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Intensity noise suppression of light field by optoelectronic feedback

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ABSTRACT

An optoelectronic feedback loop intended to suppress intensity noise of a light field is introduced in this paper. A maximum intensity noise reduction of 10 dB is experimentally achieved between frequency of 0–140 kHz on a 1064 nm DPSS continuous wave single-frequency solid-state laser. After optimization and miniaturization, this system is expected to be widely used as a simple "Noise-Eater".

1. Introduction

Diode-pumped solid-state (DPSS) lasers with single frequency, narrow line width and high power has been widely used in many aspects of fundamental physics research, such as gravitational wave detection [1], high precision spectroscopy [2], quantum information processing [3] and cold atoms manipulation [4,5]. However, the high power DPSS laser has great noises at low frequencies (<1 MHz). The noise includes cavity relaxation oscillation [6] and other technical noise, which is much higher than the shot noise level. The high intensity noise can reduce the measurement accuracy and the coherent time of quantum state, thus it limits the application of DPSS laser. Several different methods of suppressing the intensity noise of light field has been achieved, such as injection locking, [7,8] optoelectronic feedback [9–11] and mode cleaner [12,13]. Compare to other methods optoelectronic feedback is much simpler and easily realized. As early as 1986, Robertson et al. [14] suppressed intensity noise of an argon laser by using electronic feedback loops, and then in 1995, Taubman et al. [15] analyzed the feedback loop in quantum theory. The idea of feedback loops is to compare the laser intensity noise with a very stable reference and then feed the difference signal (error signal) to a modulator in the light path or directly to LD drive current. In the experiment of Harb et al. [9], they adopted the later way and suppressed relaxation oscillations in DPSS lasers, but the primary problem associated with this system is the sharp 180° phase change across the resonant relaxation oscillation (RRO) [16], which, in practice, is difficult to be electronically compensated. So it is technically challenging to reach the high-gain limit for a given system. Then, the methods of adding modulator in the light path are necessary. In this paper, the intensity noise of DPSS laser is suppressed by a photoelectric negative feedback to an acousto-optic modulator (AOM) in the light path. The intensity noise is reduced greatly between 0 and 140 kHz frequency by choosing the appropriate feedback gain.

2. Principle analysis

The theoretical principle is shown in Fig. 1. The basic idea is by detecting part of the laser power (reflection light in Fig. 1) and then feeding the noise back to front modulator. The input laser beam can be written in the linearized form [17]:

$$\hat{A}_{in}(\omega) = A_{in} + \delta\hat{A}_{in}(\omega) \tag{1}$$

where $\hat{A}_{in}(\omega)$ is the field annihilation operator, A_{in} is the classic steady-state value of the field, and $\delta\hat{A}_{in}(\omega)$ is a zero mean operator which includes all the classic and quantum noises. Assuming that the modulation of the feedback loop does not affect steady state valve of the filed but just adds a small fluctuating term δr, the laser field is:

$$\hat{A}'_{in}(\omega) = \hat{A}_{in}(\omega) + \delta r \tag{2}$$

After the feedback loop, the small fluctuating term δr can be written as $\delta r = \sqrt{\eta_1 \varepsilon} g(\omega)\delta\hat{A}_{el}(\omega)$ and $g(\omega)$ is gain of feedback circuit. The laser beam is then split by a beam splitter with intensity reflectivity ε. The reflected and the transmitted beam can be written as:

$$\hat{A}_t(\omega) = \sqrt{1-\varepsilon}\hat{A}'_{in}(\omega) + \sqrt{\varepsilon}\delta\hat{A}_{vac} \tag{3}$$

$$\hat{A}_f(\omega) = \sqrt{\varepsilon}\hat{A}'_{in}(\omega) - \sqrt{1-\varepsilon}\delta\hat{A}_{vac} \tag{4}$$

where $\delta\hat{A}_{vac}$ is the vacuum noise fluctuation from the unused port of the beam splitter. Then the reflected beam is detected by detector D1 with efficiency η_1, and feed the photocurrent back to the

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modulator. The transmitted beam is detected by detector D2 with efficiency η_2. The out-of-loop and in-loop fields are given by:

$$\hat{A}_{el}(\omega) = \sqrt{\eta_1}\hat{A}_f(\omega) - \sqrt{1-\eta_1}\delta\hat{A}'_{vac} \tag{5}$$

$$\hat{A}_{out}(\omega) = \sqrt{\eta_2}\hat{A}_t(\omega) - \sqrt{1-\eta_2}\delta\hat{A}''_{vac} \tag{6}$$

where $\delta\hat{A}'_{vac}$ and $\delta\hat{A}''_{vac}$ are vacuum fluctuation noise from two detectors in the measurement.

From Eq. (1) to (6), we can get:

$$\delta\hat{A}_{el}(\omega) = \frac{\sqrt{\eta_1\varepsilon}\delta\hat{A}_{in}(\omega) - \sqrt{\eta_1(1-\varepsilon)}\delta\hat{A}_{vac} - \sqrt{1-\eta_1}\delta\hat{A}'_{vac}}{1-\eta_1\varepsilon g(\omega)} \tag{7}$$

$$\begin{aligned}\delta\hat{A}_{out}(\omega) = {} & \sqrt{\eta_2(1-\varepsilon)}\delta A_{in}(\omega) + \sqrt{\eta_2(1-\varepsilon)}\sqrt{\eta_1\varepsilon}g(\omega)\delta\hat{A}_{el}(\omega) \\ & + \sqrt{\eta_2\varepsilon}\delta\hat{A}_{vac} - \sqrt{1-\eta_2}\delta\hat{A}''_{vac}\end{aligned} \tag{8}$$

$$\begin{aligned}\delta\hat{X}_{A_{el}} &= \delta\hat{A}_{el} + \delta\hat{A}^{+}_{el} \\ \delta\hat{X}_{A_{out}} &= \delta\hat{A}_{out} + \delta\hat{A}^{+}_{out} \\ \delta\hat{X}_{A_{in}} &= \delta\hat{A}_{in} + \delta\hat{A}^{+}_{in} \\ \delta\hat{X}_{A_{vac}} &= \delta\hat{A}_{vac} + \delta\hat{A}^{+}_{vac} \\ \delta\hat{X}_{A'_{vac}} &= \delta\hat{A}'_{vac} + \delta\hat{A}'^{vac+} \\ \delta\hat{X}_{A''_{vac}} &= \delta\hat{A}''_{vac} + \delta\hat{A}''^{+}_{vac}\end{aligned} \tag{9}$$

By using Eq. (9) we obtain the quadrature,

$$\delta\hat{X}_{A_{el}} = \frac{\sqrt{\eta_1\varepsilon}\delta\hat{X}_{A_{in}} - \sqrt{\eta_1(1-\varepsilon)}\delta\hat{X}_{A_{vac}} - \sqrt{1-\eta_1}\delta\hat{X}_{A'_{vac}}}{1-\eta_1\varepsilon g(\omega)}, \tag{10}$$

$$\begin{aligned}\delta\hat{X}_{A_{out}} = {} & \sqrt{\eta_2(1-\varepsilon)}\delta\hat{X}_{A_{in}} + \sqrt{\eta_2(1-\varepsilon)}\sqrt{\eta_1\varepsilon}g(\omega)\delta\hat{X}_{A_{el}} \\ & + \sqrt{\eta_2\varepsilon}\delta\hat{X}_{A_{vac}} - \sqrt{1-\eta_2}\delta\hat{X}_{A''_{vac}},\end{aligned} \tag{11}$$

Assuming D1 and D2 have same quantum efficiency $\eta_1 = \eta_2 = \eta$, then substituting Eq. (10) into Eq. (11) we get:

$$\begin{aligned}\delta\hat{X}_{A_{out}} = {} & \frac{\sqrt{\eta(1-\varepsilon)}\delta\hat{X}_{A_{in}}(\omega) + (1-\eta g(\omega))\sqrt{\eta\varepsilon}\delta\hat{X}_{A_{vac}}}{1-\eta\varepsilon g(\omega)} \\ & - \frac{g(\omega)\sqrt{\eta^2\varepsilon(1-\varepsilon)(1-\eta)}\delta\hat{X}_{A'_{vac}} + (1-\eta\varepsilon g(\omega))\sqrt{1-\eta}\delta\hat{X}_{A''_{vac}}}{1-\eta\varepsilon g(\omega)}\end{aligned} \tag{12}$$

Intensity noise spectrum of the output field can be defined as:

$$V_{out}(\omega) = \left\langle |\delta\hat{X}_{A_{out}}|^2 \right\rangle. \tag{13}$$

From Eq. (12) and (13), we can get:

$$\begin{aligned}V_{out}(\omega) = {} & \frac{\eta(1-\varepsilon)V_{in}(\omega) + \left|1-\eta g(\omega)\right|^2 \eta\varepsilon V_{vac}(\omega)}{\left|1+G(\omega)\right|^2} \\ & + \frac{\left|g(\omega)\right|^2\eta^2\varepsilon(1-\varepsilon)(1-\eta)V'_{vac}(\omega) + \left|1+G(\omega)\right|^2(1-\eta)V''_{vac}(\omega)}{\left|1+G(\omega)\right|^2}\end{aligned} \tag{14}$$

where $G(\omega) = -\eta\varepsilon g(\omega)$ is the transfer function of the feedback system, which includes the electronic gain $g(\omega)$ and the optical attenuation. The noises from the beam splitter and the non-unity detector efficiency are on the level of the quantum noise limit (QNL), which means $V_{vac}(\omega) = V'_{vac}(\omega) = V''_{vac}(\omega) = 1$. $V_{in}(\omega)$ is the intensity noise spectra of the input field.

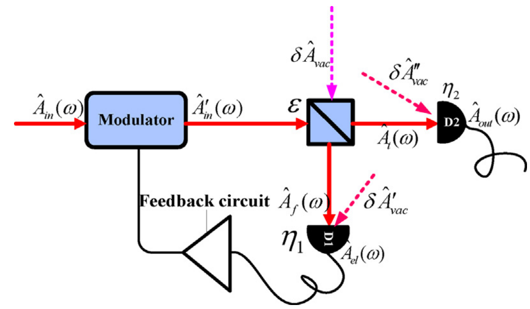

Fig. 1. Schematic diagram of noise eater with all vacuum items.

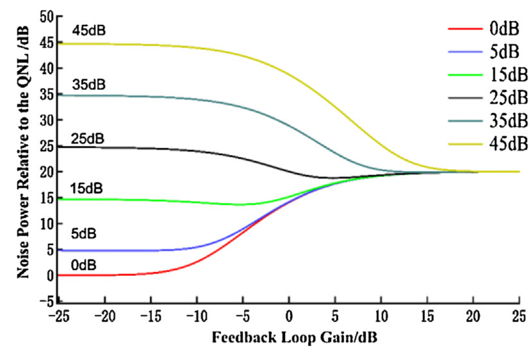

Fig. 2. Theoretic calculation plot of the noise levels for the gain of feedback loop at different laser noises when $\varepsilon = 0.01$, $\eta = 0.95$.

Then Eq. (14) can be written as:

$$V_{out}(\omega) = 1 + \frac{1-\varepsilon}{\varepsilon}\frac{\eta\varepsilon(V_{in}(\omega)-1) + |G(\omega)|^2}{|1+G(\omega)|^2}, \tag{15}$$

Fig. 2 shows the noise relative to the QNL of the out-of-loop light field as a function of the gain of feedback loop at different input light field noises. We find that when the gain of feedback loop takes appropriate value, the noise of the out-of-loop light field can be effectively suppressed. In the high-gain limit the out-of-loop noise is found to be a constant which only depends on the intensity reflectivity ε of beam splitter and the detector efficiency η.

From Eq. (15), we get the optimum gain of the feedback loop for suppressing classical noise:

$$G(\omega)_{opt} = \eta\varepsilon(V_{in}(\omega) - 1), \tag{16}$$

The optimum gains relative to the different input laser noise are shown in Fig. 3. We can see that, when the input laser noise increases, the large optimum gain is required.

By the optimum gain, the minimum out-of-loop noise spectrum is obtained:

$$V^{opt}_{out}(\omega) = 1 + \frac{\eta(1-\varepsilon)(V_{in}(\omega)-1)}{1+\eta\varepsilon(V_{in}(\omega)-1)} \tag{17}$$

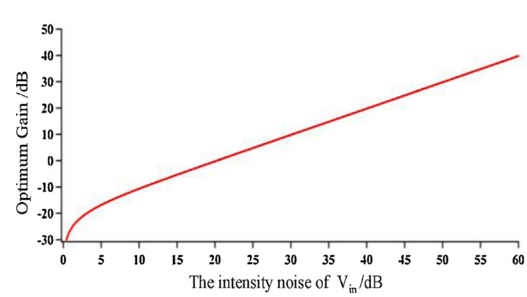

Fig. 3. Optimum gain of the feedback loop for the different input laser noise.

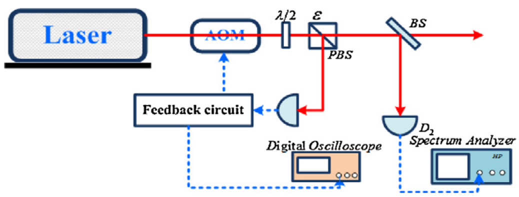

Fig. 4. Schematic diagram of a laser power control system: acousto-optic modulator (AOM); $\lambda/2$: half-wave plate; $\eta_1\eta_2$: the quantum efficiency of photo-detectors D_1 and D_2; PBS: polarizing beam splitter.

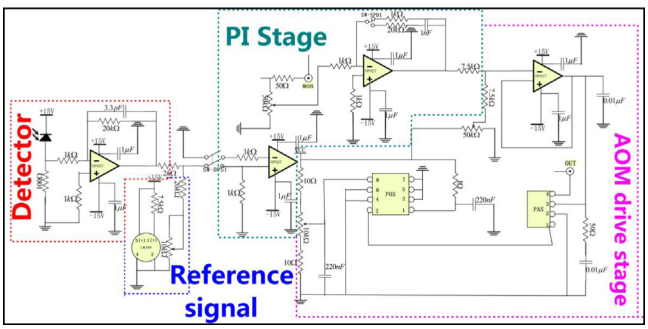

Fig. 5. Block diagram of feedback control circuit.

From the above equation, when the reflectivity ε is constant the output of minimum noise $V_{out}^{opt}(\omega)$ will increase with increasing input noise $V_{in}(\omega)$ and when input noise $V_{in}(\omega)$ is constant the output of minimum noise $V_{out}^{opt}(\omega)$ will decreases with increasing reflectivity ε. This is obviously a spectrum which is, in most situations, larger than the QNL, so it is impossible to use this electro-optical negative feedback loops obtain the squeeze light.

3. Experiment scheme and analysis

A schematic of the experimental arrangement for noise suppression is shown in Figs. 4 and 5 is the diagram of feedback control circuit. The output of DPSS laser (Model DPSS F-IVB-200, 1064 nm, Yuguang company) is incident on an AOM (Model 3110-197, Crystal Technology Inc.), which is controlled by a RF signal source. The RF signal source is composed of voltage controlled oscillator (POS-100, Minicircuits) and attenuator (PAS-3, Minicircuits). The beam of +1 order diffraction from AOM is then divided by a PBS. By adjusting the front half wave plate only 1.5 mW light is reflected and detected by the detector in feedback control circuit. After being amplified the optical electric signal is compared with a very stable voltage reference signal V_{ref}. This difference signal is the feedback error signal, which is amplified and finally feed back into the PAS by an integrator. The transmitted light of PBS is the main beam to be used. Part of this beam is reflected by a beam splitter and detected by detectorD_2 (New Focus 2001). The optical electric signal is then analyzed by a spectrum analyzer (HP 4395A).

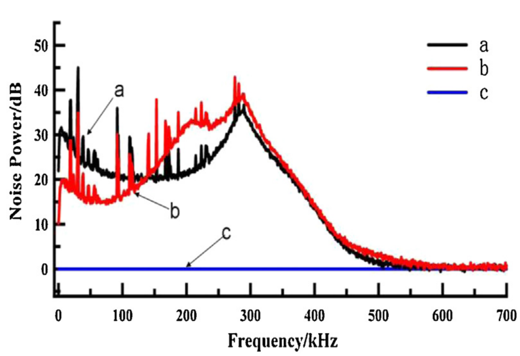

Fig. 6. Shows a: the noise spectrum of the free running laser system, b: the noise spectrum with feedback control, c: the quantum noise level for an equivalent Poissonian photocurrent (the electronic noise has been subtracted from the three curves).

In the experiment, when the integrator is closed and loop gain is adjusted to achieve the maximum intensity-noise suppression we obtain the experimental results shown in Fig. 6. Curve a is the spectra for DPSS laser free running; curve b is after the feedback loop is closed; curve c is the shot noise limit level. From the graph, we can see that the intensity noise is reduced greatly between 0 and 140 kHz, which is mainly limited by the bandwidth of feedback system. However, the intensity noise is rising due to the feedback gain changing from negative feedback to positive feedback.

4. Conclusions

In this paper we theoretically analyzed optoelectronic feedback loop and then, by using an optoelectronic negative feedback loop with AOM as the intensity transducer, the intensity noise of DPSS laser can be suppressed between 0 and 140 kHz. This laser intensity noise suppression system is simple and low cost, which can be widely used in the dipole trap for cold atoms and other high precision measurement.

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