Simultaneous experimental generation of vacuum squeezing and bright amplitude squeezing from a frequency doubler

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Both vacuum-squeezed and bright amplitude-squeezed states of light are experimentally generated from a frequency doubler with a semimonolithic Fabry–Perot configuration consisting of a type II nonlinear crystal and a concave mirror. Vacuum squeezing of 3.2 ± 0.1 dB and amplitude squeezing of 1.3 ± 0.2 dB are obtained simultaneously at a pump power of 8 mW. The two quadrature-squeezed optical fields that are generated are of identical frequency at 1080-nm wavelength and orthogonal polarization. Optimizing the input pump power by 19 mW yields as much as 5.0 ± 0.2 dB of maximum vacuum squeezing. The advantages of the system are its simplicity and multiple utility. © 2005 Optical Society of America

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Since the first squeezed state of light was observed through four-wave mixing by Slusher *et al.*,[1] many methods, such as optical parametric downconversion,[2] optical frequency doubling,[3–5] and the Kerr effect in optical fiber,[6] have been used to generate quadrature-squeezed states. Doubly[3,4] and singly[5] resonant frequency doublers were designed to produce the squeezing of either fundamental or second-harmonic light. Until now, the best measured vacuum squeezing of 7 dB from a type I optical parametric oscillator and amplitude squeezing of 6.5 dB from a type I optical parametric amplifier (OPA) were generated by Lam *et al.*[7] and Schneider *et al.*,[8] respectively. Subsequently, squeezed states of light have been successfully applied to quantum-optical measurements,[9–12] nonclassical excitation of atoms,[13] and quantum information.[14,15] Although OPAs are powerful tools for efficiently generating squeezed states of light, a set of OPAs operating at a given state can usually produce only one type of squeezed state of light.[2,8] Frequency doublers consisting of type I $\chi^{(2)}$ nonlinear crystal have been used to generate amplitude squeezing of infrared and green light simultaneously.[3,5,16] In this Letter we report the generation of a vacuum-squeezed state of 3.2 ± 0.1 dB and a bright amplitude-squeezed state of 1.3 ± 0.2 dB simultaneously from a simple doubly resonant second-harmonic generator (doubler) consisting of a type II crystal with a pump power of 8 mW. As much as 5.0±0.2 dB of maximum vacuum squeezing was observed at a pump power of 19 mW.

The theoretical calculations in Refs. 17 and 18 show that, below the oscillation threshold[19] of mode a_s in the doubler, a vacuum-squeezed mode with an average intensity close to zero and an amplitude-squeezed mode a_p with nonzero average intensity can be obtained. The variances of the quantum fluctuations for mode a_p and mode a_s, $V_{\delta Xp}$, and $V_{\delta Ys}$, respectively, are[18]

$$V_{\delta Xp} = 1 - \frac{4\gamma_p^c \mu \alpha_p^2}{(\gamma_p + 3\mu\alpha_p^2)^2 + \Omega^2}, \qquad (1)$$

$$V_{\delta Ys} = 1 - \frac{4\gamma_s^c \mu \alpha_p^2}{(\gamma_s + \mu\alpha_p^2)^2 + \Omega^2}, \qquad (2)$$

where α_p is the average amplitude of the bright subharmonic mode in the doubler, $\gamma_{p(s)} = \gamma^{\text{loss}} + \gamma_{p(s)}^c$ is the total decay rate for mode $\alpha_{p(s)}$, and $\gamma^{\text{loss}} = \gamma_p^{\text{loss}} = \gamma_s^{\text{loss}}$ and $\gamma_{p(s)}^c$ are the decay rates that correspond to the intracavity passive loss and the transmission coefficient of the output coupler, respectively. $\mu = \kappa^2/2\gamma_b$, where κ is the effective nonlinear coupling parameter and γ_b is the total decay rate of harmonic mode b in the doubler. Ω is the analyzed noise frequency. Obviously, both Eqs. (1) and (2) are smaller than a normalized vacuum noise level of 1 for any possible parameters. Therefore, output modes a_p and a_s are the amplitude-squeezed and the vacuum-squeezed states of light, respectively. Minimizing Eqs. (1) and (2), we can obtain the optimal circulation subharmonic powers for producing maximum squeezing. Substituting the optimal powers into Eqs. (1) and (2), we got the minimal variances of two output modes:

$$V_{\delta Xp\ \min} = 1 - \frac{2}{3}\frac{\gamma_p^c}{(\gamma_p + \sqrt{\gamma_p^2 + \Omega^2})}, \qquad (3)$$

$$V_{\delta Ys\ \min} = 1 - \frac{2\gamma_s^c}{(\gamma_s + \sqrt{\gamma_s^2 + \Omega^2})}. \qquad (4)$$

It is well known that the 1080-nm wavelength of a Nd:YAlO$_3$ (Nd:YAP) laser can produce type II 90° noncritical phase matching in an α-cut KTP crystal, so walk-off and the polarization mixing effect can be minimized.[20,21] The experimental setup is shown in Fig. 1. The Nd:YAP laser is a homemade frequency-stabilized cw laser with a ring resonator.[22] The pump laser is locked onto the resonant frequency of the cleaner. The frequency stability of the pump laser is better than ±1.3 MHz. After the light has passed through the mode cleaner, the noise of the laser

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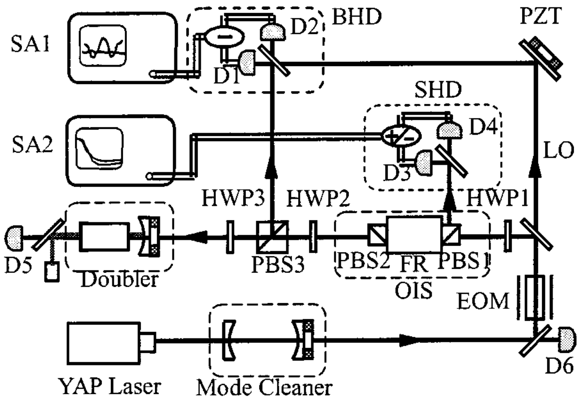

Fig. 1. Schematic diagram of the experimental setup: D1–D4, low-noise detectors; other abbreviations defined in text.

above 2 MHz is reduced to the level of the shot-noise limit. The frequency doubler has a semimonolithic configuration consisting of a concave mirror and a 10-mm-long KTP crystal. The concave mirror of 50-mm radius of curvature was coated with a 5.7% transmitter for 1080 nm and with a high reflector for 540 nm. It serves as both an input and an output coupler of the doubler for 1080 nm. A facet of KTP (inside the cavity) was coated for antireflection at both 1080 and 540 nm. The other facet serves as the output coupler of the second-harmonic wave at 540 nm (high reflection for 1080 nm, 17% transmission for 540 nm). The total length of the doubler is 53 mm. A phase electro-optic modulator (EOM) is used to modulate the phase of the pump laser to provide the discrimination signals for the frequency-locking system of the doubler. Polarizing beam splitters PBS1 and PBS2, as well as a 45° Faraday rotator, construct an optical isolator (OIS) to prevent optical feedback from entering the pump laser. A half-wave plate (HWP1) and PBS1 combine as a power adjuster for adjusting the input power of the doubler. Half-wave plate HWP2 makes 45° polarization rotation of the incident light. HWP3 is used for rotating the polarization of the input laser to distribute the pump power equally to the two intrinsic polarization directions of the type II KTP crystal. For higher frequency-doubling efficiency, the doubler is operated at the resonance of the two subharmonic modes with orthogonal polarization and the near resonance of the harmonic mode and below the oscillation threshold of the mode a_s. The finesse of the doubler for the harmonic mode is much smaller than that for the subharmonic modes (20 and 75, respectively), so the two sharp resonant peaks of the subharmonic modes generally are within the flat resonating envelope of the harmonic mode. Scanning the cavity length of the doubler with the piezoelectric transducer (PZT) and observing the transmission peaks of the two subharmonic modes on an oscilloscope, and at the same time carefully tuning the temperature of KTP crystal to make the two peaks overlap, produces resonance in this case. Then we actively lock the resonant cavity length of the doubler onto the frequency of the pump laser by a standard fm sideband technique.[23] The output squeezed optical fields from the doubler come back along the path of the input laser. Vacuum-squeezed light with its polarization perpendicular to that of the pump laser is reflected by polarizing beam splitter PBS3, its noise is measured by a balanced homodyne detection system (BHD), and the noise power spectrum is recorded by a spectrum analyzer (SA1). The local oscillator light (LO) is taken directly from the pump laser, and its phase is scanned by a piezoelectric transducer placed in the way of the local oscillator. The polarization of the output bright amplitude-squeezed light is parallel to that of the input pump laser. After the light has passed through half-wave plates HWP3 and HWP2 and the Faraday rotator (FR), its polarization is rotated by 90° and the bright light beam is reflected by beam splitter PBS1. Its amplitude noise is detected by a self-homodyne detection system (SHD) and analyzed by spectrum analyzer SA2. Photodiodes D5 and D6 are used for extracting the optical signals needed by the frequency-locking systems of the doubler and the pump laser, respectively.

Figures 2(a) and 2(b) are the noise power spectra measured simultaneously by the balanced homodyne detector and the self-homodyne detector, respectively,

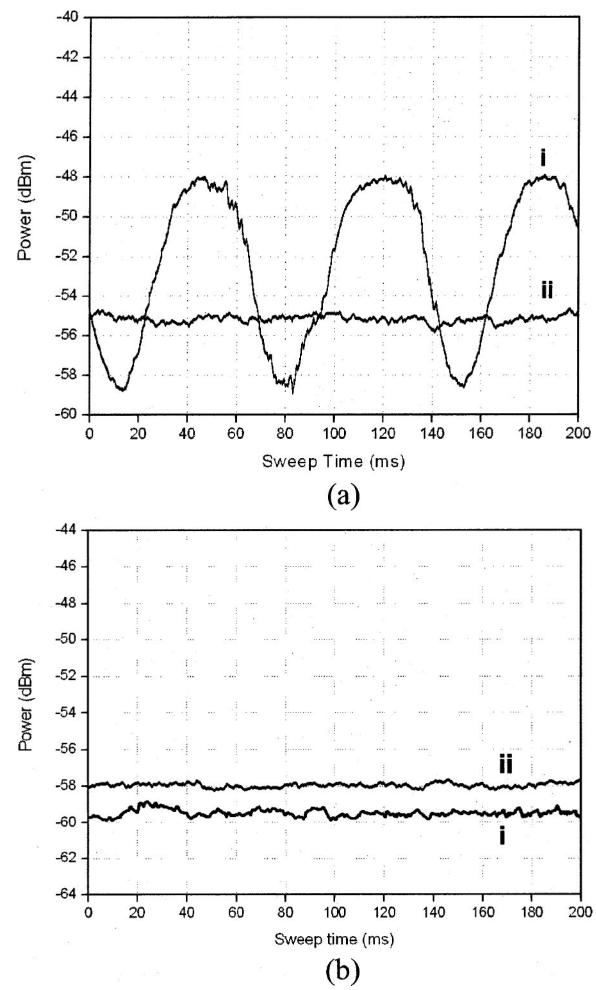

Fig. 2. Experimental results. (a) i, Observed local-oscillator phase-dependent noise power of vacuum-squeezed state of light; ii, the corresponding shot-noise limit. (b) i, Observed amplitude noise power; ii, the shot-noise limit. Measured frequency, 3 MHz; resolution bandwidth, 300 kHz; video bandwidth, 100 Hz.

at a pump power of 8 mW. Vacuum squeezing of 3.2±0.1 dB (~52% at 3 MHz) and amplitude squeezing of 1.3±0.2 dB (~25% at 3 MHz) are observed simultaneously. By adjusting the input power to optimize the vacuum squeezing we record the maximal vacuum squeezing of 5.0 ± 0.2 dB (~68%) at a pump power of 19 mW. When the resonance is broken down, we readjust the locking system and can then retrieve the squeezing.

According to Eqs. (1) and (2), the theoretically calculated optimal pump powers for amplitude and vacuum squeezing for the parameters of our system are 7.7 and 23 mW, respectively, in reasonable agreement with the experimentally measured values of 8 and 19 mW. In Fig. 2, traces i and ii show the noise power spectra of the squeezed states of light and the corresponding shot-noise limits, respectively. For our frequency doubler the transmission coefficient of the output mirror and the intracavity loss are 5.7% and 0.3%, and thus $\gamma_{p(s)}^{c}$ and $\gamma_{p(s)}^{\text{loss}}$ are 70 and 3.68 MHz, respectively. The quantum efficiency of the photodetectors (Epitaxx ETX500) is 96%. The beam transmission losses for bright amplitude-squeezing and vacuum-squeezing modes are approximately 8% and 2%, respectively. The homodyne efficiency (for detection of vacuum squeezing) is 90%. Substituting these values into Eqs. (3) and (4), we calculate bright amplitude squeezing of 1.44 dB and vacuum squeezing of 6.9 dB, which are higher than the experimentally measured values, probably because the measured parameters used for the calculation are better than the real parameters in the experimental system.

In conclusion, we have produced vacuum-squeezed and amplitude-squeezed states of light simultaneously from a simple frequency doubler. The two quadrature-squeezed states with an identical frequency of 1080 nm can be applied and can be combined to generate the entangled state of light by an optical beam splitter.[24] Thus the system presented might have extensive applications for quantum measurement and quantum information.

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