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Single photon beat note in an acousto-optic modulator-based interferometer

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We present in the following a quantum optics experiment appropriate for advanced undergraduate students with former experience in quantum optics. It extends classical single photon setups to the time dependent domain. We demonstrate self-heterodyning of heralded single photons using a Mach-Zehnder like interferometer where beamsplitters are replaced by two acousto-optic modulators (AOMs). The single photon beat note is recorded over time at the frequency difference between the RF generators driving the AOMs, which makes it observable directly on a human time scale, i.e., with periods above a fraction of a second. To compare with our observations, we tailor the standard quantum optics formalism for beam splitters to take into account the frequency shifts associated with the AOMs. © 2020 American Association of Physics Teachers.

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I. INTRODUCTION

Experimental demonstrations can greatly enhance the learning curve in quantum physics, as it complements the usual theoretical approach of a very abstract and non-intuitive topic. The wave-particle duality is very often illustrated with an interference buildup with single photons or single electrons in an interferometer (see, for instance, Refs. 1 and 2 for electrons and Refs. 3 and 4 for photons). In these experiments, the wave is split spatially into two parts, and the recombination forms an interference pattern that appears over time as events are recorded one at a time. This shows that a photon or electron does interfere with itself.

Quantum optics experimental demonstrations for undergraduate or graduate students have become available in the early 2000s owing to technological developments.^{5,6} They are nowadays widespread, and we refer to Ref. 7 for a quite comprehensive review. Single photon interferences with a Mach-Zehnder interferometer and a spontaneous parametric down-conversion source are one of the most popular experiments. We extend this classical demonstration replacing the beam splitters by acousto-optic modulators (AOMs). Each of them shifts the reflected beam by a tunable frequency. As a consequence, we produce single photon Fock states associated with an unusual bichromatic field mode. Such single photons are thus in a non-stationary state and exhibit periodic oscillations in both time and space termed beat note. Contrary to a previous realization,⁸ our apparatus allows an arbitrary small frequency difference between the two field components. It allows direct observation of beat notes with the roll mode of an oscilloscope. Moreover, most demonstration experiments deal with the spatial or polarization degrees of freedom of single photon states. Here, we manipulate optical frequencies, which widens the range of controllable optical fields observables (see, for instance, Ref. 9). Naturally, our setup is intended for students already trained in

experimental quantum optics as an introduction to advanced concepts such as quantum coherence.

This article is organized as follows. We first quickly present how AOMs may be used as beam splitters and introduce an original matrix approach to describe the different modes involved in the interferometer. We then depict the experimental setup before we discuss our main results. A more detailed analysis of quantum beam splitters and AOMs, as well as extra experimental data, is postponed in a separate Supplementary Material.¹⁰

II. AOMs AS BEAM SPLITTERS

In an AOM, a piezoelectric transducer generates an acoustic wave of angular frequency Ω in a transparent medium [Fig. 1(a)]. Through the photoelastic effect, it creates a periodic perturbation of the refractive index that propagates at the sound velocity v_s . The medium behaves as a thick grating of spatial period Λ and wavevector $K = 2\pi/\Lambda = \Omega/v_s$, leading to Bragg diffraction of an incident optical wave. Since

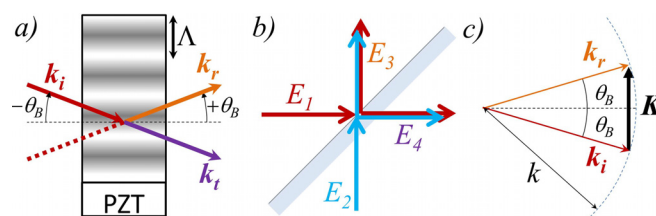


Fig. 1. AOMs as beam splitters. $\mathbf{k}_{i,r,t}$ represent light wavevectors of common modulus k . \mathbf{K} is the acoustic wavevector. (a) Sketch of an AOM. An incoming light beam (\mathbf{k}_i , red) at Bragg incidence θ_B is partially reflected (\mathbf{k}_r , orange) and transmitted (\mathbf{k}_t , purple) by diffraction on an acoustic wave of wavelength Λ generated by a piezoelectric transducer (PZT). A similar process occurs at symmetric incidence (red dotted line). (b) E_{1-4} are the field modes impinging on and emerging from a usual optical beam splitter. (c) Bragg diffraction interpreted as energy and momentum conservation of an incoming photon absorbing a phonon of the acoustic wave.

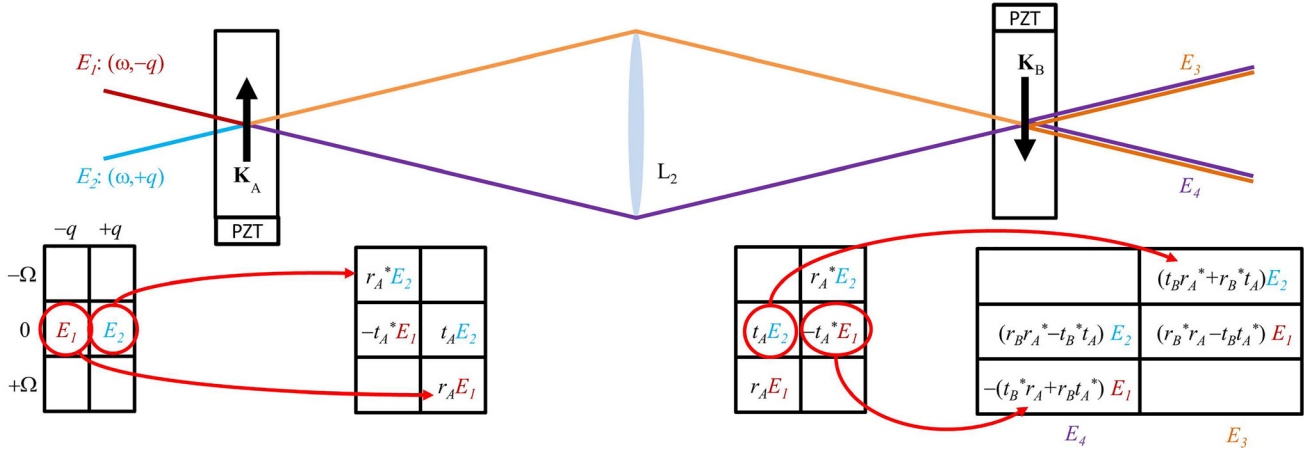


Fig. 2. Upper part: simplified scheme of our interferometer with two AOMs as beam splitters. The lens L_2 conjugates the beam waist in the first AOM into the second AOM in a $2f$ - $2f$ configuration. Lower part: matrices representing the propagation of the amplitudes of the different modes in angular frequency $(-\Omega, 0, \Omega)$ and transverse momentum $(-q, +q)$ with $q = K/2$. Thin red arrows outline the reflection processes in each AOM which depend on the direction of propagation of the acoustic wave (thick black arrows). In practice, light is actually sent from only one input ($E_2 \equiv 0$). From a quantum optics point of view, single photons are injected at port 1 and vacuum at port 2. The input field state is thus $|\psi\rangle = |1\rangle_1|0\rangle_2$.

the grating is time-dependent, optical wavelength is slightly modified during the process.

In the context of a quantum optics experiment, we adopt here a complementary corpuscular point of view to derive the Bragg condition: AOMs can be thought as coherent sources of phonons of energy $\hbar\Omega$ and momentum $\hbar\mathbf{K}$. Incoming photons of energy $\hbar\omega_i$ and momentum $\hbar\mathbf{k}_i$ may absorb or emit a stimulated phonon. Energy and momentum conservation put the following constraints on the reflected photon energy $\hbar\omega_r$ and momentum $\hbar\mathbf{k}_r$:

$$\hbar\mathbf{k}_r = \hbar\mathbf{k}_i \pm \hbar\mathbf{K} \quad \text{and} \quad \hbar\omega_r = \hbar\omega_i \pm \hbar\Omega, \quad (1)$$

where the $+$ and $-$ signs hold for absorption and emission processes.

For typical AOMs, $v_s \approx 4 \text{ km s}^{-1}$, and so $\Lambda \approx 60 \mu\text{m}$ at $\Omega/2\pi \approx 70 \text{ MHz}$. The wavelength of the photons is $\lambda = 2\pi c/\omega \approx 810 \text{ nm}$; therefore, $K \ll k_i$, and hence,

$$|\mathbf{k}_r|^2 = |\mathbf{k}_i|^2 \pm 2\mathbf{k}_i \cdot \mathbf{K} + |\mathbf{K}|^2 \simeq |\mathbf{k}_i|^2. \quad (2)$$

Let us decompose the incident wavevector $\mathbf{k}_i = \mathbf{k}_{\parallel} + \mathbf{k}_{\perp}$ into its parallel and perpendicular components with respect to \mathbf{K} . Equation (2) then reads $\mathbf{k}_{\parallel} \simeq \mp \mathbf{K}/2$. We have thus

$$\mathbf{k}_i = \mathbf{k}_{\perp} \mp \mathbf{K}/2 \quad \text{and} \quad \mathbf{k}_r \simeq \mathbf{k}_{\perp} \pm \mathbf{K}/2. \quad (3)$$

The incident and reflected beams propagate symmetrically at angles $\pm\theta_B$ from the axis with $\sin\theta_B = K/(2k)$ (Bragg condition). A rigorous treatment is derived in the supplementary material.¹⁰

We have thus a simple picture of an AOM acting as a beam splitter. The two symmetric output ports correspond to Hermitian conjugate processes of phonon emission and absorption which results in opposite momentum transfers and frequency shifts on the incoming photons [Fig. 1(c)].

III. BEAM SPLITTER MATRIX GENERALIZATION

For a usual optical beam splitter, the input and output field states are represented by the vectors $(E_1, E_2)^{\top}$ and $(E_3, E_4)^{\top}$.

The linear relationships between them are conveniently expressed in matrix form as^{11,12}

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} r & -t^* \\ t & r^* \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = U \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}. \quad (4)$$

In order to confirm that AOMs can be considered as beam splitters, we give in the Supplementary Material¹⁰ a classical derivation of the *beam splitter matrix* U and a wave approach of AOM theory to show that they are actually properly described by such a matrix and identify the relevant phases.

We take $r = -ir_{\max}e^{-i\Omega t}$ and $t = \sqrt{1 - |r|^2}$.

For AOMs operated at Bragg angle, we saw before that beams have only two possible transverse wavevectors $\pm K/2 = \pm q$. Reflection is associated with an angular frequency change $\pm\Omega$, while the transmitted beam remains at the same frequency. The field states are thus represented by a 3×2 *mode matrix* containing the amplitudes of its $(-\Omega, 0, +\Omega) \times (-q, +q)$ components (Fig. 2, bottom left).

Interaction with an AOM consists in amplitude redistribution among these six components. In principle, the beam splitter matrix can be replaced by a 4-rank tensor. However, it is a large object, hard to visualise, with $3^2 \times 2^2 = 36$ coefficients of which, however, only four are non-zero. In practice, simple sketches like the red arrows depicted in Fig. 2 are more intuitive and easily implemented in computer algebra. Notice that if the acoustic wave propagates downwards $\mathbf{K} \rightarrow -\mathbf{K}$ momentum exchanges are reversed, and so are the red arrows.

The use of one such AOM as a beam splitter is a conventional technique known as *heterodyning* to improve signal-to-noise ratio in interferometric metrology.¹³ The meaningful phase information is indeed translated to RF/HF frequencies where technical noise is greatly reduced. However, in the context of quantum optics, it significantly complicates data acquisition⁸ since the single photon rate is usually (much) lower than the AOM's modulation frequency, i.e., we have (much) less than one photon per period.

For demonstration and pedagogical purposes, we have independently developed a double heterodyning scheme in

which two AOMs are used to shift the signal up and back to frequencies low enough that the beat note can be real-time recorded with a convincing signal-to-noise ratio on an oscilloscope.

IV. EXPERIMENTAL SETUP

Our experimental setup is depicted in Fig. 3. It consists of essentially three parts outlined by (online) color boxes. We use a conventional single photon source (red box) based on spontaneous parametric down conversion.^{5,6,14,15} A 30 mW, 405 nm laser diode pumps a 1 mm-long crystal of beta-barium borate (BBO) producing photon pairs, whose wavelengths are both centered at 810 nm via type-I down-conversion. Crystal orientation is such that photons are emitted in separate directions $\sim 3^\circ$ apart from the pump laser direction. At 50 cm downstream, beams are separated enough to be injected into multimode fibers after passing a 10 nm bandwidth interference filter.

Down-converted photons are produced simultaneously. One photon, labeled by a subscript 0, is directly sent into a 5 m-long multimode fiber connected to an avalanche photodiode (APD) that triggers the coincidence detection module. It heralds the presence of the second photon which is directed towards the interferometer with a 2 m-long multimode fiber.

The detection module (black box) consists of several single photon detectors based on silicon avalanche photodiodes (APD₀₋₁) connected to a FPGA card (Altera DE2-115). This card is programmed in order to provide counts N_i on each channel and coincidences between all channels C_{ij} within a tunable time-window of 9–20 ns. For this experiment, we measure counts N_0 , N_1 , and coincidences C_{01} . All data (counts and coincidences) are sent to a computer via a RS232 interface. Acquisitions programs are inspired from those provided by Beck and co-workers.^{16,17}

Our interferometer (blue box) is built to be as symmetric as possible, using Crystal Technology #3080 AOMs. The beam waist of the incoming photons from the fiber coupler FC₂ is imaged on AOM_A by lens L_1 . Then it is further

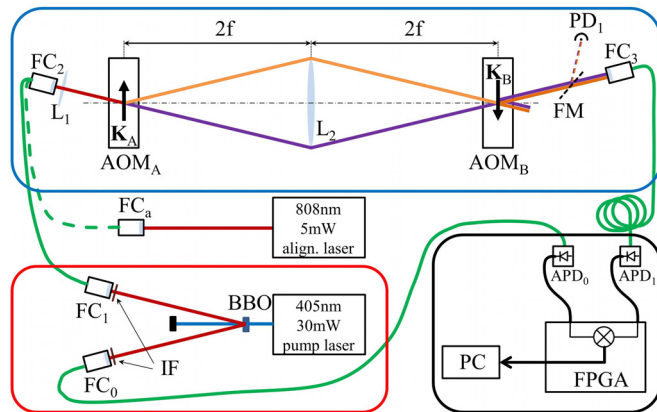


Fig. 3. The experimental setup is made of a single photon source (red box, lower left), a detection module (black box, lower right), and the interferometer (blue box, top). The meaning of the different labels is L: lens; FC: fiber coupler; APD: avalanche photodiode; IF: interference filter; FPGA: field programmable gate array; PC: personal computer. Green lines represent multimode fibers. For alignment purposes and classical light operation, we use an extra fiber-coupled (green dashed line) 808 nm laser. A flip mirror (FM) is lifted and light directed on conventional linear photodiodes (PD).

imaged on AOM_B with the help of lens L_2 in a $2f$ - $2f$ configuration. One output port is then coupled into a 2 m-long multimode fiber and directed toward an avalanche photodiode connected to the detection module. The overall length between FC₂ and FC₃ is typically 2 m. For a 9 ns coincidence window, the path-length \mathcal{L}_0 of the heralding photon (FC₀-APD₀) and \mathcal{L}_1 that of the interfering photon (FC₁-APD₁) should be equal to better than 1 m. Assuming a typical $n = 1.5$ refraction index of the fibers, we have $\mathcal{L}_0 \approx 1.5 \times 5 = 7.5$ m and $\mathcal{L}_1 \approx 1.5 \times (2 + 2) + 2 = 8$ m.

The acoustic waves travel in opposite directions in both AOMs so that the frequency shifts almost cancel. The coherence length L_c of our parametric down-conversion source is determined by the spectral width of the filters. L_c is thus on the order of 0.1 mm here. The $2f$ - $2f$ configuration of our interferometer ensures that both AOMs are conjugate, which translates into an equal path length of both arms of the interferometer. The symmetry of the setup makes the path-length difference of second order with respect to small misalignments and displacements and probably plays a key role in the success of the experiment, especially since the coherence of the source is so low.

Alignments are made easy by a separate fiber-coupled 808 nm laser that can be plugged in place of the single photon source at FC₂. At the output side, a flip mirror is lifted up and beams are directed towards conventional linear photodiodes. Classical beat notes are then recorded on an oscilloscope [Fig. 4(a)].

The two AOMs are driven by a dual output waveform generator, which allows a phase control between the outputs to ensure their phase coherence. They are operated at angular frequencies Ω_A and Ω_B around their nominal frequency of 70 MHz.

Let us first assume *homodyne operation* $\Omega_A = \Omega_B = \Omega$. We can follow the propagation of the different modes according to the pictorial approach presented in Sec. II and in the lower part of Fig. 2. The role of the lens L_2 is to deflect the beams towards the second AOM. Due to the symmetry of the setup, it reverses the transverse momentum of the photons $\pm q \rightarrow \mp q$. This translates in the exchange of the column of the mode matrix. The effect of the second AOM is then calculated taking into account the opposite direction of the acoustic wave. In practice, light is injected from only one port, e.g., $E_2 = 0$. The fields at the two output ports are then

$$\begin{aligned} E_3 &= (r_B^* r_A e^{i\phi_{up}} - t_B t_A^* e^{i\phi_{down}}) E_1^0 e^{-i\omega t}, \\ E_4 &= -(t_B^* r_A e^{i\phi_{up}} + r_B t_A^* e^{i\phi_{down}}) E_1^0 e^{-i(\omega+\Omega)t}, \end{aligned} \quad (5)$$

where explicit time dependence has been added for the sake of clarity. $\phi_{up} = \phi_0 + \delta\phi$ and $\phi_{down} = \phi_0 - \delta\phi$ represent the phaseshifts accumulated along the upper and lower arms of the interferometer. Notice that even if the two paths have the same optical length \mathcal{L} the upper one is run along at a slightly higher frequency and presents an extra phase shift $-\Omega\mathcal{L}/c$.

In the ideal case of a perfectly balanced interferometer, all reflection and transmission coefficients are real and equal ($|r_{A,B}| = |t_{A,B}| = 1/\sqrt{2}$). The output amplitudes are then $E_3^0 = ie^{i\phi_0} E_1^0 \sin \delta\phi$ and $E_4^0 = -e^{i\phi_0} E_1^0 \cos \delta\phi$. Static complementary fringes are expected at the two output ports, when the phase difference $\delta\phi$ is scanned almost as in a conventional Mach-Zehnder interferometer. The only difference is

the angular frequency shift Ω at output #4 which is not resolved here.

Heterodyne operation is much more interesting. It corresponds to the case in which AOMs are driven at different angular frequencies $\Omega_A = \Omega$ and $\Omega_B = \Omega + \delta\Omega$. Our formalism is easily adapted adding an extra $\exp(-i\delta\Omega t)$ to the reflection coefficient r_B of the second AOM. Then, still for a perfectly balanced interferometer, we find

$$\begin{aligned} E_3^0 &= ie^{i\phi'_0} E_1^0 \sin(\delta\Omega t/2 + \delta\phi), \\ E_4^0 &= -e^{i\phi'_0} E_1^0 \cos(\delta\Omega t/2 + \delta\phi), \end{aligned} \quad (6)$$

with $\phi'_0 = \phi_0 + \delta\Omega t/2$. We now expect complementary beat notes at the two output ports.

In a quantum formalism, we would consider the fields as operators (\hat{E}_3 and \hat{E}_4) and the quantum state would be expressed in the basis of the input modes as $|\psi\rangle = |1\rangle_1 |0\rangle_2$, where $|1\rangle_1$ is a single-photon Fock state in mode 1 and $|0\rangle_2$ is the vacuum state for mode 2. The expression of output mode \hat{E}_3 should include the contribution of the mode \hat{E}_2 even if it is in the vacuum state. We can therefore write

$$\begin{aligned} \hat{E}_3 &= i \sin(\delta\Omega t/2 + \delta\phi) e^{i\phi'_0} \hat{E}_1 \\ &\quad + i \cos(\delta\Omega t/2 + \delta\phi) e^{i\phi'_0} \hat{E}_2 e^{-i\Omega t}. \end{aligned} \quad (7)$$

The APD measures a photodetected current on mode 3, which is proportional to $\langle \psi | \hat{E}_3^\dagger \hat{E}_3 | \psi \rangle \propto \sin^2(\delta\Omega t/2 + \delta\phi)$, oscillating at the angular frequency $\delta\Omega$. It is not surprising to find the same result as in the classical treatment: quantum optics textbooks tell us that when we are dealing with linear optics in a counting regime, classical and quantum optics behave similarly.

V. EXPERIMENTAL RESULTS

The experiment can be run in essentially three different ways that we now detail successively.

A. Classical beat notes

As shown in Fig. 4, purely classical beat notes are observed when the 808 nm alignment laser is used. We have recorded them for a wide range of frequency differences, from mHz up to almost 1 MHz constrained by our photodiodes' bandwidth. Using the synchro output of the waveform generator, we have also observed the expected temporal shift when scanning the relative phase of the two AOMs. These findings confirm the overall coherence of our setup and, in particular, of AOMs as beam splitters.

B. Classical counting mode

The same kind of signals has been recorded in the count rate of individual photons emanating from the down-conversion source as shown in Fig. 4(b). However, even if photons are detected as well separated events, with a mean temporal delay far exceeding the transit time into the interferometer (i.e., with less than one photon at a time into the interferometer), these are not considered as true single photon experiments. In such low light experiments, the photon statistics remain classical (Poissonian): The delay distribution between two successive photons is a decreasing

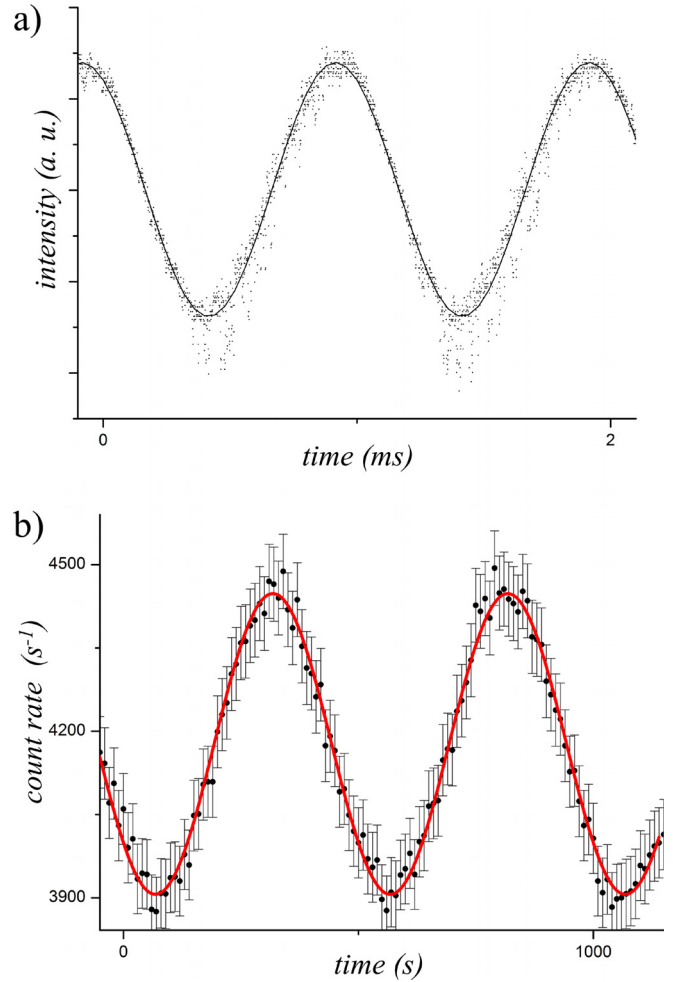


Fig. 4. Classical beat notes. (a) Light flux from the 808 nm alignment laser is in the mW range and easily detected on conventional linear photodiodes. AOMs are operated at 1 kHz frequency difference for convenient visualization on an oscilloscope (AC mode). (b) The down-converted photons flux is many order of magnitude smaller. Detection relies on avalanche photodiodes (APD) and the count rate drops to a few 10^3 s^{-1} . AOMs are then operated at 2 mHz frequency difference for high signal-to-noise ratio. The graph represents the raw count rate at APD_1 ; the source may be considered as a strongly attenuated classical one.

exponential and thus maximal at zero delay (photon bunching), much like a weak coherent state. See, for example, Ref. 18 for an early experiment of photons heterodyning using low light levels.

C. Single photon beat notes

Figure 5 shows true single photon beat notes, where the parametric down-conversion source is now associated with the FPGA module described earlier to detect coincidences rates between APD_0 and APD_1 . The results are obtained when the output photons are detected in coincidence with the heralding photon. Using single quantum events with coincidence counts ensures that we are using true single-photons. It has been carefully checked by Okawa and co-workers that the photons in coincidence diffracted by AOMs have an almost perfect photon anti-bunching behavior ($g^{(2)}(0) = 0$) and that “the single-photon properties remain unchanged after the frequency conversion” in the AOMs.⁸ Accidental coincidences (less than 1 per second) can be neglected here given our count rates.

We demonstrated experimentally that beat notes are actually observed at port #3 (see Supplementary Material for a discussion of simultaneous recording of the two output ports¹⁰). As interaction with AOMs is a coherent process, they persist at the single photon level. It means that output photons are interfering with themselves. More precisely, such photons are elementary excitations of bichromatic field modes.¹⁹ These modes are by essence not eigenstates of the energy and are thus non-stationary: their two frequency components produce a beat note at any given position. They are also spatially inhomogeneous as their two wavelengths produce Moiré fringes along the propagation axis at any given time. Orders of magnitude employed in our experiment give rise to somewhat puzzling features: for typical frequency differences of a fraction of a Hertz, the beat notes occur on a few second time scale but the spatial mode period extends over millions of kilometers.

VI. CONCLUSION AND OUTLOOK

An AOM acting as a beam splitter provides both momentum and energy transfer to incoming photons at the Bragg angle. With two such beam splitters, we realized non-stationary single photon states with periodic amplitude in both space and time. Such states are far from the naive picture of a photon being the particle counterpart of a plane wave. Indeed, both electromagnetism and quantum theory are linear, and so any superposition of solutions of Maxwell equations is an acceptable field mode to which quantum mechanics associates elementary excitations, i.e., photons. The striking single photon beat notes observed here are simply the quantum counterpart of a coherent bi-chromatic plane wave, and if we further broaden the spectrum, we may obtain the extreme case of a single photon femtosecond laser pulse. In the early 1960s, Feynman was amazed by the advent of laser technology and envisioned: “Soon, no doubt, someone will be able to demonstrate two sources shining on the wall, in which the beats are so slow that one can see the

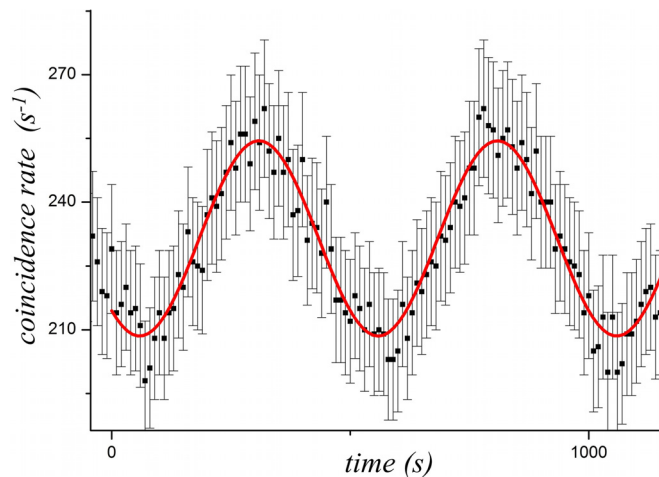


Fig. 5. Coincidence rate between the interferometer output [APD_1 see Fig. 4(b)] and heralding photons recorded on APD_0 . Such a coincidence detection ensures, up to negligible random accidental coincidences, that both photons come from the same down-conversion event. A single photon passes through the interferometer yet exhibiting a beat note. From a quantum optics point of view, the output field state is an excitation of a superposition of modes of two different frequencies. Such a state has not a definite energy and is thus non-stationary.

will get bright and dark!”²⁰ We have done a step forward as here, one can see single photons beating on an oscilloscope screen.

This experiment may be considered as a photonic analogue of early day atom interferometry setups using detuned separated oscillatory fields as beam splitters. These experiments searched for off-diagonal terms of the density matrix of thermal atomic beams.^{21–23} Non-stationary beam splitters induce energy transfer and thus produce mixing of different energy components in the incoming particles’ spectrum. The setup presented here would naturally allow the investigation of the same kind of questions about coherence of photon sources.

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Pair of Parabolic Mirrors

This pair of parabolic mirrors can be used for a several lecture demonstrations. If a pocket watch is found, it can be placed at the focal point of one of the mirrors. A small earphone placed at the focal point of the other will then pick up the sound. A small, hot object placed at one focus will be imaged at the other focus. In earlier days a glowing coal was used as the source, and the detector was a small bit of guncotton or phosphorous! This pair of mirrors is in the demonstration room of the University of Utah. (Picture and text by Thomas B. Greenslade, Jr., Kenyon College)