Interference of dissimilar photon sources

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Abstract

If identical photons meet at a semi-transparent mirror they appear to leave in the same direction, an effect called “two-photon interference”. It has been known for some time that this effect should occur for photons generated by dissimilar sources with no common history, provided the measurement cannot distinguish between the photons1. Here we report a technique to observe such interference with isolated, unsynchronized sources whose coherence times differ by several orders of magnitude. In an experiment we interfere photons generated via different physical processes, with different photon statistics. One source is stimulated emission from a tuneable laser, which has Poissonian statistics and a neV bandwidth. The other is spontaneous emission from a quantum dot in a p-i-n diode2,10 with a µeV linewidth. We develop a theory to explain the visibility of interference, which is primarily limited by the timing resolution of our detectors.

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Two-photon interference is at the heart of many optical quantum information processing protocols but to be scalable these proposals require large numbers of identical photons in predetermined states. This leads to the question: what is the minimum requirement to observe interference between two sources? Since the first demonstration of two photon interference[3] the proto-typical experimental arrangement has used parametric down-conversion to create photon pairs by exciting a crystal with a strong laser. Experiments have been reported where a heralded photon interferes with a weak Poissonian source [5, 7], though in these cases both photon streams were derived from the same laser. Recently, interference between distinct but nominally identical down-conversion sources has been demonstrated with separate pump lasers [6, 8]. On-demand zero-dimensional photon sources are attractive for scalable quantum-information processing as they naturally create only one photon at a time [4], however care must be taken to ensure spectral jitter and dephasing do not distinguish each photon. Indistinguishable single-photon emission was demonstrated with a semiconductor quantum dot [9] and a single atom [10] by optically exciting a single source twice in quick succession. More recently, it has been shown that two identical zero-dimensional sources excited with the same laser can generate indistinguishable photons [11–14]. From a fundamental point of view it would be interesting to be able to interfere sources that are not similar. Such interference effects can be used to determine the spectral density matrix of a single photon [7]. Also potential applications of quantum information processing will in future require interactions between distributed sources, either for quantum computing [15] or interfacing weak lasers commonly used in quantum cryptography with the more exotic sources being investigated for quantum repeaters and memories. Here we report a demonstration of interference between non-classical emission from an electrically excited InAs quantum dot and a commercially available semiconductor laser.

To understand our experiment it is useful to consider idealized sources incident from opposite sides on a 50/50 semi-transparent mirror (as illustrated in Fig. 1 (a)). Two detectors at the outputs of the mirror measure the probability of two photons leaving the mirror at the same time. If we assume photons from both sources have perfect overlap in energy, space and time but no mutual coherence then we must only consider the probabilities of the sources emitting a certain number of photons. The laser obeys Poissonian statistics, \( \langle \psi_a | \psi_a \rangle = \exp (-\alpha^2) \sum_n n_a^{2n_a} \alpha^{2n_a} (n_a | n_a) \) and for the quantum light source \( \langle \psi_b | \psi_b \rangle = (1 - \eta) (0_b | 0_b) + \eta (1_b | 1_b) \). In our notation \( \eta \) and \( \alpha^2 \) are proportional to the proba-
FIG. 1: Interference of a single-photon source with a weak Poissonian source. (a) Shows a schematic of the experiment. (b) Shows the predicted correlation function at zero time delay, $g^{(2)}(0)$ for parallel (black) and orthogonal (red) photons as a function of the intensity ratio of the sources, $\eta/\alpha^2$. Shown in blue is the resulting visibility of two-photon interference, $(g^{(2)}_\perp(0) - g^{(2)}_\parallel(0))/g^{(2)}_\perp(0)$.

There are a number of ways the detectors can collect one photon each: either they collect both photons from the laser (with probability $2RT\alpha^4/4$) or they collect one photon from the laser and one from the single photon source. This second possibility can occur if both photons are reflected (with probability proportional to $R^2\eta\alpha^2/2$) or if they are both transmitted ($T^2\eta\alpha^2/2$). However, if the two sources are indistinguishable then interference will occur leading the latter two terms to cancel when $R = T$. These joint-detection probabilities $g^{(2)}(0)$ are normalized to the probability of detecting two photons at different times, $(\eta + \alpha^2)^2$. Equation 1a gives the probability of a detecting a photon in both outputs at the same time when the sources have parallel polarisations and are indistinguishable. A useful control measurement is to measure data with the sources orthogonally polarised, so
the photons are entirely distinguishable and no interference occurs (1b).

\[
g_{\parallel}^{(2)}(0) = \left(1 + \frac{\eta}{\alpha^2}\right)^{-2} \tag{1a}
\]

\[
g_{\perp}^{(2)}(0) = \left(1 + \frac{2\eta}{\alpha^2}\right) \left(1 + \frac{\eta}{\alpha^2}\right)^{-2} \tag{1b}
\]

Fig. 1 (b) plots \(g_{\perp}^{(2)}(0)\) and \(g_{\parallel}^{(2)}(0)\) versus the ratio of source intensities, \(\eta/\alpha^2\). For \(g_{\parallel}^{(2)}(0)\), all coincidence counts at time delay zero are due to multi-photon emission from the laser, which falls as \(\eta/\alpha^2\) increases. Using this simple analysis we can make the surprising prediction that the visibility of two-photon interference, \((g_{\perp}^{(2)}(0) - g_{\parallel}^{(2)}(0))/g_{\perp}^{(2)}(0)\), can approach unity as \(\eta/\alpha^2\) increases.

We now determine the coherence properties of the two sources used in our experiment. Single-photon interference measurements were carried out using a free space Michelson interferometer with a variable time delay [17] (Fig. 2 (a)). The interference pattern as a function of delay is measured using an avalanche photodiode (D1). Looking at emission from the \(X^-\) state of the quantum dot source [16] on its own we see that the interference has a fringe contrast which varies as \(A_0 e^{-|t|/\tau_{coh}}\) where \(A_0\) is the fringe contrast at zero delay, \(t\) the delay time and \(\tau_{coh}\) the coherence time. For the dot studied here \(\tau_{coh} = 285\) ps at 100\(\mu\)A. This characteristic exponential variation in contrast is an indication that the state has a Lorentzian line-shape in energy of width 4.4\(\mu\)eV. Thus we can be sure that homogeneous processes dominate the line broadening mechanisms [18]. We note that the maximum fringe contrast observed at zero time delay, \(A_0\), is below unity due to the finite spatial overlap of light that travels along the two arms of the interferometer. Separately, we have shown the coherence time of this source is sufficient to post-select interference events between successive photons emitted by the source. The other source we employ is an external cavity solid-state laser diode which can be tuned several hundred \(\mu\)eV using a piezo-electric actuator. This source has a coherence time of 1\(\mu\)s, which is three orders of magnitude longer than we are able to probe with our Michelson interferometer. Thus, the fringe contrast is constant at \(A_0\) over the range of delays we probe.

In our experiment, to obtain a finite visibility of two-photon interference these sources must have the same energy to within the sum of their linewidths [10]. However, our spectrometer and CCD system only have a spectral resolution \(\sim 100\mu\)eV. Hence, to ensure spectral indistinguishability we employ a scheme based on single-photon interference, the layout of which is shown in Fig. 2 (a). Clearly the two photons have orthogonal polarisation
FIG. 2: Measurements of single-photon interference. (a) Layout for the experiment (b) Predicted fringe contrast as a function of the energy difference between the sources and the delay in the Michelson interferometer. (c) Experimental fringe contrast for the dot and laser signals combined at 380 ps delay as the bias applied to the piezo-electric stack tunes the laser wavelength (black). Also, shown are the fringe contrasts of the laser (red) and dot (blue) at the same delay, measured separately. Error bars represent standard deviations determined from least-squares fits to the data.

at the detectors and so will not give rise to two-photon interference. However, the single-photon interference patterns of the separate sources have a period given by their wavelength. Thus, when both sources are detected at the same time we observe “beating” in the intensity at the detector. The period of the beats is inversely proportional to the energy difference between the states. We have developed a simple model to illustrate how the single-photon interference fringe contrast, normalized to $A_0$, varies with both the energy difference between the sources and interferometer delay (Fig. 2 (b)). We consider only the case where the sources appear to have the same intensity on the detectors.

In practice, we set the interferometer delay to a fixed value and measure the fringe contrast as a function of the piezo-voltage applied to the laser, which results in a near-linear variation in laser energy. As can be seen in Fig. 2(c), the fringe contrast varies cosinusoidally as a function of the energy splitting between the two sources. For a delay of 380ps the period of the cosine variation is $34\mu eV$. With a least squares fit to the experimental data we can ensure degeneracy with an error estimated below $1\mu eV$, less than the line-width of the broader source. Using this method we have experimentally verified that the sources’ wavelengths remain stable within the accuracy of this measurement over 24 hours.
FIG. 3: Measurements of photon statistics. (a) experimental layout for two-photon interference between the sources. Intensity correlation functions, recorded for (b) the quantum light source only, (c) the laser only, with both sources having (d) orthogonal and (e) parallel polarisations. These plots show the measured data (black), predicted correlations for infinitely fast detectors (blue) and for the measured detectors’ response function (red).

We are now able to perform the two-photon interference experiment using the apparatus in Fig. 3a. The co-linear and oppositely polarised photons are passed to an interferometer made of polarisation-maintaining optic fibre. The first, polarising, coupler $C_A$ ensures every photon from the dot takes the upper path to the final non-polarising, 50/50 coupler $C_B$ and every photon from the laser takes the lower path. This design increases the probability of the two photons reaching the final coupler from opposite sides by a factor of four, relative to previous experiments [9]. Correlations at the outputs of $C_B$ are measured with two silicon avalanche photodiodes (APDs). A half-wave plate in the path taken by the laser photon switches its polarisation between being parallel and orthogonal to the quantum dot’s photon every few minutes. This allows us to build up the correlations for the case where the photons are and are not interfering within the same integration time. Thus any slow drift in the
position of the sources, or the fibres, which might change the ratio of their intensities at the detectors, is averaged out between pairs of measurements. During the course of each measurement the ratio of intensities is stable to within 5%.

Fig. 3(d) and (e) shows experimental data recorded for equal intensity sources. The measurement of $g_{\perp}(\tau)$ shows a dip at time-zero due to the anti-bunched nature of the quantum light source, as expected. More strikingly, we can see a clear difference between the measurements for parallel and orthogonal polarisations, which is a result of two-photon interference. This finite visibility constitutes the main result of our experiment and occurs due to interference between photons from the weak laser and the anti-bunched source despite their different linewidths and lack of common history.

To further quantify this result a full analysis, including non-ideal source parameters, allows us to calculate the correlation as a function of time (equation 2).

$$g_{\phi}^{(2)}(\tau) = R_f(\tau) \otimes \left[ \frac{2\eta^2(1 - \gamma^2 \cos^2(\phi) \exp\left(-\frac{\tau}{\tau_{coh}}\right)) + (\eta^2 g_{HBT}^{(2)}(\tau) + \alpha^4)}{(\eta + \alpha^2)^2} \right]$$

(2)

Where $\phi$ is the angle between the polarisations of the two photons, $\gamma = \langle \psi_a | \psi_b \rangle$ a measure of the overlap of the two photon’s wave-functions, $R_f$ the detection system response function and $R = T$. We note that in the case where $g_{HBT}^{(2)}(0) = 0$, $\gamma=1$ and $\tau = 0$ this reverts to the form given in equations 1a and 1b as expected. In this experiment $\eta$ and $\alpha^2$ are of the order of $10^{-3}$. Separately we measure the photon statistics of our sources using a Hanbury-Brown and Twiss (HBT) arrangement (equivalent to Fig. 3(a) with only one source operational at a time). For the laser the auto-correlation function $g_{HBT}^{(2)}(\tau) = 1$ (Fig. 3(c)) as would be expected for a photon source with Poissonian statistics. For the QD source we expect anti-bunched emission with a dip at time zero. We can predict the precise shape of this auto-correlation [18, 19] using the independently measured radiative lifetime (985ps), the contribution from background and dark counts (which sum to 0.04 of the signal from the quantum state) and the resolution of our detection system (a Gaussian with width 428ps). This model suggests $g_{HBT}^{(2)}(0) = 0.19$, consistent with our experimental measurement (Fig. 3(b)). From these parameters we calculate $g_{\perp}^{(2)}(\tau)$ and $g_{\parallel}^{(2)}(\tau)$ for equal intensity sources being mixed. Shown as blue lines in Fig. 3(d) and (e) are the correlations that would be observed for infinitely fast detectors. However, when the response function of the detection system is included we obtain the curves shown in red. The only free parameter is the wave-function overlap $\gamma = 0.91$. 

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Finally, a series of measurements were made of the visibility of interference as a function of the intensity ratio of the two sources, $\eta/\alpha^2$. Fig. 4 shows this data and our prediction for $\gamma = 0.91$. Our theory predicts a maximum visibility will be observed for $\eta/\alpha^2 \sim 2$, which is a result of the finite width of $R_f$. The agreement between theory and experiment is good. It is remarkable that we can infer such a high overlap of the photons given the fundamental differences in the sources. We note that the maximum measured visibility of interference is set by the ratio of the coherence time of the solid state source to the response time of the detection system. In future the raw visibility could be increased by employing faster superconducting detectors or long coherence time atomic sources.

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