Experimental observation of three-color optical quantum correlations

Katiúscia N. Cassemiro, Alessandro S. Villar, Paulo Valente, Marcelo Martinelli, and Paulo Nussenzveig

Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05315-970 São Paulo, São Paulo, Brazil

Received October 23, 2006; revised December 6, 2006; accepted December 13, 2006;
posted December 14, 2006 (Doc. ID 76384); published February 15, 2007

Quantum correlations among bright pump, signal, and idler beams produced by an optical parametric oscillator, all with different frequencies, are experimentally demonstrated. We show that the degree of entanglement between signal and idler fields is improved by using information on pump fluctuations. To our knowledge this is the first observation of three-color optical quantum correlations. © 2007 Optical Society of America

OCIS codes: 270.0270, 270.6570, 190.4970.

Quantum correlations are a signature of nonclassical light generation. The optical parametric oscillator (OPO) is the best known and most widely used source of such correlations. Squeezing in the intensity difference of the twin beams that the OPO produces above threshold[1] (signal and idler) yielded the record value for squeezing of −9.7 dB.[2] Bipartite continuous variable entanglement in this system, which requires the observation of phase anticorrelations as well, although predicted in 1988,[3] was demonstrated only very recently.[4–6] The parametric process involves three fields, yet the pump field is typically treated as a classical quantity. As an exception, quantum properties of the pump were first measured by Kasai *et al.*[7] This raises a natural question: are there quantum correlations among all three fields? An affirmative answer was recently given by Villar *et al.*,[8] who investigated the problem theoretically. Here, we provide what we believe to be the first experimental affirmative answer by observing triple correlations among quadratures of pump, signal, and idler fields.

Beyond the demonstration of nonclassical light features, one should notice that all three fields have different frequencies. Interest in quantum frequency conversion developed in the early 1990s[9,10] and opens perspectives for the interaction of light with physical systems having different resonance frequencies. The above-threshold OPO produces, in general, nondegenerate twin beams, and the pump beam has approximately twice their frequencies. Three-color quantum correlations increase the number of physical systems that can be simultaneously investigated. Correlations with the pump can also be used to enhance the bipartite entanglement between the twin beams, as we show below.

Quantum correlations should exist between the phase quadrature of the pump field and the sum of phase quadratures of the signal and idler fields as a direct consequence of phase matching, $\vec{k}_0=\vec{k}_1+\vec{k}_2$, and of energy conservation, $\omega_0=\omega_1+\omega_2$. These conditions imply that phase fluctuations are related following $\delta\phi_0=\delta\phi_1+\delta\phi_2$. This qualitative argument is confirmed by detailed theoretical predictions.[3,8] Indices $j\in\{0,1,2\}$ refer to pump, signal, and idler fields, respectively. The quadratures are defined through the field annihilation operators $\hat{a}_j=\exp(i\phi_j)(\hat{p}_j+i\hat{q}_j)$, where ϕ_j is chosen so that $\langle\hat{q}_j\rangle=0$. When the OPO is detuned from exact triple resonance, this phase–phase correlation, $C_{\hat{q}_0\hat{q}_+}=\langle\delta\hat{q}_0\delta\hat{q}_+\rangle$, is partially transferred to an amplitude–phase correlation, $C_{\hat{p}_0\hat{q}_+}=\langle\delta\hat{p}_0\delta\hat{q}_+\rangle$, owing to phase noise to amplitude noise conversion[11] inside the OPO cavity $[\hat{q}_+\equiv(\hat{q}_1+\hat{q}_2)/\sqrt{2}]$. Our experiment is designed to measure joint fluctuations of a combination of $\hat{q}_+$ and $\hat{p}_0$ and compare them with the shot-noise level, which defines the standard quantum limit (SQL). This will enable us to improve the bipartite entanglement of the twin beams.

Twin beam entanglement is proved by violation of an inequality derived by Duan *et al.*[12] and Simon.[13] Van Loock and Furusawa[14] generalized it to include a third field:

$$\Delta^2\hat{p}_- + \Delta^2(\hat{q}_+ - \alpha_0\hat{p}_0) \geqslant 2, \qquad \alpha_0 = \frac{C_{\hat{p}_0\hat{q}_+}}{\Delta^2\hat{p}_0}. \tag{1}$$

Here α_0 is a parameter chosen to minimize the left-hand side of the expression above and $\hat{p}_-\equiv(\hat{p}_1-\hat{p}_2)/\sqrt{2}$. Each term $\Delta^2\hat{p}_-$ and $\Delta^2(\hat{q}_+-\alpha_0\hat{p}_0)$ is normalized to the SQL. Our attention will be focused on the corrected phase sum noise (second term above), which can be rewritten as

$$\Delta^2\hat{q}'_+ \equiv \Delta^2\hat{q}_+ - \beta_0; \qquad \beta_0 = \frac{C^2_{\hat{p}_0\hat{q}_+}}{\Delta^2\hat{p}_0}. \tag{2}$$

If $\Delta^2\hat{q}'_+<1$ and $\beta_0\neq 0$, there is a quantum correlation between $\hat{p}_0$ and $\hat{q}_+$.

The experimental setup is sketched in Fig. 1. The triply resonant type II OPO is pumped by a frequency-doubled diode-pumped Nd:YAG laser (Innolight Diabolo) at 532 nm. This laser is first transmitted through a filter cavity (bandwidth of 2.4 MHz) prior to injection into the OPO, which removes all classical noise for analysis frequencies above 15 MHz. It is important to have a shot-noise-limited pump, since excess pump phase noise is converted to

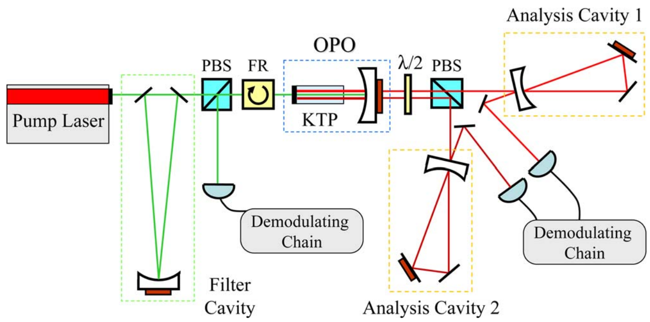

Fig. 1. (Color online) Sketch of the experimental setup. PBS, polarizing beam splitter; FR, Faraday rotator; λ/2, half-wave plate.

excess noise in $\hat{q}_+$, thus hindering twin beam entanglement.[15] The nonlinear crystal is a 10 mm long potassium titanyl phosphate from Litton. The OPO cavity input mirror is flat, directly coated on one crystal surface, with 97% reflection at 532 nm and high reflectivity ($R>99.8\%$) at 1064 nm. The other crystal surface is antireflection coated for both wavelengths ($R<3\%$ at 532 nm and $R<0.25\%$ at 1064 nm). The spherical output mirror is a high reflector for 532 nm ($R>99.8\%$) and a partial reflector for 1064 nm, $R=96\%$, with a curvature radius of 25 mm. The OPO cavity bandwidth for 1064 nm is 50 MHz, and the threshold power is 12 mW. Orthogonally polarized signal and idler beams are separated by a polarizing beam splitter. To measure their quadrature noise, each beam is reflected off an analysis optical cavity that converts phase noise to amplitude noise as a function of its detuning.[16–18] The twin beams are finally detected on high-quantum-efficiency (>93%) photodiodes (Epitaxx ETX300). Both analysis cavities have bandwidths of 14(1) MHz. Overall detection efficiency is $\eta=80\%$. The signal and idler optical frequencies differ by approximately 0.35 THz, corresponding to $\Delta\lambda=1.3$ nm in wavelength. Photocurrents are recorded as a function of time as both cavities are synchronously scanned. At the same time, amplitude fluctuations of the reflected pump beam (extracted by means of a polarizing beam splitter and a Faraday rotator) are recorded by another photodetector (EG&G FND100, quantum efficiency 60%), with an overall detection efficiency of $\eta_0=45\%$ (we are currently working to improve this value by using higher-quantum-efficiency photodiodes). Noise power spectra are obtained by direct demodulation of the photocurrents. Each photocurrent is electronically mixed with the same sinusoidal reference at the analysis frequency $\nu=27$ MHz, and the low-frequency beat signal is sampled at a 600 kHz repetition rate by an analog-to-digital card connected to a computer. Variances of these fluctuations are then calculated by taking groups of 1000 points and are finally normalized to the SQL. The shot-noise level is measured independently, either by using light at 1064 nm directly emitted from the Diabolo laser or by mixing the OPO's twin beams. Ten different values of average intensity are used for this, and linearity is checked with great precision. For each intensity, 60 averages of 10,000 acquisition points are made, allowing for an error in the shot-noise level below 0.5%.

Typical noise spectra of sum and difference of twin beam quadratures are presented in Fig. 2, as functions of the analysis cavities' detuning relative to their bandwidth, Δ. Phase noise $\Delta^2\hat{q}_\pm$ is measured for $\Delta=0.5$ and also (partially) for $\Delta\cong 1.4$. Far off ($|\Delta|\geqslant 2.5$) and on exact resonance ($\Delta=0$), the amplitude noise $\Delta^2\hat{p}_\pm$ is measured. The squeezed difference of amplitude quadratures, $\Delta^2\hat{p}_-=0.53(2)$, and the shot-noise-limited sum of phase quadratures, $\Delta^2\hat{q}_+=0.99(2)$, suffice to demonstrate bipartite entanglement, since $\Delta^2\hat{p}_-+\Delta^2\hat{q}_+=1.52(3)<2$.

Quantum correlations between pump and downconverted fields are demonstrated in the solid curve. It shows that $\Delta^2\hat{q}_+$ can be reduced by using information from the pump beam amplitude. When corrected by $\beta_0=0.13(3)$, the shot-noise-limited sum of phases $\Delta^2\hat{q}_+$ becomes squeezed: $\Delta^2\hat{q}'_+=0.86(2)$. The generalized criterion of Eq. (1) assumes the improved value $\Delta^2\hat{p}_-+\Delta^2\hat{q}'_+=1.39(3)<2$.

The behaviors of β_0, $\Delta^2\hat{q}_+$, and $\Delta^2\hat{q}'_+$ are presented in Fig. 3 as functions of pump power relative to threshold, σ. Each experimental point was taken from curves similar to those of Fig. 2. The solid curves were calculated from the standard linearized OPO theory.[15] As described in Ref. 19, the theory has to be corrected to include extra noise that is acquired by the intracavity pump field and that is not related to the parametric process. We model this by simply adding noise to the input pump field. This noise depends on the OPO cavity detuning for the pump field.[19] Since in our present experiment we do not have precise control or knowledge of OPO cavity detunings for the pump, Δ'_0, and the downconverted fields, Δ' (all normalized to the OPO cavity bandwidth for the twin beams), these are used as free pa-

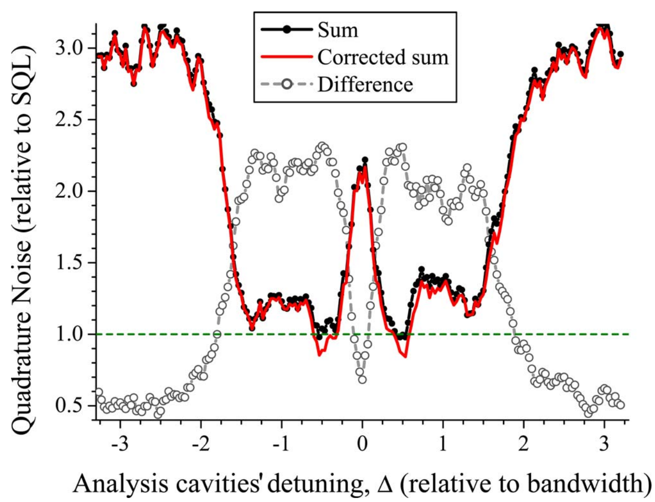

Fig. 2. (Color online) Noise spectra at 27 MHz as a function of the analysis cavities' detuning. Black curve with circles, sum of twin beam quadratures; gray curve with open circles, difference of twin beam quadratures; red curve, sum of twin beam quadratures corrected by correlations with the pump amplitude. Dashed green line, shot-noise level (error bars in the shot-noise level measurement are less than 0.5%). $\sigma=1.34$.

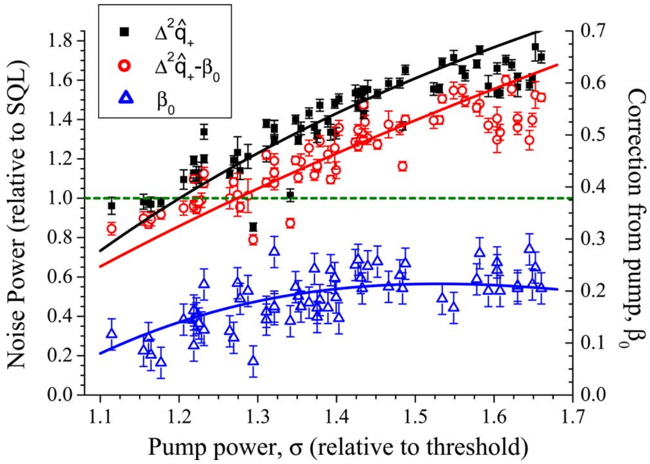

Fig. 3. (Color online) Behavior of $\Delta^2\hat{q}_+$ with and without correction owing to correlations with the pump amplitude as a function of σ. Black squares, $\Delta^2\hat{q}_+$; red circles, $\Delta^2\hat{q}'_+ - \beta_0$; blue triangles, β_0. The solid curves correspond to the physical model with pump detuning and excess noise as free parameters.

rameters to fit the data of Fig. 3. Furthermore, the excess phase noise added to the input pump, $S^{\text{in}}_{q_0}$, which is deduced from independent measurements of the reflected pump beam for $\Delta'_0=0$ and $\sigma\approx 1$ ($S^{\text{in}}_{q_0} \approx 23$), also has to be adjusted for the nonzero detunings.

We verify that $\Delta^2\hat{q}_+$ is squeezed close to threshold and its noise increases as the pump power is increased, crossing the shot-noise value at $\sigma\cong 1.2$. Its behavior was studied in detail in Ref. 19. The correction term β_0 is always nonzero, varying from $\beta_0 \approx 0.10$ to $\beta_0\approx 0.23$ for increasing σ. This is in agreement with the theoretical prediction of Ref. 8, since the degree of triple correlations should be maximum close to $\sigma=1.5$, where all fields have approximately the same intensity. In particular, for $\sigma\leqslant 1.3$, the correlation between $\hat{p}_0$ and $\hat{q}_+$ reveals or increases the squeezing value in $\Delta^2\hat{q}'_+$, attesting its quantum nature. Better control of the detunings[6] would probably decrease the scattering of the data points. The theoretical model is in good agreement with the experiment. The parameters that best fit the data are $\Delta'_0=0.2$, $\Delta'=0.26$, and $S_{q_0}=15$. From these results, we can surmise that, for $\Delta'_0=\Delta'=0$, $\hat{q}_0$ and $\hat{q}_+$ should be strongly correlated.

In summary, twin beam entanglement produced by an above-threshold OPO can be improved by using the quantum correlations with the pump beam demonstrated here. To our knowledge, this is the first experimental demonstration of three-color quantum correlations. They can be used, for instance, to increase the fidelity of quantum information distribution. The measurement of triple optical quantum correlations is a necessary first step en route to the observation of three-color entanglement in the above-threshold OPO.

This work was supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (through Instituto do Milênio de Informação Quântica). P. Nussenzveig's e-mail address is nussen@if.usp.br.

References

1. A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, C. Fabre, and G. Camy, Phys. Rev. Lett. **59**, 2555 (1987).
2. J. Laurat, L. Longchambon, C. Fabre, and T. Coudreau, Opt. Lett. **30**, 1177 (2005).
3. M. D. Reid and P. D. Drummond, Phys. Rev. Lett. **60**, 2731 (1988).
4. A. S. Villar, L. S. Cruz, K. N. Cassemiro, M. Martinelli, and P. Nussenzveig, Phys. Rev. Lett. **95**, 243603 (2005).
5. X. L. Su, A. Tan, X. J. Jia, Q. Pan, C. D. Xie, and K. C. Peng, Opt. Lett. **31**, 1133 (2006).
6. J. Jing, S. Feng, R. Bloomer, and O. Pfister, Phys. Rev. A **74**, 041804(R) (2006).
7. K. Kasai, J. G. Gao, and C. Fabre, Europhys. Lett. **40**, 25 (1997).
8. A. S. Villar, M. Martinelli, C. Fabre, and P. Nussenzveig, Phys. Rev. Lett. **97**, 140504 (2006).
9. J. Huang and P. Kumar, Phys. Rev. Lett. **68**, 2153 (1992).
10. P. Kumar, Opt. Lett. **15**, 1476 (1990).
11. T. Yabuzaki, T. Mitsui, and U. Tanaka, Phys. Rev. Lett. **67**, 2453 (1991).
12. L. M. Duan, G. Giedke, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **84**, 2722 (2000).
13. R. Simon, Phys. Rev. Lett. **84**, 2726 (2000).
14. P. van Loock and A. Furusawa, Phys. Rev. A **67**, 052315 (2003).
15. A. S. Villar, M. Martinelli, and P. Nussenzveig, Opt. Commun. **242**, 551 (2004).
16. M. D. Levenson, R. M. Shelby, A. Aspect, M. D. Reid, and D. F. Walls, Phys. Rev. A **32**, 1550 (1985).
17. R. M. Shelby, M. D. Levenson, S. H. Perlmutter, R. G. DeVoe, and D. F. Walls, Phys. Rev. Lett. **57**, 691 (1986).
18. P. Galatola, L. A. Lugiato, M. G. Porreca, P. Tombesi, and G. Leuchs, Opt. Commun. **85**, 95 (1991).
19. A. S. Villar, K. N. Cassemiro, K. Dechoum, A. Z. Khoury, M. Martinelli, and P. Nussenzveig, J. Opt. Soc. Am. B **24**, 249 (2007).