Letter

Study of induced temporal coherence
in optical parametric down conversion

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Abstract. Temporal coherence of the idler photon beam induced by a coherent input signal was studied for non-degenerate optical parametric down conversion. When the optical path difference of the interferometer is much longer than the coherence length of the spontaneous idler radiation, the experimental results show that the first-order temporal coherence of the idler photon can be induced by a coherence input signal and the interference fringe visibility is determined by the intensity of the coherent input signal.

The two-photon state generated by nonlinear optical parametric down conversion has shown non-classical behaviour in different experiments. Its statistical and coherent properties have been studied extensively [1–3]. The coherence properties of the optical fields induced by an external source in parametric down conversion have received a great deal of attention recently [4–6]. One reason for this is that the coherence and intensity measurements of idler radiation can give predictions of the coherence and intensity of the signal beams passed through the parametric amplifier. It has been proposed to use the induced coherence in fundamental quantum mechanics experiments and to realize the 'random delayed choice' single-photon interference experiment (for example [7]). It has also been used in metrology for indirect measurement of optical intensities [8] and the calibration of quantum efficiencies of photodetectors [9].

The existence of induced spatial mutual coherence of a pair of idler beams generated in two separate nonlinear crystals pumped coherently by a laser beam has been reported [5]. Wang *et al.* studied the induced interference visibility for equal optical path idler beams in a Mach–Zehnder interferometer. We report a different experiment which studied the temporal coherence of the idler photon beam induced by a coherent input signal.

The schematic diagram of the experiment is shown in figure 1. Spontaneous parametric down conversion occurred in a potassium dihydrogen phosphate crystal 5 cm long pumped by a continuous-wave single-frequency argon-ion laser operated at 351 nm. The crystal was cut for type I phase matching. The coherence length of the argon laser radiation was measured to be longer than 5 m. The wavelengths of the non-degenerate signal and idler photons were 632·8 and 788·7 nm respectively. The 632·8 and 788·7 nm ordinary-ray light cones had opening angles of 3·6 and 4·6° with respect to the extraordinary-ray 351 nm pump beam. Two spatial modes which satisfy the phase-matching conditions $\omega_s + \omega_i = \omega_p$, $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$, were selected by a set of apertures. A Michelson interferometer was used for the measurement of coherence length of the idler photon. The optical path difference could be varied
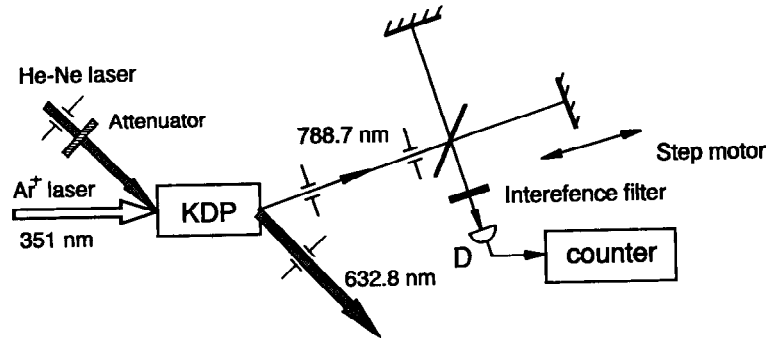
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Figure 1.   Schematic diagram of the experiment.

continuously up to a maximum of 5 cm. A Geiger mode avalanche photodiode single-photon detector with a 2·6 nm narrow-band spectral filter centred at 788·7 nm was used for the detection of the idler photon.

We first measured the first-order temporal coherence length of the idler photon without input signal. The coherence length of the 788·7 nm beam was about 240 μm. The measured coherence length of the idler beam is determined by the spectral bandwidth of the narrow-band interference filter.

The input signal radiation of a linear polarized He–Ne laser was then introduced into the 632·8 nm signal mode. The He–Ne laser beam was carefully aligned to match the 632·8 nm signal mode of the down conversion. The interference visibility of the 788·7 nm idler photon was studied for $\Delta L \gg l_{coh}$ (240 μm), where ΔL is the optical path difference of the Michelson interferometer and l_{coh} is the coherence length of the idler beam.

The electromagnetic field measured by the detector after the Michelson interferometer is in the form of

$$E^{(+)} = \sum_j f_j A_j [1 + \exp(-i\omega_j \tau)], \tag{1}$$

where $\tau = c\,\Delta L$, c is the speed of light and f_j is the interference filter spectral transmission coefficient. Here we omit irrelevant phase factors and the polarization coefficient since the signal and idler radiation have the same polarization in the type I parametric down conversion. The optical field amplitude A_j has the standard form [10]

$$A_j = a_{ij} \cosh(gl) - ia_{sj}^\dagger \sinh(gl), \tag{2}$$

where g is the parametric coupling constant and l is the length of the nonlinear crystal. For all signal and idler modes, $\omega_{sj} + \omega_{ij} = \omega_p$ are satisfied.

The input state is taken to be the idler vacuum and a product of coherent signal states:

$$|\Psi\rangle = |0\rangle_i \prod_k |\alpha_{sk}\rangle_s, \tag{3}$$

where the phases of the signal modes are random, so that

$$\overline{\alpha_{sk}^* \alpha_{sn}} = \delta_{kn} |\alpha_{sk}|^2. \tag{4}$$

For this state, the counting rate is given by

$$\bar{I} = \overline{\langle E_i^{(-)} E_i^{(+)} \rangle} = 2 \sinh^2 (gl) \sum_j f_j^2 [1 + |\alpha_{sj}|^2][1 + \cos (\omega_{ij}\tau)]. \tag{5}$$

It is convenient to write the counting rate as

$$\bar{I} = I_{vac} + I_\alpha, \tag{6}$$

where I_{vac} is the contribution due to the spontaneous down conversion obtained when there is no input, $\alpha_{sk} = 0$, and I_α is the intensity of idler photon beam induced by the input signal.

The interference filter may be taken to have a Gaussian spectral distribution centred on the angular frequency Ω_i:

$$f_j = f \exp \left(-\frac{(\omega_{ij} - \Omega_i)^2}{2\sigma^2} \right). \tag{7}$$

The He–Ne laser radiation also may be taken to have a Gaussian distribution

$$|a_{sj}|^2 = |\alpha|^2 \exp \left(-\frac{(\omega_{sj} - \Omega_s)^2}{\mu^2} \right) = |\alpha|^2 \exp \left(-\frac{(\omega_{ij} - \Omega_i)^2}{\mu^2} \right), \tag{8}$$

where Ω_i and Ω_s are the centre frequencies for the idler and signal beams respectively and μ and σ are the width of the Gaussian spectral profile for the He–Ne input signal and the filter respectively. Recall that $\omega_{sj} = \omega_p - \omega_{ij}$. Since the coherence length of the He–Ne laser beam was measured to be much greater than the coherence length of the idler beam, $\mu \ll \sigma$.

Converting the sums to integrals and using the fact that Ω_s and Ω_i are much greater than σ, it is easy to show that

$$I_{vac} = 2f^2 (\pi\sigma^2)^{1/2} \sinh^2 (gl) \, [1 + \exp (-\tfrac{1}{4}\sigma^2\tau^2) \cos (\Omega_i\tau)] \tag{9}$$

and

$$I_\alpha = 2f^2 (\pi\Sigma^2)^{1/2} \sinh^2 (gl) |\alpha|^2 [1 + \exp (-\tfrac{1}{4}\Sigma^2\tau^2) \cos (\Omega_i\tau)], \tag{10}$$

where

$$\frac{1}{\Sigma^2} = \frac{1}{\sigma^2} + \frac{1}{\mu^2} \approx \frac{1}{\mu^2}. \tag{11}$$

For $\Delta L \gg l_{coh}$, $\sigma\tau \gg 1$ so that the last term in equation (9) is negligible. Using equation (11) now gives the intensity $\bar{I}$:

$$\bar{I} = 2f^2 (\pi\sigma^2)^{1/2} \sinh^2 (gl) \left(1 + \frac{\mu}{\sigma} |\alpha|^2 [1 + \exp (-\tfrac{1}{4}\mu^2\tau^2) \cos (\Omega_i\tau)] \right). \tag{12}$$

The fringe visibility of the idler photon is seen from equation (12) to be

$$V = \exp (-\tfrac{1}{4}\mu^2\tau^2) \frac{1}{1 + \sigma/\mu|\alpha|^2}. \tag{13}$$

The temporal coherence of the idler photon depends on the parameters of the coherent input signal radiation. The visibility reduces to zero when there is no signal input because the interference term in equation (9) has been dropped since we have taken $\sigma\tau \gg 1$. If we introduce the intensity $\langle I_{vac} \rangle$ of spontaneous down conversion
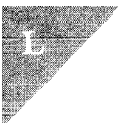
and the intensity $\langle I_\alpha \rangle$ of the induced idler photon beam obtained by averaging equations (9) and (10) over a period of fringes, the fringe visibility becomes

$$V = \exp\left(-\tfrac{1}{4}\mu^2\tau^2\right)\frac{1}{1 + \langle I_{\text{vac}}\rangle/\langle I_\alpha\rangle},\qquad(14)$$

which can easily be tested experimentally. V, $\langle I_{\text{vac}}\rangle$ and $\langle I_\alpha\rangle$ in equation (14) are all measured quantities; no curve fitting is required. The physical meaning of equation (14) is easy to understand. If the intensity induced by the coherent input signal is large compared with that of the spontaneous idler photon beam, that is $\langle I_{\text{vac}}\rangle/\langle I_\alpha\rangle \ll 1$, the visibility is close to unity for $\mu\tau \ll 1$.

Figure 2 shows the idler photon interference pattern for $\Delta L = 1$ mm, which is about five times longer than the coherence length of the spontaneous idler beam. No
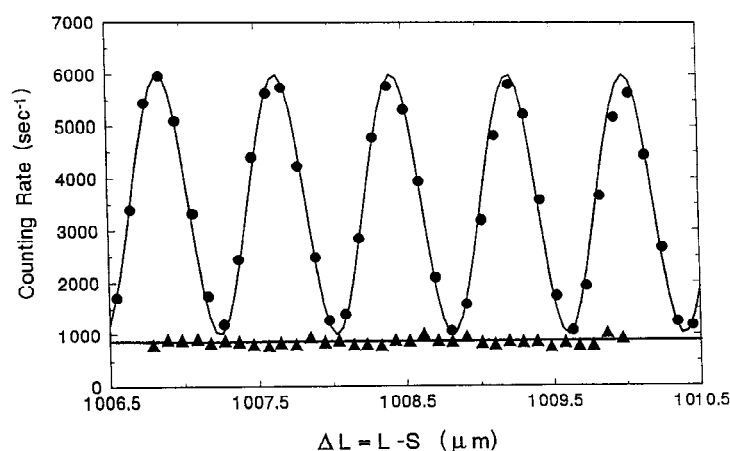

Figure 2. Counting rate for optical path difference $\Delta L = 1$ mm: (▲), spontaneous parametric down conversion (no input signal).
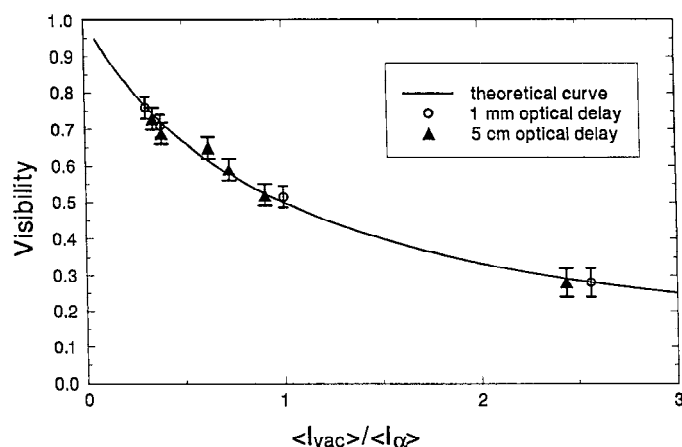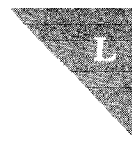

Figure 3. Interference visibility measurement for induced idler photon beam at different intensities of the input signal: (○), 1 mm optical delay; (▲), 5 cm optical delay; (———), curve calculated from equation (14).

interference was observed in the case of spontaneous parametric down conversion. However, a $71\% \pm 2\%$ inteference visibility was measured when $\langle I_{vac}\rangle/\langle I_\alpha\rangle = 0.38$.

Figure 3 reports the interference visibility measurements of idler photon when ΔL of the interferometer was set to be 5 cm. The solid curve is a theoretical curve calculated from equation (14). A $52\% \pm 3\%$ visibility was observed for $\langle I_{vac}\rangle/\langle I_\alpha\rangle = 0.91$, and higher value of visibilities were achieved in the case of $\langle I_{vac}\rangle/\langle I_\alpha\rangle \ll 1$. These measured values agree with the theoretical calculation.

It is also interesting to note that from equation (13) the value of $|\alpha|^2$, the average number of photons per unit volume per unit angular frequency interval of the input signal beam, can be estimated by the measurement of the interference visibility of the idler beam. It requires exact mode matching between the input signal and the parametric down-conversion mode. In the experiment, we found that it was not that difficult to achieve 'exact mode match' by careful alignment. A 5% accuracy can be achieved by such an estimation. The value of the parametric coupling constant g can be determined as well.

In conclusion, we have studied the induced temporal coherence properties of the idler photon in a parametric down-conversion process. The induced coherence of the idler photon is determined by the intensity of the coherent input signal. This result is similar to the result found by Wang *et al.* for the induced mutual spatial coherence in two separated nonlinear crystals.

Acknowledgment

References

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