Frustrated Two-Photon Creation via Interference

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We demonstrate the suppression and enhancement of the spontaneous emission of entangled photon pairs in parametric down-conversion using suitably placed external mirrors. The mirrors permit interference between two possible ways of creating the photon pair. In principle these mirrors can be placed at an arbitrarily large distance from the crystal. The effect is of first order in the intensity of the down-conversion radiation.

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Modification of the spontaneous emission of an atom by its surrounding environment was first suggested some years ago [1]. Recently the phenomenon has been investigated in various elegant experiments involving atoms close to mirrors [2], in high finesse microwave cavities [3], in optical cavities [4], and in three-dimensional dielectric media [5]. In a simple description light propagating from an atom placed close to a mirror can reach a detector either directly or via reflection in the mirror. When the two paths cannot be distinguished, constructive and destructive interference effects occur between reflected and direct spontaneous emission. When the atom-mirror distance is sufficiently small, i.e., of the order of the wavelength, emission into all spatial modes can be suppressed. In contrast, in the experiment described here we show that it is possible using external mirrors to suppress or enhance the emission into a specific pair of spatial modes in parametric down-conversion for very long crystal-mirror distances. These are truly one-photon (and thus nonclassical) interference effects in the sense that we can gate detection of one photon conditionally on detection of its partner. Our arrangement is topologically similar to an experiment [6] where the case of frequency doubling was investigated, an entirely classical effect.

The entangled nature of the photon pair generated by parametric down-conversion has been utilized hitherto in a number of fundamental experiments in quantum optics. Particularly one should emphasize the experiments demonstrating the nonlocality of quantum mechanics as signified by Einstein-Podolsky-Rosen considerations and Bell's theorem [7–10]. Such experiments demonstrate in an impressive way the nonclassical interference of the emitted photons in second or even in first order [11]. The experiment described here links the nonclassical behavior of parametric down-converted photons with the emerging field of photonic semiconductors [5], in the sense that it demonstrates how the creation of a two-photon field can be manipulated by changing external boundary conditions.

Consider the process of parametric down-conversion [Fig. 1(a)]. An UV photon spontaneously converts into a pair of red photons. The state of the pair after the crystal is

$$|\Psi\rangle = \alpha|1\rangle_{s_1}|1\rangle_{i_1} + \cdots , \tag{1}$$

where α is the amplitude for emitting the photon pair into the spatial modes $|\,\rangle_{s_1}$ and $|\,\rangle_{i_1}$. This amplitude is very small ($|\alpha| \ll 1$) and thus we neglect all terms $O(|\alpha|^2)$. For reasons of simplicity we only consider emission into the modes mentioned. The pump beam is assumed to be a coherent state (or a classical field) and therefore it is essentially unchanged by removing one photon. An important feature, however, is that the transmitted pump and the created photon pair (as a whole) are

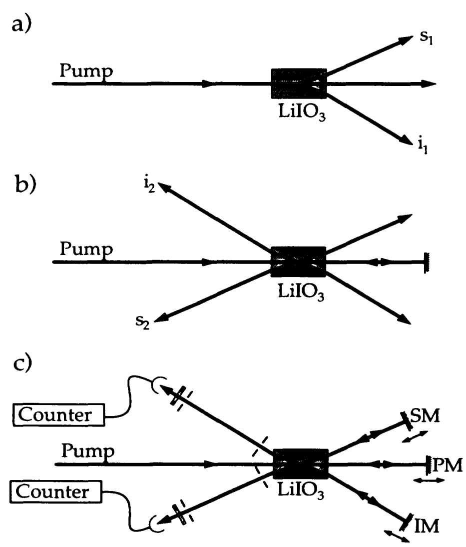

FIG. 1. Principle of the experimental setup: (a) In the standard setup of parametric down-conversion an entangled photon pair may be emitted into the two outgoing modes shown. (b) The pump is reflected back onto itself such that another possibility for creating the photon pair arises. (c) The first modes of the down-converted photons are also reflected back. Thus the two possible ways of creating the photon pair may now interfere. The diaphragms serve to define one single mode and filters select out energy matched pairs.

still coherent to each other because of energy conservation and hence unitarity in the down-conversion process [12].

Next consider the experiment in Fig. 1(b). In this case the pump is retroflected back into the crystal and therefore there is a second possibility for the process of down-conversion to occur. For simplicity we take into account only those modes which are emitted into directions opposite to the first modes. There again a phase relation exists between emitted photon pair and pump. Therefore the state is now of the form

$$|\Psi\rangle = \alpha|1\rangle_{s_1}|1\rangle_{i_1} + e^{i\phi_p}\alpha|1\rangle_{s_2}|1\rangle_{i_2}, \quad (2)$$

where ϕ_p includes the phase difference accumulated by the pump beam between the two emission processes.

Now, finally we reflect the first signal-idler modes back through the crystal such that they overlap with the second signal-idler modes [Fig. 1(c)]. Thus we may set $|\rangle_{s_1} \to |\rangle_{s_2} =: |\rangle_s$ and $|\rangle_{i_1} \to |\rangle_{i_2} =: |\rangle_i$ and the resulting two photon as emitted by the down-conversion into the modes state takes the form $|\rangle_i$ and $|\rangle_s$:

$$|\Psi\rangle = \alpha(e^{i\phi_p} + e^{i(\phi_s+\phi_i)})|1\rangle_s|1\rangle_i, \quad (3)$$

where ϕ_s and ϕ_i are the phases accumulated by the first signal and idler, respectively, to their mirror and back. Again terms of $O(|\alpha^2|)$ are neglected. Equation (3) makes the remarkable prediction that the signal and the idler count rates both vary as

$$I_i = I_s = 2I_0\left\{1 + \cos(\phi_i + \phi_s - \phi_p)\right\}, \quad (4)$$

where $I_0 \propto |\alpha|^2$ is the rate of photon emission into either mode without mirrors present.

Formally speaking the state of Eq. (3) is not entangled anymore yet it still carries the signature of the entanglement of Eq. (2) through the fact that the intensity oscillations are modulated by the sum of the two phases ϕ_i and ϕ_s. Furthermore, the intensities I_i and I_s are varying in an identical way. Thus varying, say, the position of the idler mirror varies both intensities with the period as given by the idler wavelength. Our new result can be interpreted such that the two possible ways of emission of the photon pair into the modes $|\rangle_s$ and $|\rangle_i$ interfere whenever it is not possible to determine whether the pair was created by the first or the second passage of the pump.

A more complete theoretical approach has to take into account the finite coherence lengths of the pump beam and of the down-converted radiation. It then follows that the mean distance from the crystal for all three mirrors is essentially a free parameter. However, the crystal-mirror path length for the pump should not differ by more than the coherence length of the pump (a few meters in our experiment) from the distances from the crystal to the signal and the idler mirror. Recall in contrast that in the experiments with atomic sources it was necessary to place the radiating sample close to the mirrors (within the coherence length of the spontaneously emitted light) in order to see a modification of the spontaneous emission. Here it is only the *relative* position of signal and idler mirror which has to lie within the coherence length of the spontaneously emitted down-converted light (≈ 260 μm in our experiment).

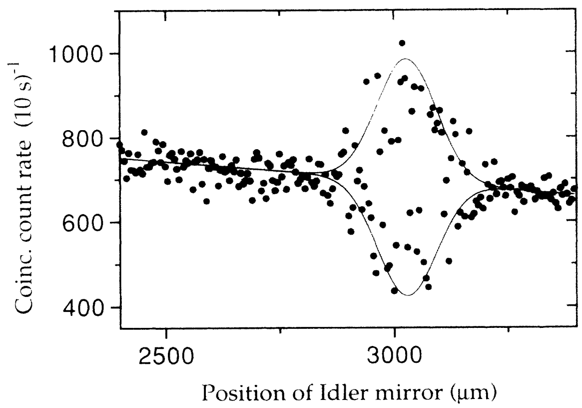

FIG. 2. Variation of the signal-idler coincidence rate during a coarse scan of the idler mirror. The intensity oscillations indicate the region where interference occurs. The lines are a guide to the eye. The slight decrease of the count rate is due to a small reduction of the laser intensity with the time.

In our experiment the source of the two photons is a nonlinear crystal of $LiIO_3$ optically pumped by the 351.1 nm line of a single-mode argon-ion laser. Apertures are placed to satisfy the phase matching conditions for signal and idler photons at wavelengths 632.8 nm and 788.7 nm, respectively. This down-conversion light is further limited to a bandwidth of 5 nm by employing interference filters. The two beams are detected using silicon avalanche photodiodes operating in the Geiger mode [13]. The pulses are amplified, pulse shaped, and then both directly counted individually for each detector and sent to a time to amplitude converter which operates as a coincidence counter. Both the singles count rates and the coincidence count rate are recorded on a personal computer which is also used to control the positions of the mirrors. The external mirrors are arranged as in Fig. 1(c) and they are placed at a distance of about 120 mm from the crystal initially equal to each other within about ± 1 mm. There are no slits, mirrors, or diaphragms between the crystal and any of the three mirrors. For high visibility interference effects the two interaction regions within the crystal must overlap and the two signal (idler) modes should be indistinguishable. This is guaranteed by placing two small diaphragms separated by 90 cm in both the signal and idler beam between the crystal and detectors, which are about 1.2 m from the crystal. If these apertures are closed to their smallest diameter (≈ 0.8 mm), the bandwidth of the parametric light reaching the detectors is only limited by them (to a half-width of about 1.7 nm) and no longer by the bandwidth of the interference filters. A single diaphragm in the pump

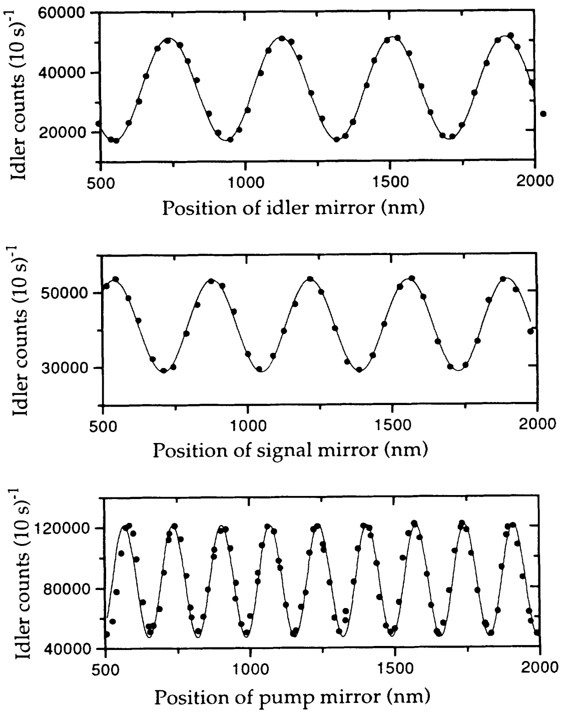

FIG. 3. The idler count rate is shown in dependence on the displacement of signal, idler, and pump mirrors. The oscillation period of these idler fringes in all three cases is given by half of the wavelength of the photons in the beam whose mirror is translated.

beam placed some meters before the crystal is used to align the reflected pump beam such that it returns on itself. A 1 m focal length lens weakly focuses the pump beam at the pump mirror guaranteeing that the pump beam diameter in the crystal is smaller than the smallest mode selection apertures.

The relative positions of the signal and idler mirrors are scanned, initially using a stepper motor stage. In initial experiments coincidence detection was chosen (Fig. 2) to separate only those photons belonging to a pair from the background. A variation in the coincidence rate locates the optimum mirror position. The fringes could then be observed scanning either of the three mirrors with resolution much shorter than the wavelength using piezodriven stages. By careful adjustment of the aperture positions the effect can be improved to give high visibility interference in the singles count rates.

Figure 3 shows the idler fringes obtained if one moves alternatively signal, idler, or pump mirror. In agreement with Eq. (4) the fringe period is given by half the wavelength of the beam whose mirror is scanned. The slight quantitative discrepancy is due to drift of the mirror mounts. Higher mean count rates in the pump mirror scan are owed only to the different laser power used in this particular measurement. The results of Fig. 3 clearly show that all three mirrors together define the boundary condition for emission of the idler and hence also for the

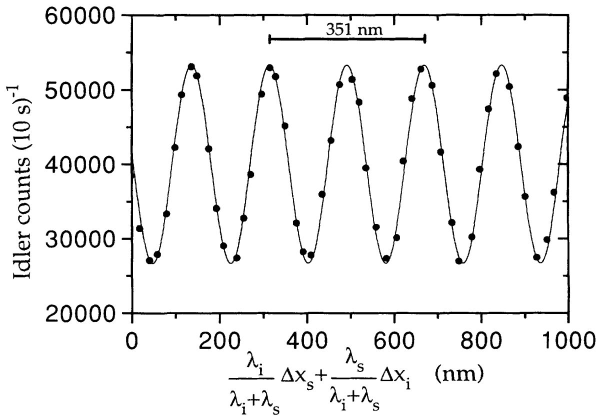

FIG. 4. Measurement of idler count rate when both signal and idler mirror are translated simultaneously. The abscissa represents a weighted sum of these displacements and it corresponds to an equivalent displacement of the pump mirror.

signal photon.

This is demonstrated even more strikingly when the signal and the idler mirror are translated *simultaneously* in the same direction. Using the phase matching condition one can convert the signal- and idler-mirror displacement into an equivalent pump-mirror displacement.

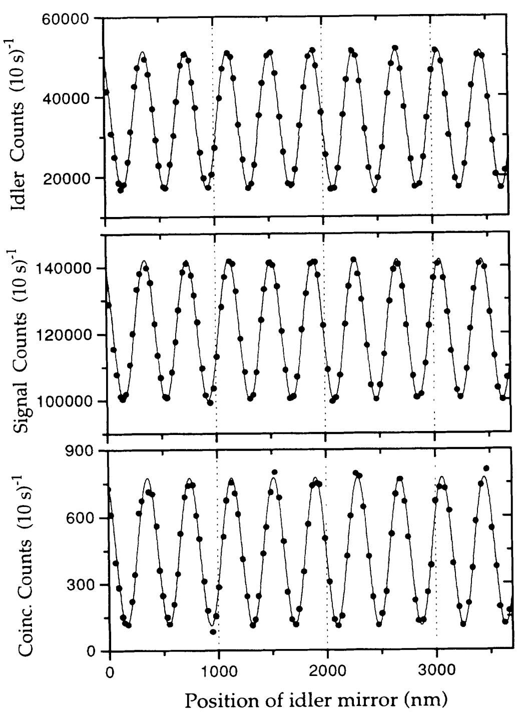

FIG. 5. Simultaneous measurement of signal count rate, idler count rate, and coincidence count rate as a function of the displacement of the idler mirror. The phase agreement of these oscillations shows clearly that the boundary condition controlling the emission of both photons in the entangled state can be controlled by changing the position of just one of the mirrors.

As a function of that quantity the idler count rate thus measured (Fig. 4) varies with a period of half the pump wavelength. These results show that it is only the sum of the phases experienced by signal and idler which controls the emision of the photon pair. Because of the entangled nature of the two-photon state neither signal nor idler enjoy a well defined phase on their own because neither of them is in a pure state. Any phase shift applied on either photon is really a phase shift acting on the joint tensor product state of both photons.

Finally Fig. 5 shows signal count rate, the idler count rate, and the coincidence count rate as measured as a function of the idler mirror position. These results again exhibit some interesting features. First, note that all three measured curves vary in the same way in both period and phase. This is again a consequence of Eq. (4) and thus of the fact that the mirror positions define the boundary condition for emission of the photon pair in both modes. Furthermore, the fringe visibilities can be quite high in the experiment. The maximum visibilities we observed were 51.7% for the idler beam and 17.3% for the signal beam, respectively. We ascribe this difference to the fact that the signal beam leaves the crystal under a smaller angle because of its lower wavelength. Therefore the signal detector sees a larger volume inside the crystal and thus a higher (noninterfering) background count rate.

This explanation is supported both by an estimate based on the sizes of the diaphragms used and with the variation of the phase matching condition with direction and by the fact that the absolute modulation in the signal beam is of about the same absolute magnitude as that in the idler beam. Furthermore, the visibility of the coincidence count rate is quite high, the maximum we measured was 86%. This again supports the explanation just given since reduction of background is all that a measurement of the coincidence count rate implies in our experiment.

Finally, when the signal mirror was removed, two interesting experimental observations were made. First, there was no variation of the idler intensity with idler mirror position, clearly indicating that we are observing a two-photon effect. Second, the constant idler intensity then observed was just the mean intensity of the fringes seen with the signal mirror in place. Thus at the intensity maxima of the fringes we see a coherent enhancement of the emission of the photon pair into the modes measured.

In conclusion, we would like to emphasize again that we have for the first time observed the suppression and enhancement of the spontaneous creation of an entangled photon pair through manipulation of its macroscopic joint boundary condition. The effect may be fully understood as interference between two possible ways for emission to occur rather than interference of the photons themselves.

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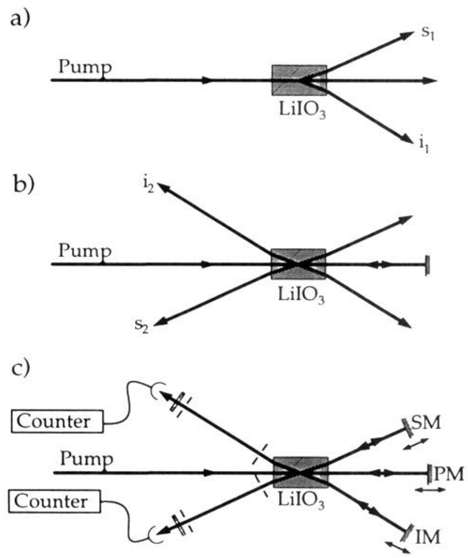

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