Singapore.

REFERENCES

[1] Kimble, H. J., "The quantum internet," *Nature* **453**, 1023–1030 (2008).

[2] Duan, L.-M., Lukin, M. D., Cirac, J. I., and Zoller, P., "Long-distance quantum communication with atomic ensembles and linear optics," *Nature* **414**, 413–418 (2001).

[3] Hong, C. K., Ou, Z. Y., and Mandel, L., "Measurement of subpicosecond time intervals between two photons by interference," *Phys. Rev. Lett.* **59**(18), 2044–2046 (1987).

[4] Loudon, R., [*The Quantum Theory of Light; 3rd ed.*], Oxford Univ. Press, Oxford (2002).

[5] Briegel, H. J., Dür, W., Cirac, J., and Zoller, P., "Quantum repeaters: The role of imperfect local operations in quantum communication," *Phys. Rev. Lett.* **81**, 5932–5935 (Dec. 1998).

[6] Dyckovsky, A. M. and Olmschenk, S., "Analysis of photon-mediated entanglement between distinguishable matter qubits," *Phys. Rev. A* **85**, 052322 (May 2012).

[7] Meyer, H. M., Stockill, R., Steiner, M., Le Gall, C., Matthiesen, C., Clarke, E., Ludwig, A., Reichel, J., Atatüre, M., and Köhl, M., "Direct photonic coupling of a semiconductor quantum dot and a trapped ion," *Phys. Rev. Lett.* **114**, 123001 (2015).

[8] Bennett, C. H., Brassard, G., Crépeau, C., Jozsa, R., Peres, A., and Wootters, W. K., "Teleporting an unknown quantum state via dual classical and einstein-podolsky-rosen channels," *Phys. Rev. Lett.* **70**, 1895–1899 (Mar. 1993).

[9] Bouwmeester, D., Pan, J., Mattle, K., Daniell, M., Zeilinger, A., and Weinfurter, H., "Experimental quantum teleportation," *Nature* **390**(6660), 575–579 (1997).

[10] De Martini, F., Bužek, V., Sciarrino, F., and Sias, C., "Experimental realization of the quantum universal not gate," *Nature* **419**(6909), 815–818 (2002).

[11] Żukowski, M., Zeilinger, A., Horne, M., and Ekert, A., "''event-ready-detectors'' bell experiment via entanglement swapping," *Phys. Rev. Lett.* **71**, 4287–4290 (Dec. 1993).

[12] Pan, J.-W., Bouwmeester, D., Weinfurter, H., and Zeilinger, A., "Experimental entanglement swapping: Entangling photons that never interacted," *Phys. Rev. Lett.* **80**(18), 3891–3894 (1998).

[13] Leong, V., Kosen, S., Srivathsan, B., Gulati, G. K., Cerè, A., and Kurtsiefer, C., "Hong-Ou-Mandel interference between triggered and heralded single photons from separate atomic systems," *Phys. Rev. A* **91**, 063829 (June 2015).

[14] Srivathsan, B., Gulati, G. K., Chng, B., Maslennikov, G., Matsukevich, D., and Kurtsiefer, C., "Narrow band source of transform-limited photon pairs via four-wave mixing in a cold atomic ensemble," *Phys. Rev. Lett.* **111**, 123602 (2013).

[15] Gulati, G. K., Srivathsan, B., Chng, B., Cerè, A., Matsukevich, D., and Kurtsiefer, C., "Generation of an exponentially rising single-photon field from parametric conversion in atoms," *Phys. Rev. A* **90**, 033819 (Sep 2014).

[16] Srivathsan, B., Gulati, G. K., Cerè, A., Chng, B., and Kurtsiefer, C., "Reversing the temporal envelope of a heralded single photon using a cavity," *Phys. Rev. Lett.* , 163601 (Oct. 2014).

[17] Kaur Gulati, G., Srivathsan, B., Chng, B., Cerè, A., and Kurtsiefer, C., "Polarization entanglement and quantum beats of photon pairs from four-wave mixing in a cold Rb-87 ensemble," *arXiv* (May 2015).

[18] Darquié, B., Jones, M. P. A., Dingjan, J., Beugnon, J., Bergamini, S., Sortais, Y., Messin, G., Browaeys, A., and Grangier, P., "Controlled single-photon emission from a single trapped two-level atom," *Science* **309**, 454–456 (July 2005).

[19] Aljunid, S. A., Maslennikov, G., Wang, Y., Lan, D. H., Scarani, V., and Kurtsiefer, C., "Excitation of a single atom with exponentially rising light pulses," *Phys. Rev. Lett* **111**, 103001 (2013).

[20] Tey, M. K., Chen, Z., Aljunid, S. A., Chng, B., Huber, F., Maslennikov, G., and Kurtsiefer, C., "Strong interaction between light and a single trapped atom without the need for a cavity," *Nature Physics* **4**(12), 924–927 (2008).

[21] Clauser, J. F., "Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect," *Phys. Rev. D* **9**, 853–860 (Feb. 1974).

[22] Grangier, P., Roger, G., and Aspect, A., "Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences," *Europhys. Lett.* **1**, 173 (1986).

[23] Hong, C. K. and Mandel, L., "Experimental realization of a localized one-photon state," *Phys. Rev. Lett.* **56**(1), 58–60 (1986).

[24] Jen, H. H., "Spectral analysis for cascade-emission-based quantum communication in atomic ensembles," *J. Phys. B: At. Mol. Opt. Phys.* **45**, 165504 (2012).

[25] Legero, T., Wilk, T., Hennrich, M., Rempe, G., and Kuhn, A., "Quantum Beat of Two Single Photons," *Phys. Rev. Lett.* **93**, 070503 (Aug. 2004).