Observation of time correlation function of multimode two-photon pairs on a rubidium D\textsubscript{2} line

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We report the generation of a type-I multimode two-photon state on a rubidium D\textsubscript{2} line (780 nm) using periodically poled KTiOPO\textsubscript{4} crystals. With a degenerate optical parametric oscillator far below threshold, we observe an oscillatory correlation function, the cross-correlation between two photons shows a cavity bandwidth of about 7.8 MHz. We also use a Fabry-Pérot etalon to filter its most longitudinal modes and observe its time correlation function. The experimental data are well fitted to theoretical curves. This system could be utilized for demonstrating storage and retrieval of narrowband photons in Rb atomic ensembles, which is important for long-distance quantum communication. © 2008 Optical Society of America

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Sources for creating entangled photon pairs are essential parts of many quantum information protocols and quantum optical experiments, such as quantum cryptography [1], teleportation [2, 3], dense coding [4], quantum computation [5] and others. To date, the most widely used way of obtaining the entangled photon pairs is the spontaneous parametric down-conversion (SPDC) [6] in a nonlinear crystal. In quantum information field, quantum memory must be used in order to realize the long-distance quantum communication, therefore transferring quantum state between the light and the memory is the key point for realizing such long-distance communication. Recently, there are many primitive experiments in this field [7–9], in which, an atomic system like a hot atomic vapor cell or a cold atomic cloud of Rb or Cs, is used as a quantum memory, and a photon is used as a flying bit. The key point to realize the efficient coupling between the atom and the photon is how to get a photon which has a comparable bandwidth with the natural bandwidth of the atom. This requirement excludes sources such as molecules in solid-state matrices [10], nitrogen-vacancy centers at room temperature [11] and quantum dots [12]. There are some possible methods for generating...
a narrow band photon: one is based on the spontaneous Raman scattering in an atomic system, which has been used in schemes shown in Refs. [7–9], but the experimental effort is high. Another one is based on SPDC with a nonlinear crystal in a cavity, as been demonstrated in Ref. [13]. Following this work, several groups [14–16] recently performed the almost same experiments as in Ref. [13]. Our group is now involving in the realization of the quantum memory based on a cold Rb atomic ensemble (D$_2$ line at 780 nm) trapped in a magneto-optical trap. We plan to transfer the quantum state between an atomic ensemble and a narrow-band single photon, which we hope to prepare by the SPDC in a ring cavity. In this work, we report the experimental generation of a multimode two-photon state at 780 nm via a degenerate optical parametric oscillator (OPO) far below threshold. This wavelength corresponds to the D$_2$ line of Rb atom. We have observed the oscillatory correlation of multimode two-photon pairs. This is, to our best knowledge, the first time to get this kind oscillatory correlation function at Rb D$_2$ line. Cross-correlation between two photons shows a cavity bandwidth of 7.8 MHz. Besides, our experiment is different from others: in Ref. [13], a bigger and more expensive Ti: Sapphire laser is used as the fundamental light for the second harmonic generation in a cavity. Our fundamental source is a small and relatively cheap grating-stabilized external cavity diode laser (ECDL) (Toptica DL100), and its frequency is locked to the transition line D$_2$ of Rb$^{87}$ atom (780 nm) by the saturated absorption technique. In Ref. [14], a pair of cw type-I down converters, one rotated by 90°, in a ring cavity to produce polarization-entangled photons. In this experiment, Ti: Sapphire laser and KbNO$_3$ are used. In our experiment, a periodically poled KTiOPO$_4$ (PPKTP), which has larger nonlinear coefficient, is used to compensate the relative lower power of the diode laser. In Ref. [15], a cw type-II down converter is used to get a narrow-band photon pair at 795 nm with an ECDL at 397.5 nm. In our experiment, the pump laser at 390 nm for OPO is from frequency doubling of the 780 nm laser in a cavity. In our experiment, a double resonant OPO is used. In Ref. [16], a single resonant OPO is used to prepare a narrow-band photon. The OPO is locked by Hansch-Couillaud method. Furthermore, we use a Fabry-Pérot etalon to filter most longitudinal modes of the photons and observe its time correlation function. The results show that there is no oscillatory correlation in this case.

The theory of the output from an OPO far below threshold has been discussed in Ref. [17,18]. Since the large bandwidth of PDC photons, there are numerous nondegenerate conjugate pairs together with degenerate pairs. The nondegenerate pairs are located at two sides of degenerate frequency of OPO($\omega_0$) with a spacing of $\Delta \Omega_{\text{opo}}$ ($\Delta \Omega_{\text{opo}}$ is the free spectrum range of the OPO cavity). The output operator is given by the following equation: $\omega_{\pm m} = \omega_0 \pm m \Delta \Omega_{\text{opo}}$, where $m$ is an integer.
\[ \omega_0 \pm m \Delta \Omega_{\text{opo}}, m = 0, 1, 2 \cdots \] \[ a_{\text{out}}(\omega + \omega_m) = G_1(\omega)a_{\text{in}}(\omega_m + \omega) + g_1(\omega)a_{\text{in}}^\dagger(\omega_m - \omega) \]
\[ + G_2(\omega)b_{\text{in}}(\omega_m + \omega) + g_2(\omega)b_{\text{in}}^\dagger(\omega_m - \omega), \]

(1)

with

\[ G_1(\omega) = \frac{\gamma_1 - \gamma_2 + 2i\omega}{\gamma_1 + \gamma_2 - 2i\omega}, \quad g_1(\omega) = \frac{4\epsilon\gamma_1}{(\gamma_1 + \gamma_2 - 2i\omega)^2}, \]
\[ G_2(\omega) = \frac{2\sqrt{\gamma_1\gamma_2}}{\gamma_1 + \gamma_2 - 2i\omega}, \quad g_2(\omega) = \frac{4\epsilon\sqrt{\gamma_1\gamma_2}}{(\gamma_1 + \gamma_2 - 2i\omega)^2}. \]

(2)

Here \( a_{\text{in}}(\omega) \) and \( b_{\text{in}}(\omega) \) represent the vacuum mode entering the OPO cavity and the unwanted vacuum mode coupled-in due to losses in the system, respectively. \( \gamma_1 \) and \( \gamma_2 \) are the coupling constants for \( a_{\text{in}} \) and \( b_{\text{in}} \), respectively. \( \epsilon \) is the single pass parametric amplitude gain. The intensity correlation function of two down-converted photons is defined as

\[ \Gamma^{(2)}(\tau) = \langle \hat{E}(-)(t)\hat{E}(-)(t + \tau)\hat{E}(+)(t + \tau)\hat{E}(+)(t) \rangle. \]

(3)

with

\[ \hat{E}(+)(t)[\hat{E}(-)(t)]^\dagger = \frac{1}{\sqrt{2\pi}} \int d\omega \hat{a}(\omega) e^{-i\omega t}. \]

(4)

From Eqs. (1),(2),(3), and (4) and with some calculations one can find that \[ \Gamma^{(2)}(\tau) = |\epsilon|^2 \left( \frac{F}{F_0} \right)^2 \left[ \left( \frac{2|\epsilon|(2N + 1)}{\Delta \omega_{\text{opo}}} \right)^2 \right. \]
\[ + \left. e^{-\Delta \omega_{\text{opo}}|\tau|}\frac{\sin^2[(2N + 1)\Delta \Omega_{\text{opo}}\tau/2]}{\sin^2(\Delta \Omega_{\text{opo}}\tau/2)} \right]. \]

(5)

Here \( \Delta \omega_{\text{opo}} \) is the bandwidth of the OPO. \( \tau \) represents the delay time. \( 2N + 1 \) represents the number of modes of the output optical fields from OPO. \( F \) and \( F_0 \) is the finesse of the OPO with and without loss, respectively. The detail explanation of this formula can be shown in Ref. [19]. One of the key points to observe the oscillatory correlation function is that \( \tau_{\text{opo}} = 2\pi/\Delta \omega_{\text{opo}} \), which is round-trip time of the OPO cavity, must larger than the resolving time of detectors, \( \tau_D \). In our first experiment, \( \tau_D \) and \( \tau_{\text{opo}} \) are 220 ps and 1.63 ns, respectively, therefore \( \tau_D < \tau_{\text{opo}} \) in our experiment.

In this paper, we obtain multimode narrowband two-photons with a PPKTP crystal via an OPO far below threshold, and observe the oscillatory correlation function of multimode two-photon pairs. That, to the best of our knowledge, is the first time to get the oscillatory correlation function at Rb D_2 line. A schematic drawing of the experiment set-up is
Fig. 1. Experiment setup. DL100_780, an external-cavity diode laser operated at 780nm; ISO, optical isolator; EOM, electro-optic modulator; OPO, far below threshold degenerate optical parametric oscillator; SAR, saturated absorption resonator; PD1 and PD2, fast photodetector for cavity locking; PD3 and PD4, avalanche photodetectors; CFD, constant-fraction discriminator; pTA, picosecond time analyzer.

shown in Figure 1. A cw ECDL with 780 nm wavelength is used to produce UV light at 390 nm via a ring cavity. A 10 mm long type-I phase matched PPKTP crystal with a domain period of 2.95 µm is used as the doubler. The frequency of the laser is locked to the transition line D2 of Rb87 atom (780 nm) by the saturated absorption technique. The frequency of the doubling cavity is locked to laser frequency by PDH method [20]. Please refer to Ref. [21] for detail about frequency doubling. The OPO cavity is composed of two concave mirrors of curvature radius 80 mm and two plane ones. The concave mirror (M3) has partial transmission about 5% at 780nm and works as an output coupler, while the others are high reflectance mirrors. The round-trip length of the cavity is 480 mm correspond to 0.625 GHz free spectral range (FSR) and 1.6 ns τopo. The distance between two spherical mirrors is about 100 mm, and a 10 mm long PPKTP is placed between two spherical mirrors resulted in a waist of 40 µm inside the crystal. The temperature of the crystal is controlled by a home-made thermoelectric cooler with the stability of 0.02°C. The OPO cavity is locked to laser frequency by PDH method [20]. A chopper is used to cut the photons of locking light reflected from the surface of the crystal to avoid possible background noise. The colored glass filer is used to cut the UV light. The triangle cavity is used to get mode-matched between two bow-tie-type ring cavities. The outputs from OPO are coupled into a 50/50 fiber beam-splitter (NEWPORT P22S780BB50). The outputs of the beamsplitter are input.
Fig. 2. Observed the oscillatory correlation function of multimode two-photon pairs. The coincidence counts are accumulated in 70 seconds. The pump power is about 15 $\mu$W. The fitted parameters of curve line are as follow: $C_1 = 93$, $C_2 = 0$, $\Delta \omega_{\text{opo}}/2\pi = 7.8$ MHz, $\tau_0 = 59$ ns, $\tau_{\text{opo}} = 1.63$ ns, $\tau_D = 220$ ps.

to single photon detectors (PekinElmer SPCM-AQR-14-FC). The outputs of the detectors are sent to a coincident circuit for coincidence counting, which mainly consist of a picosecond time analyzer (ORTEC, pTA9308) and a computer.

Figure 2 shows the coincidence counts of multimode two-photons at about 15 $\mu$W pumping power. The points are the measured data, and the line is the fitted curve using Eq. (6) [19]

$$\Gamma_c^{(2)}(\tau) = C_1 \left[ C_2 + e^{\Delta \omega_{\text{opo}}|\tau - \tau_0|} \right] \times \sum_n \left[ 1 + \frac{2|\tau - n\tau_{\text{opo}} - \tau_0| \ln 2}{\tau_D} \right] \times \exp \left( -\frac{2|\tau - n\tau_{\text{opo}} - \tau_0| \ln 2}{\tau_D} \right),$$

(6)

Considering the probability distribution of the timing jitter of detectors ($p(\tau)$), Eq. (5) needs to be averaged over $p(\tau)$, which is assumed to be proportional to $\exp(-2|\tau| \ln /\tau_D)$ here. We sum all the modes from $n=-N$ to $n=N$. $C_1$ and $C_2$ are constant, which represent the coincidence counts from the background and that from the different photon pairs, respectively. The results of the simulation are as follow: $C_1 = 93$, $C_2 = 0$, $\Delta \omega_{\text{opo}}/2\pi = 7.8$ MHz, $\tau_0 = 59$ ns, $\tau_{\text{opo}} = 1.63$ ns, $\tau_D = 220$ ps. The data is accumulated in 70 seconds with 4.88 ps time bins revolution. The theoretical curve fits the experiment data quite well. The pTA has a range
of dead time at the beginning of each scan, which is about 45 ns. So the left part of this comb-like wavepacket isn’t included in Figure 2.

We also put a Fabry-Pérot (FP) etalon with 13 GHz FSR and 1 GHz bandwidth after

![Graph](image)

Fig. 3. The data shown in this figure are accumulated in 30 minutes. The pump power is about 90 µW. There is no obvious or regular oscillatory time correlation function.

the out port of the OPO to filter most longitudinal modes of two-photon state. According to our 0.625 GHz ∆Ω_{opo}, only less 10% longitudinal modes can be preserved. In this case, \( \tau_{opo} \) is about 77 ps and is more less than \( \tau_D \). So the oscillatory of time correlation function like Fig. 2 will disappear. In the experiment, we use a temperature controller to finely turn the etalon’s length, in order to let the degenerate frequency of OPO(\( \omega_0 \)) have a maximum transmission. The result is shown in Fig. 3, from which we could find there is no obvious or regular oscillatory time correlation function. Another thing we want to mention is that there are many small unregular peaks on the wavepacket, for the two-photon state after the etalon is not perfect single mode.

In conclusion, we observed the oscillatory correlation function of multimode two-photons at 780 nm, which corresponds to D_{2} transition of Rb atoms. The fitting line from Eq. (6) almost overlaps with the experimental data. These results clearly show the good correlation between the two photons in a pair. The bandwidth of the photons is about 7.8 MHz, which could make the efficient coupling between the photons and Rb atoms possibly. We also use a FP etalon to filter its most longitudinal modes and observe its time correlation function.

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