Measurement of Time Delays in the Parametric Production of Photon Pairs

S. Friberg, C. K. Hong, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 13 December 1984)

The spread in time intervals between the two photons produced in the process of spontaneous parametric down-conversion in a potassium dihydrogen phosphate crystal has been measured with a time resolution of the order of 100 psec. The correlation time is found to be independent of the coherence time of the pump photons or of the propagation time through the crystal, consistent with recent theoretical predictions.

PACS numbers: 42.50.+q, 32.80.Wr, 42.65.−k

The process of spontaneous parametric down-conversion, in which pump photons incident on a nonlinear dielectric are split into two highly correlated lower-frequency signal and idler photons, is one of a relatively small group of optical phenomena requiring field quantization for a description. It was first investigated experimentally in 1970 by Burnham and Weinberg,[1] and has been treated theoretically numerous times,[2–5] although usually by simplified models in which only a few quantized field modes are introduced. Exceptions are the calculations of Mollow[4] and our most recent treatment,[5] which are both multimode analyses that also describe the time correlation between the photons.

The first experiments demonstrated that the two down-converted photons are produced "simultaneously," at least within the 5–10-nsec resolving time of the counting electronics.[1] It was surmised that the delay time or correlation time T_c between the two photons might be determined by the coherence time, or the reciprocal bandwidth, of the incident light, which was of order 10^{-10} sec and therefore far beyond the limit of resolution of the experiment.[1] Other conjectures were that the transit time of the light through the nonlinear crystal provides the upper limit on the photon delay times T_c. This transit time was of order 150 psec in the first experiments,[1] and was therefore also beyond the resolution limit.

We wish to report the results of new experiments with both a narrow-band single-mode laser and a broadband laser as source, and with more than an order of magnitude greater time resolution, that show unambiguously that the time delay T_c between the two down-converted photons is independent of the bandwidth of the incident light, and can be even shorter than the propagation time through the nonlinear crystal. These results are consistent with the conclusions reached in a recent theoretical treatment,[5] according to which the intrinsic value of T_c is determined by the bandwidth of the down-converted photons, although the measured value depends also on the detector resolving time, and is therefore limited more by practical than by fundamental considerations.

An outline of the experiment is shown in Fig. 1. The 2-mm-wide light beam from a (Spectra Physics model 171) argon-ion laser oscillating at 351.1 nm is passed through an 8 cm long × 2 cm × 2 cm crystal of potassium dihydrogen phosphate (KDP), whose optical axis makes an angle of 50.35° with the normal to the crystal surface. The light produced in the process of down-conversion emerges in cones with their axes centered on the laser beam, whose angle depends on the wavelength, and it is focused into concentric rings in the focal plane of the lens. The propagation time through the KDP crystal is 402 ± 3 psec. A small mirror at the center of the lens acts as a beam stop for the uv laser beam, and there is a further beam stop at the focus of the lens. A field lens is located in the focal plane, and the field is dissected into two semicircles by a 45° mirror, which directs a portion of the one semicircle via an interference filter onto the entrance slit of detector A, while the other semicircle is passed

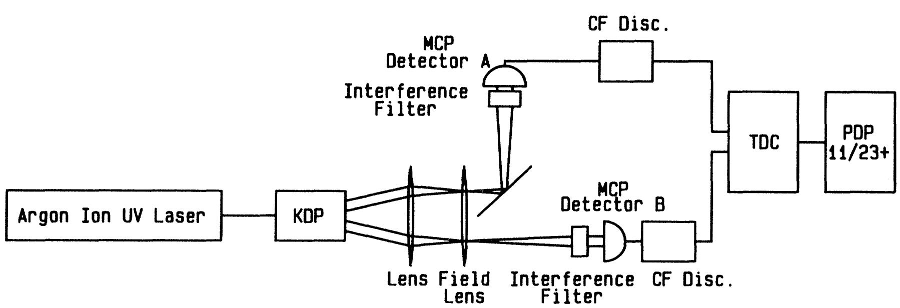

FIG. 1. Outline of the apparatus.

through another filter to the entrance slit of detector B. The two filters are tuned to two conjugate signal and idler frequencies $\omega(\mathbf{k}_1)$ and $\omega(\mathbf{k}_2)$ (within a passband of 6×10^{12} Hz) satisfying the index-matching, or energy- and momentum-conserving, conditions

$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2, \quad \omega(\mathbf{k}_0) = \omega(\mathbf{k}_1) + \omega(\mathbf{k}_2), \tag{1}$$

in which $\mathbf{k}_0$ is the wave vector of the incident laser beam. In the experiments the frequencies $\omega(\mathbf{k}_1)$ and $\omega(\mathbf{k}_2)$ correspond to wavelengths of 660 and 750 nm, respectively. The light emerging from the two interference filters is allowed to fall on two microchannel-plate photomultipliers (Hamamatsu R1645), whose transit-time spread is of order 100 psec. The photoelectric pulses are fed to two constant fraction discriminators, where the pulses are standardized, and then to the start and stop inputs of a time-to-digital converter (TDC), that digitizes the time interval τ between start and stop pulses in units of $T_R = 50$ psec, and passes the information to the computer memory. After many counting cycles, the number of events $n(\tau)$ in delay channel τ provides a measure of the probability that a conjugate photon pair is detected with a time separation τ, after accidental events are subtracted out. After N_s start pulses, the expected number of accidental events in any channel is approximately $N_s R_2 T_R$, where R_2 is the total photon counting rate at the stop input. In practice, $N_s R_2 T_R$ was of order 1 or 2 per 50-psec channel. In order to save processing time, only those events were recorded in which a start pulse was actually followed by a stop pulse within 100 nsec.

The results of measurements in which the argon laser was operated in a single mode at wavelength $\lambda = 351.1$ nm with the help of an etalon inside the cavity are shown in Fig. 2(a). The pump power was about 10 mW, which led to a correlated-photon-pair detection rate of about 1/sec. The absolute values of the delay were increased artificially by delaying cables, and are not significant. The interesting quantity is the spread of delay times T_c between the two down-converted photons, which is about 150 psec when measured at half height of the distribution. A more precise measure of spread is provided by the standard deviation of the distribution, which is 168 ± 5 psec. Examination of the laser linewidth with a uv Fabry-Perot interferometer showed that this was certainly below the resolution limit of 25 MHz, which corresponds to a coherence time of the pump field greater than about 40 nsec. This time exceeds the correlation time of the down-converted photons by more than 2 orders of magnitude.

Figure 2(b) shows the results of other measurements in which the etalon was removed, and the argon laser was operated in a multimode configuration, with a bandwidth of order 1500 MHz, or a coherence time well below 1 nsec. The laser power was again about 10 mW. This time the standard deviation is 185 ± 7 psec. The two distributions are very similar, despite the fact that the coherence times of the pump photons differed by several orders of magnitude.

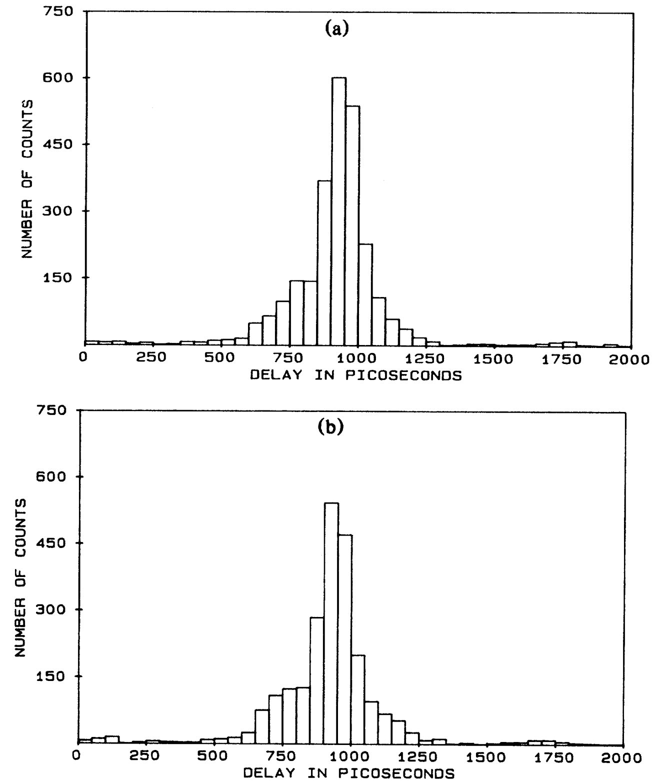

FIG. 2. The measured time-delay distributions (a) for a single-mode laser (number of correlated photon pairs detected is 2542), and (b) for a multimode laser (number of correlated photon pairs detected is 2301).

Finally, we would like to make some estimate of the intrinsic delay times T_c between the two down-converted photons, after instrumental effects are subtracted out. A lower bound on T_c is provided by the bandwidths $\Delta\omega$ of the detected down-converted light beams, which are largely determined by the filters and are of the order of 6×10^{12} Hz. T_c therefore has to be greater than 0.1 psec.

In our experiment the measured spread of delay times is dominated by the 100-psec transit-time spread of the electrons in each of the two microchannel-plate detectors. Let us make the very rough assumption that for coincident photons these transit-time spreads, together with other electronic trigger time spreads, result in a Gaussian distribution of measured delays with a standard deviation of not less than 140 psec. Assuming that the intrinsic delay-time distribution when convolved with the instrumental distribution gives rise to the observed distribution, we can arrive at an upper bound on the width of the intrinsic distribution. For Gaussian distributions this leads to upper limits on the intrinsic spread of delay times T_c between signal and idler photons of 91 and 120 psec for the single-mode and multimode pump beams, respectively. These figures are both shorter than the 400-psec transit time of the light through the KDP crystal. Our experiment is therefore at least consistent with the conclusions reached in a recent theoretical treatment,[5] according to which the measured correlation time should be of the order of the resolving time when this exceeds $1/\Delta\omega$, and of order $1/\Delta\omega$ otherwise.

The exceedingly short time interval between signal and idler photons, even when the incident pump photon has a very long coherence time, implies that the emitted photons have a substantial energy spread, and it suggests some interesting possible applications.[6] The phenomenon is a reflection of the fact that while the sum of signal and idler photon energies is very well defined, the energy of each individual down-converted photon is not.

This work was supported by the U.S. Office of Naval Research and by the National Science Foundation.

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