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Dependence of the squeezing and anti-squeezing factors of bright squeezed light on the seed beam power and pump beam noise

Xiaocong Sun,[1] Yajun Wang,[1,2] Long Tian,[1,2] Shaoping Shi,[1] Yaohui Zheng,[1,2,*] and Kunchi Peng[1,2]

[1]The State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China
[2]Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China
*Corresponding author: yhzheng@sxu.edu.cn

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We demonstrate the dependence of the squeezing and anti-squeezing factors on the seed beam power at different pump beam noise levels. The results indicate that a seed field injected into the optical parametric amplifier (OPA) dramatically degenerates the squeezing factor due to noise coupling between the pump and seed fields, even if both the pump and seed fields reach the shot noise limit. The squeezing and anti-squeezing factors are immune to the pump beam noise due to no noise coupling when the system operates for the generation of squeezed vacuum states. The squeezing factor degrades gradually as the pump beam intensity noise and seed beam power is increased. The influence of the two orthogonal quadrature variations is mutually independent of each other.

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Squeezed states can partially eliminate the limiting effects of quantum noise and offer the potential of improving the performance of optical devices. It is an extremely important resource to achieve quantum measurement beyond the shot noise limit [1,2], quantum imaging beyond the diffraction limit [3,4], and dense quantum information process [5]. Optical parametric oscillator (OPO) and optical parametric amplifier (OPA) are two of most successful systems for squeezed state generation, which have continually held the record for the largest amount of quantum noise reduction. Therefore, OPO and OPA are natural choices for producing large squeezing magnitude.

OPO and OPA have the same underlying second order nonlinearity. However, the OPA process has a coherent seed light injection at the fundamental wave. The output has a coherent amplitude and is a bright squeezed state. Whereas the OPO is seeded by vacuum field, without coherent amplitude output and is a squeezed vacuum state resource [6]. The type of squeezed light is desirable is dependent on its applications. In interferometer, squeezed vacuum states are usually used to reduce the cross-interference influence due to no coherent amplitude [7]. Bright squeezed states have coherent amplitude, which can be used in spectroscopic measurement [8], velocimetry [9], LIDAR [10], quantum key distribution [11], and quantum teleportation [12–14]. Furthermore, a silicon-chip-based cavity optomechanical magnetometer that used bright squeezed state allows a 20% improvement in magnetic field sensitivity [15].

Since the first experimental demonstration of squeezed states based on the OPO succeeded in 1986 [16], intensive researches are carried out to increase the squeezing factor in the last thirty years [17–26]. Under the motivation of gravitational waves detection, a 10 dB squeezed vacuum state was detected for the first time at the University of Hanover in 2007 [20]. Subsequently, the squeezing strength was gradually increased, reaching the maximum value of 15 dB at l064 nm based on periodically poled $KTiOPO_4$ (PPKTP) [21].

For the squeezed vacuum state, the squeezing factor is immune to the pump beam intensity noise and is mainly limited by the total loss and phase fluctuation [27,28]. The presence of a seed beam for the generation of bright squeezed state leads to a dramatic degradation of the squeezing at audio frequencies due to the pump intensity noise coupling via the intracavity fundamental beam. The squeezing degradation is also dependent of the seed beam power, which is disadvantageous to the power increase of bright squeezed state [28]. However, at MHz region, the classical noise of seed and pump beam is thoroughly cancelled in the literatures. The research about the influence of the seed beam with shot noise limit (SNL) on the squeezing factor of bright squeezed state has not been studied prior to this work.

In this Letter, we report the results of demonstrating the dependence of the squeezing and anti-squeezing factors on the pump beam noise and seed beam power. The squeezing and anti-squeezing factors are independent of the pump beam noise due to no noise coupling for the generation of squeezed vacuum states. A seed beam that is injected into the OPA results in gradual degradation of the squeezing factor due to noise coupling enhancement with the increase of the seed beam power, even if both the pump and seed fields have no classical noise. Furthermore, the influence of two orthogonal quadrature variations is mutually independent of each other.

According to the equations of motion for nonlinear interaction processes, the amplitude and phase quadrature variances at the output of the OPA on resonance can be given by [28]

$$\begin{aligned} V^{\pm}(\Omega) = \frac{1}{C(\Omega)}\{ & C_s(\Omega)V_s^{\pm}(\Omega) + C_{\nu s}^{\pm}(\Omega)V_{\nu s}^{\pm}(\Omega) \\ & + C_{ls}(\Omega)V_{ls}^{\pm}(\Omega) + a^2[C_p(\Omega)V_p^{\pm}(\Omega) \\ & + C_{\nu p}(\Omega)V_{\nu p}^{\pm}(\Omega) + C_{lp}(\Omega)V_{lp}^{\pm}(\Omega)]\}. \end{aligned} \tag{1}$$

The superscript "+/−" represents the amplitude and phase quadrature, respectively. We can find from Eq. (1) that the intensity noise corresponding to the quadrature amplitude variances while the phase noise related to the quadrature phase variances. The quadrature variances relate to seed beam variances $V_s^{\pm}$, the pump beam variances $V_p^{\pm}$, vacuum fluctuations from intracavity loss causing by the seed and pump beam $V_{ls}^{\pm}$ and $V_{lp}^{\pm}$, vacuum fluctuations entering through the output coupler caused by the seed and pump beam $V_{\nu s}^{\pm}$ and $V_{\nu p}^{\pm}$, noise due to detuning fluctuations in the OPA, other noise sources, such as cavity detuning and phase matching fluctuations, are not discussed here. The coefficients in Eq. (1) are

$$C^{\pm}(\Omega) = [a^2\epsilon^2 \mp b\epsilon(i\Omega + \gamma_b) - (\Omega - i\gamma_a)(\Omega - i\gamma_b)]^2, \tag{2}$$

$$C_s(\Omega) = \left[2i\sqrt{\gamma_a^{\mathrm{in}}}\sqrt{\gamma_a^{\mathrm{out}}}(\Omega - i\gamma_b)\right]^2, \tag{3}$$

$$C_p(\Omega) = \left[2\epsilon\sqrt{\gamma_a^{\mathrm{out}}}\sqrt{\gamma_b^{\mathrm{in}}}\right]^2, \tag{4}$$

$$C_{\nu s}^{\pm}(\Omega) = [a^2\epsilon^2 \mp b\epsilon(i\Omega + \gamma_b) - (\Omega + 2i\gamma_a^{\mathrm{out}} - i\gamma_a)(\Omega - i\gamma_b)]^2, \tag{5}$$

$$C_{\nu p}(\Omega) = \left[2\epsilon\sqrt{\gamma_a^{\mathrm{out}}}\sqrt{\gamma_b^{\mathrm{out}}}\right]^2, \tag{6}$$

$$C_{ls}(\Omega) = \left[2i\sqrt{\gamma_a^{\mathrm{out}}}\sqrt{\gamma_a^{l}}(\Omega - i\gamma_b)\right]^2, \tag{7}$$

$$C_{lp}(\Omega) = \left[2\epsilon\sqrt{\gamma_a^{\mathrm{out}}}\sqrt{\gamma_b^{l}}\right]^2, \tag{8}$$

where ϵ is the nonlinear coupling parameter and Ω is the frequency detuning relative to the carrier frequency. a and b are the amplitudes for the fundamental and harmonic fields. γ_a and γ_b are the total decay rates of the fundamental and harmonic fields. The parameters γ_a^{in}, γ_a^{out} and γ_a^{l} (γ_b^{in}, γ_b^{out}, and γ_b^{l}) are the decay rates of intracavity fundamental (harmonic) field due to the input coupler, output coupler, and loss, respectively. The first three terms of Eq. (1) are independent of the presence of the seed beam, determined by the pump factor and total loss of squeezed state generation system [11]. For the case without the seed beam ($a = 0$), the last three terms are absent, the influence of the pump beam noise on the quadrature variances is thoroughly eliminated. For bright squeezed states, a $\neq 0$, the pump beam noise can be transferred to the downconversion beam through the coupling with the seed beam. The coupling factor scales with the pump beam noise and the seed beam power. For certain setup of bright squeezed states generation, the output power is proportional to the seed beam power. Thus, this is the main challenge for higher power output of the bright squeezed states. Even if the pump and seed beam reach the SNL, the influence does still exist.

A schematic of our experimental setup is illustrated in Fig. 1. The laser source of our experiment is a home-made continuous-wave single-frequency Nd:YVO_4 laser at 1064 nm. Three mode cleaners (MC) are adopted not only to provide spatial-temporal filtering and polarization purifying for the downstream experiment but also as an auxiliary cavity for high-efficiency mode-matching. The MCs ensure the quadrature noises of the seed and pump beams meet the SNL above 2 MHz at full power. It would be specially mentioned that an electro-optic amplitude modulator (EOAM) and an electro-optic modulator (EOM) is inserted between the MC532 and OPA in our setup to conveniently manipulate the pump intensity and phase noise. The two modulators are independently driven by two channels of the function generator with white noise output at the frequency range of from 0 to 10 MHz. Thus, the additional noise imposed on the pump beam is uniform in the frequency range of between 2.1 and 3.5 MHz measurement frequency. The assembly of half-wave plate and polarization beam splitter applied in the infrared path to adjust the seed beam power injected into the OPA.

Our OPA is a semi-monolithic cavity consisting of a piezo actuated concave mirror and a PPKTP crystal and its parameters are the same as that of Ref. [23]. In order to ensure the results are taken, no experimental parameters other than the seed beam power and pump beam intensity and phase noise are varied during the measurement cycle. The squeezed light is directed toward a BHD to detect the noise level. The BHD has a common mode rejection ratio of 75 dB [29,30].

During the measurement of squeezed vacuum states, the OPO is kept on resonance by manually applying offset voltage to the piezo. Meanwhile, the measured noise variance is minimized by adjusting the phase between the local oscillator and squeezed state. Due to the integrated design of the OPO, the squeezing factor is passively stable at the timescale of several minutes.

During measurement of bright squeezed states, all data is taken under the conditions that the OPA cavity length and relative phase is actively controlled by using the mutual-compensation

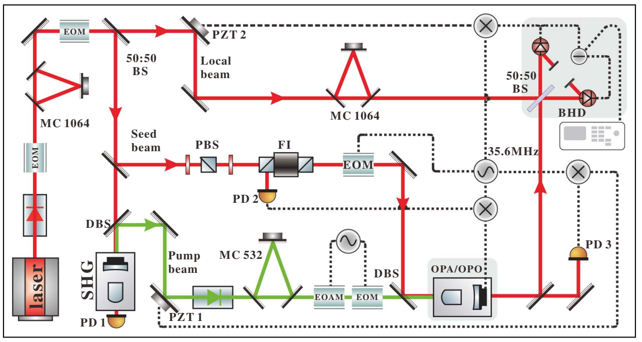

Fig. 1. Schematic of the experimental setup. MC, mode cleaner; PBS, polarization beam splitter; FI, faraday isolator; EOM, electro-optical modulator; OPA, optical parametric amplifier; OPO, optical parametric oscillator; DBS, dichroic beam splitter; SHG, second harmonic generation; EOAM, electro-optic amplitude modulator; PZT, piezoelectric transducer; PD, photodetector; BHD, balanced homodyne detection.

scheme [23]. The phase modulation signal is imprinted on the seed beam to generate error signal for all three control loops [31,32]: the error signal for stabilizing the OPA cavity length on resonance is demodulated from the photodetector PD2 placed in the reflected end of the OPA; the error signal of locking the relative phase between the pump and signal beams is obtain from the photodetector PD3 output. The relative phase between the local oscillator (LO) and the signal beam is locked by demodulating the output signal of the homodyne detector and feeding back to the PZT2 on the optical path of the LO beam. In the downstream experiment, the relative phase between the pump and signal beams is locked to π. Therefore, the squeezing factor corresponds to quadrature amplitude variance, and the anti-squeezing factor represents quadrature phase variance. When the seed beam power is less than 15 mW, the amplitude of the error signal is insufficient to obtain a stable locking for the OPA cavity and relative phase. So the dependence of the squeezing and anti-squeezing level on the seed beam power is measured at the seed beam power of more than 15 mW.

First, the squeezing (amplitude) and anti-squeezing (phase) quadrature variances without the seed beam injected are measured under conditions of different intensity and phase noise of the pump beam. The directly observed squeezing and anti-squeezing level are 12.3 dB and 16.8 dB, respectively, and are independent of the pump beam noise. So the squeezing factor of squeezed vacuum states is immune to the pump beam noise.

Figure 2 presents the measured results of the squeezing and anti-squeezing level at the seed beam power of 15 mW and the analysis frequency from 2.1 to 3.5 MHz that is the minimum power for the stable locking of the OPA cavity and relative phase. Due to the severe impedance mismatching of the OPA, its transmission is very low and only 0.4% [32]. All traces are recorded by a spectrum analyzer (Agilent N9020A with the uncertainty of 0.2 dB). In order to avoid the influence of the saturation effect of the BHD on the measurement of bright squeezed light, all data is recorded at the LO power of 2 mW. Trace (a) corresponds to the shot noise of 2 mW LO power and is measured with the squeezed light blocked. Traces (b) and (d) show the quantum noise of the squeezing and anti-squeezing when the phase offset between the signal light and the local light is locked to minimum (red line) and maximum (blue line). The directly observed squeezing and anti-squeezing level are 11.8 dB and 16.1 dB, respectively. Trace(c) shows the electronic noise of the BHD. The electronic noise is 18 dB below the shot noise at analysis frequency of 2.1 MHz and 16 dB of 3.5 MHz. Limited by the photodetector bandwidth, we do not measure the quantum noise at higher analysis frequency.

In order to quantify the dependence of the squeezing and anti-squeezing level on the pump beam noise, we first measure the intensity and phase noise of the pump (seed) beam with and without the additional modulation. The intensity noise is measured by self-homodyne detection technique [33].The phase noise is obtained by employing an optical cavity to rotate the noise ellipse of light, which is converted into amplitude noise at half detuning [34]. The completely measured results show that the intensity and phase noise reach SNL above the analysis frequency of 1.9 and 2.1 MHz without additional modulation, respectively, and they increase independently with the output amplitude of the function generator.

The bottom of Fig. 3 presents the dependence of the squeezing factor on the seed beam power at different additional intensity noise of the pump beam at the analysis frequency of 3 MHz. All of the data are dark-noise corrected and normalized to the vacuum reference. At the seed beam power of 15 mW, the squeezing factor is 11.8 dB. The quadrature amplitude squeezing factor decreases gradually with the increase of the seed beam power due to the noise coupling enhancement between the pump and seed waves. Until the seed beam power reaches 115 mW, the squeezing strength reduces to 9.4 dB. The red solid line is the theoretical result, and the red dots indicate the measured squeezing factor without additional amplitude modulation. Limited by the saturation effect of the BHD, we cannot accurately measure the squeezing and anti-squeezing strength at the seed beam power of more than 115 mW. By

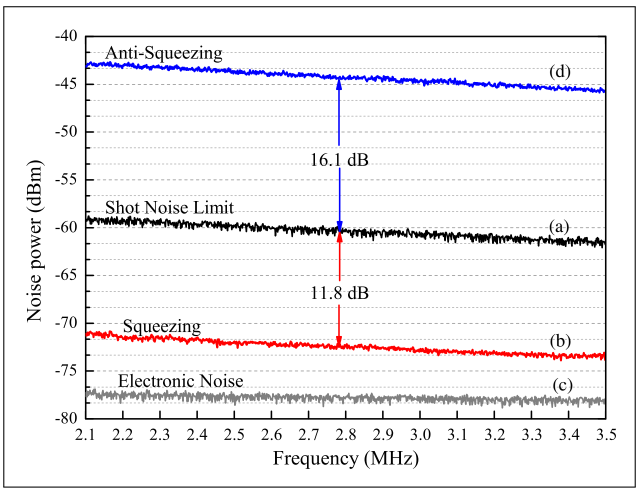

Fig. 2. Balance homodyne measurements of the quadrature amplitude and phase variances. Resolution bandwidth (RBW): 300 kHz and video bandwidth (VBW): 200 Hz. The electronic noise is not subtracted.

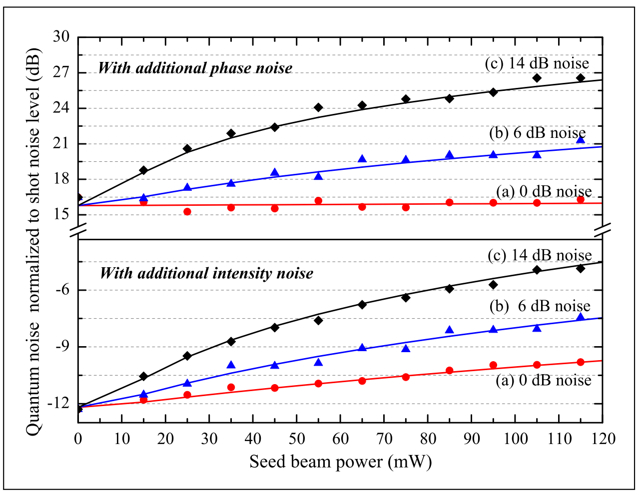

Fig. 3. Balance homodyne measurements of the quadrature amplitude variances with seed beam power at different pump beam noise. Analysis frequency: 3 MHz, RBW: 300 kHz and VBW: 200 Hz.

changing the output amplitude of function generator, we impose the additional intensity noise with 6 dB (14 dB) on the pump beam. The experimental and theoretical results are shown by the blue (black) line and blue (black) dots of Fig. 3, which follows the same trend as that of without additional intensity noise. The squeezing factor shows a more rapid decrease with the seed beam power when the pump beam has higher intensity noise. Therefore, in order to increase the output power of bright squeezed state and retain the squeezing factor, we should suppress the intensity noise of the pump beam as much as possible. By manipulating the quadrature phase noise of the pump beam, we also observe the dependence of the squeezing factor on the phase noise of the pump beam. The research results show that the squeezing factor is unchanged with the variation of phase noise, which confirms that the influence of two orthogonal quadrature variations is mutually independent of each other.

We repeatedly measure the variation of the anti-squeezing factor (quadrature phase) with seed beam power at different additional pump beam phase noise at the analysis frequency of 3 MHz, shown in the top of Fig. 3. Due to the noise coupling enhancement with the increase of the seed beam power, the anti-squeezing factor increases inch by inch. But the change of the anti-squeezing factor is slower compared to that of the squeezing factor (2.4 dB), which can be explained by the difference of the coefficient $C(\Omega)$. The measured values are in good agreement with the theoretical analysis. Similarly, the anti-squeezing factor does not vary with the quadrature amplitude noise of the pump beam, which verifies the correctness of the theoretical analysis.

We have presented the results of demonstrating the dependence of the squeezing and anti-squeezing factors on the seed beam power at different additional pump beam noise. The squeezing factor decreases gradually with the increase of the seed beam power due to the noise coupling enhancement between the pump and seed waves, even though no additional noise is imposed. The squeezing factor shows a rapider decrease as the seed beam power increases when the pump beam has higher intensity noise. The change of the anti-squeezing factor is slower with the seed beam power compared to that of the squeezing factor (2.4 dB), which can be explained by the difference of the coefficient $C(\Omega)$. By manipulating the quadrature amplitude (phase) noise of the pump beam, we also observe the dependence of the squeezing (anti-squeezing) factor on the amplitude (phase) noise of the pump beam. Without the seed beam injected, the squeezing factor is independent of the intensity and phase noise of the pump beam. Research results indicate that the influence of two orthogonal quadrature variations is mutually independent of each other.

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REFERENCES

1. R. Schnabel, N. Mavalvala, D. E. Mcclelland, and P. K. Lam, Nat. Commun. **1**, 121 (2010).
2. LIGO Scientific Collaboration, Nat. Phys. **7**, 962 (2011).
3. M. A. Taylor, J. Janousek, V. Daria, J. Knittel, B. Hage, H. A. Bachor, and W. P. Bowen, Nat. Photonics **7**, 229 (2013).
4. M. A. Taylor, J. Janousek, V. Daria, J. Knittel, B. Hage, H. A. Bachor, and W. P. Bowen, Phys. Rev. X **4**, 011017 (2014).
5. N. C. Menicucci, Phys. Rev. Lett. **112**, 120504 (2014).
6. P. K. Lam, T. C. Ralph, B. C. Buchler, D. E. McClelland, H. A. Bachor, and J. Gao, J. Opt. B Quantum Semiclass. Opt. **1**, 469 (1999).
7. G. M. E. Oelker, M. Tse, J. Miller, F. Matichard, L. Barsotti, P. Fritschel, D. E. McClelland, M. Evans, and N. Mavalvala, Optica **3**, 682 (2016).
8. E. S. Polzik, J. Carri, and H. J. Kimble, Phys. Rev. Lett. **68**, 3020 (1992).
9. Y. Q. Li, P. Lynam, M. Xiao, and P. J. Edwards, Phys. Rev. Lett. **78**, 3105 (1997).
10. Z. Dutton, J. H. Shapiro, and S. Guha, J. Opt. Soc. Am. B **27**, A63 (2010).
11. D. Gottesman and J. Preskill, in *Quantum Information with Continuous Variables* (Dordrecht, 2003), pp. 317.
12. J. Feng, Z. Wan, Y. Li, and K. Zhang, Opt. Lett. **42**, 3399 (2017).
13. M. Huo, J. Qin, J. Cheng, Z. Yan, Z. Qin, X. Su, and K. Peng, Sci. Adv. **4**, eaas9401 (2018).
14. B. F. F. Kaiser, A. Zavatta, V. D'Auria, and S. Tanzilli, Optica **3**, 362 (2016).
15. B. Li, U. B. Hoff, L. S. Madsen, S. Forstner, V. Prakash, C. Schäfermeier, T. Gehring, W. P. Bowen, and U. L. Andersen, Optica **5**, 850 (2018).
16. L. Wu, H. J. Kimble, J. L. Hall, and H. Wu, Phys. Rev. Lett. **57**, 2520 (1986).
17. Y. Takeno, M. Yukawa, H. Yonezawa, and A. Furusawa, Opt. Express **15**, 4321 (2007).
18. M. S. Stefszky, C. M. M. Lowry, S. S. Y. Chua, D. A. Shaddock, B. C. Buchler, H. Vahlbruch, and D. E. McClelland, Classical Quantum Gravity **29**, 145015 (2012).
19. T. Eberle, S. Steinlechner, J. Bauchrowitz, V. Handchen, H. Vahlbruch, M. Mehmet, H. M. Ebhardt, and R. Schnabel, Phys. Rev. Lett. **104**, 251102 (2010).
20. H. Vahlbruch, M. Mehmet, S. Chelkowski, B. Hage, A. Franzen, N. Lastzka, and R. Schnabel, Phys. Rev. Lett. **100**, 033602 (2008).
21. H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, Phys. Rev. Lett. **117**, 110801 (2016).
22. S. Shi, Y. Wang, W. Yang, Y. Zheng, and K. Peng, Opt. Lett. **43**, 5411 (2018).
23. W. Yang, S. Shi, Y. Wang, W. Ma, Y. Zheng, and K. Peng, Opt. Lett. **42**, 4553 (2017).
24. T. Serikawa, J. I. Yoshikawa, K. Makino, and A. Frusawa, Opt. Express **24**, 28383 (2016).
25. O. Morin, J. Liu, K. Huang, F. Barbosa, C. Fabre, and J. Laurat, J. Vis. Exp. **87**, e51224 (2014).
26. M. Huo, J. Qin, and Y. Sun, Acta Sin. Quantum Opt. **24**, 134 (2018).
27. S. Dwyer, L. Barsotti, S. S. Y. Chua, M. Evans, M. Factourovich, D. Gustafson, and M. Landry, Opt. Express **21**, 19047 (2013).
28. K. McKenzie, N. Grosse, W. P. Bowen, S. E. Whitcomb, M. B. Gray, D. E. McClelland, and P. K. Lam, Phys. Rev. Lett. **93**, 161105 (2004).
29. X. Jin, J. Su, Y. Zheng, C. Chen, W. Wang, and K. Peng, Opt. Express **23**, 23859 (2015).
30. H. Zhou, W. Wang, C. Chen, and Y. Zheng, IEEE Sens. **15**, 2101 (2015).
31. Z. Li, W. Ma, W. Yang, Y. Wang, and Y. Zheng, Opt. Lett. **41**, 3331 (2016).
32. Z. Li, X. Sun, Y. Wang, Y. Zheng, and K. Peng, Opt. Express **26**, 18957 (2018).
33. X. Guo, X. Wang, Y. Li, and K. Zhang, Appl. Opt. **48**, 6475 (2009).
34. O. Llopis, P. H. Merrer, H. Brahimi, K. Saleh, and P. Lacroix, Opt. Lett. **36**, 2713 (2011).