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A portable multi-purpose non-classical light source

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Abstract

A compact and portable multi-purpose non-classical light source (volume about 300 × 400 × 500 mm^3) has been designed and built. A laser diode-pumped intracavity frequency-doubled Nd:YAP/KTP laser and a semi-monolithic non-degenerate optical parametric oscillator (NOPO) are closely integrated on an invar steel base. Above the oscillation threshold of the NOPO (~3 mW), the twin beams with an intensity quantum correlation of 5.9 dB were obtained; when a signal of subharmonic wave, which is out of phase to the pump field, was injected into the NOPO, bright two-mode quadrature amplitude-squeezed light of 2.1 dB and an EPR beam with amplitude anticorrelation and phase correlation was produced at a pump power of milliwatt order. The features of compactness, portablility, low pump threshold, and versatility make the device useful for developing practical non-classical light sources.

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Keywords: Non-degenerate optical parametric oscillator (NOPO); Multi-purpose; Non-classical light source; Twin beams with intensity quantum correlation; Bright two-mode quadrature amplitude-squeezed light; EPR beam

Optical parametric down conversion in a cavity with $\chi^{(2)}$ nonlinear crystal is well suited for the generation of continuous-wave (CW) light fields with high quantum noise reduction. Single- and two-mode squeezed vacuum, squeezed coherent state light fields [1–4], intensity correlated twin beams [5–7], and quantum entangled Einstein–Podolsky–Rosen (EPR) beams with the correlation of amplitude quadratures and the anticorrelation of phase quadratures [8,9] have been generated with optical parametric oscillators (OPOs) and amplifiers (OPAs). These non-classical light fields have also been used to make quantum measurements beyond the shot-noise-limit (SNL) [6,10], high sensitivity spectroscopies [11,12], and quantum non-demolition measurements [13,14]. The rapid progress in quantum information science, especially the success of applying the squeezed-state entanglement to realize highly efficient and unconditional teleportation [15,16] has led to a wide interest as to possibilities of two-mode squeezed states of light and EPR beams.

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In [15], a ring subthreshold degenerate optical parametric oscillator (DOPO) with two counter-propagating pump beams was used to generate two independent squeezed light fields, which emerge from the DOPO on the separate paths and then are combined by a beam-splitter to produce EPR beams. It is more efficient to produce the two-mode squeezed state of light and EPR beams from a non-degenerate optical parametric amplifier (NOPA) via a type-II phase-matching frequency down conversion process [9]. A Nd:YAP(Nd: $YAlO_3$) laser operating at 1080 nm and its SHG at 540 nm can satisfy the type-II non-critical phase-matching condition in an α-cut KTP crystal, we used a lamp-pumped Nd:YAP laser system to obtain different types of non-classical light [2,9]. Considering the important applications of two-mode squeezed-state light in quantum information science, we have designed and built a compact, portable, low pump threshold, and multi-purpose non-classical light source, in which an all-solid-state intracavity frequency-doubled ring Nd:YAP (Nd:$YAlO_3$) laser and a semi-monolithic non-degenerate optical parametric oscillator (NOPO) consisting of a type-II KTP($KTiOPO_4$) and a concave mirror are integrated on an invar steel base with a total volume about $300 \times 400 \times 500$ mm^3, Fig. 1 shows a photograph of the optical part of this apparatus. Above the oscillation threshold of the NOPO ($\sim$3 mW), twin beams with an intensity quantum correlation of 5.9 dB were obtained; by injecting frequency-degenerate and orthogonal polarization seed waves into the NOPO, bright two-mode quadrature amplitude-squeezed-state light of 2.1 dB is produced under a quite low pump power (the order of milliwatts) via a parametric deamplification. Since the non-degenerate signal and idler modes can be easily separated by a polarized beam-splitter (PBS), a NOPA operating in frequency degenerate and polarization non-degenarate can serve as a bright EPR source. This all-solid-state system can stably generate non-classical light for over 1 h when the active frequency-stability system of the OPO is turned on. Compared with our lamp-pumped system [2], the system's pump threshold was drop, stability was improved and volume was reduced significantly. The ability of the Nd:YAP/KTP system to provide two-mode squeezed vacuum state, bright two-mode phase quadrature-squeezed-state light and EPR beams with correlation of amplitude quadratures, and anticorrelation of phase quadratures has been experimentally demonstrated and discussed in the previous publication [2,8,9]. Although in the old systems, the pump sources were lamp-pumped Nd:YAP lasers occupying a larger volume and having a lower stability, the perfor-

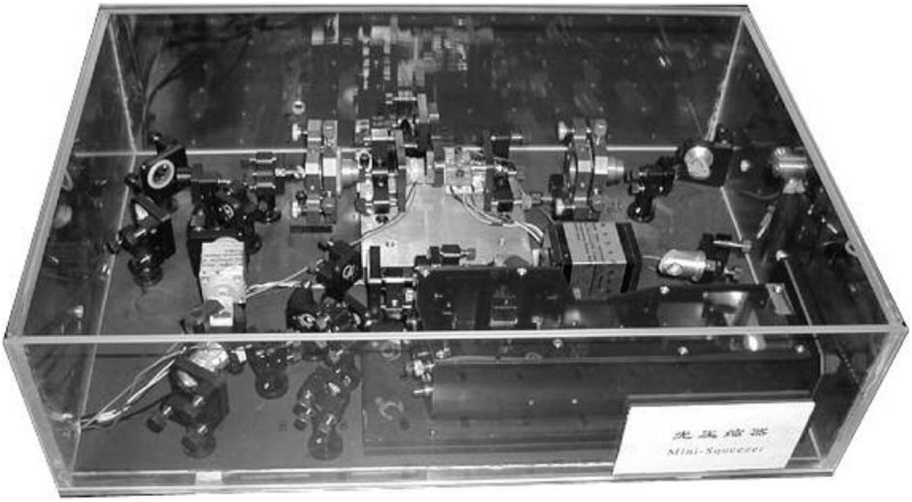

Fig. 1. Photograph of the optical parts of the portable non-classical light source.

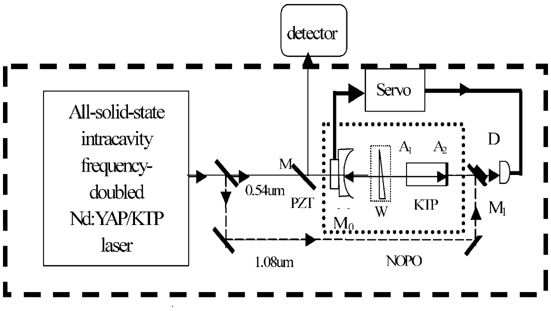

Fig. 2. Schematic of the experimental setup.

mances and operation principle of the new device are the same as the old ones. Therefore, the new device should have the potential to produce a variety of non-classical light fields.

The configuration of the non-classical light source is shown schematically in Fig. 2. A home-made diode-pumped intracavity frequency-doubled Nd:YAP laser with four-mirror bow-tie ring cavity configuration serves as the light source, which we have reported in [17], in which a *b*-axis cut Nd:YAP rod of 2 mm diameter and 4 mm length is pumped by a 2.5 W diode-laser bar (Coherence Corporation, Model S-81-2700c-200-h). The laser cavity consists of two concave mirrors with a radius of curvature $R = 50$ mm and two plane mirrors. The total length of the ring cavity is 330 mm, and the distance between the two concave mirrors is ~55 mm. An α-cut KTP crystal measuring $3 \times 3 \times 10$ mm^3 is located in the middle of the two concave mirrors and used as the frequency doubler. The temperature of the KTP is actively stabilized at the phase-matching temperature of about 63 °C with a precision of ±0.01 °C. A Faraday rotator and a half-wavelength plate at 1080 nm is placed in the cavity to ensure the laser's unidirectional operation. A pump power of 1.8 W gives a single-frequency output power of over 110 mW at a wavelength of 540 nm. The power fluctuation is less than ±1% during 3 h and the frequency float is less than 3 MHz/min in the free running case.

The NOPO consists of an α-cut KTP crystal 10 mm in length and a concave mirror M_0 with a 30 mm radius of curvature. The KTP crystal is placed in a specially designed oven and is actively temperature-controlled by an electronic feedback system to achieve type II non-critical phase-matching around 63 °C with a precision of a few mK. The two facets (A_1 and A_2) of KTP crystal are polished flat; A_1 is coated AR and A_2 is coated HR at both 540 and 1080 nm, respectively. The concave mirror with transmission T_1 (1080 nm) = 3% and T_2 (540 nm) = 11% is placed 23 mm from the A_1 facet of the crystal to serve as both the input and the output coupler. The semi-monolithic cavity was chosen for its mechanical stability, lower intracavity loss, compact, and greater versatility relative to the monolithic construction. The 540 nm pump light and 1080 nm injected seed wave from the laser are carefully mode-matched with the NOPO. The measured finesse, free spectral range, and linewidth of the cavity at 1080 nm are 180, 4.8 GHz, and 22 MHz, respectively.

In the OPO with high finesse for the signal and idler fields of near degenerate frequencies and low finesse for the pump field, at least a pair of signal and idler modes can resonate within a pump resonance peak; therefore triply resonant operation is possible only by adjusting the temperature of crystal around the phase-matching point.

The measured minimum oscillation threshold of NOPO is about 3.1 mW in the case of an exactly triple resonance of signal, idler, and pump modes. The measured wavelengths of the down converted twin infrared beams at the temperature of 63.54 °C are $\lambda_1 = 1080.030$ nm and $\lambda_2 = 1079.996$ nm.

The KTP crystal in the NOPO is also used as the electrooptical modulator and a modulation voltage at 23.2 MHz is impressed on it by two copper electrodes in contact with the crystal faces perpendicular to the optical axis to provide the error signal for cavity locking. The subharmonic leakage from the A_2 facets is monitored by the high-speed detector D. Mixing the detected signal with the modulation source of the pump waves and low-pass filtering results in a dispersion type error signal, that can be fed back to the PZT mounted on M_0 so that the cavity on-resonance can be locked by a servo loop (in our system a home-built proportional–integral–differential (PID) is applied to provide the electronic feedback control).

The output signal and idler beams from the input and output coupler M_0 are separated from the backreflected harmonic pump beams by a dichroic mirror M and detected by a self-homodyne detector consisting of a half-wave plate, a polarized beam-splitter, two focussed lens, and a pair of InGaAs pin photodiodes (EpitaxxETX500, diameter: 500 μm), which is tilted at the Brewster angle to the polarization plane of the monitored beams in order to reduce the reflection loss on the photodiode surface. The output photocurrents from the photodiodes are amplified and subtracted, the noise on the resulting difference is monitored by a spectrum analyzer. As shown by Heidmann et al. [5], when the axis of the half-wave plate is parallel the polarization direction of the polarized beam-splitter, the half-wave plate plays no roles and the measured signal is the intensities difference spectrum between the twin beams. When the half-wave plate is rotated to the polarization of the signal and idler beams to 45° relative to the polarization direction of the polarized beam-splitter, the system of half-wave plate and polarizing beam-splitter acts like a usual 50% beam-splitter, the measured signal in the intensity difference gives the shot-noise level as the sum of the intensities of the twin beams, which is the equivalent of a white noise intensity at frequencies higher than 2 MHz. In the low-frequency domain, the large excess noise of the laser dominates the measurement, the noise on each beams of homodyne detector cannot be completely rejected in the difference process of homodyne detector, so we detect the squeezing at the frequency higher than 2 MHz [18]. The experimentally measured squeezing spectrum of intensity difference fluctuation between the signal and idler beams is displayed in Fig. 3, in which trace (a) is the shot-noise-limit measured by rotating the polarization of the output signal and idler beam to 45° relative to the polarization direction of the polarized beam-splitter, and trace (b) is the squeezed noise power spectrum. The measured maximum squeezing is 5.9 dB below the shot-noise-limit at 3 MHz, taking into account the measurement efficiency (91%) and that the real squeezing of the output field from NOPO should be 7.2 dB, which is quite close to the theoretically calculated value (7.8 dB) [5].

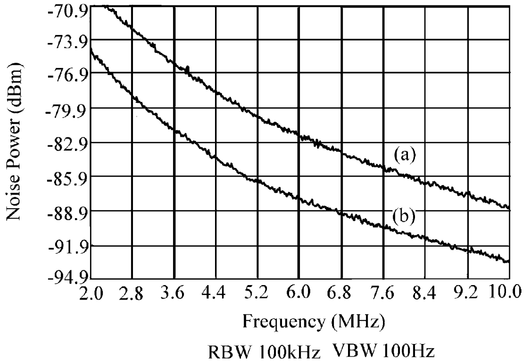

Fig. 3. Noise power spectrum of intensity difference between twin beams: (a) shot noise limit (SNL), (b) noise spectrum of intensity difference between twin beams.

To generate two-mode quadrature-squeezed-state light, the NOPO must be operated in the exact frequency degenerate state. Above the oscillation threshold, multiplicity of modes and mode-hopping lead to an inherent instability of the NOPO so that it is almost impossible to get the quadrature-phase-squeezed light of the coupled mode. To obtain stable quadrature-phase-squeezed-state light, the system should be operated below the oscillation threshold (it is called NOPA when the NOPO operated below the oscillation threshold) and by means of an injected seed wave to ensure the frequency-degeneration of the signal and idler modes. For high conversion efficiency, the NOPA should be operated at the simultaneous resonance of pump field, signal and idler modes. An optical wedge (W) is inserted in the NOPA to compensate for the dispersion between the pump and subharmonic fields. In this case, the measured finesse of the NOPA is 110 at 1080 nm and the total extra intracavity loss is increased to 2.3% due to the loss of the optical wedge. When the length of cavity is scanned by the PZT mounted on the output coupler (M_0), the transmission peaks of the three longitudinal modes can be monitored with an oscilloscope. To obtain a frequency-degenerate and balanced signal and idler output, a seed wave (4 mW) at 1080 nm from the laser is mode-matched and injected into the NOPA from the HR side (facet A_2), the seed beam polarized at 45° relative to the *b*-axis of the KTP crystal is decomposed into signal and idler seed waves with identical intensity and orthogonal polarizations along the b and c axes, respectively, which correspond to the vertical and horizontal polarization in our configuration. The temperature of the KTP crystal is actively maintained at the temperature for type-II non-critical phase-matching (63 °C) to produce frequency degenerate and orthogonal polarization subharmonic waves. By fine tuning the crystal temperature, the birefringence between signal and idler waves in the KTP can be compensated in order to reach the double resonance. Then by slowly adjusting the thickness of the optical wedge (W) in the laser beam, the triple resonance occurs when the three peaks on the oscilloscope overlap. Once the triple resonance occurs, the modulated subharmonic wave field back-reflected from the A_2 facet is detected by the photodetector D, and the detected ac photocurrent is mixed with the modulation signal to yield an error signal in the servo loop so that the PZT mounted on M can actively stabilize the cavity.

In the case of three modes resonance, the signal and idler modes are in-phase so that the bright superposed mode is at a 45° polarization with respect to the b-axis. The relative phase between the injected subharmonic signal and the harmonic pump wave is controlled by the PZT mounted on Mirror M_1. The maximum parametric amplification or deamplification is at a relative phase $\varphi_{\mathrm{rel}} = \varphi_{2\omega} - \varphi_{\omega} = 0°$ or $\varphi_{\mathrm{rel}} = 180°$, respectively. By operating the NOPA in the parametric deamplification state with a second harmonic pump power of 16 mW and the injected subharmonic light of 3 mW before the facet A_2, quadrature amplitude-squeezed light with the total power of $\sim$3.4 μW can be obtained. The polarization of the transmitted two-mode squeezed-state field of light is rotated 45° with respect to the horizontal direction by using a half-wave plate (HWP) of 22.5° relative to the b-axis. The squeezing light is detected by a self-homodyne detector. All optical surfaces between the NOPA cavity and the detectors are antireflection coated. The propagation loss of the subharmonic wave is 4%. The quantum efficiencies of the photodiodes are 92%. The total detector efficiency is about $\eta = 88\%$. The ac photocurrents from the self-homodyne detector are combined in a hybrid junction to generate the sum and difference photocurrents i_+, i_- which are sent to HP8590L spectrum analyzers. The measured noise powers $V_{\mathrm{det}}(i_-)$ scales the shot-noise level; $V_{\mathrm{det}}(i_+)$ stands for the noise power of the quadrature amplitude of the squeezed-state light [9].

Fig. 4 shows the measured variances $V_{\mathrm{det}}(i_+)$ and $V_{\mathrm{det}}(i_-)$ at 3 MHz as a function of the relative phases between the injected subharmonic and the pumping harmonic wave. The curves (a) and (b) show the noise powers of $V_{\mathrm{det}}(i_+)$ and $V_{\mathrm{det}}(i_-)$. Curve (c) is the shot noise level of the injected subharmonic seed wave while the pumping light field is blocked. A maximum quadrature amplitude squeezing of up to 2.1 dB was measured at the π phase difference between the subharmonic and the harmonic waves. Taking into account the total propagation efficiency (88%) and the electronic noise floors ($\sim$77 dB around 3 MHz), the real squeezing of the output field from NOPA should be 3.0 dB (the theoretical expectation of $\sim$3.2 dB).

By rotating the half-wave plate (HWP) from 22.5° to 0° relative to the b-axis of the KTP crystal, the quantum correlated signal and idler beams with orthogonal polarizations become separated by the polarizer P and spatially separated bright

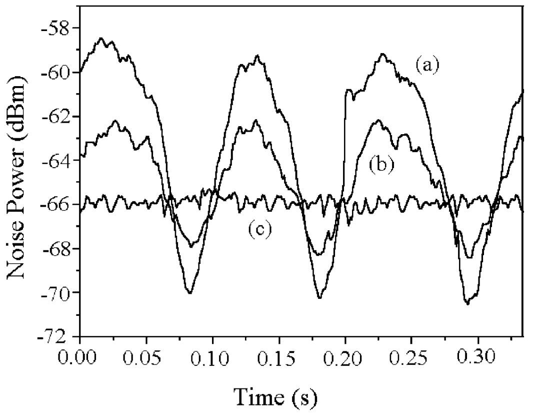

Fig. 4. Variances of the ac photocurrents i_- and i_+, generated at a self-homodyne detector. The curves (a) and (b) show the noise power of $V_{\mathrm{det}}(i_+)$ and $V_{\mathrm{det}}(i_-)$; curve (c) is the measured shot noise level for the case when the optical parametric oscillator is not pumped. Video bandwidth: 10 kHz, video bandwidth: 30 Hz.

EPR beams can obtain for which the inferred EPR correlation between the signal and idler mode due to the quadrature squeezing is 1 [19]. The signal and idler modes of the two-mode quadrature-phase-squeezed state with limited squeezing are non-ideal EPR beams with imperfect quantum entanglement between the quadrature amplitudes. Important application of these to quantum information science has been proposed and experimentally demonstrated [9]. We should also mention that there are amplitude anticorrelations and phase correlations between the two halves of the EPR beam generated from a parametric deamplification, which is different from what was published in [8,9] where the EPR beam with amplitude correlation and phase anticorrelation was obtained from the parametric amplification. Of course, if our system operates based on the models of parametric oscillation and amplification, it should also be able to produce vacuum and bright quadrature phase-squeezed state light fields, which have been demonstrated experimentally in our previous publications [2,9].

In conclusion, we developed a compact, portable, and multi-purpose non-classical light source that is able to provide different types of non-classical light fields including intensity correlated twin beams, bright and vacuum quadrature amplitude, and phase-squeezed state and EPR beams for different operating conditions. The stability, reliability, and practicability of this system are insured by its integrated configuration consisting of a LD-pumped YAP/KTP laser and semi-monolithic optical oscillator. The system is geared for development of practical devices that provide non-classical light fields for experimental research and quantum information processing. The squeezing degree is limited by the quality of optical elements comprising the NOPO; if an output coupler with a higher transmission is available and intracavity losses can be reduced, the squeezing degree can be significantly increased.

Acknowledgements

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