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AMPLITUDE SQUEEZED LIGHT FROM A LASER

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I. Introduction

Intensity squeezed light has been successfully generated using semiconductor lasers with sub-poissonian pumping.[1] Control of the pumping statistics is crucial and is achieved by a large series resistor which regulates the pump current; its sub-poissonian statistics are then transferred to the laser output. The sub-poissonian pumping of other laser systems is not so simple however, and their potential as squeezed state sources is apparently diminished. Here we consider a conventional laser incoherently pumped well above threshold, and allow for pump depletion of the ground state. In this regime subpoissonian photon statistics and squeezed amplitude fluctuations are produced.

II. Theoretical model

The atomic level scheme for the laser is indicated in fig. 1. We follow the notation of Lax and Louisell,[2] where $\hat{N}_i$ (i = 0,1,2) are the atomic population operators and $\hat{n}$ the laser mode photon number operator. The quantum Langevin rate equations are given by

$$\frac{d}{dt}\hat{N}_0 = -w_{20}\hat{N}_0 + \Gamma_1\hat{N}_1 + w_{02}\hat{N}_2 + \hat{G}_0$$

$$\frac{d}{dt}\hat{N}_1 = -(\Gamma_1 + \Pi\hat{n})\hat{N}_1 + (w_{12} + \Pi\hat{n})\hat{N}_2 + \hat{G}_1$$

$$\frac{d}{dt}\hat{N}_2 = w_{20}\hat{N}_0 + \Pi\hat{n}\hat{N}_1 - (\Gamma_2 + \Pi\hat{n})\hat{N}_2 + \hat{G}_2$$

$$\frac{d}{dt}\hat{n} = -\gamma\hat{n} + \Pi\hat{n}\,(\hat{N}_2 - \hat{N}_1) + \hat{G}_p.$$

Above threshold the mean inversion $D = N_2 - N_1$, is fixed at a constant value independent of pumping.

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The calculation of the quantum noise properties proceeds by linearizing the equations of motion about the semiclassical steady states to calculate the variance σ^2 in photon number, about the steady state mean value n . The Mandel Q-parameter, and amplitude squeezing spectrum normalized to unit shot noise can then be constucted from the mean and variance[3]

$$Q = \frac{\sigma^2 - n}{n}; \quad V(\omega) = 1 + 2Q\frac{1}{1 + (\omega/\gamma)^2}$$

where $Q > 0$, $= 0$, and < 0, correspond to superpoissonian, poissonian and subpoissonian photon statistics, respectively, and ω is the spectral offset from the laser frequency. Subpoissonian photon statistics, and concomitant intensity squeezing ($V < 1$) in the output are signatures of the quantum mechanical nature of the electromagnetic field.

For the case where all spontaneous emission from the excited state goes to ground ($w_{12} = 0$) adiabatic elimination of the atomic fluctuations leads to the equation for photon number fluctuations, for $n >> n_s$ (the saturation photon number), and dropping carets for notational simplicity

$$\frac{d}{dt}\Delta n = -\gamma\Delta n + G(t),$$

where

$$G(t) = \frac{1}{1 + \frac{w02}{\Gamma_1} + \frac{2w20}{\Gamma_1}}G_2 - \frac{\frac{w02}{\Gamma_1} + \frac{2w20}{\Gamma_1}}{1 + \frac{w02}{\Gamma_1} + \frac{2w20}{\Gamma_1}}G_1 + G_p .$$

We then find

$$\sigma^2 = n - \frac{\frac{2w20}{\Gamma_1}}{\left(1 + \frac{w02}{\Gamma_1} + \frac{2w20}{\Gamma_1}\right)^2} n + O(n_s)$$

so that the intracavity photon statistics are sub-poissonian, with intensity squeezing ($V < 1$) in the output. Fig. 2 shows the intensity squeezing at the laser frequency ($\omega = 0$, in the rotating frame of reference), as a function of pump rate, for three different values of the stimulated emission coefficient Π. With increase in Π, the degree of squeezing saturates at around 45% below shot noise level. Analysis of this result indicates that the predicted subpoissonian photon statistics and squeezing are due to a reduction in the role of pump noise and spontaneous emission from the upper atomic level, when w_{20} is increased from the undepleted pump regime (where the photon statistics are poissonian and the output is shot noise limited), towards Γ_1. For larger pump rates these noise terms continue to decrease, and one might expect the degree of squeezing to increase. However spontaneous emission from the lower lasing level, which has little effect on squeezing in the undepleted pump regime provided only that $\Gamma_1 >> \Gamma_2$, becomes increasingly important as the pump rate is increased (even for $\Gamma_1 >> \Gamma_2$), and this random noise causes the degree of squeezing to be reduced with yet further increase in pump power. The two opposing tendencies may be seen by inspection of the pump rate dependence of the coefficients of the noise terms in the equation for G(t).

The results presented are consisitent with fully numerical solutions of a three level laser obtained by Ralph and Savage. Note that the squeezing properties of the laser were also recently considered in ref. 5. After our conference presentation we received a preprint by Ritsch et al,[6] which contains closely related results.

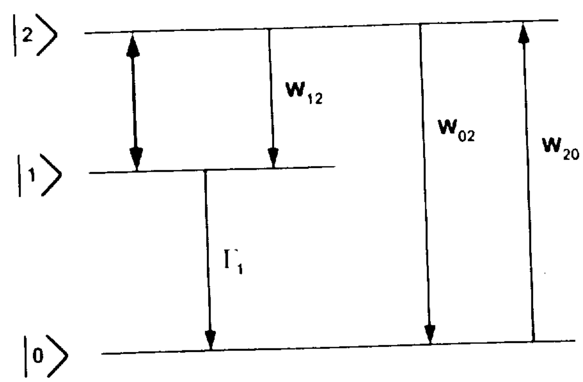

Fig.1: Atomic level scheme

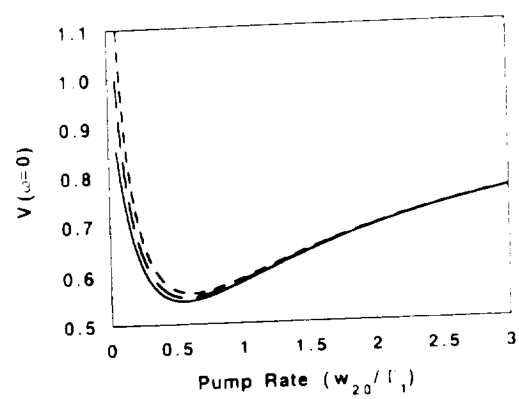

Fig.2: Amplitude squeezing versus pumping

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