Generations of correlated and entangled photon pairs have been extensively studied in various systems in recent years, since they are essential for applications in quantum communication and computation [1]. An optical parametric oscillation system based on the $\chi^{(3)}$ parametric down-conversion process in a nonlinear crystal is a common way to generate strongly correlated and entangled photon pairs or light beams in either below $\omega_1$ or above $\omega_3$ its threshold condition. In the multi-level atomic systems, the $\chi^{(3)}$ processes, such as Raman scattering and wave mixing via atomic spin coherence, play key roles in producing correlated and entangled photons [5–11]. Bright photon pairs have been generated in cold as well as hot atoms with or without an optical cavity [5–11]. At the same time, intensity correlations have also been widely studied in various situations, such as in electromagnetically induced transparency (EIT) configuration with a magnetic field [12], atomic optical parametric oscillation [13], four-wave mixing process [14,15], and six-wave mixing process [16].

In this letter, we report an experimental study of simultaneously generating the bright Stokes and anti-Stokes fields via only one pump field in a Doppler-broadened atomic medium confined in an optical ring cavity. The phenomenon of vacuum-induced absorption has been observed rather than the vacuum-induced transparency as reported in [17], in which a cavity with much higher finesse was used. By using an external Fabry–Perot (FP) cavity to separate the generated Stokes and anti-Stokes fields, we are able to investigate the correlations and anticorrelations of the intensity noises between the two generated (Stokes and anti-Stokes) fields and the pump field. This is different from [13] and [18], as here we investigate three-field correlations in an optical parametric oscillator (i.e., pump, Stokes, and anti-Stokes fields) which, to the best of our knowledge, has not been reported.

The experimental setup is shown in Fig. 1, which is similar to the one used in [19]. A three-mirror optical ring cavity consists of an input mirror M1 and an output mirror M2 with 3% and 1.4% transmissivities, respectively, and a third mirror M3, with reflectivity larger than 99.5%, mounted on a piezoelectric transducer (PZT) for cavity frequency scanning and locking. The ring cavity length is ~37 cm. The rubidium vapor cell is ~5 cm long with Brewster windows, and is wrapped in $\mu$-metal sheet for magnetic field shielding and in heat tape for controlling the atomic density. The empty cavity finesse is about 100. When the atomic cell and PBS are included, the cavity finesse degrades down to about 40. An additional frequency-stabilized diode laser is used to lock the optical ring cavity (not shown in Fig. 1). A single mode laser (Toptica DL 100) is used as the pump field, which is injected into the cavity through PBS1, and is detected by D1 after interacting with the atoms. The cavity output is directly detected by D2 (with M4 down). The FP cavity, PBS3, $\lambda/4$ waveplate, and D3 & D4 are used to investigate the spectral components of the cavity output field with M4 up.

We first measure the cavity transmission spectra with the pump field frequency scanning across the transition $F = 3 \leftrightarrow \bar{F}$ in $^{85}$Rb D1 line. Without heating the Rb cell, there is no cavity transmission observed by D2. By increasing the Rb cell temperature to ~80°C (corresponding to an atomic density of $1.5 \times 10^{13}$ cm$^{-3}$), several peaks appear in the cavity transmission spectrum [Fig. 2(c)], and at the same time, some absorption dips appear in the free space spectrum detected by D1 [Fig. 2(b)]. Figure 2(a) is the saturated absorption
spectrum as a reference from another Rb cell. Since it is important to know the spectral components in the cavity transmission peaks, a 10 GHz FP cavity (Thorlabs SA210) is used to analyze each peak. By locking both the pump field frequency and the cavity length properly, we are able to make the ring cavity output frequency stand on each peak. By scanning the FP cavity length, we find that peaks 1 and 2 in Fig. 2(c) have different frequency components. The frequencies of all peaks labeled 2 are the same as the pump field, and they are separated by ~822 MHz, which is the free spectral range (FSR) of the optical ring cavity without the medium, while there are two different frequencies in peak 1, either up-or down-shifted by ~3 GHz from the pump frequency, which is the $^{85}$Rb ground-state hyperfine splitting frequency, as shown in Fig. 3. We attribute the appearances of the peaks labeled 2 as either Raman scattering among the Zeeman sublevels [19] or Faraday rotation [20], while the peak 1 is from the wave-mixing processes, for which the frequency relationship is satisfied between the Stokes, anti-Stokes, and the pump fields; i.e., $\omega_{\text{as}} + \omega_{s} = 2\omega_{p}$. In Fig. 2(b), one can see that the absorption is increased at the position of peak 1, which can be referred to as “vacuum-induced absorption” (in respect to the “vacuum-induced transparency” reported in [17]), since the Stokes and anti-Stokes fields are generated from vacuum and they enhance the absorption of the pump field. The amount of the induced absorption is about the same order of the saturated absorption, which is about 1% of the pump field power. The reason for an enhanced absorption instead of an enhanced transparency can be understood as follows: the Stokes and anti-Stokes fields are first generated from spontaneous Raman scattering; then the stimulated Raman scattering or wave-mixing process becomes dominant, which promotes the absorption of the pump field. In the current process, the generated Stokes and anti-Stokes fields are always much weaker than the pump field, which is different from the experiment reported in [17]. In that experiment, the cavity finesse is more than two orders higher than ours; therefore, the field grown from the spontaneous Raman scattering can become much stronger than the pump (probe in [17]) field. Therefore, transparency is observed due to EIT. This process is different from the standard frequency conversion in four-wave-mixing (FWM). First, in the standard FWM, normally more than one beam is involved. Second, in the current case, the cavity modes (initially in vacuum) determine the position of the absorption peak; i.e., when the cavity is detuned, the absorption peak moves accordingly, just as in the “vacuum-induced transparency” case [17], where the transmission window moves as the cavity is detuned.

Next, we measure the oscillation thresholds for both Stokes and anti-Stokes fields at a higher temperature ($T \sim 95$ °C). When the pump power is lower than 4.5 mW, there is no detectable cavity output. By increasing the pump power, the gain overcomes the losses in the cavity, and the system starts to oscillate, as shown in Fig. 4. At the maximum pump power under the current experimental condition, no saturation can be observed. Both Stokes and anti-Stokes fields have similar threshold behavior.

Finally, we study the noise correlation and anti-correlation properties between the Stokes, anti-Stokes, and the pump fields under far above-threshold condition. By using another homemade FP cavity (FSR = 750 MHz) and fixing the FP cavity length at the anti-Stokes peak, the anti-Stokes field passes through the FP cavity and is detected by D4, while the Stokes field is reflected and detected by D3. The temporal signal traces of the Stokes, anti-Stokes, and pump fields, respectively, are shown in Fig. 5(a). The cross-correlation function $G_{ij}(\tau)$ between the intensity noises of any two fields can be calculated by [12–15].
In conclusion, we have experimentally observed the simultaneous generations of the bright Stokes and anti-Stokes fields with one pump field in a ring optical cavity containing hot rubidium atoms. The correlation and anticorrelation properties between these three fields have been investigated. Although quantum correlations have not been measured in the current setup, we believe that this system can be a good candidate for multiphoton correlation source in quantum information processing as predicted in [21].

We acknowledge the funding support of the National Science Foundation.

References


Fig. 5. (Color online) (a) Typical temporal waveforms of the Stokes (curve i, black), anti-Stokes (curve ii, red), and pump (curve iii, blue) beams. Cross correlations $G^{(2)}(\tau)$ for (b) the Stokes and the anti-Stokes, (c) the Stoke and the pump, and (d) the anti-Stokes and the pump fields, respectively. The experimental parameters are: $T = 95$ °C and $P_p = 25$ mW.

$$G_{i,j}^{(2)}(\tau) = \frac{\langle \delta I_i(t) \delta I_j(t + \tau) \rangle}{\sqrt{\langle [\delta I_i(t)]^2 \rangle \langle [\delta I_j(t + \tau)]^2 \rangle}},$$

where $\delta I_{i,j} = I_{i,j} - \langle I_{i,j} \rangle$, $\langle \rangle$ is the temporal averaging; and $\tau$ is the selected time delay between the two signals. The cross-correlation functions $G_{i,j}^{(2)}(\tau)$ for the Stokes and the anti-Stokes, the Stokes and the pump, and the anti-Stokes and the pump fields are shown in Figs. 5(b)–5(d), respectively. The degrees of cross correlations at zero time delay are calculated to be $G_{s,as}^{(2)}(0) = 0.95$, $G_{s,sp}^{(2)}(0) = -0.84$, and $G_{p,as}^{(2)}(0) = -0.87$, respectively. The delay between the Stokes and anti-Stokes fields [9] is not shown here since the time scale used in the current experiment (∼1 ms) is much larger than the typical delay time (∼1 μs) [9]. The physical picture of the above results can be understood as follows: one atom absorbs two pump photons and then emits one Stokes photon and one anti-Stokes photon simultaneously; therefore, the Stokes and anti-Stokes fields should be correlated just as in the optical parametric oscillator with a $\chi^{(2)}$ nonlinear crystal [4], while the Stokes (or anti-Stokes) and the pump fields should be anticorrelated.