Twin-beams Statistics for Strong Pumping

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Twin-beams generated by non degenerate optical parametric oscillators exhibit squeezing in the intensity difference. Here we report intensity noise correlation and single beam spectra for pump power up to 14 times the threshold value. The degree of correlation of the two beams is practically independent of pump level. The single beam spectra confirm presence of relaxation oscillation.

Key words: Quantum Noise; Twin Beams; Optical Parametric Oscillators.

1. Introduction

Twin beams generated by cw optical parametric oscillators (OPO) show intensity difference quantum noise reduction below the shot-noise level (SNL) as predicted by Reynaud et al. [1] and proved experimentally in different configurations [2]. At powers higher than four times the threshold also the single beam intensity noise should reduce below SNL in some frequency range [3], an effect competing with relaxation oscillations [4]. In this paper we report a study of correlations spectra in two bulk α-cut KTP triply resonant OPOs.

2. Experimental Setup

The experimental layout is shown in Figure 1. The pump beam is provided by an Nd:YAG self-doubled dual wavelength laser. The lenses of focal f_1 and f_2 match the beam to the cavity *TEM*00 mode with a coupling ≥ 85%. A half-wave plate ($\lambda/2_1$) and a polarizing beam splitter PBS$_3$ act as beam attenuator, while a second half-wave plate ($\lambda/2_2$) selects the pump polarization for the OPO cavity. The maximum pump power available at the input mirror is 115 mW.

The OPOs consist of two concave mirrors with equal curvature radius $R = 25.68$ mm and a non-linear crystal placed at the cavity center. The α-cut KTP 10 mm long crystal is AR coated at both wavelength. The front mirrors is HR coated at the IR wavelengths and designed to give a value for the pump build-up of about 10. The two output mirrors used have a transmittivity (@1064 nm) of $T_A = 2.3\%$ and $T_B = 5.1\%$, respectively. The OPOs operated not far from degeneracy ($\delta\lambda = \lambda_s - \lambda_i \simeq 40$ nm). The crystal temperature is activity stabilized with residual fluctuations of less than 1 mK over 10 minutes. The cavity length is stabilized on pump resonance with residual fluctuations of less than 0.1 nm.

Single beam measurements, for the highest pump powers, have been obtained in the thermal self-locking regime [5]. In this case the system can deliver higher IR power (up to 4 mW per beam) with a residual stability of 2.6% over 4 minutes.

Correlation measurements have been carried out with a balanced homodyne detector consisting of a halfwave plate ($\lambda/2_3$), a polarizing beamsplitter (PBS$_1$) and two equally amplified high quantum efficient photodiodes (PD$_1$ and PD$_2$; ETX300). The total quantum efficiency, including all optical losses, of the detection system is $\eta = 0.90 \pm 0.01$. The signal and idler beams are cross polarized. Rotating the beams polarization of 45° with respect to the polarizing beam-splitter (PBS$_1$) axis it is possible to calibrate the shot-noise level [2]. A few percent of unbalance in the mean photocurrent of PD$_1$ and PD$_2$ inevitably reduces the common mode rejection, roughly 10 dB, so that the difference signal in the mixed configuration reflects accurately the shot noise level above 5 MHz.

To measure the single beam noise characteristic, an additional polarizing beam-splitter (PBS$_2$, drawn dashed in Fig. 1) is placed at the cavity exit. At the two BS outputs (p- and s-polarizations transmitted and reflected,

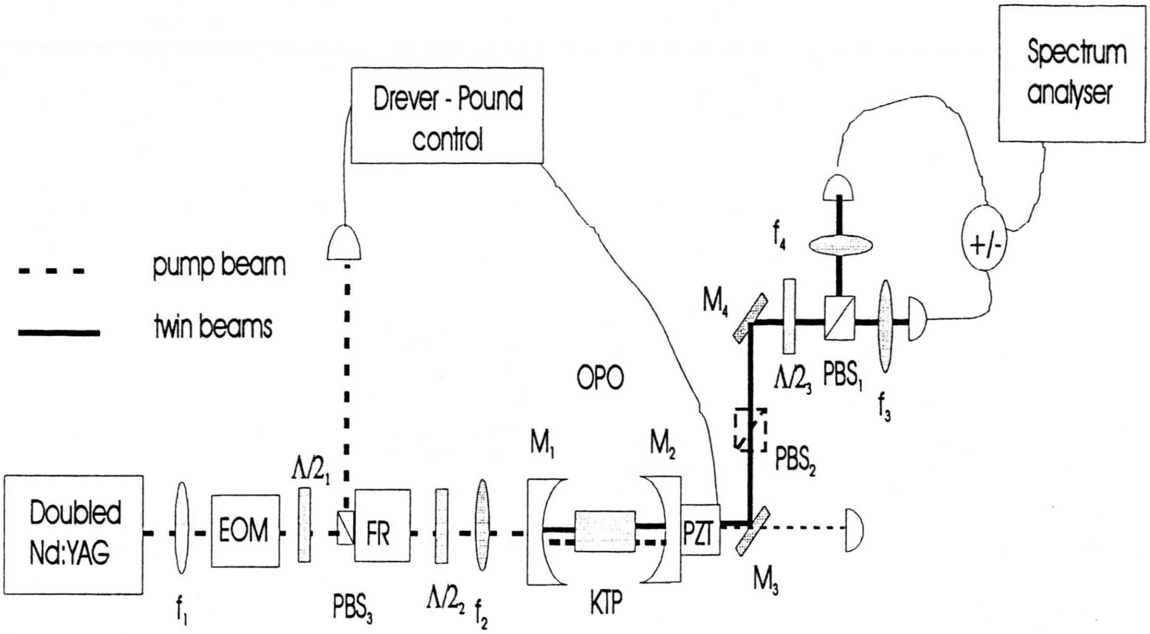

Fig. 1. Experimental set-up. An Nd:YAG frequency doubled laser pumps the α-cut KTP TRO. The optical cavity length is actively stabilized by means of Pound-Drever technique. A balanced homodyne detector allows to analyze either the twin-beams quantum correlation or the noise spectrum of the single beam selected by an additional polarizing beam-splitter (drawn dashed) placed outside the cavity.

respectively) a balanced direct detection scheme provides [6] sum and difference signals, measuring respectively the total and shot noise levels. The AC currents of the two homodyne photodiodes are sent to a combination of power splitter and combiner giving the sum and difference. The final signal is fed to a spectrum analyzer (freq. span 0–40 MHz; RSB 300 kHz).

3. Correlation Spectra

In a simplified model the squeezing spectrum of the twin-beams intensity difference goes as

$$S(\Omega) = 1 - \frac{\varepsilon\eta}{1 + \left(\frac{\Omega}{\Omega_c}\right)^2} \tag{1}$$

with Ω_c the cavity bandwidth, η the total detection quantum efficiency, and ε the mean output coupling, defined as the ratio between the transmittivity of the ending mirror and the total loss per round trip, averaged on the two modes. Changing M_2 transmittivity results in a change of ε, Ω_c and of the threshold, which depends inversely on the product of the signal and idler finesse.

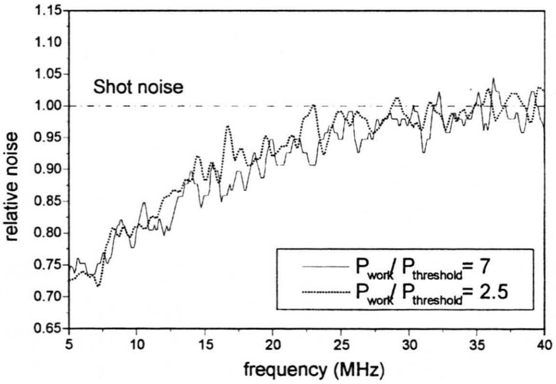

Fig. 2. Noise reduction versus frequency obtained with low threshold OPA_A at different pump powers (2.5 and 7 times the threshold). There is 26% noise reduction at 7 MHz in both cases.

With OPO_A we have measured correlation and single beam spectra with thresholds ranging between 5.7 and 10 mW. The degree of correlation measured for different input powers has given a constant value, as shown in Fig. 2, reporting the noise reduction for pump powers 2.5 and 7 times the threshold.

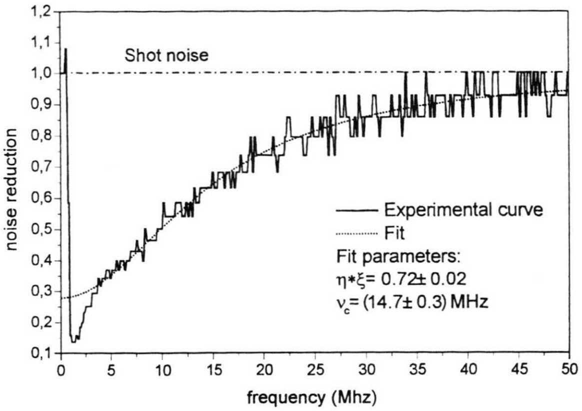

Fig. 3. Noise reduction (60% noise reduction at 7 MHz) versus frequency obtained with OPO_B. The fit of the experimental curve with (1) starts from 5 MHz where the common mode rejection allows reliable shot noise calibration.

With OPO_B ($\varepsilon = 0.80$) we have observed a higher degree of correlation. The threshold was 55 mW at its minimum. In Fig. 3 (115 mW pump intensity and threshold of about 65 mW) we observe in the correlation spectra a noise reduction of 70%@7 MHz. For all the considered OPO configurations the measured reductions were in agreement with the expected values.

4. Spectral Properties of Single Beams

A single beam (signal or idler) shows a very large amount of excess noise which extends beyond the pump noise frequency range, as a result of the parametric interaction. While quantum theory [3] predicts amplitude squeezing for a single beam at pump power at least four times the threshold, Boller et al. [4] have recently found in the measured single beam spectra evidence of highly damped relaxation oscillations at a frequency ν_R of the order of the OPO cavity bandwidth given by

$$\nu_R = \frac{1}{4\pi}\sqrt{\gamma_p(\gamma_s+\gamma_i)\left(\sqrt{\frac{P}{P_{th}}}-1\right)-\gamma_p^2}\,, \qquad (2)$$

where $\gamma_{p,s,i}$ are the cavity damping frequencies for the pump (p), signal (s) and idler (i) mode, respectively. These oscillations are observed when the damping rate of the cavity at the pump frequency is of the same order of the other ones. Since most of the previous characterizations of these devices were carried out in the so-called adiabatic limit ($\gamma_p \gg \gamma_s, \gamma_i$), these oscillations were not evident. On the contrary we have carried out extensive measurements on a generator with $\gamma_p \lesssim 3\gamma_s = 3\gamma_i$, i.e. strongly resonant on the pump.

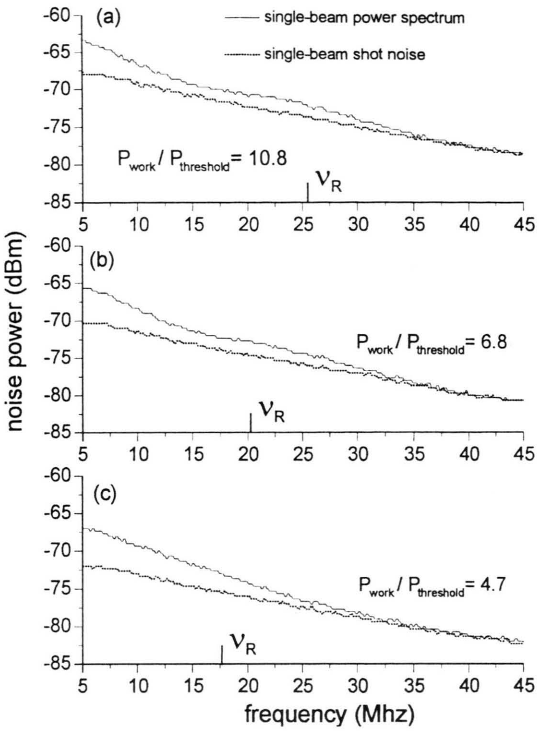

Fig. 4. Intensity noise for a single beam at different pump powers. OPO_A threshold ranges between 11 and 13 mW.

In Fig. 4 we present the noise spectra of a single beam from OPO_A for three different values of the ratio between the pump power injected into the cavity and the threshold. The shot noise calibration has been obtained by switching between the sum and difference signal in a balanced direct detection scheme [6].

We see that at low pumping (up to 4 times the threshold) the noise spectrum goes toward the SQL as expected in a typical laser-like intensity noise profile. For higher pump powers a region appears where the noise is about 2 dB above the SNL. The peak frequency of this region increases slowly with the pump intensity (see (2)), and qualitatively agrees with the $\left(\sqrt{P/P_{th}}-1\right)^{1/2}$ law. The main difference between our spectra and the one reported in [4] seats in the fact that in the latter case the low frequency excess noise is ≈ 40 dB above the SQL. In our system it was only ≈ 5 dB above the SQL. Consequently, while they got a spectrum dominated by the relaxation oscillations, we have observed the competition between the quantum noise reduction and the relaxation oscillations. The noise reduction, that does not reach the shot noise level, appears as a depression at frequencies lower than the relaxation oscillations that dominate the higher part of the spectra.

A complete model including the relaxation oscillations in the linearized theory of OPO will be presented and discussed elsewhere.

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