

Wideband and high frequency stabilization of an injection-locked Nd:YAG laser to a high-finesse Fabry-Perot cavity

Mitsuru Musha

Spacetime Astronomy Section, National Astronomical Observatory, 2-21-1 Ohsawa, Mitaka-shi, Tokyo 181, Japan

Ken'ichi Nakagawa

Tokyo Institute of Polytechnics, 1583 Iiyama, Atsugi, Kanagawa 243, Japan

Ken-ichi Ueda

Institute for Laser Science, University of Electro-Communications, 1-5-1 Chōfugaoka, Chōfu City, Tokyo 182, Japan

Received April 15, 1997

High frequency stabilization of a 2.2-W injection-locked laser-diode-pumped Nd:YAG laser to a high-finesse optical cavity has been realized by frequency control of the master laser. With the help of an external electro-optical modulator, the feedback bandwidth was extended to 1 MHz and the frequency noise relative to the reference cavity was suppressed to 3×10^{-4} Hz/Hz^{1/2} below 1 kHz. This feedback laser system is an ideal laser source for gravitational wave detectors, which require both ultralow frequency noise and high output power. © 1997 Optical Society of America

The investigation of laser interferometric gravitational wave antennas for observation of gravitational waves has progressed in many countries.¹⁻³ The light source for a laser interferometric gravitational wave antenna requires cw TEM₀₀ high-power laser light with high frequency stability. Frequency stability of laser light as low as 10⁻⁶ Hz/Hz^{1/2} is necessary below the expected gravitational wave frequency of 1 kHz for the requisite sensitivity for gravitational wave detection of $h = 10^{-21}$.⁴ For such sensitivity an input laser power of ~1 kW is needed to overcome the laser shot noise. Although introduction of the power recycling technique relaxes this stringent requirement, the required laser power is still several tens of watts.

In our gravitational wave detection project, which we call TAMA,³ a Michelson-type Fabry-Perot laser interferometric gravitational wave antenna was constructed with an arm 300 m long. For the light source of our 300-m laser interferometer we developed a laser-diode (LD)-pumped high-power (>10 W) Nd:YAG laser with excellent frequency stability. Using an end-pumped slave laser, we achieved single-frequency output of 10 W by means of an injection-locking technique with a monolithic LD-pumped master Nd:YAG laser.⁵ This feature resulted in fairly good frequency stabilization of this laser. The remaining problem was the lack of a feedback bandwidth to yield a high enough feedback gain with a high phase margin.

We describe high frequency stabilization of an injection-locked laser. We made a 2.2-W injection-locked Nd:YAG laser and stabilized the frequency noise to a high-finesse reference cavity by the Pound-Drever technique.⁶ According to the injection-locking theory, the frequency noise of the master laser is reproduced in that of the injection-locked laser below locking range frequency.⁷ By controlling the frequency of the master laser light we suppressed the frequency noise of the injection-locked laser.

The geometry of the slave laser is shown in Fig. 1. The laser gain medium is a 1% Nd-doped YAG rod with a diameter of 3 mm and a length of 7 mm. This laser head is placed within a figure-8-shaped ring cavity with two curved and two flat highly reflecting mirrors; the radius of curvature of both curved mirrors is 500 mm. One of the flat mirrors is used as an output coupler whose reflectivity is 95%. The cavity length is 454 mm, which corresponds to a free spectral range of 660 MHz. The Nd:YAG rod is end-pumped by a fiber-coupled LD array (SDL-3450-P5) whose maximum output power is 10 W at the applied current of 22 A. A commercial 200-mW LD-pumped Nd:YAG laser with nonplanar ring oscillator (NPRO; Lightwave 122-200) is used as a master laser. With 70 mW of injected light from the master laser, the slave laser generates unidirectionally linearly polarized TEM₀₀ single-frequency oscillation with

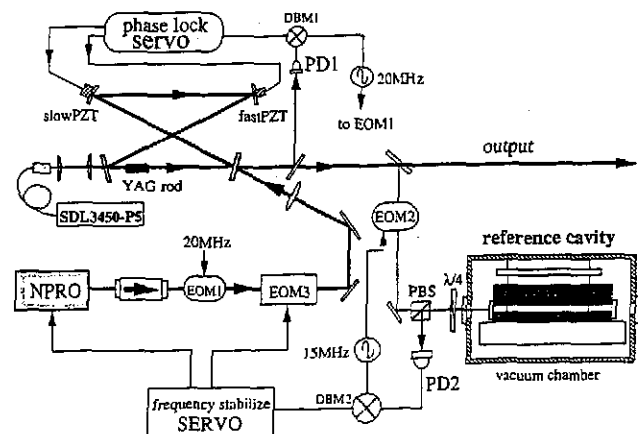


Fig. 1. Schematic of the frequency stabilization of an injection-locked laser: PBS; polarized beam splitter; $\lambda/4$, quarter-wave plate. Other abbreviations are defined in text. PD1, PD2, photodetectors.

a maximum output power of 2.2 W. Stable injection locking is obtained with a phase-locking servo by the Pound-Drever technique. The length of the slave laser cavity is controlled by fast and slow piezoelectric transducers (PZT's). The bandwidth of the phase-locking servo is 25 kHz, and the residual frequency noise between the master and the slave lasers is obtained from the error signal of the phase-locking servo, as shown in Fig. 2. The locking range of this injection-locked laser, which is evaluated from the discrimination signal of the phase-locking servo, is 1.1 MHz at the maximum output power of 2.2 W.

To stabilize the frequency fluctuation of the injection-locked laser by using the Pound-Drever technique we compare the slave laser output with the resonant frequency of the stable reference cavity, and the error signal is fed back only to the master laser part. A schematic diagram of the frequency-stabilized injection-locked laser is also shown in Fig. 1. A part of the injection-locked laser light is picked off by a beam splitter and is phase modulated at 15 MHz by EOM2. With a pair of mirrors and lenses, the divided light is mode matched to a longitudinal mode of the reference cavity. After passing through a polarized beam splitter and a quarter-wave plate, the light is introduced into the reference cavity and the reflected light from the reference cavity is detected by a photodetector (PD2; Fujitsu FID13Y13TX), where the PD input power is 14 mW. The reference Fabry-Perot cavity consists of two highly reflective mirrors; one is flat and the other is concave, with a radius of curvature 1000 mm. The spacer inserted between the two mirrors is made of low-thermal-expansion glass and is 272 mm long. The finesse of the reference cavity is evaluated to be 55,000. To avoid externally caused disturbances we hung the reference cavity by a double-pendulum suspension with eddy-current dumping, and all those components were contained in a vacuum chamber to keep the pressure below 10^{-5} Torr (details were given in a previous paper⁸). The photocurrent from PD2 is demodulated with a double-balanced mixer (DBM2) into the error signal, and the error signal is amplified at the frequency servo circuit. The slow component of the servo signal is fed back to a PZT that is bonded to the YAG crystal of the 200-mW NPRO, whose feedback bandwidth is limited to 80 kHz by the mechanical resonant frequency of the YAG crystal. The fast component of the servo signal is fed back to an external wideband EOM phase transducer made of LiNbO_3 (EOM3), which is placed at the optical path of the master laser light. By controlling the phase of the master laser light with both the wideband EOM phase transducer and the PZT in the 200-mW NPRO, we achieved a 1-MHz feedback bandwidth. The relative frequency noise of the injection-locked laser, which is evaluated from the error signal, is shown in Fig. 3 as a thin curve. The relative frequency noise is suppressed to 3×10^{-4} Hz/Hz^{1/2} below 1 kHz. The bold curve in Fig. 3 indicates the relative frequency noise of the frequency-stabilized

master laser whose frequency is locked to the same reference cavity by use of the same servo loop as for the present injection-locked laser.

According to injection-locking theory⁹ the frequency fluctuation $\delta\omega_{IP}$ of an injection-locked laser with a phase-locking servo is expressed in a Laplace formalism as

$$\delta\omega_{IP}(s) = \left[\frac{\Delta f_{\text{lock}}}{s + \Delta f_{\text{lock}}} + \frac{G_p(s)}{1 + G_p(s)} \frac{s}{s + \Delta f_{\text{lock}}} \right] \delta\omega_s(s) + \frac{1}{1 + G_p(s)} \frac{s}{s + \Delta f_{\text{lock}}} \delta\omega_m(s), \quad (1)$$

where $\delta\omega_m$ and $\delta\omega_s$ are frequency fluctuations of a master and a slave laser in the free-running state, $G_p(s)$ is the open-loop gain of the phase-locking servo, and Δf_{lock} is the locking range of the injection-locked laser. Because locking range Δf_{lock} is larger than 1 MHz in the present case, the second term in the factor of $\delta\omega_m$ is negligible, and at frequencies much smaller than Δf_{lock} the factor of $\delta\omega_s$ also becomes negligible when the open-loop gain of the phase-locking servo is high. In that case $\delta\omega_m$ becomes

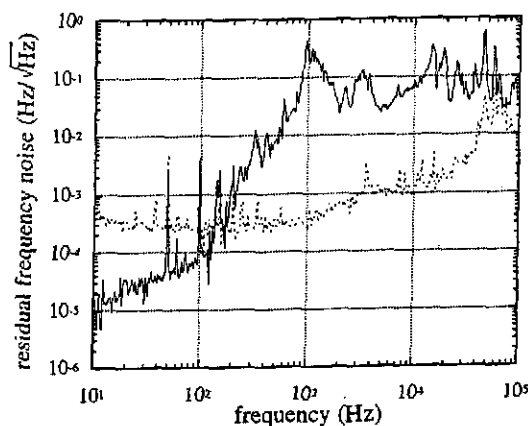


Fig. 2. Residual frequency noise spectrum of the injection-locked laser. Solid curve, the residual frequency noise between the master and the slave lasers. Dotted curve, the relative frequency noise of the frequency-stabilized injection-locked laser.

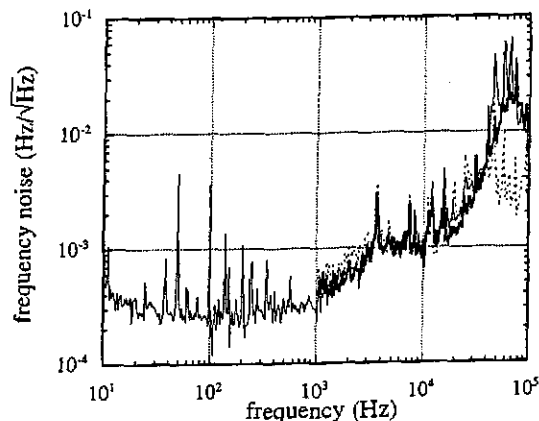


Fig. 3. Noise spectra of a frequency-stabilized laser. Thin curve, the frequency noise of the injection-locked laser; bold curve, that of the master laser. Dotted curve, the frequency noise of the injection-locked laser when the servo gain at high frequency increases.

dominant over the second term; hence the frequency fluctuation of the master laser is reproduced in the injection-locked laser. The second term is observed as residual frequency noise and will exceed the first term at larger frequencies. The observed frequency-noise spectrum of the master laser in free-running state is $\sim 10^3/f$ Hz/Hz^{1/2}, where f is the Fourier frequency. As can be seen from Fig. 2, the residual frequency noise is less than the frequency noise of the free-running master laser below 10 kHz.

When the injection-locked laser is stabilized to a reference cavity with frequency fluctuation $\delta\omega_{ref}$, and assuming that the second term in the factor of $\delta\omega_m$ in Eq. (1) is negligible, the fluctuation of the injection-locked laser, $\delta\omega_{IPf}$, is expressed as

$$\delta\omega_{IPf}(s) \approx \frac{1}{s + \Delta f_{lock} + \Delta f_{lock} G_{freq}(s)} \left[\Delta f_{lock} \delta\omega_s + \frac{s}{1 + G_p(s)} \delta\omega_m + \Delta f_{lock} G_{freq}(s) \delta\omega_{ref} \right], \quad (2)$$

where $G_{freq}(s)$ is the open-loop gain of the frequency-stabilized servo. When the frequency of the injection-locked laser is locked to the reference cavity, $\delta\omega_{IPf}$ should be equal to $\delta\omega_{ref}$, and the first two terms must be much smaller than the third one. As the frequency increases, the factor of $\delta\omega_s$ increases and the factor of $\delta\omega_m$ decreases; that is, the suppression of the residual frequency noise becomes weaker at large frequencies even if the frequency-stabilized servo gain maintains a high level. This tendency was observed in the present experiment, as we describe below.

The relative frequency noise of the frequency-stabilized injection-locked laser is shown in Fig. 2, together with the residual frequency noise. Although the residual frequency noise is larger than the stabilized frequency-noise level above 15 Hz, it is also suppressed by the frequency-stabilized servo, and, as Fig. 3 shows, the frequency noise of the injection-locked laser is suppressed as much as that of the frequency-stabilized master laser. Above 10 kHz the residual frequency noise is larger than the frequency noise of the free-running master laser. According to Eq. (1), the influence of the residual frequency noise on the injection-locked laser becomes comparable with that of the master laser in this frequency range. As Fig. 3 shows, several resonant peaks are observed in the frequency noise of the frequency-stabilized injection-locked laser above 40 kHz, which correspond to those of the residual frequency noise (Fig. 2).

When the frequency-noise suppression gain increases at a higher frequency range, the relative frequency noise of the injection-locked laser is suppressed to 2×10^{-3} Hz/Hz^{1/2} at 100 kHz, as shown in Fig. 3. Although the frequency-noise level is more suppressed, the resonant peaks from the residual frequency noise above 40 kHz still remain on the frequency-noise spectrum, and this observation agrees with the explanation given above in relation to Eq. (2); the part of the frequency noise of the injection-locked

laser at a high frequency range that comes from the master laser is suppressed, but that which comes from the slave laser is less suppressed. From this result it is said that we can get wide servo bandwidth by inserting an EOM phase modulator into the optical path of the master laser, though the effect of the residual frequency noise is observed at the frequency-noise spectrum at a high frequency range where the residual frequency noise is comparable with the frequency noise of the free-running master laser.

In conclusion, we made a LD end-pumped Nd:YAG ring laser, and, by injecting light from 200-mW NPRO, generated cw TEM₀₀ single-frequency laser oscillation with a power of 2.2 W. Stable injection locking is obtained to control the slave laser cavity length with two PZT's whose bandwidth is 25 kHz. The frequency noise of the injection-locked laser is stabilized to a high-finesse Fabry-Perot cavity by a fed-back error signal to both the master laser and the EOM phase transducer that is placed at the master laser light whose servo bandwidth is 1 MHz. The relative frequency noise of the injection-locked laser follows that of the frequency-stabilized master laser below 40 kHz and is suppressed to 2×10^{-4} Hz/Hz^{1/2} below 1 kHz. Although the resonant peaks that come from the slave laser are observed in the frequency-noise spectrum above 40 kHz, the relative frequency noise at 100 kHz is suppressed to 2×10^{-3} Hz/Hz^{1/2}. The present result suggests that the frequency of an injection-locked chain of lasers can be stabilized only through stabilization of the master laser.

M. Musha is a research fellow of the Japan Society for the Promotion of Science. This research is partially supported by a science grant-in-aid for scientific research from the Ministry of Education, Science, and Culture of Japan (07NP1101,8202).

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