Development of a 100-W, single-frequency Nd:YAG laser for large-scale cryogenic gravitational wave telescope

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Abstract. We have built a 100-W injection-locked Nd:YAG laser for a Japanese next-generation gravitational wave detector. A 2-W master laser was directly injected to a high-power slave laser, which led to coherent radiation of 100 W at 1064 nm.

1. Introduction

The detection of gravitational waves (GWs) from violent astronomical events, such as supernovae or coalescence of binary neutron stars, is one of the most exciting topics in physics, and there are projects all over the world aiming to achieve the first direct detection of a GW.

In Japan, a new project to build a Michelson interferometer, named large-scale cryogenic gravitational wave telescope (LCGT), is in the planning stage [1]. The important features of the interferometer as the next-generation interferometer beyond the TAMA 300 project [2] are that the whole interferometer will be located at Kamioka mine, where the seismic motion is much quieter than that of the TAMA site, and that cryogenic mirrors will be used to reduce the thermal fluctuations of the optical path length. Because of the quiet environment and the reduced thermal fluctuations, the interferometer will be operated with extremely high sensitivity, which is limited by the quantum noise of the shot noise (above 70 Hz) and the radiation pressure noise (from a few hertz to 70 Hz). Since the frequency of the target GW is expected to be around a few hundred hertz, reducing the shot noise is crucial to improving the interferometer sensitivity. The shot noise can be estimated by the formula

\[ h_{\text{shot}} = \sqrt{\frac{h\lambda f_{\text{cut}}}{8FLG_{\text{power}}P_0}} \left(1 + \frac{f^2}{f_{\text{cut}}^2}\right), \]  

(1)

where \( h \) is Planck’s constant, \( \lambda \) is the wavelength of the laser beam, \( f_{\text{cut}} \) is the bandwidth of the interferometer, \( F \) is the finesse of the arm cavity, \( L \) is the arm length, \( G_{\text{power}} \) is the power recycling gain and \( P_0 \) is the laser power. According to equation (1), the shot noise is inversely proportional to the square root of the laser power. Therefore, by using a high-power laser as the light source of the GW detector, the sensitivity of the interferometer can be improved. Substituting the parameters of the LCGT interferometer into equation (1), the required output...
power of the laser source becomes 150 W for detecting a GW from a binary system located at 200 Mpc.

In addition to the high output power property, the laser should oscillate in a linearly polarized and diffraction-limited mode. At the same time, the frequency noise and the intensity noise of the laser should be well below the required level to avoid contamination of GW signals [3]. Assuming a common mode rejection ratio of 40 dB for the interferometer performance, the intensity noise and frequency noise of the laser should fulfill the following requirements:

- Intensity noise less than $10^{-8} / \sqrt{\text{Hz}}$ at 100 Hz,
- Frequency noise less than $10^{-7} \text{Hz} / \sqrt{\text{Hz}}$ at 100 Hz.

Up to date, no laser meets these requirements at an output power of over 100 W.

There are two possible ways to make a high-power laser with such excellent beam quality: one is to use a master-oscillator power-amplifier (MOPA); the other is to use the injection locking technique [4–6].

The former one is used to amplify a low-power master laser by an amplifier, which is a rather simple way to enhance the output power at a single frequency. However, because of a lack of mode selectivity, the MOPA scheme is vulnerable to amplified spontaneous emission (ASE) and parasitic oscillation; also, it is difficult to scale the output power from a few watts to over 100 W while retaining good beam quality. To avoid beam degradation, saturated amplification is a feasible way in which the amplification gain is saturated due to the high power density of the master light, and ASE can be suppressed. Therefore, it is preferable to use the MOPA technique to amplify a high-power laser (more than 10 W when the beam diameter is on the order of a few millimeters) to an even higher power level.

In injection locking, a low-power, single-frequency master laser is injected into a high-power slave laser to realize high-power laser oscillation at single frequency. Due to the mode selectivity of the slave cavity, an injection-locked laser can generate a high output power of good beam quality. However, a tight feedback control system is required to keep the slave laser injection locked for a long period, and thus the whole system becomes complicated. Also, the frequency region over which injection locking remains is limited by the locking range,

$$\Delta v_{\text{lock}} = \Delta v_{\text{slave}} \sqrt{\frac{P_m}{P_s}},$$

where $\Delta v_{\text{slave}}$ is the linewidth of the slave cavity; $P_m$ and $P_s$ are the power of the master laser and the slave laser, respectively. Equation (2) shows that the slave power cannot be much higher than the master power due to the dependence of the locking range on the power ratio.

Taking into consideration each characteristic of MOPA, or injection locking, we designed the laser source for the LCGT, as shown in figure 1. In the current design, injection locking of a Nd:YAG laser (oscillation wavelength: 1064 nm) will be used in the first power amplification stage to realize a 100-W, single-frequency output; then, the output of the injection locked laser will be amplified to 150 W by Nd:YAG amplifiers. The amplified output will be picked off and locked to a frequency reference to pre-stabilize the laser frequency. The power fluctuation will be stabilized by controlling the amplifier current [7].

While high-power lasers exceeding 100 W have been reported for the injection-locking configuration [8, 9], or MOPA [10, 11], we will apply both techniques to our laser. The reason is not only that we can take advantage of both techniques, but also that we can deal with the stabilization process of the frequency noise and the intensity noise separately (see figure 1).

Currently, we are constructing an injection-locked laser and characterizing the output. In this article, the current status of the development of the laser system for LCGT is presented.
Figure 1. Schematic diagram of the LCGT laser. EOM, Electro-optic modulator; PZT, Piezoelectric transducer; PBS, Polarizing beam splitter.

2. Free running slave laser
For the injection-locked laser system, we have built a high-power slave laser [12–14]. The laser module, which was manufactured by a research group of Mitsubishi Electric Corporation [15], has two Nd:YAG rods and one quartz rotator. The Nd:YAG rod is placed in a ceramic chamber and side-pumped by laser diode arrays. A quartz rotator is used to rotate the polarization and to cancel the thermally induced birefringence.

With two laser modules, we constructed a ring laser, which generated a maximum output power of 121 W. The slave cavity was designed to compensate for the thermal lensing effect in the higher pumping region by using convex mirrors with a radius of the curvature of 20 cm.

We measured the \( M^2 \) of the free-running slave laser by enforcing unidirectional oscillation with an intra-cavity Faraday rotator (FR) [13]. \( M^2 \) is a factor showing the spatial beam quality of a Gaussian beam and is unity when the beam is a perfect Gaussian mode. The result showed that the \( M^2 \) was better than 1.2 regardless of the aperture of the FR; thus, the output beam of the slave laser was almost diffraction-limited. A good spatial mode was achieved because the beam size at the Nd:YAG rod position was designed to expand by optimizing the cavity length, and the higher order spatial modes of the slave cavity were truncated by the rod aperture.

3. Injection locking
We tested the injection locking of the 121-W ring laser to a 2-W master oscillator: a monolithic ring Nd:YAG laser (NPRO, InnoLight model Mephisto 2000 NE) [16]. The optical layout of the injection locking experiment is shown in figure 2. The master laser was phase modulated at 15 MHz by an electro-optic modulator (EOM) and injected into the slave cavity. The error signal between the phase of the master laser and the slave laser was acquired by the Pound-Drever-Hall (PDH) technique [17]; a fraction of the output of the injection-locked laser was picked off and demodulated by mixing the phase-adjusted 15-MHz oscillator signal. The error signal was amplified and fed back to a piezo-electric transducer (PZT) of the slave laser cavity to control the frequency of the slave laser.

The slave laser was injection locked to the master laser with a maximum output power of over
100 W, which was limited by the stability of the slave cavity mode. When the strong thermal lens effect pulled the cavity mode into the unstable region, the lateral mode was split in two, or more, instead of a circular mode. The output power of the injection-locked laser and the reverse wave of the free-running slave laser were examined (see figure 3). From measurements, the slave laser was kept injection locked for more than 6 hours with an output power of over 100 W, while the reverse wave was suppressed. The thermal drift of the slave laser caused a frequency drift from the master frequency, and thus the effective power, which can be used for injection locking, was changing [14].

The $M^2$ for the injection-locked laser was 1.14 in the horizontal direction and 1.09 in the vertical direction. The polarization ratio of the injection-locked laser was better than 20:1, which was linearly polarized in the horizontal plane. The polarization of the slave laser was determined by a subtle difference in the loss between the vertically and horizontally polarized modes.

The open-loop transfer function of the feedback servo of the PDH technique, measured at an output power of 80 W, is shown in figure 4. The error signal was amplified and applied to the PZT. The PZT resonance at 30 kHz was eliminated by a notch filter and the unity gain frequency (UGF) was 8 kHz. The measurable frequency bandwidth of the transfer function was limited above 2 kHz; this is because sinusoidal signals applied to the system were amplified with the high servo loop gain at the lower frequencies and thus the injection-locked laser became

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**Figure 2.** Schematic diagram of the injection-locking experiment.

**Figure 3.** Time trace of the output power (upper line) and the reverse wave (lower line) of the injection-locked laser.
unstable or unlocked due to the perturbations. There is small phase margin ($\sim 10^\circ$) for the current feedback servo, and thus the circuit needs to be modified to improve the stability of injection locking; optimizing the circuit is in progress now. Also, we recently replaced the PZT; a result from a preliminary experiment showed that the resonance peak was shifted at 42 kHz. However, the dynamic range of the new actuator was half the previous one, which would affect the long-term stability of injection locking. In order to compensate for the long-term drift of the slave frequency, a PZT with a wide dynamic range will be used along with the installed one.

4. Frequency stabilization
In order to fulfill the requirement of frequency fluctuation, the high-power laser needs to be stabilized to a frequency reference.

A rigid ring cavity made of three high-quality mirrors and a super invar spacer is used as a frequency reference to pre-stabilize the injection-locked laser. The free spectral range of the cavity is 714 MHz and the measured finesse is 5300 for the s polarization and 460 for the p polarization. When the ring cavity length was swept by a PZT, the transmitting characteristics of the picked off light of the injection locked laser showed a large peak of the TEM$_{00}$ mode, while the higher order modes were much smaller than the fundamental mode (see figure 5), and therefore verified the good spatial beam quality.

Frequency-stabilization experiments are now under way, and we expect that the injection-locked laser will be phase locked to the frequency reference and the frequency stability can be examined before long.

5. Conclusion
We have developed an injection-locked Nd:YAG laser with an output power of 100 W. The beam quality of the injection-locked laser was characterized; the $M^2$ was better than 1.2, which showed that the output mode was diffraction-limited, and the polarization ratio was better than 1:20. The transfer function of the PDH locking servo was investigated. A frequency-stabilization experiment is now under way.
Figure 5. Transmitted light of the reference cavity for the p-polarized light of the injection locked laser. The small peaks between the fundamental modes are transmission of the second order and the forth order Gaussian modes, which are supposed to be eliminated by mode matching perfectly.

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