Solid State Laser Intensity Noise Reduction

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1 Introduction

Intensity stable laser sources are required for both applied and fundamental research fields, such as telecommunications or gravitational wave antenna research. The aim of this collaboration between the Australian National University and Laser Zentrum Hannover is to examine techniques for producing stable light sources that are operating at their fundamental limit as set by the quantum properties of the light.

Two types of techniques are possible for stabilising the intensity noise of a laser system, classical or non-classical intensity stabilisation. Classical intensity stabilisation covers the techniques that rely on linear behaviour of both the controlled and the controllers in the stabilisation process. Non-classical, on the other hand, depends on some non-linear behaviour of some section of the stabilisation process such as the $\chi^3$ non-linear susceptibility of a medium. This latter case can produce lasers with outputs that are squeezed states, and hence have intensity noise that is lower than the quantum noise limit, $\text{QNL}$. Non-classical intensity control will be discussed by M. Taubmann in the talk entitled ‘A reliable source of squeezed light, and an accurate theoretical model’ in these proceedings.

In this paper we will discuss active intensity control and injection locking intensity control which are both forms of classical intensity control.

2 Active Intensity Control

The basic design for an active intensity control system is shown in figure 1. This diagram illustrates the main components of the control system, namely, the laser to be controlled; an intensity detector in the form of a photodetector (PD); the control electronics that are used to ensure that the correct signals are used in the control loop; and some device that converts the electrical signals into intensity signals on the laser light. The effect of the intensity control system is monitored on a PD that has its signal suitably amplified and is connected to an RF Spectrum Analyser (SA) so that the RF spectral density intensity noise can be recorded.

This control system be analysed using conventional control theory [1]. The expected noise suppression is given by the simple expression:

$$S(f) = \left(\frac{1}{1+G(f)}\right)$$

(1)

where $S(f)$ is the residual noise in the control loop and $G(f)$ is the complex open-loop gain.

In an ideal classical system $S(f)$ would continually decrease as $G(f)$ increased. However, the quantum noise of the light being detected by the PD in the control loop [2] limits the achievable
noise reduction. This is because the quantum fluctuations of the light injects uncorrelated noise into the control loop, and hence can add intensity noise if $G(f)$ is too large. The minimum excess noise with respect to the quantum noise limit (QNL) is given by the relation:

$$\Delta Noise(dB) = 10\log_{10}\left(1 + \frac{t_2}{t_1}\right)$$  \hspace{1cm} (2)$$

Figure 1. Experimental design for a basic intensity noise control system. In this diagram PD refers to a photodetector.

where $t_1$ is the photocurrent detected by the PD in the control loop and $t_2$ is the photocurrent detected by the detector monitoring the output of the control system. The lower limit for the intensity control is thus 3dB above this quantum noise limit when $(t_2/t_1) \approx 1$.

Figure 2. Experimental results for the suppression of intensity noise in an diode pumped Nd:YAG miniature ring laser system. A: relaxation oscillation; B: noise suppression; C: QNL; D: electronic noise level. For further information see ref. [2].

The advantages of using this type of control system is that large classical intensity oscillations, such as resonant relaxation oscillations [3], that occur in solid state laser systems, can be reduced by many orders of magnitude. This cannot be achieved easily by other methods. The disadvantage is that this technique will never completely reduce the noise to the QNL and in general there will be an increase in noise at certain frequencies of the intensity noise spectrum due to loop stability considerations.

3 Injection Locking Intensity Control

Injection locking is an established field of research dating back to the 1960s [4, 5, 6] but until recently it has been extremely difficult to investigate its properties for several reasons including: the lack of stable low noise light sources and of a suitable quantum theory that takes into account the full dynamics of the coupled cavity and laser systems. A conventional injection locked laser system consist of a high power laser (the slave laser) which is locked to a low power, low noise laser (the master laser), see figure 3.

Injection locking is a phenomena that occurs when the injected master laser mode has a wavelength that lies simultaneously inside the gain bandwidth of the slave laser and is near a longitudinal mode of the slave cavity [3]. We are concerned primarily with the intensity noise spectrum of the injection locked system when the master and slave wavelengths are nearly identical.

We have developed a fully quantum mechanical model that can accurately describe the cascaded laser cavity system, and performed a set of experiments to test the validity of the model and to attempt to understand the properties of the injection locking process.