DEVELOPMENT OF HIGH POWER AND HIGHLY-STABILIZED LIGHT SOURCE FOR GRAVITATIONAL WAVE DETECTOR

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ABSTRACT

High-power and highly-stabilized lasers are indispensable for the laser interferometric gravitational wave detector, and we have developed the injection-locked Nd:YAG laser and coherent addition of the injection-locked lasers. The frequency noise of the injection-locked laser was locked to both a stabilized high-finesse Fabry-Perot cavity and saturated absorption of iodine molecules for wideband frequency stabilization. For increasing the output power, coherent addition of two injection-locked lasers has been performed, and intensity and frequency noise characteristics of the coherently-added laser was investigated.

INTRODUCTION

The construction of laser interferometric gravitational wave antennas have been promoted in many countries, which aim for confirmation of the theory of general relativity or for establishing new gravitational wave astronomy. The strain sensitivity of the gravitational wave detector should be higher than 1x10^{-22} /ˆHz at the observation frequency range around 300 Hz, and a high power with highly-stable light source is indispensable for realizing such a high sensitivity. The requirements for the light source are the frequency noise of less than 3x10^{-6} Hz/ˆHz and the intensity noise of less than 2x10^{-8} /ˆHz at the observation frequency range around 300 Hz. Not only frequency and intensity stability, higher output power is also required to decrease shot-noise limited level of the gravitational wave detector.
A commercial 200-mW LD-pumped monolithic Nd:YAG laser called NPRO with the wavelength of 1.064μm (Lightwave electronics 122-200) has been used as a light source of our prototype 20-m gravitational wave antenna from its low intrinsic frequency and intensity noise and its controllability. As the output power of NPRO is limited up to 2W from its configuration, the injection-locked Nd:YAG laser has been developed for our current 300-m gravitational wave detector, TAMA300[1], in which output power of 10W was required. Though the injection-locked laser has the same frequency noise as the stable master laser at lower frequency range, the further frequency stabilization is needed to satisfy the required frequency noise level. In the present symposium, the frequency stabilization of the injection-locked laser and the coherent addition of injection-locked lasers are presented.

FREQUENCY STABILIZATION OF AN INJECTION-LOCKED LASER

In order to evaluate frequency and intensity noise characteristic of the injection-locked laser, a prototype 2-W injection-locked laser has been made. The master laser was a NPRO (Lightwave electronics 122-200) with the output power of 150 mW. A slave laser consisted of a bow-tie cavity with two flat and two concave mirrors whose FSR was 660 MHz. A Nd:YAG rod within the bow-tie cavity was end-pumped by a fiber-delivered 10-W LD-array. A 70-mW injected light from the master laser allowed the slave laser to generate unidirectional, linear-polarized, single frequency, TEM_{00} oscillation with the output power of 2 W at the pump power of 10 W. The master laser light was phase modulated at 20 MHz by an electro-optic modulator (EOM), and stable injection locking was obtained by means of phase locking servo with the FM sideband technique, in which the length of the slave cavity was controlled by two PZTs glued to the two cavity mirrors. The key techniques for highly frequency stabilization are high-gain and wide bandwidth servo circuit and stable frequency references. An optical resonance of high-finesse Fabry-Perot cavity was used for the short-term frequency reference. Our rigid Fabry-Perot cavity consisted of two highly reflective mirrors and the ultra-low-expansion glass ceramic (ULE) spacer placed between them. The free spectral range (FSR) and finesse of the cavity were 545 MHz and 55000, respectively. The Fabry-Perot cavity was placed on a V-shaped aluminum bench, which was suspended from a ceiling of the vacuum chamber by five molybdenum wires in order to isolate it from mechanical vibrations caused from outside, forming a double pendulum. This suspension system improved stability of the Fabry-Perot cavity by more than 50 dB at 100 Hz[2], and the stability of the Fabry-Perot cavity as a frequency reference was evaluated to be 2x10^{-2} Hz/ˆHz at the Fourier frequency of 300 Hz[3]. The light from the injection-locked laser was phase modulated at 15 MHz, and introduced into the Fabry-Perot cavity. The frequency noise signal was detected from the reflected light of the Fabry-Perot cavity by FM sideband technique, and filtered and amplified into the control signal. According to the injection-locked theory, the frequency noise of the injection-locked laser is dominated by that of the master laser light. As the locking range frequency of our injection-locked laser is more than 1.2 MHz, the error signal was fed back to the master laser light to suppress the frequency noise of the injection-locked laser. With the aid of an EOM, more than 700 kHz of servo bandwidth was obtained which overcame the control bandwidth of the master laser (70 kHz). The frequency noise estimated from the error signal was suppressed down to $2x10^{-4}$ Hz/ˆHz below 1 kHz, which is the same level as that of the frequency-stabilized master laser. It is shown that the frequency noise can be completely controlled by the master laser at a low frequency range, and no additional frequency noise is observed which comes from the phase noise between master and slave laser. The absolute frequency noise of the injection-locked laser was suppressed down to $2x10^{-2}$ Hz/ˆHz which was limited by the stability of the Fabry-Perot cavity. Though acquired stabilized frequency noise level of the injection-locked laser is lowest as the desktop experiment, this noise level does not satisfy the required frequency noise level of the gravitational wave antenna. A 10-W injection-locked Nd:YAG laser which was made by SONY company[4] has been installed in TAMA300, and the further frequency stability was obtained when one arm of the 300-m Fabry-Perot Michelson interferometer was used as a frequency reference, which satisfied the required frequency noise level of TAMA300[5].

SHORT AND LONG-TERM FREQUENCY NOISE SUPPRESSION

Though the high finesse Fabry-Perot cavity with rigid spacer or one arm of the long-baseline interferometer has high short-term frequency stability, its long-term frequency stability is worse due to thermal expansion of the spacer or drift of the ground. For the stable operation of the interferometer, the long-term frequency stability of the laser is also needed as well as short-term frequency stability. Moreover, if the interferometer is locked to an absolute frequency reference, it can be used for two purposes: gravitational wave detector and strain meter for the geophysical purpose. Therefore, the wideband frequency stabilization of the injection-locked laser was tried, in which two frequency references were used. The schematic diagram of the two-reference-locked injection-locked laser is shown in Fig.1.

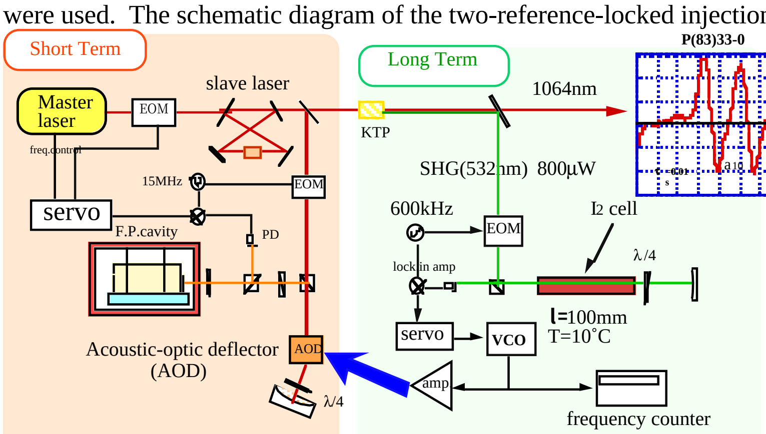

Fig.1

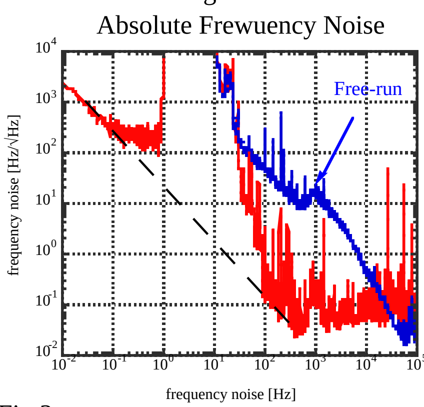

Fig.2

Fig.1 Experimental setup of a short- and long-term frequency stabilized injection-locked Nd:YAG laser. The frequency noise of injection-locked laser is stabilized to both high-finesse rigid Fabry-Perot cavity and saturated absorption of iodine molecules, simultaneously through AOD.

Fig.2 The red lines are measured frequency stability of the rigid Fabry-Perot cavity: below 1 Hz is estimated from the dual-reference locked laser, and between 100 Hz and 500 Hz were estimated from the mode-cleaner of the 20-m prototype gravitational wave antenna[3] The dotted line indicates expected stability of the rigid Fabry-Perot cavity as a frequency reference.

Saturated absorption of $^{127}I_2$ (hyperfine component a_{10} of the ro-vibrational transition P(83)33-0) was used as a long-term frequency reference. The second harmonics of the injection-locked Nd:YAG laser around 532nm was generated from KTP crystal, and the saturated absorption signal was obtained from an iodine cell whose length was 100 mm and temperature of which was controlled at 10¡C within 0.1¡C. The phase of the second harmonics light was modulated at 600 kHz, and error signal was obtained by FM sideband technique. The error signal was applied to the acousto-optic deflector (AOD) through voltage-controlled oscillator (VCO), and the frequency of the fundamental light was shifted proportional to the error signal. The frequency-shifted infrared light was introduced into the high-finesse Fabry-Perot cavity, and the error signal from the reflected light was fed-back to the master laser, which was similar to the Fabry-Perot cavity locking scheme mentioned above. In this scheme, the frequency of the injection-locked laser was stabilized simultaneously to two references with independent servo loops. The unity-gain frequencies of the iodine locking and the cavity locking servo loops are 700 Hz and 80 kHz, respectively. Both servo loops are maintained more than 1 hour[6]. The drift of the resonant frequency of the rigid Fabry-Pereot cavity was measured to be 1.4 MHz/h, and the evaluated stability of the rigid Fabry-Perot cavity is shown in Fig.2 as a red line. Bandwidth of the iodine locking servo determines the frequency stability of the laser. When the bandwidth of the iodine locking servo is more than 100 Hz, low S/N of the iodine saturated absorption signal degrades the frequency stability of the laser at higher frequency range. According to the numerical simulations, the frequency of two-reference-locked laser shows the best stability when the servo bandwidth of the iodine locking servo is 10 Hz.

COHERENT ADDITION OF TWO INJECTION-LOCKED LASER

For the future gravitational wave detector with the strain sensitivity of higher than $2x10^{-22}$ /^Hz, higher output power more than 100W is required to decrease shot-noise limited level of the interferometer. The output power of a stable end-pumped slave laser is limited up to 20W due to thermal lensing and thermal birefringence of the Nd:YAG crystals. There are two candidates for increasing output power of the master laser while the stability of the master laser is maintained, master oscillator and power amplifier (MOPA) and coherent addition of injection-locked lasers. Though the MOPA system is relatively easier way to increasing output power, it has disadvantages that the intensity noise of the MOPA increases by the gain of its power amplifier. The coherent addition of injection-locked laser is, on the other hand, expected to have no additional intensity and frequency noise compared with a source injection-locked laser. Therefore we made coherently-added two injection-locked lasers, and the addition efficiency and intensity, frequency noise characteristic were investigated. The schematic diagram of the coherent addition of two injection-locked lasers is shown in Fig.3. The laser light from the 500-mW NPRO (Lightwave electronics 124-500) was divided by a 50/50 beamsplitter(BS1), and were injected into two slave lasers. The output of these two injection-locked laser were recombined on another 50/50 beam splitter(BS2), which was similar to the Mach-Zender interferometer configuration. Because the frequency of the two injection-locked laser is the same as that of the master laser, one of the outputs from BS2 can be kept bright interference condition by controlling the length of the optical path of the injection-locked laser. The demodulated signal which detected from the dark port was fedback to the PZT1 to control the path length of the injection-locked laser2.

ig3

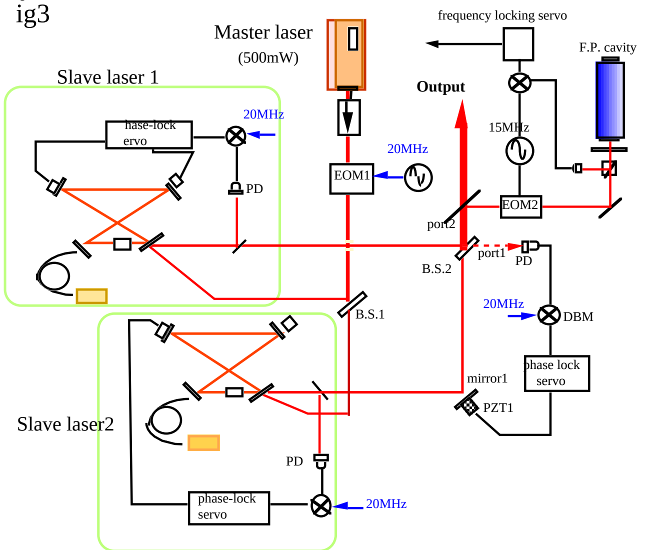

Fig.4

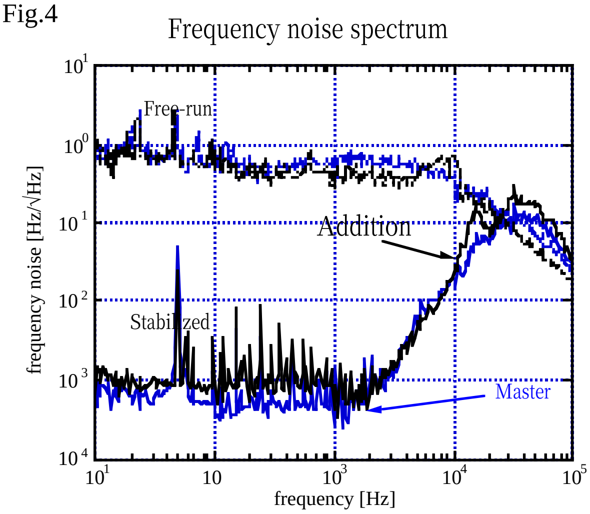

Fig.3 Experimental setup of coherent-addition of two injection-locked lasers. The frequency noise of the coherently-added laser was estimated by using rigid Fabry-Perot cavity.

Fig.4 Frequency noise spectrum of the Master laser (blue line) and coherently-added injection-locked lasers (black line). Dotted lines indicate the frequency noises under free-running condition and solid lines indicate suppressed frequency noises.

The phase locking servo bandwidth between two injection-locked lasers was 10 kHz, and relative phase noise was suppressed down to $1x10^{-5}$ rad/^Hz below 100 Hz. The addition efficiency $\eta = P_{add}/(P_{slave1}+P_{slave2})$ was kept more than 0.9 for an incident power between 2W and 4.8W, and maximum addition efficiency of 0.92 was obtained at the incident power of 4.4W[7].

The frequency noise of the coherent added laser was locked to the rigid high-finesse Fabry-Perot cavity mentioned above, and the frequency noise of the master and the coherently-added laser are shown in Fig.4. The frequency noise was suppressed to the same level as that of the frequency-stabilized master laser, and no additional frequency noise caused from phase noise between two injection-locked laser was observed below locking range frequency.

Figure 5(a) shows the relative intensity noise spectrum of the coherently-added laser. The intensity noise of the coherently-added laser above 100 kHz was almost the same level as that of injection-locked laser. The intensity noise of the coherently-added laser below 100 kHz, however, was worse the that of the injection-locked because the beam fluctuation of the injection-locked lasers. At a lower frequency range below the relaxation oscillation frequency of the slave laser, the intensity noise of the injection-locked laser was dominated by the pumpLDs of the slave laser, and the intensity noise of the coherently added laser was suppressed down to $1x10^{-7}$ /√Hz by controlling applied electric current to two pump LDs. Figure5(b) shows the intensity noise correlation between two injection-locked lasers. The intensity noise of two injection-locked laser was detected independently by two PDs, and these intensity noise signals were combined electrically in phase (sum) and π-phase (diff). The sum and diff signal shows much difference above 100 kHz, which means that the intensity noise of two injection-locked lasers were strongly correlated to each other. By using the intensity noise correlation of the two injection-locked lasers, we tried to suppress the intensity noise of the coherently-added laser.

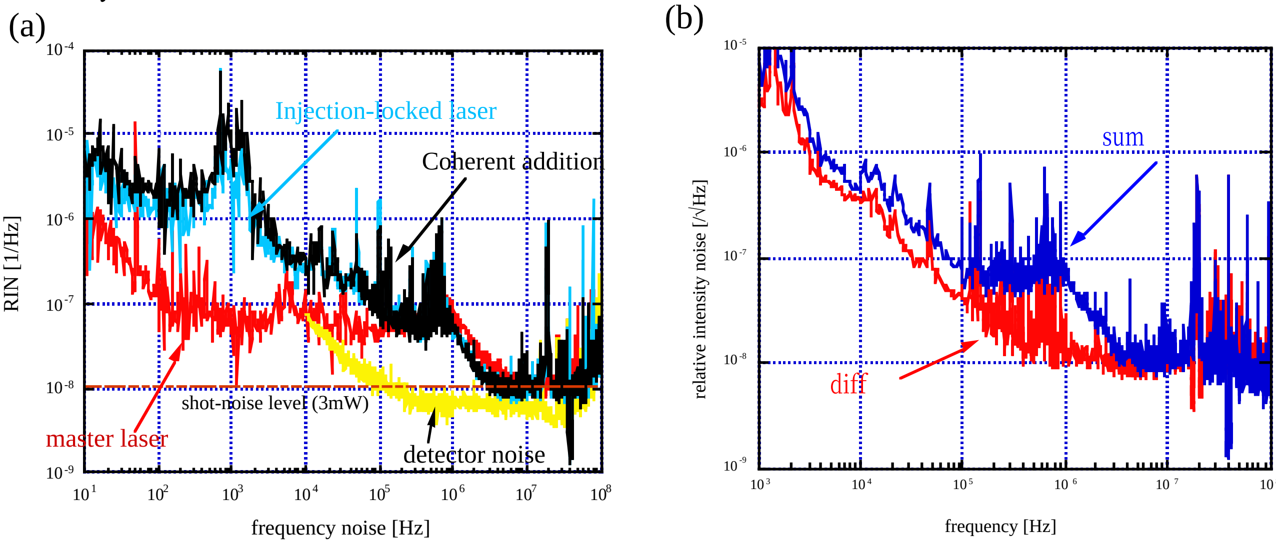

Fig.5 (a) The intensity noise spectrum of master laser, injection-locked laser , and the coherently-added laser
(b)The intensity noise correlation of two injection-locked lasers. The intensity noise of two injection-locked laser was summed electrically in 0 phase (sum) and π-phase (diff).

The polarization maintaining single-mode optical fiber with the length of 30m was inserted between master laser and slave laser 1 to make π phase delay of the intensity noise at 5 MHz, and the intensity noise of the coherently-added laser was suppressed by 0.5 around 5 MHz.

CONCLUSIONS

We have developed injection-locked laser and coherently added laser for the light source of the gravitational wave antenna. The frequency noise of the injection-locked laser was stabilized to both Fabry-Perot cavity and saturated absorption of iodine molecules, which has the highest frequency stability as a desktop experiment. It can be also used as the light source for high-precision spectroscopy. For increasing output power, coherent addition of two injection-locked lasers was studies. The highest addition efficiency of 0.92 was achieved, which is higher than ever reported. The frequency noise of coherently-added laser was suppressed by controlling master laser, while intensity noise was controlled by the pump laser of the slave laser, and the frequency and intensity noise of coherently-added laser were suppressed to the same level as those obtained from the single injection-locked laser. Consequently, the coherently-added laser acted as a high-power injection-locked laser from its noise characteristic and controllability, which is suitable for a high-power light source for the future gravitational wave detector.

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