Generation of tripartite quantum correlation among amplitude-squeezed beams by frequency doubling in a singly resonant cavity

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(Received 15 October 2014; published 26 February 2015)

We present a technique for generation of tripartite quantum-correlated amplitude-squeezed light beams, using frequency doubling in a singly resonant cavity with two output ports. The two-output second-harmonic (SH) beams are both nonlinearly coupled to the common fundamental beam even though they have no direct interaction. The nonlinear coupling produces noise reduction of amplitude for each beam and quantum correlations among three beams. In our first experiment, we measured amplitude squeezing of 0.5, 0.8, and 0.6 dB for the fundamental beam and two output SH beams, respectively. Meanwhile, quantum correlation of 0.6 dB between the two amplitude-squeezed SH beams and quantum anticorrelation of 0.6 and 0.8 dB between the squeezed fundamental beam and each of the SH beams were observed around the range of optimum conversion efficiency. This opens an alternate way to produce tripartite-quantum-correlated systems.

DOI: 10.1103/PhysRevA.91.023833 PACS number(s): 42.50.Dv, 42.25.−p, 03.67.Dd

Continuous wave light beams that exhibit nonclassical statistics and quantum correlation are of interest in studies of quantum mechanics and for a number of applications that include precision measurements beyond the shot-noise limit and quantum information such as quantum communications, quantum key distribution, and quantum teleportation [1–3]. As a matter of fact, the optical Einstein-Podolsky-Rosen entangled state, which is the essential quantum source for implementing continuous variable quantum information, is a two-mode entangled state consisting of two submodes with quantum correlations between both the quadrature amplitude and the quadrature phase [4]. Generation and application of bipartite quantum entanglement have been extensively investigated both theoretically and experimentally [5–9]. With the development of quantum communication techniques, quantum correlation among more than two parties is going to be the key ingredient for advanced quantum network systems. Especially, the generation of lights with quantum correlation at different frequencies is more important since they are able to link quantum information between communication and storage in the nodes, in which atoms, trapped ions, or fiber windows are employed [10,11].

A number of different techniques for the generation of quantum correlations among multiple beams have been proposed and experimentally implemented. Each of the schemes has its advantages and disadvantages. For example, one of the approaches is to combine independent squeezed states, which are generated from optical parametric oscillators (OPOs), on beam splitters [12,13]. Owing to the availability of high-quality nonlinear material, it is easy to get high-level quantum correlations. However, it is impossible to generate lights with quantum correlation at different frequencies. Other proposals, such as cascaded nonlinearities, also have this shortcoming [14,15]. Recently, it was also demonstrated that a standard triply resonant above-threshold OPO was able to directly produce pump-signal-idler tripartite quantum entanglement in both theory and experiment [16,17]. Its significant advantage is that is able to generate quantum correlations at different frequencies. However, the level of quantum correlations still needs to be further improved for applications. Furthermore, the entanglement between subharmonic and harmonic waves, which span an octave in optical frequency, was also realized by the use of an optical parametric amplifier [18,19]. Most of the abovementioned approaches are based on parametric down conversion. Their inconvenience is their incapability of generating a nonclassical state whose wavelength is shorter than that of pump light. In particular, light at short wavelength is of high interest to increase the resolution in imaging and lithography and to increase the sensitivity in phase measurements. Furthermore, future quantum memories based on trapped atoms, ions, or atomic ensembles will potentially use shorter wavelengths, up to the visible spectrum. Hence, generation of nonclassical lights at short wavelength is more important.

The inverse process of down conversion, second-harmonic generation (SHG), is the most effective method to convert light with a long wavelength into light with a short wavelength. Most of laser lights in the visible regime were produced by SHG. Twenty years ago, its capability of generating amplitude-squeezed light was experimentally demonstrated [20]. This opened the way to produce nonclassical states with short wavelength that are not accessible by parametric down conversion. Later, it was also experimentally demonstrated that the fundamental fields were squeezed because of the cascaded nonlinear interaction between the subharmonic and harmonic waves [21]. One of the advantages of the SHG system is its simplicity, since OPOs are usually pumped by second-harmonic (SH) lights. However, the task is much more challenging, since the generated nonclassical light beam has high average power. The generated beams with high power are also another specialty. Recently, it was proposed to produce

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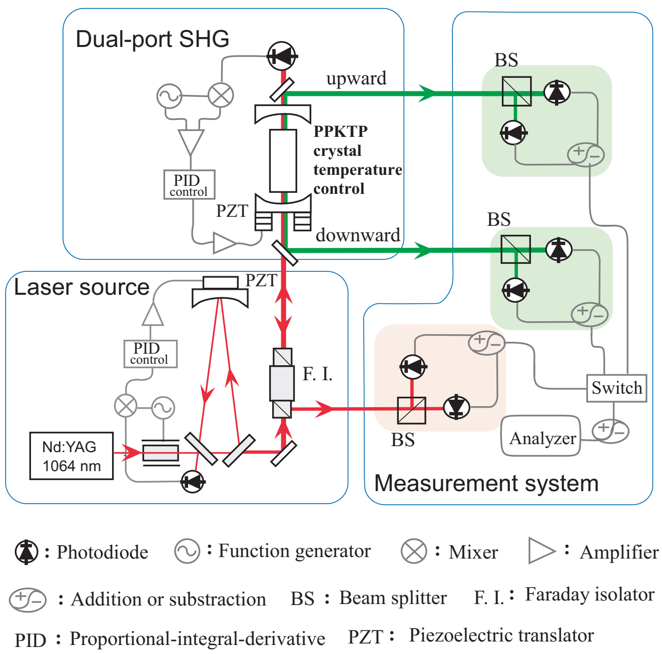

FIG. 1. (Color online) Schematic diagram for generation of tripartite-quantum-correlated amplitude-squeezed beams.

tripartite entanglement by SHG. It has been theoretically shown that tripartite entanglement among the two fundamental fields and SH fields can be directly yielded in the process of type-II SHG [22,23]. Using a singly resonant dual-port cavity SHG, generation of tripartite entanglement among the two SH fields and the fundamental field has also been proposed [24]. Moreover, it has been demonstrated that the two output SH fields of the dual-port SHG system exhibit nonclassical intensity correlation in experiment [25,26]. However, experimental confirmation of tripartite quantum correlation is more interesting for the future application of quantum information and communications.

In this paper, we experimentally demonstrate the generation of tripartite-quantum-correlated amplitude-squeezed beams by dual-port cavity enhanced SHG. Three amplitude-squeezed beams at different wavelengths are generated with one system. Meanwhile, any two of three outputs exhibit quantum correlation or quantum anticorrelation. We also investigate detailed conditions further realizing tripartite entanglement with SHG. Bipartite-quantum-correlated amplitude squeezing using conditional preparation techniques and SHG has been reported [27,28]. Our experimental results clearly verify the capability of generation of the tripartite quantum state using dual-port cavity parametric up conversion.

A schematic of the entire experiment is shown in Fig. 1. The main laser source was a commercially available continuous wave Nd:YAG laser system at 1064 nm with a maximum output power of 2 W. The laser linewidth was quoted from the manufacturer as 1 kHz. The experiment was very sensitive to spectral noise and spatial mode-matching inefficiencies. To filter the extra-noise of pump laser and get an efficient mode-matching factor in the SHG cavity, the output laser beam was first transmitted through a high-finesse optical resonant, or mode cleaner. It was a ring cavity consisting of two indentical flat input-output mirrors with reflection of $R = 99.9\%$ and a mirror with a 1 m radius of curvature and reflection of $R = 99.99\%$, at normal incidence, and it had a total resonator length of 56 cm. We observed a finesse of 1500; this provided a cavity linewidth of about 300 kHz. Frequency spectra for the intensity noise of the 20-mW laser field after mode cleaner were measured. The result showed that the intensity noise of the transmitted light was the shot-noise limit from the analyzed frequency of 3 MHz. The locking of the mode cleaner was via the Pound-Drever-Hall technique. Using an electro-optic mmodulator (EOM) with a modulation frequency of 20 MHz, the light was phase modulated before it was injected into the mode cleaner. A resonant photodetector was placed in the reflection port of the cavity and was used for the error signal generation, while the dc output of this detector can be used for light intensity monitoring. The obtained error signal was feedback to the mode cleaner cavity after passing through a proportional-integral-derivative controller.

A Faraday isolator was set in the input light between the SHG cavity and the mode cleaner for eliminating the back-reflection and outputting the fundamental field. To observe intensity squeezing and quantum correlation among the fundamental field and the SHG fields, we designed a frequency doubler to reach the optimum conversion efficiency at low input power. Thus, the resulting output powers were still low enough not to saturate the photodiodes of the balanced detector. We adopted a standing-wave cavity configuration. The cavity consisted of two mirrors with a radius of curvature of 50 mm and a 15-mm-long periodically poled $KTiOPO_4$ (PPKTP) crystal with both end faces antireflection coated at 532 and 1064 nm. The length of the cavity was 55 mm and created a mode for the resonant 1064-nm light with a $\sim$50-μm waist at the center of the PPKTP crystal. The fundamental field input-output mirror, which was mounted on a piezoelectric translator, was coated for partial transmission of 5% at 1064 nm and antireflection at 532 nm for separating the downward SH field. Another mirror was coated for high reflectivity at 1064 nm and high transmission at 532 nm for outputting the upward SH field. Hence, only the fundamental field was resonant in the cavity and the dual-port SHG cavity can provide two SH outputs and one fundamental output. The measured finesse of the cavity is about 110, and the free spectral range is 5 GHz. Thus the cavity has a linewidth (full width at half maximum) of $\gamma_c = 45$ MHz. Phase matching was realized by actively controlling the temperature of PPKTP. Stable operation of SHG can be achieved by locking the cavity on the frequency of the fundamental field via a dither-locking technique. Thanks to the high nonlinearity of PPKTP, our design results in the optimum conversion efficiency of 50% being reached with an input power of only about 60 mW in the experiment.

For measuring the intensity noise, each of the outputs of the dual-port SHG is sent into a balanced detection system. The light is split into two equal parts by a 50:50 beam splitter (BS). Each output of the beam splitter is detected with a high efficiency photodiode. The ac photocurrents are amplified and combined in a hybrid junction to generate the sum or difference currents, i_+ or i_-. These currents are sent to a spectrum analyzer that records the noise powers $V_{\rm det}(i_+)$ and $V_{\rm det}(i_-)$. $V_{\rm det}(i_-)$ measures the shot-noise level; $V_{\rm det}(i_+)$ is proportional to the intensity noise of the beam. For the measurement of the fundamental field, a balanced detection system based on two InGaAs photodiodes (JDSU, ETX500, quantum efficiency of 90%) is adopted; meanwhile, two Si photodiode (Hamamatsu Photonics, S5973-02, quantum efficiency of 88%) are employed for measuring the SH fields. To accurately measure the intensity noise of input light, the noise power spectra of the sum hybrid junction and the difference hybrid junction should be balanced as well as possible. The unbalance between our homemade splitter and combiner is less than 0.2 dB at the analysis frequency range from 1 to 10 MHz. To interrogate the quantum correlation between two light beams (beam1, beam2), the noise power of subtraction or addition of the resulting photocurrents from the two sets of balanced detection systems is further investigated using a spectrum analyzer. The subtraction of the two difference currents $[i_-(1),i_-(2)]$ gives the shot-noise limit, while the subtraction of the two sum currents $[i_+(1),i_+(2)]$ gives the quantum correlation between beam 1 and beam 2. On the other hand, the addition of the two difference currents $[i_-(1),i_-(2)]$ gives the shot-noise limit, while the addition of the two sum currents $[i_+(1),i_+(2)]$ gives the quantum anticorrelation between beam 1 and beam 2.

Observation and characterization of intensity squeezing and quantum correlation between the fundamental field and the SH fields with the SHG process are restricted by the SHG system. First, the fundamental beam should be mode matched to the SHG enhancement cavity as well as possible. Thanks to the mode cleaner, a cleaned TEM_{00} beam is spatially matched into the SHG cavity with an efficiency of 95%. Second, the frequency doubler should be pumped around the optimum conversion efficiency. Third, the powers of the reflected fundamental field and the two SH fields should be balanced. For the input fundamental field power of 70 mW, which is a little higher than the optimum conversion power of 60 mW, we obtained a total SH output power of 33 mW (upward SH power of 18 mW and downward SH power of 15 mW) and a reflected fundamental light power of 19 mW. We locked the SHG cavity to be resonant with the laser frequency; the system was stably operating more than half an hour. All the noise spectra measurements were carried out under this condition.

Figure 2 gives the normalized intensity noise spectra for fundamental, upward, and downward SH fields. The analysis frequency range in Fig. 2 is 2–14 MHz. A noise reduction of 0.5 dB is observed for the fundamental field, and noise reductions of 0.8 and 0.6 dB are observed for the upward and downward green lights, respectively. This can be understood as follows. The upward vacuum field of 532 nm and the intracavity fundamental field create the upward SH output. Meanwhile, the downward vacuum field of 532 nm and the intracavity fundamental field create the downward SH output. Although two SH outputs are produced from two independent vacua modes, they are both nonlinearly coupled to the common fundamental beam. This nonlinear coupling produces noise reduction of amplitude for each beam and quantum correlations among three beams. In principle, the generated squeezings in two SH fields are independent of each other. According to theory, the intensity noise variances of fundamental and SH fields with respect to the shot-noise level

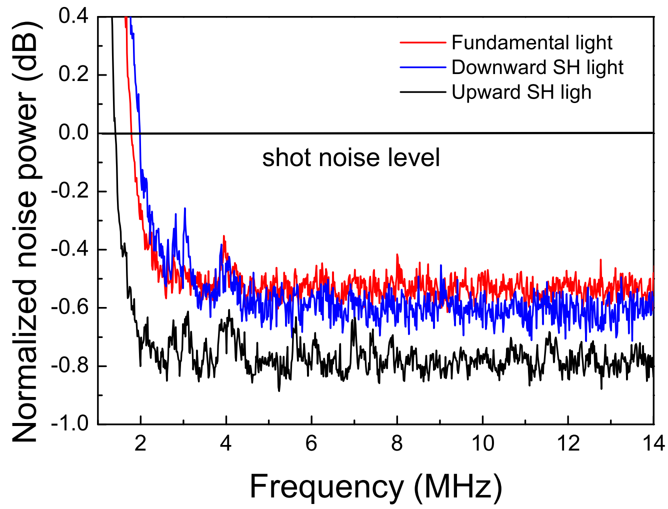

FIG. 2. (Color online) Normalized noise spectra of fundamental light, upward SH light, and downward SH light. The resolution bandwidth and the video bandwidth of the spectrum analyzer are 300 kHz and 300 Hz, respectively. All results are obtained with 5 times averaging.

are given by [28]

$$V1_{\mathrm{sq}} = 1 - \frac{T_1}{T_1 + T_2}\frac{4d}{(1+3d)^2 + (2f/\gamma_c)^2}, \tag{1}$$

$$V2_{\mathrm{sq}} = 1 - \frac{8d^2}{(1+3d)^2 + (2f/\gamma_c)^2}, \tag{2}$$

where T_1 is the transmission of the output coupler, T_2 is the extra loss of the SHG cavity for the fundamental field, f is the detection frequency, and $d = \mu|\alpha|^2/\gamma_c$ is a pump parameter relating to the fundamental power inside the cavity ($|\alpha|^2$), two-photon damping rate of nonlinear crystal (μ), and cavity linewidth (γ_c). Then, the detectable intensity variance is $V_{\mathrm{det}} = \eta V_{\mathrm{sq}} + 1 - \eta$. We determined the parameter d by fitting the measured intensity noise power of the fundamental field and the abovementioned parameters. The fitting yielded $d = 1.3$. It gives a reasonable agreement with the power conversion in SHG since the optimum conversion efficiency is achieved when $d = 1$. In principle, the best squeezing in the fundamental field is obtainable when $d = 1/3$. Unfortunately, significant improvement of the squeezing level was not observed with decreasing the power of the input fundamental power. On the other hand, the squeezing level slightly reduced with the increase of power of the input fundamental field and it completely disappeared at an input fundamental power of 130 mW. Supposing the pump parameter of $d = 1.3$, Eq. (2) implies that more than 3.5 dB of noise reduction is obtainable for the SH field. The observed noise reduction is far lower than expected. Possible reasons for the discrepancy are the transfer of the fundamental phase noise (the linewidth of laser light) to the harmonic wave, the increase of subharmonic loss under the SHG process, the inaccuracy of locks, etc. It has been experimentally observed that the phase noise sufficiently conversed into the amplitude noise in a detuning cavity [29]. Noise reduction is slightly improved with the increase of power

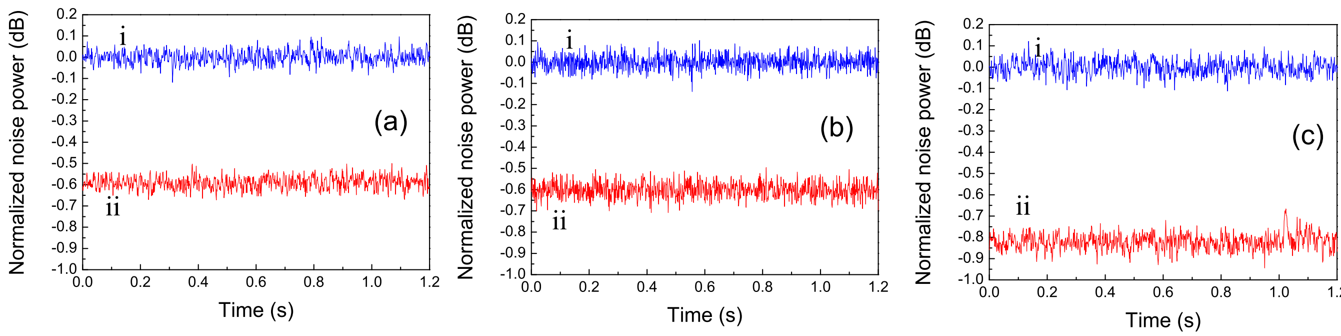

FIG. 3. (Color online) Observation of quantum correlation and quantum anticorrelation among the fundamental field and two SH fields. (a) Quantum correlation between two SH fields. (b) Quantum anticorrelation between the fundamental field and the upward SH field. (c) Quantum anticorrelation between the fundamental field and the downward SH field. Curve (i) is the normalized shot-noise level. Curve (ii) is the noise power of the photocurrent difference between two SH lights for panel (a) and is the noise power of the photocurrent sum between fundamental and SH lights for panels (b) and (c). The parameters of the spectrum analyzer are the same as those in Fig. 2.

of the input fundamental field, and it is never better than 1 dB even at an input fundamental power of 130 mW.

To measure the quantum correlation between the two SH fields, the subtraction of two outputs from two SH balanced detection systems was recorded. A gain between two balanced detection systems was introduced since their input powers were a little unbalanced. The gain between two balanced systems was optimized to obtain maximum quantum correlation. The measured quantum correlation at an analysis frequency of 4 MHz is shown in Fig. 3(a), in which curve (i) gives a normalized shot-noise level when two difference currents [i_-(upward SH), i_-(downward SH)] are subtracted, and curve (ii) shows the quantum correlation when two sum currents [i_+(upward SH), i_+(downward SH)] are subtracted. It can be seen that curve (ii) is 0.6 dB below curve (i), which clearly indicates the quantum correlation between the two SH fields. We characterize the quantum anticorrelation between the fundamental field and each of the SH fields in the same manner. In this time, the additions of two outputs of the fundamental field balanced detection system and one of the SH balanced detection systems are investigated. The measured quantum anti-correlations are shown in Figs. 3(b) and 3(c). Averaging the noise of both traces determines the quantum anticorrelation level to be 0.6 and 0.8 dB below the shot-noise level, respectively. To our knowledge, this is the first experiment to generate tripartite-quantum-correlated amplitude-squeezed light beams. Both the quantum correlation and quantum anticorrelations were investigated when the power of input fundamental light varied in the range of 50–130 mW. It seems that they are insensitive to the power of input fundamental light.

In principle, the tripartite quantum correlation in the dual-port SHG can be observed in a broad range of pump power. It is, however, a trade-off between the noise reduction of the fundamental beam and the noise reduction of the SH beam. The best noise reduction in the fundamental beam is obtainable when the pump parameter is $d = 1/3$, meanwhile the maximum noise reduction of $8/9$ can be achieved when the doubler is operated at input power of infinity ($d \gg 1$). For observation of both quantum correlation among three beams and noise reduction for each beam of three beams, the SHG system was operating at input power near the optimal conversion efficiency, i.e., $d \approx 1$ was selected. Neither the detection efficiency nor the propagation efficiency was taken into account for correcting the measured results. The experimental results clearly indicate the capability of generating tripartite-quantum-correlated amplitude-squeezed light beams with parametric up conversion. This method should also have applications in producing quantum state light with short wavelength. It is also of interest to produce quantum light sources for the quantum repeater, since SHG is one of the convenient ways to produce light at atomic transition frequencies in the visible and near infrared. On the other hand, there remains the challenge of improving the noise reduction for each of the light fields and the quantum correlation among them. Considerable improvement of noise reduction for the SH can be performed by more accurate locking of the enhancement cavity.

In conclusion, we have presented an experimental generation of tripartite-quantum-correlated amplitude-squeezed light beams using a dual-port cavity enhanced SHG. We measured amplitude squeezing of 0.5, 0.8, and 0.6 dB for the fundamental beam, the upward SH beam, and the downward SH beam, respectively. Meanwhile, quantum correlation of 0.6 dB between the two amplitude-squeezed SH beams and quantum anticorrelation of 0.8 dB between the squeezed fundamental beam and each of the SH beams were observed around the range of optimum conversion efficiency. All the quantum properties were produced by the nonlinear coupling between the fundamental field and the SH fields in the enhancement cavity. This type of coupling has been also predicted to be used to generate tripartite entanglement between three different wavelengths and our work may be seen as a step in that direction.

This work was supported by JSPS KAKENHI Grant No. 26390078. T.L. was suppoted by the National Natural Science Foundation of China (NSFC) (Grant No. 61307006) and the Natural Science Foundation of Shanxi Province, China (Grant No. 2013011035-4).

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