LIGO-P000011-00-D

Diode-pumped Nd:YAG Laser Intensity Noise Suppression Using A Current Shunt

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Abstract

A current shunt actuator has been used to stabilize the intensity of a 10-W cw Nd^{3+}:YAG laser. The current shunt developed exhibited a better actuator response than the pump diode current adjust actuator provided with the laser. Using the current shunt actuator, the relative intensity noise was suppressed from $\sim 10^{-5}\, 1/\sqrt{\mathrm{Hz}}$ to below $\sim 5 \times 10^{-7}\, 1/\sqrt{\mathrm{Hz}}$.

I. INTRODUCTION

One of the most challenging goals in experimental physics is the direct detection of gravitational waves. A number of large-scale laser interferometer gravitational-wave detectors are currently under construction: the US LIGO Project; the French-Italian VIRGO Project; the British-German GEO600 Project; the Japanese TAMA300 Project and the Australian ACIGA Project, presently in the early planning stages.

Michelson-type laser interferometer gravitational-wave detectors detect the differential length change between the two arms of the interferometer. Thus if the laser interferometer is to achieve its design strain sensitivity then it must be isolated from noise sources that can induce a change in the optical path length or contrast defect, such as the laser intensity noise. Interferometric gravitational-wave detectors use heterodyne techniques in the fringe detection process which transforms the gravitational-wave signal into the radiofrequency (rf) region to achieve a sensitivity limited by the shot noise of the detected light. The intensity noise has components at the rf frequency which cannot be removed by means of an active stabilization scheme[2] and has components in the expected gravitational-wave band (10 Hz — 5 kHz). Intensity noise results in unbalanced radiation pressure effects on the test masses of the interferometer, due to imbalance of the mirror masses and imbalance of the cavity storage times. The effects of radiation pressure vanish with complete symmetry of the mechanical and optical parameters of the interferometer arms. In practice such symmetry is hard to obtain, hence the need for intensity stabilization.

Two common approaches to stabilizing the intensity of a laser utilize either an electro-optic modulator or an acousto-optic modulator. Because both modulators rely on crystals as the active medium, the beam can be distorted through thermal effects or birefringence. Due to the limited power handling of the crystals, this approach is not necessarily scalable to high powers. Described here is an alternative approach, applied to the LIGO 10-W laser, which does not result in an optical insertion loss and, in principle, is scalable to high power.

II. THE LASER

The 10-W cw diode-laser pumped Nd^{3+}:YAG laser is a master-oscillator-power-amplifier (MOPA) configuration developed by Lightwave Electronics Corp. under contract with the LIGO Project[1]. The MOPA system employs a Model 126-1064-700 NPRO (non-planar ring oscillator) master oscillator and a double-pass amplifier scheme. The amplifier chain consists of four Nd^{3+}:YAG rods, each pumped by a pair of 20-W laser diode bars. A schematic diagram of the laser is shown in Figure 1.

III. LASER STABILIZATION USING POWER SUPPLY ACTUATORS

Two actuators were initially provided for controlling the intensity of the laser: the power actuator on the master oscillator and the AC current adjust actuator. The power actuator controls the current to the laser diode pumping the NPRO crystal. Because of cross coupling between intensity noise and frequency noise — the result of optical path length changes in the gain medium caused by variations in the absorbed pump power — the power adjust actuator was not used to control the intensity of the laser. The AC current adjust actuator controls the current to the power amplifier pump diodes. No measureable cross coupling to frequency noise was observed in the band of interest—100 Hz to 10 kHz—when the AC current adjust actuator was used.

The measured characteristics of the AC current adjust actuator are shown in Figure 2. The magnitude response of the AC current adjust actuator clearly exhibits multiple poles at less than 100 kHz, making the design of a fast, high gain control servo based on this actuator extremely difficult. If this actuator was used, it would necessitate direct current modulation of the 20 A diode power supply to achieve intensity stabilization. An alternative approach would be to shunt a small amount of current around the laser diodes, thus modulating the diode current. A similar approach was previously carried out on an Argon ion laser where a shunt was employed in the main power supply[3].

IV. INTENSITY STABILIZATION USING A CURRENT SHUNT

To address these problems, a new actuator, the current shunt actuator, was developed to modulate the current flowing through the power amplifier pump diodes. A schematic of the current shunt actuator is shown in Figure 3. The current shunt was placed in parallel to the power amplifier pump diodes and was designed to carry approximately 100–200 mA. A design constraint placed on the current shunt was that it be a current sink so that it could modulate the current flowing through the diodes but that it could not be a current source so that it posed no risk to the diodes. Having to regulate a smaller current would result in a better dynamic response from the current shunt actuator. In addition the current shunt was placed so as not to affect the power amplifier pump diode protection circuitry provided with the laser. The measured characteristics of the current shunt actuator are shown in Figure 4.

A schematic of the intensity stabilization scheme is shown in Figure 5. A small fraction of the output of the laser was incident on a photodetector. The output of the photodetector, forming the error signal, is input to the intensity stabilization servo. The control signal from the servo determines the modulation applied by the current shunt to the power amplifier pump diode current sample in order to stabilize the output intensity.

Figure 6 shows the measured free-running and stabilized relative intensity noise, along with the LIGO pre-stabilized laser requirement. For frequencies between 10 Hz and 1 kHz the stabilized relative intensity noise is less than $2 \times 10^{-7}\ 1/\sqrt{\mathrm{Hz}}$ and above 1 kHz the relative intensity noise is $6 \times 10^{-7}\ 1/\sqrt{\mathrm{Hz}}$.

The measured performance characteristics of the current shunt actuator is influenced by the reactive electromagnetic interference (EMI) suppression components integral to the laser diode bus design. The effect of these components is to reduce the effectiveness of the laser diode current modulation by resisting rapid changes in current. It was not possible to remove these proprietary EMI suppression components as they were internal to the laser power amplifier head. The high frequency response characteristics of the transfer function shown in Figure 4 is largely attributable to the need to modulate laser current through the impedance of the EMI suppression circuitry. This circuitry contributes a pole at approximately 2 kHz.

It should be noted that an additional pole exists in the conversion of laser diode current modulation to intensity modulation. This pole is associated with the lifetime of the upper laser level and is unavoidable. The frequency of this pole is in the vicinity of 2 kHz.

An implementation of the current shunt intensity modulation approach would benefit from being closely coupled with the engineering of the laser EMI protection scheme, as the two presently worked in opposition. In a collaborative effort between the LIGO Project and Lightwave Electronics, the current shunt scheme was integrated into the laser amplifier head. The newly implemented current shunt was not hindered by the EMI suppression components. The measured transfer function of the new current shunt actuator is shown in Figure 7. Figure 8 shows the measured stabilized relative intensity noise achieved with the use of the integrated current shunt actuator and a single pole feedback servo with a unity gain frequency of approximately 30 kHz. For frequencies below 30 kHz the stabilized intensity noise spectrum is approximately flat at $2 \times 10^{-7}\ 1/\sqrt{\mathrm{Hz}}$.

A current shunt actuator for controlling the intensity of a 10 W cw Nd^{3+}:YAG laser, has been developed and tested. The principle of the current shunt actuator should be applicable to higher power lasers where the use of electro-optic modulators or acousto-optic modulators may be impractical or undesirable because of absorption.

V. ACKNOWLEDGEMENTS

This research is supported by the National Science Foundation under cooperative agreement PHY–9210038. The authors would like to acknowledge Frank Adams, Joe Alonis, Shannon Gomes and Glen Truong of Lightwave Electronics for their cooperation in implementing the current shunt. In addition we thank Stan Whitcomb for his support and encouragement during the writing of this paper.

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FIGURES

FIG. 1. The LIGO 10-W Laser is a MOPA-configured laser with the output of a non-planar ring oscillator amplified by a double-pass power amplifier. CL: cylindrical lens. PBSC: polarizing beamsplitter cube. SL: spherical lens. HWP: half-wave plate. FR: Faraday rotator. TFP: thin film polarizer. MOPM: master oscillator power monitor. PAPM: power amplifier power monitor.

FIG. 2. The transfer function of the AC current adjust actuator. In addition to the pole associated with the upper laser level lifetime, multiple poles due to the electronics are also present making the design of a high gain servo extremely difficult.

FIG. 3. The current shunt actuator is placed in parallel to the diode bus and samples 100–200 mA of the diode current. Regulation of a smaller current should result in a better dynamic response than that exhibited by the AC current adjust actuator.

FIG. 4. The transfer function of the current shunt actuator. A sinusoidal modulation is applied to the current shunt actuator and the laser response is measured by a photodetector to yield the transfer function.

FIG. 5. The intensity stabilization scheme. A photodetector monitors a small fraction of the laser output. The output of the photodetector is input to the intensity stabilization servo, which controls the modulation applied by the current shunt actuator.

FIG. 6. The measured relative intensity noise measured at the servo error point achieved with the use of the current shunt. The line drawn is the LIGO pre-stabilized laser intensity noise requirement.

FIG. 7. The transfer function of the integrated current shunt.

FIG. 8. The relative intensity noise achieved with the integrated current shunt actuator. The result was achieved with a relatively simple single pole feedback servo. A: In-the-loop stabilized relative intensity noise. B: Out-of-loop sensor stabilized relative intensity noise. C: The LIGO PSL relative intensity noise requirement. D, E: In-the-loop and out-of-loop free-running intensity noise.

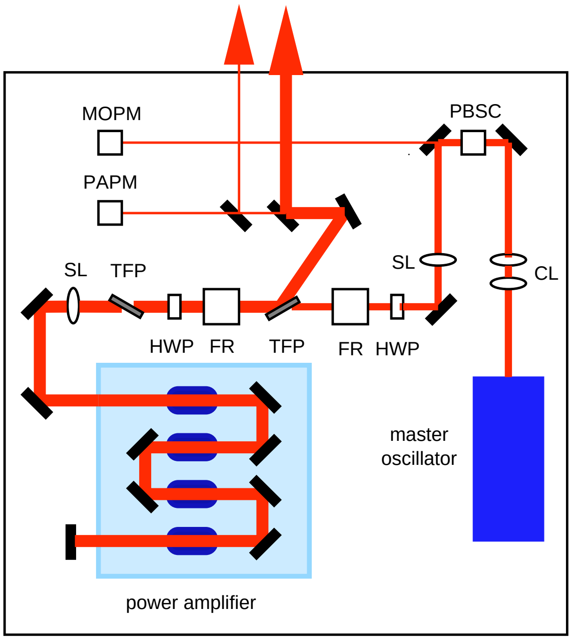

FIGURE 1
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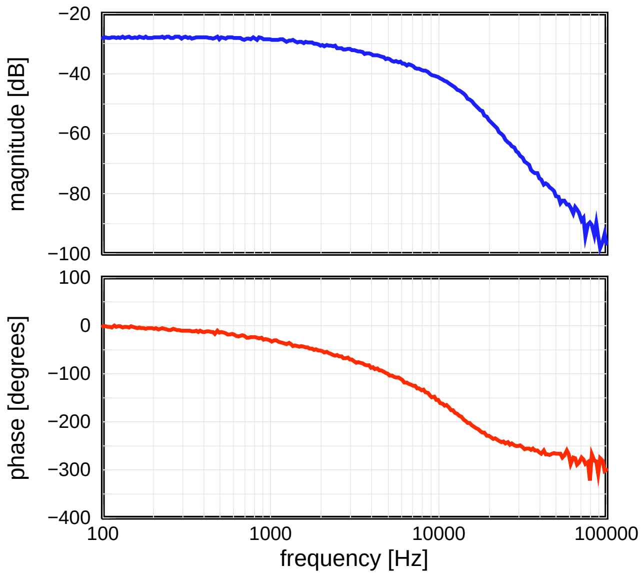

FIGURE 2

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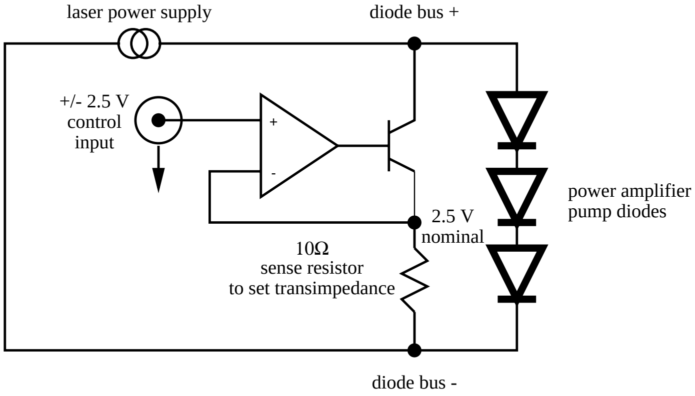

FIGURE 3
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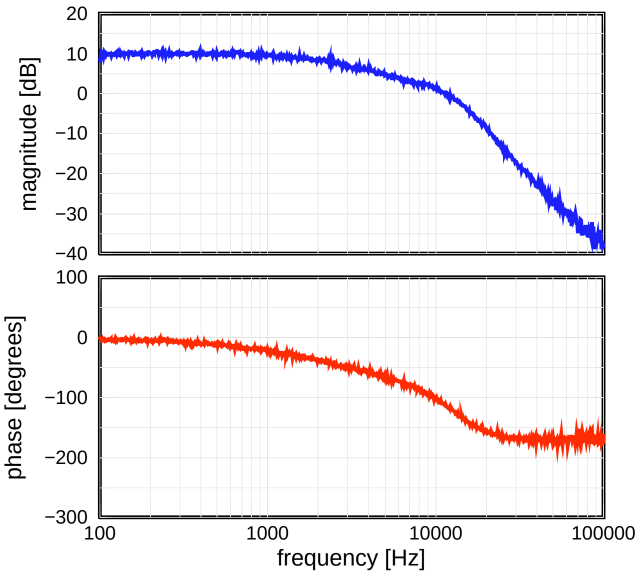

FIGURE 4

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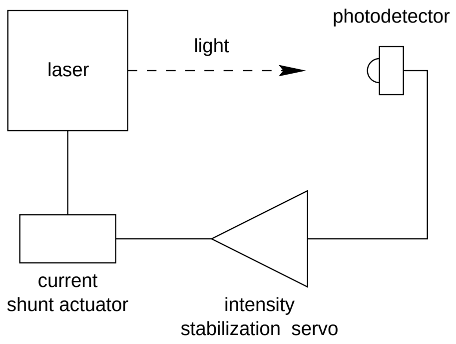

FIGURE 5
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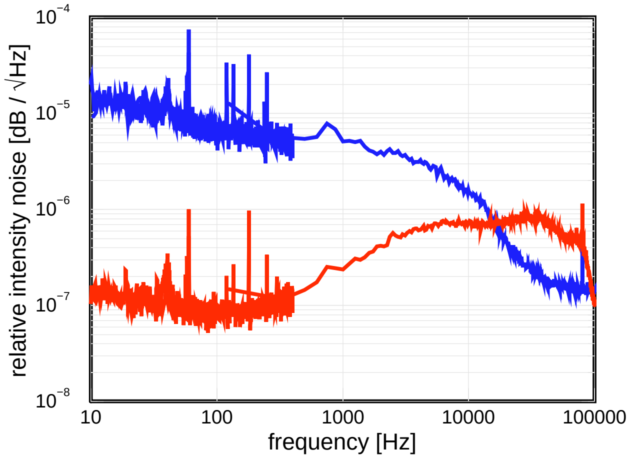

FIGURE 6
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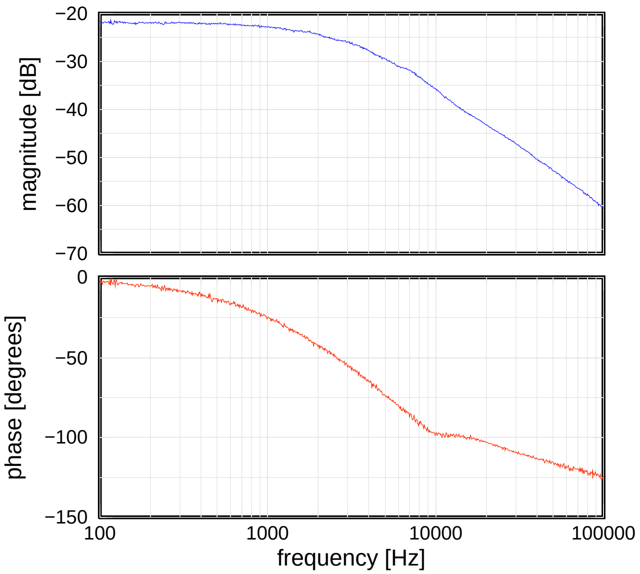

FIGURE 7

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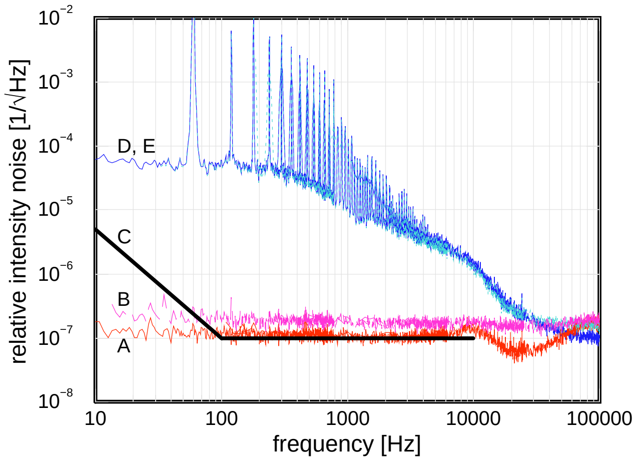

FIGURE 8

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