Indistinguishable Photon Pairs from Independent True Chaotic Sources

Amir Nevet,1,* Alex Hayat,1,2 Pavel Ginzburg,1,3 and Meir Orenstein 1

1Department of Electrical Engineering, Technion, Haifa 32000, Israel
2Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada
3Department of Physics, King’s College London, London WC2R 2LS, United Kingdom

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Indistinguishability of events in quantum mechanics is manifested by interference between their probability amplitudes. We report a unique kind of interference occurring between indistinguishable events of photon-pair emission, where each photon of the pair is emitted from a distinct true chaotic light source and has a different energy. The indistinguishability results in an interference which is observed as an ultrafast modulation of the second-order coherence function, measured on a femtosecond time scale by two-photon absorption in a semiconductor photomultiplier tube.

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Interference, one of the most fundamental concepts in physics, has been subject to a lively debate for many decades. The classical description, which allows interference between waves regardless of their origin, was contradicted by Dirac’s statement that “Each photon interferes only with itself. Interference between different photons never occurs” [1]. This statement was confronted soon after by a demonstration of interference between two independent lasers [2]. This apparent conflict between the classical and the quantum descriptions of coherence also caused the difficulty to accept the results of the Hanbury Brown–Twiss (HBT) experiment [3], where a second-order coherence measurement was introduced, allowing the characterization of light coherence properties by intensity correlations. These controversies were among the triggers that initiated the rapidly growing field of quantum optics, which widely employs two-photon interference effects for applications as well as for tests of the foundations of quantum-physics, including the interplay between light quanta and coherence [4]. It became evident that interference is a much more general concept than the one-particle phenomenon described by Dirac. Two-photon interference was shown to result from the indistinguishability of two-particle paths [Fig. 1 inset (I)], and was demonstrated using nonclassical light with same-color photons generated either in different sources [5–7], or in a single source at different times [8,9], using different-color photons originating in a single source [10], as well as using a single pseudothermal light source [11], described by Scarcelli et al. as: “each pair of independent photons interfering with itself.” However, interference between independent true chaotic light sources has not been observed before.

Second-order interference between pseudothermal light sources with chaotic-like spatial correlations between photons, generated using a spatially-randomized laser, was proposed as a simpler alternative to entangled-photon interference in quantum optical applications [12] and was demonstrated experimentally [13]. Other light properties previously considered exclusively nonclassical were demonstrated with pseudothermal light sources, including high-resolution diffraction [14], subwavelength interference [15], and the investigation of photon interaction effects on the statistics of pseudothermal light [16]. However, in a pseudothermal source the photons are generated initially within a single laser, and therefore despite the lack of mutual spatial coherence, mutual temporal coherence is maintained. Moreover, interference between photons emitted from the same source has the drawback that the photons may have interacted, e.g., through the

FIG. 1 (color online). Experimental setup: two chaotic sources Source 1 and Source 2 are combined using a 50/50 fiber coupler, enter a Michelson interferometer through a λ0 > 1 μm long-pass filter, and are detected by TPA in a GaAs PMT. Insets are schematic diagrams of two-particle path interference for two-color photon pairs (I) with two detectors for simultaneously emitted photons (II) by TPA for photons emitted at different times.
collective mechanism of lasing, or through the interactions which determine the energy distribution of a thermal source. Pseudothermal sources have been used previously due to their long coherence times, whereas observing statistical properties of true chaotic sources by conventional methods has been prevented by the slow response of photon detectors and electronics, limited to the picosecond scale [17]. Recently, two-photon absorption (TPA) in a semiconductor-based photomultiplier tube (PMT) was employed for a photon-bunching measurement of true chaotic light sources implemented by amplified spontaneous emission (ASE) from an Er\textsuperscript{3+}-doped fiber amplifier (EDFA) and by a halogen lamp, having femtosecond-scale coherence times [18]. Observation of two-photon interference between two independent true chaotic light sources emitting photons of different energies can fully address the “different photon” aspect of Dirac’s statement and enable possible future applications based on chaotic sources.

Here we demonstrate interference between indistinguishable amplitudes of different-energy photon-pairs generated either in two sources within a single device or in two completely independent true chaotic light sources. This observation extends the concept of interference to pairs of particles with different energies that have never interacted, and are mutually-incoherent—both spatially and temporally. The two-color interference is manifested in a modulation of the ultrafast second-order temporal coherence measurement, \(g^{(2)}(\tau)\), obtained in a Michelson interferometer by TPA in a PMT (Fig. 1), whereas the different-energy photons are verified to have no mutual coherence by first-order coherence measurements.

TPA is a nonlinear optical process that combines detection of two photons with femtosecond time-scale multiplication. In this realization of two-photon interference, both photons are detected simultaneously and at the same spatial location; however, the emission times of the photons in continuous sources are undefined within their coherence time. Therefore, in this scheme an event of early photon emission from the first source (s1) and a later emission from the second source (s2) interferes with an event of the opposite time order [Fig. 1 inset (II)]. Two-photon interference between different photon emission times was recently shown to have unique quantum characteristics [19], and is widely employed in photon time-energy schemes with Franson interferometers [20]. These concepts can benefit from a chaotic source. Specifically, two-color interference between chaotic sources was recently predicted to produce higher resolution than its quantum counterpart in ghost imaging [21].

The expression for the second-order coherence function is given by [22]:

\[
g^{(2)}(t_1, t_2) = \frac{\text{Tr}[\rho E^{(-)}(t_1)E^{(-)}(t_2)E^{(+)}(t_2)E^{(+)}(t_1)]}{\text{Tr}[\rho E^{(-)}(t_1)E^{(+)}(t_1)]\text{Tr}[\rho E^{(-)}(t_2)E^{(+)}(t_2)]}
\]

where \(E^{(+)}\) and \(E^{(-)}\) are the positive and negative frequency parts of the electric field operators at time points \(t_1\) and \(t_2\), \(\rho\) is the density operator describing the detected radiation, and \(\text{Tr}\) is the trace operation. The transition rate of either atomic or semiconductor TPA of two fields is proportional to \(\text{Tr}(\rho E^{(-)}_1 E^{(-)}_2 E^{(+)}_2 E^{(+)}_1)\) [23]; therefore, \(g^{(2)}(t_1, t_2)\) can be obtained from the TPA-induced photocurrent in a semiconductor device. Chaotic light is modeled as an incoherent statistical mixture of photon-number states, where assuming low light intensity (equivalent to low detection efficiency in our case) allows neglecting number states higher than two [24]. For two independent chaotic sources with central frequencies \(\omega_1\) or \(\omega_2\), the density operator is proportional to (up to an overall normalization factor):

\[
\rho_{\text{chaotic}} = |0\rangle\langle 0| + \left(\sum_{k,s} \alpha_{1,k,s}|1^{(\omega_1)}_{k,s}\rangle\langle 1^{(\omega_1)}_{k,s}| \otimes |0^{(\omega_2)}\rangle\langle 0^{(\omega_2)}| + \sum_{k,s} \alpha_{2,k,s}|1^{(\omega_2)}_{k,s}\rangle\langle 1^{(\omega_2)}_{k,s}| \otimes |0^{(\omega_1)}\rangle\langle 0^{(\omega_1)}| \right)
\]

where \(|\alpha_{1,k,s}|^2\) and \(|\alpha_{2,k,s}|^2\) are proportional to the probability of detecting a single photon with wave number \(k\) and polarization \(s\) from sources 1 and 2, respectively. Defining \(\tau = t_1 - t_2\) as the time difference between the two arms of the interferometer, and assuming equal intensities of the two sources, the terms leading to the interference are:

\[
\sum_{k,s,m,n} \langle 1^{(\omega_1)}_{k,s}, 1^{(\omega_2)}_{m,n}|E_{m,n}^{(-)}(0)E_{k,s}^{(-)}(\tau)E_{m,n}^{(+)}(\tau)E_{k,s}^{(+)}(0)|1^{(\omega_1)}_{k,s}, 1^{(\omega_2)}_{m,n}\rangle \\
\propto e^{-i(\omega_2 - \omega_1)\tau} g_1^{(1)}(\tau)g_2^{(1)}(\tau),
\]

\[
\sum_{k,s,m,n} \langle 1^{(\omega_1)}_{k,s}, 1^{(\omega_2)}_{m,n}|E_{k,s}^{(-)}(0)E_{m,n}^{(+)}(\tau)E_{k,s}^{(+)}(\tau)E_{m,n}^{(-)}(0)|1^{(\omega_1)}_{k,s}, 1^{(\omega_2)}_{m,n}\rangle \\
\propto e^{i(\omega_2 - \omega_1)\tau} g_1^{(1)}(\tau)g_2^{(1)}(\tau),
\]

where \(g_{1(2)}^{(1)}(\tau)\) is the first-order coherence for source 1 (2). The resulting expression for the second-order coherence is:

\[
g^{(2)}(\tau) = 1 + |g_1^{(1)}(\tau)|^2 + |g_2^{(1)}(\tau)|^2 + 2\text{Re}[g_1^{(1)}(\tau)g_2^{(1)*}(\tau)]\cos[(\omega_2 - \omega_1)\tau]
\]

According to Eq. (3), a modulation is expected in \(g^{(2)}(\tau)\) corresponding to the beating at the difference frequency of the two sources, which should be significant within the coherence times of the sources [Fig. 1 inset (II)]. It should be noted that since chaotic sources are “classical” sources, the second-order coherence function obtained in Eq. (3) as a result of quantum considerations, as well as the interpretation of the experimental results throughout the paper,
could be also derived from classical theory. However, a quantum modeling is more comprehensive than the classical one as was demonstrated in many works in the field of ghost imaging.

In our experiments, second-order interference between photons from several different chaotic sources was examined, implemented by two different EDFAs generating ASE. The output powers were controlled using the variable gain and using constant fiber attenuators, attaining a level of $\sim 200 \, \mu W$ at the detector. The Michelson interferometer and the detector were placed inside a light-shield to reduce background detection. A dark-count level of 140 counts/sec was subtracted from the measurements. The radiation generated a signal level on the order of $10^4$ counts/sec, which corresponds to less than $10^{-8}$ counts per coherence-time, maintaining a good accuracy for the extraction of $g^{(2)}(\tau)$ from the TPA-induced current. Each source, by its specific design, exhibited a different spectrum at the wavelength range of 1.5–1.6 $\mu m$, as well as different coherence times, dictating the structure of its second-order coherence function.

First, $g^{(2)}(\tau)$ measurements for each of the two sources were conducted. Light from the source was sent into a Michelson interferometer through a long-pass filter (> 1 $\mu m$), and was focused on a GaAs PMT, analyzed for TPA responsivity at this spectral range in [18]. The measured TPA count dependence on the displacement of one mirror of the interferometer results in interferograms [Fig. 2(a) and 2(c)] containing a term proportional to $g^{(2)}(\tau)$, which is extracted by averaging out the high-frequency oscillating terms [18,25]. Each spectral component of each source was assumed to have both Lorentzian and Gaussian broadening, hence $g^{(2)}(\tau) = 1 + \exp\left[-\frac{2|\tau|}{\tau_{c, L}} - \pi\frac{\tau}{\tau_{c, G}}\right]$. The best fit in terms of minimal root-mean-square error for each spectral component was evaluated. The emission of Source 1 is centered at 1531.2 nm [Fig. 2(a) inset], resulting in $g^{(2)}(\tau)$ of chaotic light with a combination of Lorentzian and Gaussian broadening, and a dominant coherence-time of $\tau_{c, L} = 1170$ fs [Fig. 2(b)]. Source 2 has two dominant emission peaks at 1544.8 and 1562 nm [Fig. 2(c) inset], with dominant coherence times of $\tau_{c, G} = 565$ fs (1544.8 nm), $\tau_{c, G} = 955$ fs (1562 nm). The resulting $g^{(2)}(\tau)$ is modulated by the frequency difference of the two peaks [Fig. 2(d)], in agreement with the theoretical model given by Eq. (3) and the measured coherence times, demonstrating the interference of two chaotic light sources with different central frequencies, however, generated physically in the same device—both in Source 2. To verify that the modulation in $g^{(2)}(\tau)$ is not a result of an unintentional modulation within the source, the longer-wavelength peak of Source 2 was isolated using a 10 nm-wide band-pass filter around 1560 nm [Fig. 3(a) inset], before entering the interferometer. The resulting $g^{(2)}(\tau)$ shows that the filtered source is a simple chaotic source [Fig. 3(b)], similar to Source 1.

The most conclusive demonstration of different-color two-photon interference is when the two colors are emitted from two completely independent chaotic sources. This demonstration eliminates all other possible mechanisms for modulation of $g^{(2)}(\tau)$ such as quantum beats, occurring in specific atomic systems [26]. In this experiment we used two chaotic sources from two devices: Source 1 emitting at 1531.2 nm [Fig. 2(b)], and filtered Source 2 emitting at 1561.1 nm [Fig. 3(b)], combined using a 50/50 fiber coupler [Fig. 3(c) inset I]. The measured $g^{(2)}(\tau)$ [Fig. 3(c) and 3(d)] is modulated by a relatively high frequency [Fig. 3(c) inset II] resulting from the large spectral separation between the two emission peaks. The value of $g^{(2)}(0)$

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FIG. 2 (color online). Interferograms and their averages in normalized (norm.) units from two sources separately: (a) Source 1 (c) Source 2, having different spectra as presented in each inset. Extracted $g^{(2)}(\tau)$: (b) Source 1 (d) Source 2. Dashed black lines are theoretical fits according to Eq. (3), assuming both Gaussian and Lorentzian broadening.
is slightly below 2 since there is a small difference in the focus of the two different wavelengths on the detector.

It is important to emphasize that linear detection (where the two-photon detector is replaced by a one-photon detector) does not result in interference between two independent chaotic sources—the first-order coherence measurement, \( g^{(1)}(\tau) \), of the sum of two sources with no mutual coherence is simply the sum of the two separate first-order coherence functions with no cross terms. Since a first-order coherence function is the multiplication of a Gaussian or exponential function by a sinusoidal function at the optical frequency, the sum of two such functions at two different frequencies will have a modulated envelope [Fig. 4(a) and 4(b)]. This is, however, not an interference between the sources, and the beating frequency does not exist in the Fourier domain of the signal [Fig. 4(a) inset]—a nonlinear process such as envelope detection has to follow the measurement in order to result in a new frequency which

![Figure 3](image1.png)

**Fig. 3** (color online). Interferograms and their averages in normalized (norm.) units from: (a) filtered Source 2 (only longer-wavelength peak). The inset is the spectrum of the filtered Source 2. (c) filtered Source 2 combined with Source 1. Inset (I) presents the spectrum of the combined sources, and inset (II) shows the Fourier transform of the measured \( g^{(2)}(\tau) \). Extracted \( g^{(2)}(\tau) \) for (b) filtered Source 2 (d) filtered Source 2 combined with Source 1.

![Figure 4](image2.png)

**Fig. 4** (color online). (a) One-photon detection Interferogram and average (dark gray) of filtered Source 2 combined with Source 1. The inset shows the Fourier transform of the measurement, demonstrating that the interferogram is a simple sum of the two separate interferograms, with no interference. (b) Extracted \( \text{Re}[g^{(1)}(\tau)] \) from the measurement presented in (a). The extraction is simply subtracting the mean of the interferogram normalized to one, as opposed to filtering the high-frequency terms for extracting \( g^{(2)}(\tau) \). \( g^{(1)}(\tau) \) measurements and their theory (dark gray) for: (c) combined sources with one wavelength blocked in one interferometer arm, (d) combined sources with different wavelengths blocked in each of the two interferometer arms.
is the difference frequency. The same result could be obtained by measuring the two first-order coherence functions separately and adding them numerically afterwards, which is not the case for the second-order coherence measurement—the sum of two separate second-order measurements is not equal to the second-order measurement of the sum. Such a separate summation will show a modulation of the envelope of the interferogram, but not a modulation of $g^{(2)}(\tau)$. Since $g^{(2)}(\tau)$ of chaotic sources is related to $g^{(1)}(\tau)$ through a nonlinear operation expressed in the Siegert relation: $g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$, the modulated envelope of $g^{(1)}(\tau)$ is transformed to interference in $g^{(2)}(\tau)$.

In order to rule out any mutual coherence between the emission peaks due to internal coupling, the TPA GaAs detector was replaced by an InGaAs photon-counter, acting as a one-photon absorber at these wavelengths. Mutual coherence between the two peaks would have resulted in a beating pattern in a one-photon absorption process, even if only light from one of the sources goes through two optical paths with a changing time difference—$\tau$, while the other source has only one path. This was implemented experimentally by placing a band-pass filter in one arm of the interferometer. The measured $g^{(1)}(\tau)$ for combined sources shows only the autocorrelation of the filtered part of the spectrum with itself [Fig. 4(c)] dismissing any mutual coherence between the peaks. Moreover, if the two peaks were mutually coherent, a single optical path with a changing $\tau$ for each wavelength peak would have still resulted in a beating pattern. This was tested in our experiment by placing an additional band-pass filter around 1544 nm in the second arm, which resulted in a constant $g^{(1)}(\tau)$ [Fig. 4(d)].

In conclusion, we have demonstrated indistinguishability of different-energy photon-pair paths—manifested in interference between photons from independent true chaotic light sources in a TPA-based interferometer. The ultrafast optical multiplication by TPA enables measuring modulation of the second-order coherence function within the short coherence times of the sources, and reduces significant constraints which are posed on single photon interference schemes such as dispersion manipulation and the need for implementation of single photon sources. As applications of second-order interference are being continuously developed, e.g., in ghost imaging, these results, which shed new light on the fundamental concept of interference, may pave the way for practical realization of novel quantum technologies based on chaotic light sources.

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