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Observation of squeezing using cascaded nonlinearity

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PACS. 42.50Dv – Nonclassical field states; squeezed, antibunched, and sub- Poissonian states; operational definitions of the phase of the field; phase measurements.
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Abstract. – We have observed that the pump beam reflected by a triply resonant optical parametric oscillator, after a cascaded second-order nonlinear interaction in the crystal, is significantly squeezed. The maximum measured squeezing in our device is 30% (output beam squeezing inferred: 48%). The direction of the noise ellipse depends on the cavity detuning and can be adjusted from intensity squeezing to phase squeezing.

Squeezed light has been so far experimentally generated using three different kinds of optical devices [1]: $\chi^{(2)}$ nonlinear media, $\chi^{(3)}$ nonlinear media and semiconductor lasers. The most efficient and convenient way of producing a large degree of squeezing [2]-[4] is undoubtedly to use $\chi^{(2)}$ media which yield nonlinear effects which are at the same time significant and almost free from excess noise sources. They have nevertheless a drawback, which is that they couple light modes at different frequencies and therefore generally require a pump beam at a frequency different from the produced squeezed beam [5], which complicates the set-up. On the contrary, $\chi^{(3)}$ effects, usually less efficient or more noisy, can be self-pumped. The simplest example is a Kerr medium [6], [7] in which a light beam is more and more squeezed while it propagates through the nonlinear medium.

It has been known for a long time [8], [9] that a $\chi^{(2)}$ medium may behave like a $\chi^{(3)}$ medium when the second-order nonlinearity is used twice by some kind of cascading effect which couples back to the pump beam the modes which have been generated by the first $\chi^{(2)}$ interaction. Such an effect requires a dephasing process to occur between the two $\chi^{(2)}$ interactions, which transform, for example, parametric amplification into parametric deamplification. One can, for example, use two crystals with a dephasing plate in between, or simple propagation in a medium where the phase matching condition is not fulfilled, or an optical cavity around a $\chi^{(2)}$ crystal which can be detuned from resonance. Let us also mention than the nonlinear

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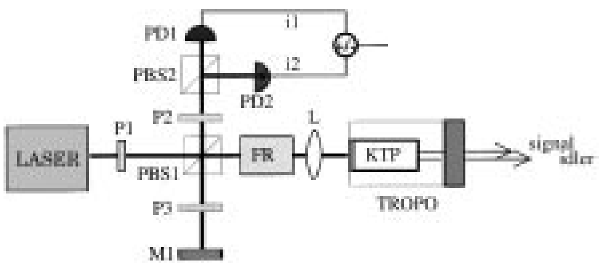

Fig. 1. – Experimental set-up. PBS1, PBS2: polarizing beamsplitters, P1, P2, P3: half-wave plates, FR: Faraday rotator, PD1, PD2 photodiodes, L: lens, TROPO: triply resonant optical parametric oscillator.

$\chi^{(2)}$ process used in the device may be either second harmonic generation or parametric down-conversion.

In this paper, we will focus on the case of parametric down-conversion in an optical cavity which is resonant for the three interacting waves: the pump beam generates signal and idler beams, which are mainly "trapped" in the resonant cavity and generate back the pump beam by sum frequency generation. In particular, when the cavity is detuned from exact resonance with the three light modes, this device exhibits a bistable behaviour [10], [11] which has been recently observed [12], and is characteristic of a $\chi^{(3)}$ medium. The full-quantum analysis of this device [13] predicts that the pump light which is coming out of the cavity after cascaded interaction with the generated signal and idler beams can be significantly squeezed, especially when one approaches the bistability turning points. This paper reports the first observation of this effect.

The experiment is displayed in fig. 1. We have used a semimonolithic triply resonant optical parametric oscillator (TROPO) consisting of a KTP crystal with a reflecting coating on one side and an antireflection coating on the other, and of an end cavity mirror mounted on a PZT stack. The total length of the device is about 2 cm. It is pumped at a wavelength $\lambda_0 = 0.53\ \mu\text{m}$ by a diode-pumped monolithic, c.w., frequency-doubled, YAG laser and generates signal and idler beams at non-degenerate wavelengths λ_1 and λ_2 which are close to 1.064 µm and can be adjusted by temperature tuning. The cavity finesse is roughly 1000 around 1.06 µm and 45 around 0.53 µm (limited by the single pass losses of the KTP crystal of about 6%). The triply resonant character of the device ensures a very low oscillation threshold, equal to 400 µW at exact triple resonance [12]. Bistability occurs in detuned configurations and can be observed when the pump intensity is larger than a few mW.

A 45° Faraday rotator (FR) is used as an optical circulator, which deviates the reflected pump beam onto a usual homodyne detection device. When the mirror M_1 is absent, this enables us to monitor the intensity noise of the reflected beam, and compare it to the shot noise level [14].

Figure 2 shows the intensity noise spectral density recorded at 29 MHz (*i.e.* outside the excess noise range of the pump laser) when the cavity length is scanned through resonance (input pump beam intensity: 8 mW, reflected intensity: 4 mW). One notices that there is a narrow dip below the shot noise level in the intensity noise in a very limited range of cavity detuning values, and that the intensity noise is larger than the shot noise outside this range. The minimum observed noise lies 24% below the shot noise level, which corresponds to 41% intensity squeezing of the pump beam when it is reflected from the OPO, if one takes into account the 30% total beam losses (propagation losses + photodiode quantum efficiency), and

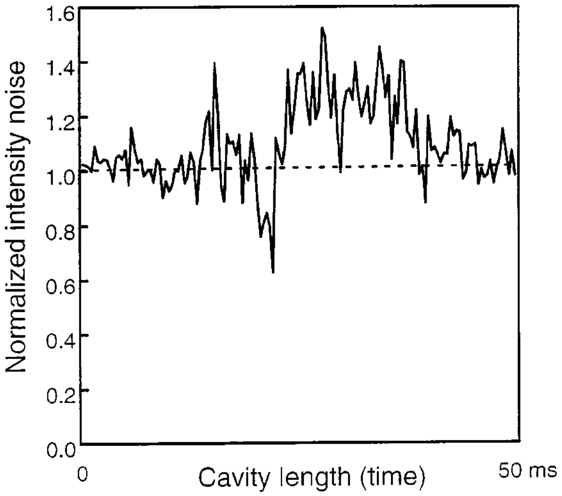

Fig. 2. – Ratio of the noise spectral density of $i_1 + i_2$ to the noise spectral density of $i_1 - i_2$ at a noise frequency of 29 MHz (giving the intensity noise spectral density normalized with respect to the shot noise level), when the cavity length is scanned through a resonance peak.

the 99% mode matching efficiency of the pump beam with respect to the OPO cavity mode.

The fast variation of the intensity noise with the cavity length has the same explanation as in the case of a Kerr medium [15]: when the cavity length is scanned, both the eccentricity and the orientation of the squeezing ellipse axis change, and intensity squeezing is only observed when its major axis is exactly perpendicular to the direction of the mean field. This only occurs for a given cavity detuning, *i.e.* around a precise cavity length. When it is not perpendicular to the mean field, the intensity noise quickly increases to a value larger than the standard quantum noise level. Figure 2 shows a rather noisy signal, because it is not possible to scan the cavity length slowly enough to average the fluctuations on the intensity noise. Nevertheless, the narrow dip can be observed in all the curves recorded in the same experimental conditions.

In order to measure the noise on the two quadrature components of the reflected pump beam, we must mix it with a local oscillator beam: this is done by slightly rotating the pump polarization, with the halfwave plate P1, so that the polarizing beamsplitter PBS1 deviates a part of the input beam to the mirror M1, which can be moved by a PZT stack. The reflected beam, rotated in polarization by a halfwave plate (P3) is then mixed with the pump beam reflected by the TROPO by the same polarizing beamsplitter. A servomechanism reacting on the OPO cavity length maintains the detuning at a given value while the local oscillator phase is scanned.

In a first set of experiments, we have used a OPO length modulation at a frequency 25 kHz and a lock-in technique on the signal + idler intensity to generate the error signal used in the loop: this ensures that the OPO operates at exact signal and idler cavity resonance. The pump mode detuning is then adjusted to the zero value by a slight variation of the crystal temperature. In these conditions, the threshold reaches its minimum value of 0.4 mW, and the reflected pump beam has a very low intensity, in the mW range even well above threshold. We have observed a significant squeezing in all this range, with a maximum value of 18% (±2%) for an input beam intensity of 1.1 mW and a reflected pump beam of 0.7 mW. Figure 3 displays the variation with intensity of the inferred squeezing at the output of the OPO, after correcting the effect of total beam losses (30%) and homodyne detection efficiency (93%).

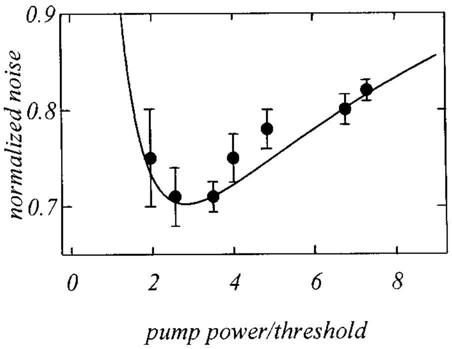

Fig. 3. – Dots: values for phase squeezing on the OPO pump beam inferred from the experimental data, corrected from the imperfections of the detection chain, as a function of the pump beam intensity normalized to the shot noise level. The experimental uncertainty on the measurement is ± 2%. Full line: theoretical predictions.

The full line gives the result of the theoretical prediction [13], taking into account the various cavity losses, which is in fair agreement with the observed squeezing. A more detailed analysis of the homodyne signal [16] shows that the light observed in this case is "phase squeezed", with a minimum noise on the quadrature component perpendicular to the mean field, and a maximum noise on the intensity component, as predicted by theory.

The zero-detuning configuration is interesting because of its very low threshold, but not for its squeezing potentialities: even in the perfect case of no extra losses, the theory [13] predicts only 50% phase squeezing, occuring at 4 times above threshold. As outlined in the introduction, some detuning is needed for an efficient cascaded nonlinearity: one can then approach the onset of bistability, and the theory predicts [13] —in the zero extra loss case— perfect squeezing on some quadrature component at the exact bifurcation point.

To explore the detuned configuration, we have used, as an error signal for the servo loop acting on the cavity length, the difference between the signal + idler mean intensity and a reference voltage: by varying this voltage, one can adjust the signal and idler detunings

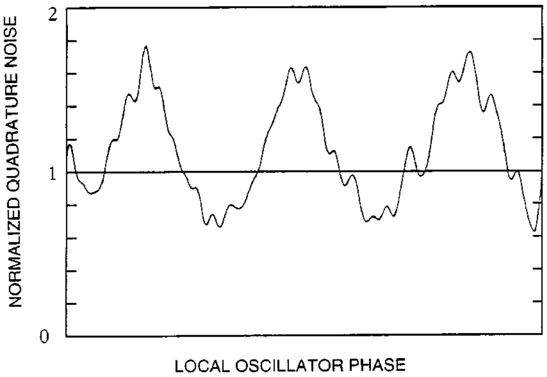

Fig. 4. – Signal of the homodyne detection as a function of the local oscillator phase in a linear scale, normalized to shot noise and after a small correction taking into account the fact that the measured beam intensity is not completely negligible as compared to the local oscillator intensity.

(which are always equal when the OPO is above threshold [13], [17]) with respect to exact cavity resonance, to a fixed value, ranging roughly between 0 and twice the cavity half-width at half-maximum. In this configuration, and with the help of an efficient stabilization servo loop on the crystal temperature, the system could stay locked for as long as 30 minutes. Figure 4 gives a typical measurement of the noise spectral density by the homodyne detection set up as a function of the local oscillator phase, at a noise frequency of 30 MHz, for an incident power of 8 mW and for a reflected pump power of 3 mW. The local oscillator intensity was in this experiment equal to 10 mW, to prevent saturation of the detection. In this configuration, the detection signal has a non-completely negligible contribution from the local oscillator fluctuations. Figure 4 gives the measured signal after correction from this effect [16], and normalized to the shot noise level. The pump beam squeezing amounts in this case to 30%, corresponding to a level of 48% squeezed light at the output of the OPO.

In conclusion, we have observed significant squeezing on the pump beam reflected by a TROPO. This simple and compact device turns out to be an interesting "quantum noise eater", which transforms any incoming light beam in the several mW range into a squeezed beam on an adjustable quadrature component. In contrast to the experiment reported in [3], using frequency doubling to generate "bright squeezed light", the present device works in a complete "passive" way: it does not need an intense pump beam of several hundred mW different from the beam which is squeezed after reflection in order to reach the parameters necessary to get a large squeezing effect. The squeezing performances of this device are presently limited by the non-negligible optical losses of our KTP crystals for the green light beam, and by the low quantum efficiency of detectors at this wavelength. A larger squeezing value could have been obtained by increasing the transmission of the coupling mirror at the pump wavelength (thus reducing the relative importance of intracavity losses), but this would have yielded higher thresholds for OPO oscillation and for the onset of bistability, and therefore a squeezing on a more intense pump beam, difficult to measure by the homodyne technique. Better results are to be expected in devices working with pump beams in the near infrared, thus generating signal and idler waves around 2 μm.

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REFERENCES

[1] See, for example: *Appl. Phys. B*, **55** (1992): special issue on "Quantum Noise Reduction in Optical Systems: Experiments".

[2] Polzik E., Carri J. and Kimble H., *Phys. Rev. Lett.*, **68** (1992) 3020.

[3] Paschotta R. and Mlynek J., *Phys. Rev. Lett.*, **72** (1994) 3807; Schneider K., *Opt. Lett.*, **21** (1996) 1396.

[4] Mertz J., Debuisschert T., Heidmann A., Fabre C. and Giacobino E., *Opt. Lett.*, **16** (1991) 1234.

[5] With the noticeable exception of pump squeezing in the nonlinear absorption due to second-harmonic generation; see: Pereira S., Min Xiao, Kimble H. and Hall J., *Phys. Rev. A*, **38** (1988) 4931; Kürz P., Paschotta R., Fiedler K. and Mlynek J., *Europhys. Lett.*, **24** (1993) 449.

[6] Schumaker B., Perlmutter S., Shelby R. and Levenson M., *Phys. Rev. Lett.*, **58** (1987) 357.

[7] BERGMAN K. and HAUS H., *Optics Lett.*, **16** (1991) 663.

[8] OSTROVSKII L., *JETP Lett.*, **5** (1967) 272.

[9] WHITE A., MLYNEK J. and SCHILLER S., *Europhys. Lett.*, **35** (1996) 425; DE SALVO R., HAGAN D., SHEIK-BAHAE M., STEGEMAN G. and VAN STRYLAND E., *Opt. Lett.*, **17** (1992) 28; OU Z., *Opt. Commun.*, **124** (1996) 430.

[10] DRUMMOND P., MC NEIL K. and WALLS D., *Opt. Acta*, **28** (1981) 211.

[11] LUGIATO L., OLDANO C., FABRE C., GIACOBINO E. and HOROWICZ R., *Nuovo Cimento D*, **10** (1988) 959.

[12] RICHY C., PETSAS K., GIACOBINO E., FABRE C. and LUGIATO L., *J. Opt. Soc. Am. B*, **12** (1995) 456.

[13] FABRE C., GIACOBINO E., HEIDMANN A., LUGIATO L., REYNAUD S., VADACCHINO M. and WANG KAIGE, *Quantum Optics*, **2** (1990) 159.

[14] KASAI K. and FABRE C., *J. Nonlin. Opt. Phys. Mater.*, **5** (1996) 921.

[15] REYNAUD S., FABRE C., GIACOBINO E. and HEIDMANN A., *Phys. Rev. A*, **40** (1989) 1440.

[16] GAO JIANGRUI, KASAI K. and FABRE C., in preparation.

[17] FABRE C., *Quantum Fluctuations in Light Beams, Les Houches, Summer School on Quantum Fluctuations*, edited by S. REYNAUD and E. GIACOBINO (Elsevier Science Publisher) 1997.