# Generation of continuous-wave bright squeezed light

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## ABSTRACT

We discuss different approaches to the generation of bright amplitude-squeezed light using second-order nonlinear effects in optical cavities. A 0.2 mW beam at 1064 nm exhibiting 4 dB squeezing has been generated using a phase-sensitive type-I parametric amplifier pumped by a frequency-doubled Nd:YAG laser. In applying frequency-doubling processes to the generation of amplitude-squeezed light, the appearance of parasitic parametric oscillation must be considered. This effect has been observed in a singly-resonant frequency doubler. We also describe recent developments in optical cavity design for doubly-resonant frequency-doubling. Finally, we show theoretically that phase-mismatched second-harmonic generation in an optical cavity can be employed to generate a strong effective Kerr nonlinearity. This system appears promising for achieving optical bistability and for generating squeezed light of high power.

**Keywords:** Non-classical light, squeezed light, amplitude squeezing, nonlinear optics, frequency conversion, second-harmonic generation, optical parametric amplification, Kerr effect, monolithic resonators.

## 1 Introduction

The generation of squeezed vacuum using optical parametric amplifiers[1,2] has until now been a superior technique to generate highly nonclassical light fields with properties suitable for applications in interferometry and spectroscopy. In these applications use is made either of the squeezed vacuum directly (e.g. for interferometry[3]), or the squeezed vacuum is superimposed at a weakly transmitting mirror with an attenuated coherent wave to obtain "bright" squeezed light (e.g. for spectroscopy[2]). The power of the bright squeezed beam is typically small, since there is a trade-off between power and degree of squeezing. While a more efficient power transfer is feasible if the above weakly transmitting mirror is one mirror of an Fabry-Perot cavity in which the coherent light is resonated, alternative schemes for bright squeezed light generation are of interest if they can provide wavelengths that are not easily reached using degenerate parametric amplifiers, notably in the visible spectral range, or if their technical implementation is simple. With this motivation, we present here some recent developments in the field of squeezed bright light generation.

# 2 Second-Harmonic Generation

## 2.1 State of the art

One successful approach for generating bright squeezed light using nonlinear optics has been doubly-resonant second-harmonic generation (DR-SHG). This method is attractive since it is possible to generate either a squeezed subharmonic[5,6] or a squeezed harmonic wave,[7] depending on the choice of the mirror transmissions of the two waves. A technical problem that has plagued the generation of squeezed light by DR-SHG is the stabilization of the cavity length so that simultaneous resonance of the laser frequency and its harmonic occur. In the Konstanz experiment,[6] which made use of a monolithic resonator, this was achieved by electro-optic tuning of the cavity length. However, due to charge mobility in the $LiNbO_3$ crystal used, screening occurred, thus limiting the time over which the stabilization worked to less than 10 s.

To overcome this problem, we have developed a hybrid monolithic cavity, in which the subharmonic wave circulates within a monolithic 4-bounce ring cavity, while the cavity for the harmonic wave is composed by external mirrors, one of which is actuated by a piezoelectric ceramic.[8] With this design we retain the advantage of a monolithic cavity for one of the two resonated waves (and thus small loss for the subharmonic wave) and provide a simpler tuning capability to achieve double-resonance. As an initial test, the cavity has been used for efficient DR-SHG of low power Nd:YAG radiation, reaching 16% (30%) conversion efficiency to the green when pumped by 1 (4) mW at 1064 nm. The double lock operated stably for hours.

In DR-SHG usually moderate pump powers in the mW range are used. Recently, higher power bright squeezed light has been demonstrated with the use of singly-resonant SHG.[9] In this first experiment a 532 nm wave with 50 mW power and 1.5 dB amplitude squeezing was produced. This technique not only opens a new power regime for squeezed light, but is also simple and reliable, permitting continuous operation for many hours.

## 2.2 Simultaneous SHG and nondegenerate parametric oscillation

Both singly- and doubly-resonant SHG are unstable against "parasitic" parametric oscillation: at sufficiently high subharmonic power the harmonic field is large enough to act as pump field for one (or more) signal/idler mode pair(s) whose frequencies are nondegenerate with the subharmonic frequency. The difference between resonance or non-resonance of the harmonic wave only appears in the dependence of the parametric gain on the distance along the crystal, which follows the position dependence of the harmonic amplitude. In the first case, the gain is constant, in the second it increases linearly from zero.

In the case of doubly-resonant SHG this quadruply resonant oscillation (QRO) has already been reported.[10] If strong bright squeezing of the fundamental wave is desired, the doubly-resonant harmonic generator can be designed with a subharmonic finesse sufficiently smaller than the harmonic finesse. In this case the QRO threshold is only slightly lower than the selfpulsing threshold,[11] at which optimum squeezing is expected. The doubler can then be operated below the QRO threshold, generating near-optimum squeezing. The squeezing achievable *above* the QRO threshold has recently been calculated by Marte,[12] who predicts that strong squeezing in the harmonic wave remains possible.

We have observed the occurrence of subharmonic-pumped parametric oscillation also in singly-resonant SHG.[13] We may call this effect triply-resonant parametric oscillation (TRO). Fig.1a indicates schematically the configuration for TRO. Subharmonic, signal, and idler are the three resonant waves, with the nonresonant harmonic wave generated by the SHG process. Fig.1b shows the output spectrum of a 7.5 mm long monolithic standing-wave frequency doubler pumped by a single-frequency Nd:YAG laser. Typical conversion efficiencies from subharmonic to signal plus idler power are around 7%. The threshold for the TRO is reached when the intracavity conversion rate from subharmonic to harmonic wave exceeds the total subharmonic loss rate. This is also the point of maximum subharmonic-to-harmonic power conversion efficiency. For the monolithic doubler used[14] the calculated TRO threshold is about 120 mW, in good agreement with the experimental observations.

## 3 Parametric Deamplification

Squeezed light at infrared wavelengths is usually generated as a squeezed vacuum by deamplification of the vacuum fluctuations that enter a subthreshold degenerate parametric amplifier (OPA). Injecting a coherent wave into the OPA represents a practical means of generating squeezed bright light; its power is of course reduced compared to the injected power. Fig 2a shows schematically the set-up for parametric amplification/deamplification. The same monolithic resonator mentioned above is employed. For practical reasons, the coherent input is not injected through the input coupler but rather through the weakly transmitting back mirror of the cavity. In the opposite case, the input beam would have to be mode-matched to the cavity and an isolator would have to be used to deflect the output beam to the detection system. In this experiment, the power transmitted through the resonator to the homodyne detection system is about 1 mW in the absence of harmonic pump power.

The noise suppression achieved is shown in Fig.2b as a function of phase between injected subharmonic and harmonic pump waves. The shot-noise reference (noise power $\Psi_-$ of photocurrent difference, detected at 4 MHz) is proportional to the output power of the squeezed wave and shows, as expected, amplification and deamplification as the relative phase is varied. The amplitude noise of the output beam (noise power $\Psi_+$ of photocurrent sum) exhibits a measured squeezing of 4 dB, at an output power of about 0.2 mW. The degree of detected squeezing is limited by the photodetection efficiency of 92%, the cavity escape efficiency of 88%, and the pump power level. Antisqueezing, corresponding to squeezing in the phase quadrature, occurs when the relative phase between subharmonic and harmonic is such that amplification takes place.

Degenerate operation, i.e. resonance between the laser frequency and the cavity mode can be maintained particularly simply in this scheme. To this end the input wave is phase-modulated and the error signal used for FM-locking is obtained from one of the homodyne detectors. This represents a simplification compared to the case of squeezed vacuum generation, where a frequency-offset locking beam is commonly used.

## 4 Resonant Effective $\chi^{(3)}$-Interactions for Quantum Optics

The use of phase-mismatched (also called "cascaded") $\chi^{(2)}$ interactions to generate an effective $\chi^{(3)}$-interaction has recently been demonstrated using pulsed laser waves.[15] Theoretical treatments of the quantum effects have been given for the traveling (i.e. pulsed) wave situation.[16] Here we point out that the effective Kerr interaction can be sufficiently strong to become accessible even in the continuous-wave regime, provided low-loss nonlinear resonators are used.[17]

Consider a singly-resonant $\chi^{(2)}$-nonlinear cavity pumped by a subharmonic input field as shown in Fig.1a, but in absence of signal and idler modes. To calculate the effect of a resonant cascaded second-order nonlinearity, we start from the propagation equations for a subharmonic wave $\omega$ coupled to its harmonic $2\omega$, in the slowly-varying envelope approximation,

$$\frac{dA_1(z)}{dz} = -b_1 A_1(z) + i\kappa\, A_1^*(z)\, A_2(z) e^{-i\Delta k z}\ , \qquad \frac{dA_2(z)}{dz} = i\frac{\kappa}{2}\, A_1(z)^2 e^{i\Delta k z}\ , \tag{1}$$

where $A_1, A_2$ are the amplitudes of subharmonic and harmonic waves, $\kappa$ is the scaled nonlinear coefficient, $z$ is the propagation distance, and $b_1$ is the subharmonic amplitude loss coefficient. As the cavity is not resonant at the harmonic frequency, the harmonic loss is neglected in Eq.(1). The phase mismatch $\Delta k = k_2 - 2k_1$ between subharmonic and harmonic waves is crucial for the cascading effect.

For the physical situation of small nonlinearity and loss, Eq.(1) may be integrated over the crystal length $L$ iteratively to second order in $\kappa L$ (Ref.[4]). To obtain the equations describing resonance effects, a self-consistency relation is imposed for the subharmonic fields at the input coupler of amplitude reflectivity $r$. We find in the high finesse limit $r \approx 1$,

$$\dot{\alpha}_1 = -\gamma\alpha_1 - \mu A|\alpha_1|^2\alpha_1 + \sqrt{2\gamma_c}\alpha_{1,in} \ . \tag{2}$$

The input and output fields are related to the circulating fields by

$$\alpha_{1,in} + \alpha_{1,out} = \sqrt{2\gamma_c}\alpha_1 \ , \qquad \alpha_{2,out} = -\sqrt{\mu}B\alpha_1^2 \ . \tag{3}$$

Here the field amplitudes of the circulating subharmonic $\alpha_1$, input/output subharmonic $\alpha_{1,in/out}$, harmonic output $\alpha_{2,out}$ waves are scaled such that $\tau|\alpha_1|^2$, $|\alpha_{1,in/out}|^2$, $|\alpha_{2,out}|^2$ are photon rates, with $\tau$ the round-trip time. The coupling ($\gamma_c$) and total decay ($\gamma$) rates for the subharmonic are defined as $\gamma_c = (1-r)/\tau$, $\gamma = \gamma_c + b_1 L/\tau$. The nonlinear coupling $\mu$ is related to the single-pass second-harmonic generation conversion efficiency (in $\mathrm{W}^{-1}$) by $E_{NL} = 2\tau^2\mu/\hbar\omega$. By energy conservation, $\mathrm{Re}A = |B|^2$. For a plane wave resonator,

$$A = -i(1 - \mathrm{sinc}(\Delta kL/2)\exp(-i\Delta kL/2))/(\Delta kL/2) \ , \qquad B = \mathrm{sinc}(\Delta kL/2)\exp(i\Delta kL/2) \ . \tag{4}$$

Thus $B$ and the real part of $A$ vanish for $\Delta kL = \pm n2\pi$, leading to zero harmonic generation ($\alpha_{2,out} = 0$), but to an intensity-dependent detuning $\chi^{(3)}|\alpha_1|^2$ in Eq.(2). The effective Kerr nonlinearity is then given by

$$\chi^{(3)} = \mu\,\mathrm{Im}A = \mp\frac{\mu}{n\pi} \ . \tag{5}$$

Physically, the situation $\Delta kL = \pm 2\pi$ corresponds to generation of the harmonic wave along the first half of the crystal length and back-conversion to the subharmonic along the second half, such that the harmonic field is zero at the endface of the crystal $z = L$, and thus also the net harmonic output from the crystal.

As is well known, associated with the Kerr nonlinearity is a minimum input power above which bistability occurs.[18] Its value for a particular detuning is (for $n = 1$)

$$|\alpha_{1,in}^{(b)}|^2 = \frac{4\pi}{3\sqrt{3}}\frac{\gamma^3}{\gamma_c\mu} \ , \qquad P_{1,in}^{(b)} = \frac{8\pi}{3\sqrt{3}}\frac{\gamma}{\gamma_c}P_{2,DRO} \ . \tag{6}$$

Here the bistability threshold power $P_{1,in}^{(b)} = \hbar\omega|\alpha_{1,in}^{(b)}|^2$ has been expressed in terms of the harmonic threshold power $P_{2,DRO}$ for doubly-resonant parametric oscillation at $\Delta kL = 0$. For low loss resonators ($2b_1L \simeq 0.4\%$, $\gamma = 2\gamma_c$) the bistability power is on the order of 50 mW and therefore easily accessible.

With Eq.(2) at hand, a large number of theoretically predicted effects have the potential of practical implementation. Apart from the generation of bright squeezed light,[19–21] these include noise-free amplification,[18] and quantum nondemolition measurements.[22] We note in passing that the appearance of a pure Kerr nonlinearity is not limited to plane-wave resonators,[8] and that even in the case $B = 0$ the TRO effect may occur.[13]

## 5 Conclusion

We have outlined some classical and quantum aspects occurring in the generation of continuous-wave squeezed light using nonlinear resonators.

The generation of squeezed light using singly-resonant SHG and parametric down-conversion has been demonstrated with excellent temporal stability. This opens, for example, the possibility of sequential squeezing, i.e. a first nonlinear device generates squeezed light that is then injected into another device which in turn reduces the fluctuations even more. Such a scheme can be implemented using two second-harmonic generators or two parametric amplifiers which stepwise reduce the variance of subharmonic or harmonic wave, respectively. Another possibility is to first generate squeezed bright infrared light using a parametric deamplifier and then to generate the harmonic with a frequency doubler with improved squeezing compared to the case of unsqueezed subharmonic input. For example, operating a doubler at the maximum efficiency point with a 3 dB amplitude-squeezed infrared pump wave, the harmonic wave is squeezed by about 4 dB for a doubler with output coupling equal to the intracavity loss, and by about 5 dB for output couplings much larger than the loss.[4] In view of the progress achieved so far, experiments to verify these predictions appear feasible.

While the exploration of the quantum effects in the recently observed QRO and TRO appears interesting, there is still the need for further study of the simpler systems based on pure SHG. To explore their potential for bright squeezed light generation further, the occurrence of parasitic parametric oscillation must be prevented. To this end, a cavity with mode selection elements could be used. Practical possibilities are the placement of an etalon inside the cavity or the addition of an external cavity, similar to the Fox-Smith interferometer used for mode selection in lasers. These additional elements will however also increase the loss of the cavity.

Finally, we have shown that a strong effective Kerr nonlinearity is expected in phasemismatched frequency doublers (as well as in frequency mixers). A range of novel phenomena related to such systems awaits experimental demonstration.

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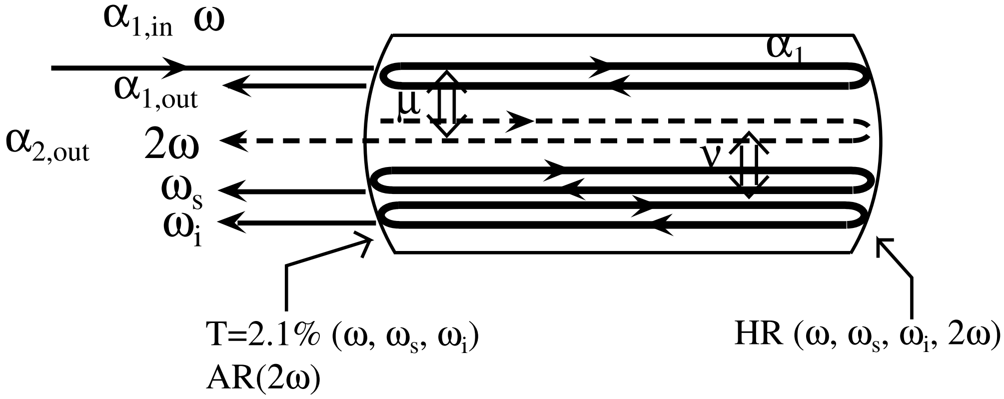
(a)




(b)

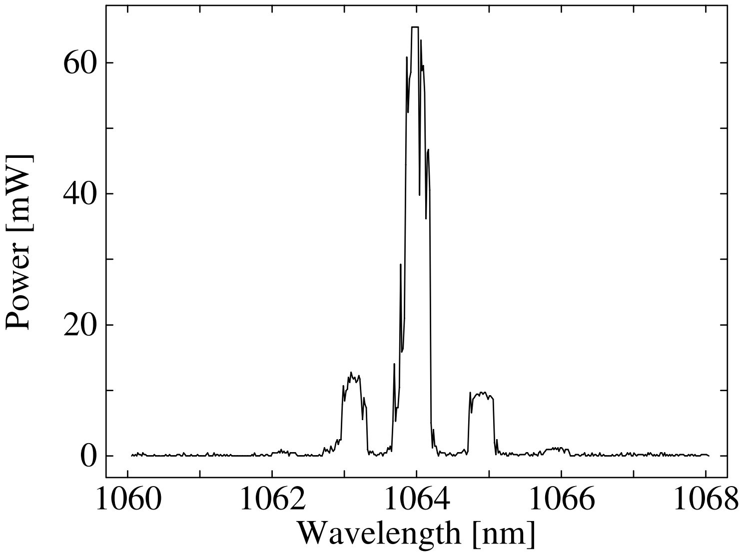



Figure 1: a) Schematic of a triply-resonant OPO (TRO). A laser wave (frequency $\omega$) is resonantly enhanced in a nonlinear cavity. The nonresonant harmonic wave acts as a pump for signal/idler mode pairs. If the round-trip gain for one of these pairs exceeds the round-trip loss, TRO occurs. b) TRO in a monolithic MgO:$LiNbO_3$ resonator. The spectrum of the infrared output of the TRO shows the injected laser wavelength and one strong signal/idler pair. A second signal/idler pair is also visible. Laser input power is about 200 mW.

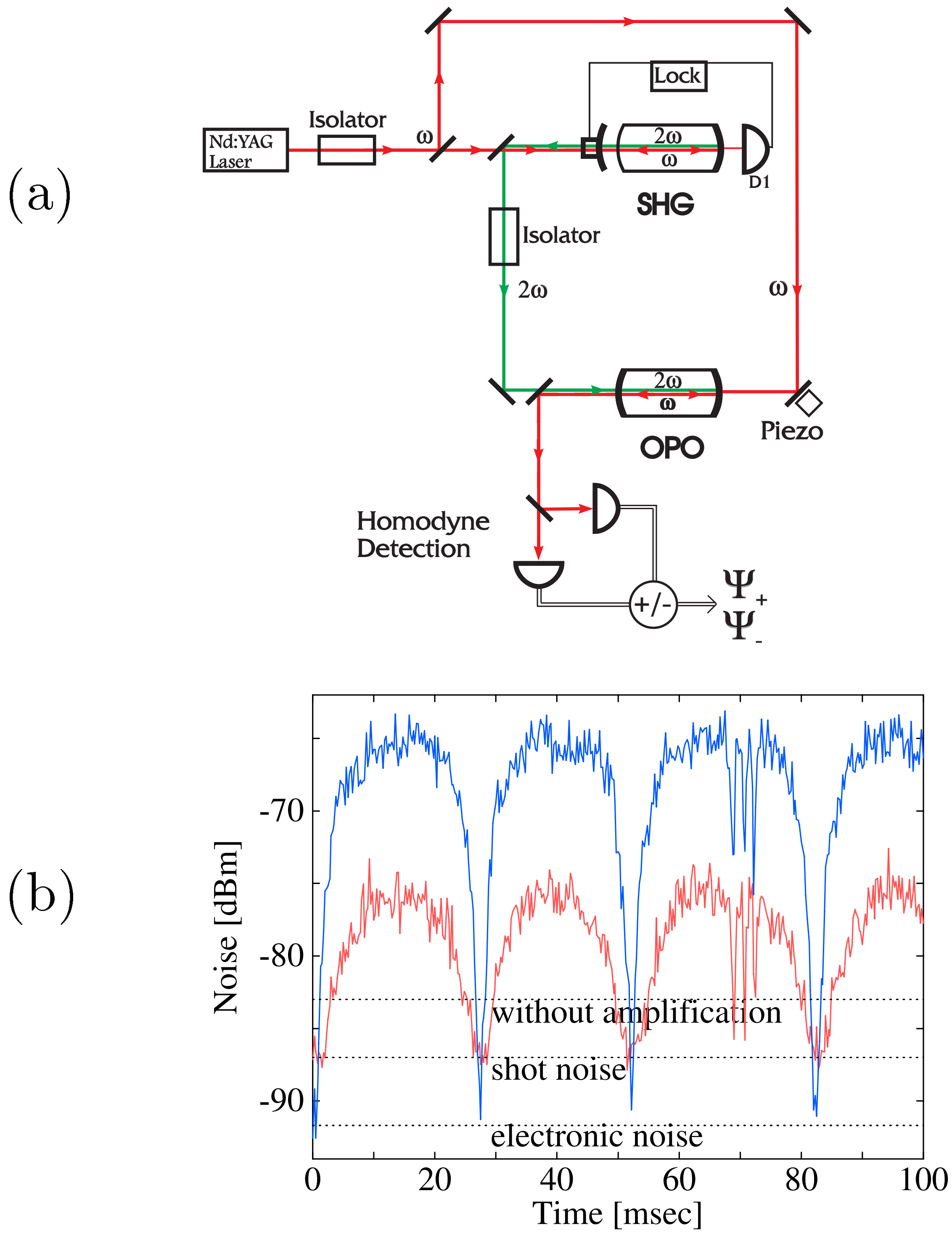



Figure 2: a) Experimental arrangement for the generation of bright squeezed light at 1064 nm using parametric deamplification. The pump wave is generated in a hemilithic $MgO{:}LiNbO_3$ frequency doubler. Left mirror of OPO cavity has 2.1% transmission, right mirror 0.04%. b) Variance of the infrared wave emitted by the OPA, as the relative phase between pump ($2\omega$) and subharmonic ($\omega$) waves is scanned. Upper trace is the amplitude noise $\Psi_+$ of the OPA output, lower trace is the vacuum noise reference $\Psi_-$. Upper horizontal line is $\Psi_-$ when pump is off. Pump power at 532 nm is about half the threshold power.