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DEVELOPMENTS OF HIGHLY FREQUENCY AND INTENSITY STABILIZED LASERS FOR SPACE GRAVITATIONAL WAVE DETECTOR DECIGO/PRE-DECIGO

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I. INTRODUCTION

Gravitational wave (GW), predicted by A. Einstein in his general theory of relativity, is temporal variation of spatial distortion caused from the change of enormous mass such as inspiral and merger of neutron star binaries, black hole binaries, explosion of supernovae, and inflation in early universe. GW propagates as a transverse wave with quadrupole motion whose strain is extremely small, $dL/L<10^{-23}$, therefore direct detection of GW is very difficult and many research institutes are trying direct observation of GW by using large laser interferometers.
However, the establishment of gravitational wave (GW) astronomy was kicked off from the first direct detection of GW by Adv.LIGO team in US last year. On the other hand, in Japan, the ground-based GW detector, b-KAGRA [1], is now under operation, and space GW detection projects have been also promoted which aim at the realization of first detection in space. DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) [2] is a triangle-shaped Fabry-Perot (F.P.) Michelson laser interferometer which consists of three satellites with 1000 km separation, and is planned to be launched in 2031 (see fig.1). As DECIGO has many technological difficulties, the milestone mission named Pre-DECIGO, which is planned to be launched in 2025, has also been promoted.

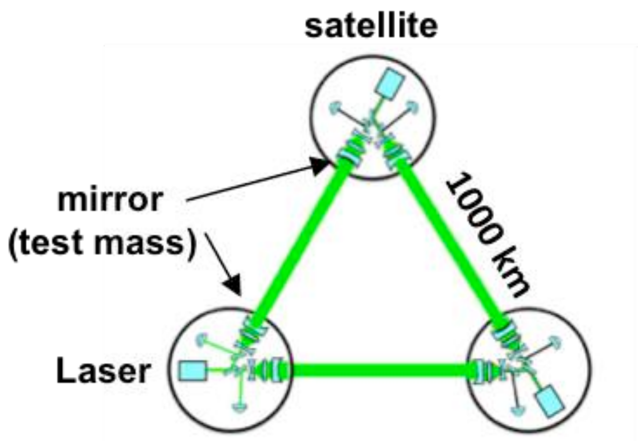

Fig.1. Preliminary design of DECIGO

In order to realize their extremely high strain sensitivity of $dL/L<10^{-23}$, we have developed frequency and intensity stabilized lasers whose frequency noise is $df<0.5$ Hz/√Hz and the intensity noise is $dI/I<10^{-8}$ /√Hz at the observation band around 1 Hz. The required values for light sources are shown in table 1.
We had started developing a prototype desktop model (DTM) for the light source of space GW detector which is based on Nd:NPRO. The detail of DTM was presented in the previous conference (ICSOS 2012) [3]. DTM is now under improvement into two breadboard models.
We have developed the breadboard model 1 (BBM1) whose light source is an Yb-doped fiber DFB laser and whose frequency is stabilized to the iodine (I_2) saturated absorption. In order to improve the short-term frequency stability around 1 Hz, we chose the I_2 absorption lines at 515 nm as the frequency reference which are narrower than those at 532 nm [4]. By using narrower I_2 saturated absorption, the short- and long-term frequency stability is expected. The frequency noise was suppressed down to 0.4 Hz/√Hz at 1 Hz evaluated from error signal [5]. In order to improve the robustness and frequency stability, our previous system has been refined, and the second BBM (BBM2) has been developed.
In the current paper, we will report the recent states of our I_2-stabilized laser for the light source of DECIGO and Pre-DECIGO.

Table 1 Requirements of the light source for DECIGO/Pre-DECIGO

project	wavelength [nm]	power [W]	frequency noise [Hz/√Hz]@1Hz	Relative intensity noise [/√Hz] @1 Hz and 200 kHz
Pre-DECIGO	515	2	1	1×10^{-8}
DECIGO	515	10	1	1×10^{-8}

II. FREQUENCY STABILIZATION

A. Experimental setup

We have developed 2 light sources, the previous one is Breadboard Model 1(BBM1), and the updated one is BBM2. The schematic of BBM1 is shown in fig.2. BBM1 consists of two parts; a light source part and a signal acquisition part. The light source is a 20-mW fiber-DFB laser (Koheras AdjusteK Y10) whose center wavelength is 1030 nm. The precision frequency control is obtained by a piezo-electric transducer (PZT) attached to the fiber, whose control bandwidth is 10 kHz, and wide tuning range is obtained by a temperature control which is more than 120 GHz (0.4 nm). The output power of the fiber-DFB laser is amplified by a handmade polarization-maintained Yb-doped fiber amplifier (YDFA) up to 200 mW. Second harmonics at 515 nm is generated by using an waveguide periodically-polled lithium niobate (WG-PPLN) crystal, and conversion efficiency of 23 % is obtained from fundamental light. An inline polarized beam splitter (PBS) divides the green light into pump and signal beams, whose polarization are s and p, respectively. The separation ratio of the green light is controlled by using an inline polarization controller (PC). The light source part of BBM1 is based on all-fiber components. Both signal and pump beams are introduced into the signal acquisition part. Two beams are passing through the 400-mm I_2 cell with Brewster windows. Both beams are collinearly counter-propagated with 5-fold configuration to obtain strong saturated absorption signal. The pump beam is phase modulated at 200 kHz by an electro-optic modulator (EOM), and the detected signal by a photo detector (PD) is demodulated at 200 kHz to obtain an offset-free frequency discrimination signal (Pound-Drever-Hall [6] and modulation transfer techniques [7]). Pressure broadening of iodine absorption line is suppressed by cooling a finger of the I_2 cell to -15 Celsius. An acousto-optic modulator (AOM) is placed at pump beam, and the 1st order diffraction is used to eliminate the interference noise. As a consequence, the frequency discrimination signal with high signal-to-noise ratio (SNR) is obtained that is used as the frequency error signal. The obtained frequency error signal is filtered into the control signal, and fed back to the frequency actuator of the laser (PZT driver) to suppress its frequency noise. The details of BBM1 were presented in the former conference (ICSO 2014) [5]
The basic configuration of BBM2 is almost the same as BBM1. The light source of BBM2 is an Yb:fiber DFB laser (The Koheras BasiK^{TM} Y10), which is an OEM module laser and more compact than that of BBM1. In BBM2, beam expander which consists of a couple of lenses is mounted in both beams to suppress the time-of-flight broadening effect.

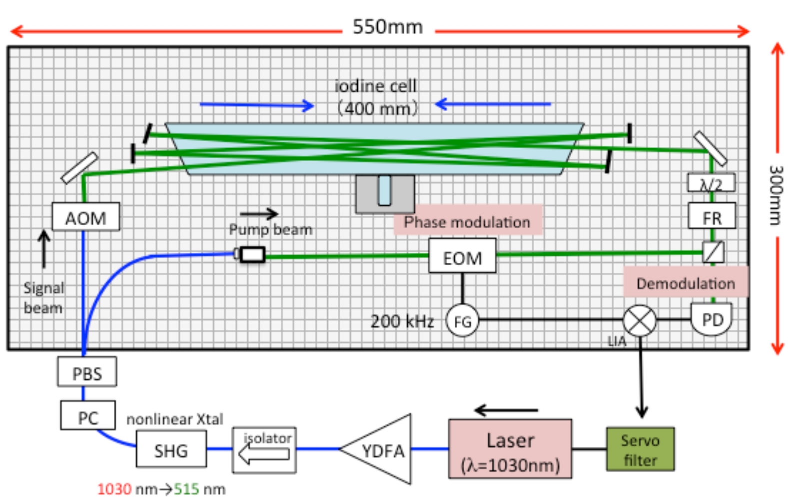

Fig.2. Schematic diagram of I_2-stabilized laser
YDFA; Yb-doped fiber amplifier, SHG; second harmonics generation

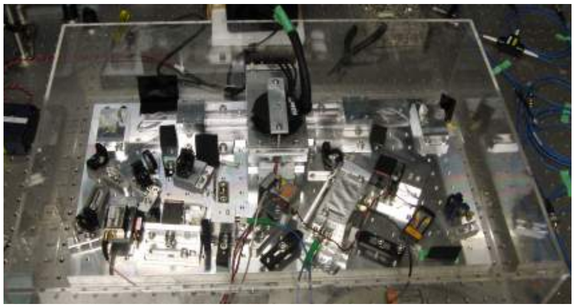

Fig.3. a signal acquisition part (BBM1)

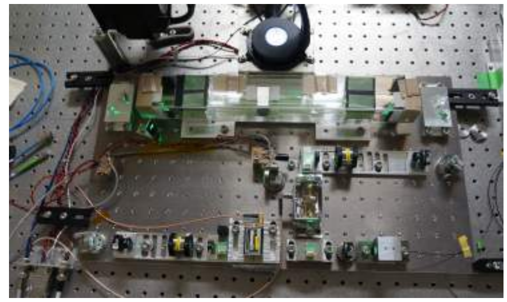

Fig.4. a signal acquisition part (BBM2)

The green light is introduced into the signal acquisition part through a fiber collimator, and in divided into signal and pump beams whose separation ratio is controlled by a half-wave plate in front of PBS. Almost all the optical components in the signal acquisition part are mounted on monolithic optical bases. Some inline components are replaced to reduce the optical power loss. The pictures of BBM1 and BBM2 are shown in fig.3 and fig.4. The signal acquisition parts of both BBMs are mounted on 35x50x2 cm aluminum breadboards.

B. Result of Frequency Stabilization

The frequency of the laser was stabilized in reference to a hyperfine component of I_2. In BBM1, the control servo bandwidth and servo gain at 1 Hz were 2 kHz and 150 dB, respectively. The frequency noise spectra evaluated from the error signal are shown in Fig.5. Red trace indicates the frequency noise of the laser at free-running state, and blue trace indicates that at stabilized state. The frequency noise was suppressed down to 0.4 Hz/√Hz below 10 Hz, which satisfies the requirement level of DECIGO and Pre-DECIGO.
In BBM2, the control servo bandwidth and servo gain at 1 Hz were 2 kHz and 120 dB, respectively. The blue trace indicates the frequency noise of the laser at stabilized state, which is shown in fig.6. The frequency noise was suppressed down to 1 Hz/√Hz under 10 Hz. Both frequency noise levels are evaluated from in-loop signal, and further precision out-of-loop evaluation is necessary.

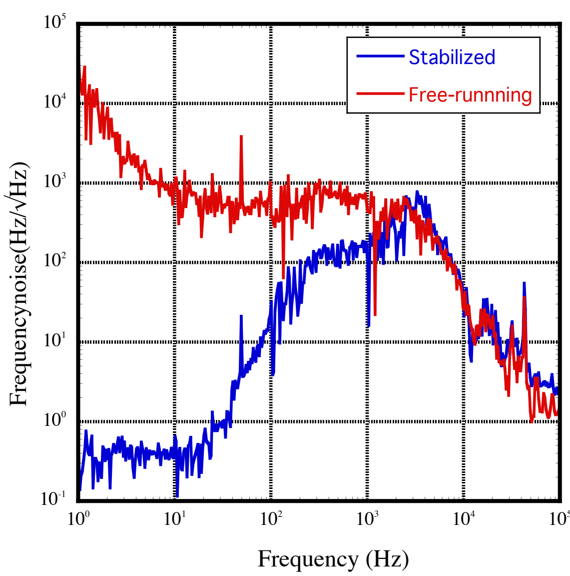

Fig.5. Frequency noise spectra of the laser (BBM1) in the free-running state (red trace) and the stabilized (blue trace)

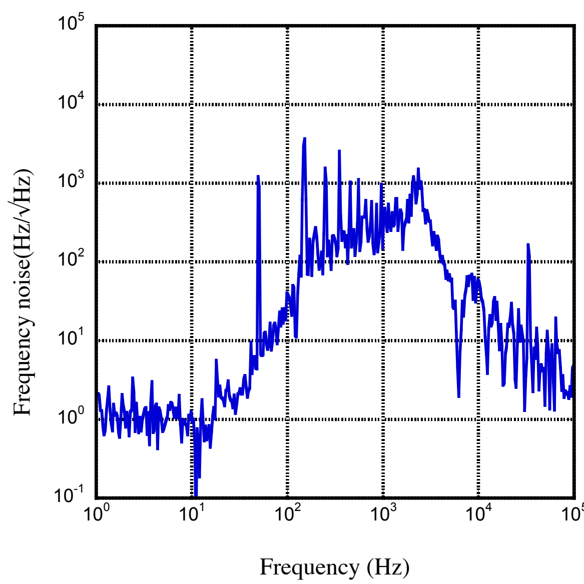

Fig.6. Frequency noise spectrum of the laser (BBM2) in the stabilized state

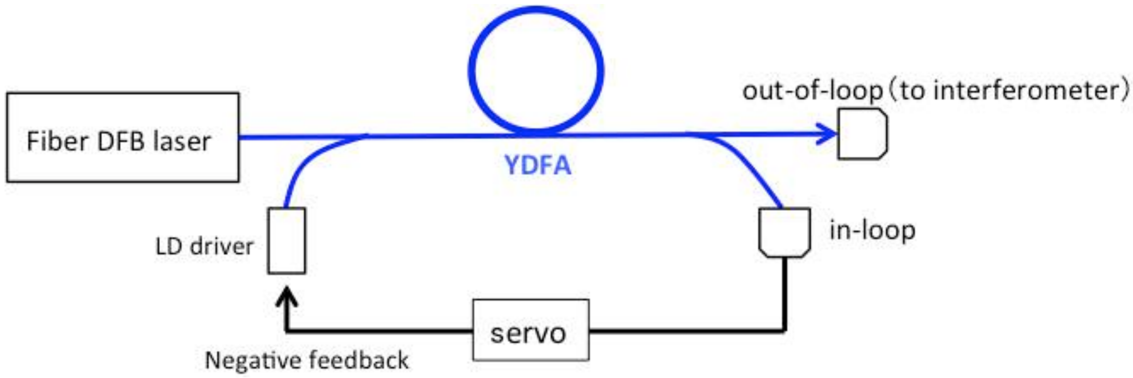

Fig.7. Schematic diagram of the intensity stabilization

III. INTENSITY STABILIZATION

A. Observation band around1 Hz

We have tried intensity stabilization of laser at observation band around 1 Hz and modulation band at 200 kHz. The required relative intensity noise (RIN) level at 1 Hz is $dI/I < 10^{-8}$ /√Hz, which comes from the designed strain sensitivity of DECIGO/Pre-DECIGO. The RIN at 200 kHz should be suppressed to the shot noise level of 10 mW ($dI/I < 10^{-8}$) which improves SNR of I_2-absorption signal, and leads to higher short-term frequency stability of the laser.

Since the light source part of BBMs consists of the fiber DFB laser and the YDFA, called MOFPA system, intensity stabilization at 1 Hz is realized by controlling the power of YDFA. Schematic diagram of intensity stabilization at 1 Hz is shown in Fig.7.

The amplified power from YDFA is divided into 2 beams; one is detected by PD (in-loop), and detected voltage signal is compared to a stable voltage reference (LINEAR TECHNONOGY Inc. LTC6655) into error signal, which is fedback to the current control of pump LD for YDFA, the other is used for the interferometer and out-of-loop evaluation of RIN. We tried two approaches of how to divide beam; by using non-polarized beam splitter (NBS) in free-space and by using fiber coupler.

Firstly, we tried to divide a portion of amplified power by using a 50:50 NBS. However, the divided ratio of the amplified power fluctuates, which comes from the coupling of polarization fluctuate of amplified power and polarization dependency of NBS. The polarization fluctuations are suppressed by inserting polarizers in front of NBS, and the polarization dependency of NBS is reduced by tilting NBS, which improves the stability of the divided ratio. We also tried to divide a portion of amplified power into 50:50 by using a 3 dB-fiber coupler. In order to suppress the additional power fluctuations caused by the mechanical vibration of fibers, the 3 dB-coupler is fixed by epoxy resin and divided beams are directly coupled 2 PDs, which is shown in fig.8. Consequently, the additional differential intensity noise between 2 ports is suppressed.

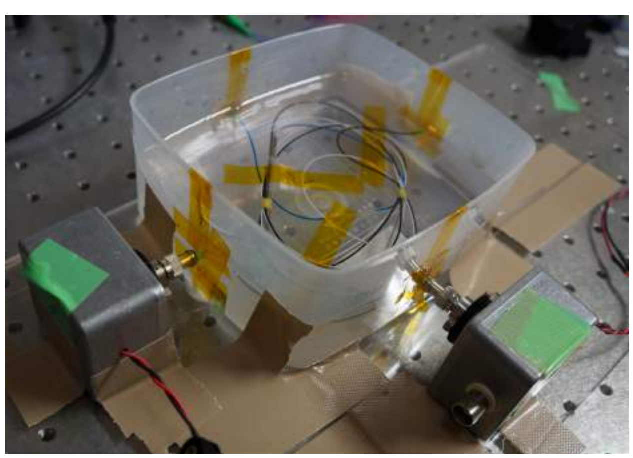

Fig.8. A fixed 3 dB-coupler by using an epoxy resin and connected PD for in-loop and out-of-loop

B. Result of Intensity Stabilization around 1 Hz

Fig.9 shows RIN spectra which were obtained from the free-space experiment. Green trace indicates intensity noise spectrum in the free-running state and black trace indicates that in the stabilized state evaluated by the error signal (in-loop). The intensity noise of in-loop was suppressed down to 10^{-8} /√Hz at 1 Hz, which is satisfies the requirement level of DECIGO and Pre-DECIGO. The out-of-loop RIN indicated by red trace was, however, worse than that of in-loop (black trace) and reaches the free-running state blow 100 Hz. Suppression of divided ratio-fluctuations improved out-of-loop RIN to 1.4×10^{-7} /√Hz at 1 Hz which is indicated by blue trace. Fig.10 shows RIN spectra which are obtained from fiber components-experiment. Black trace indicates in-loop signal (error signal), which also reached the requirement level of 10^{-8} /√Hz at 1 Hz. Red trace indicates out-of-loop signal, and fixing the fiber coupler improves the out-of-loop signal down to 1.2×10^{-7} /√Hz at 1 Hz, indicated by the blue trace.

The control servo bandwidth and servo gain of both experiments at 1 Hz were 2 kHz and 150 dB, respectively. The intensity stability of out-of-loop is limited by the stability of voltage reference. More stable voltage reference would improve the stability of out-of-loop signal.

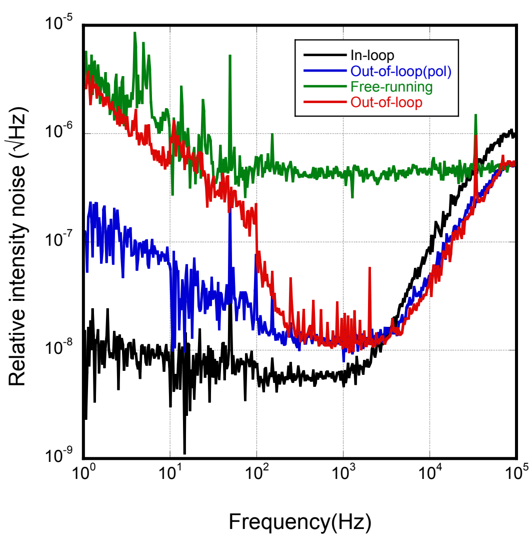

Fig.9. RIN spectra of free-space experiment. green: free-running, black: stabilized (in-loop), red: stabilized (out-of-loop), blue: stabilized (out-of-loop) whose polarization is optimized

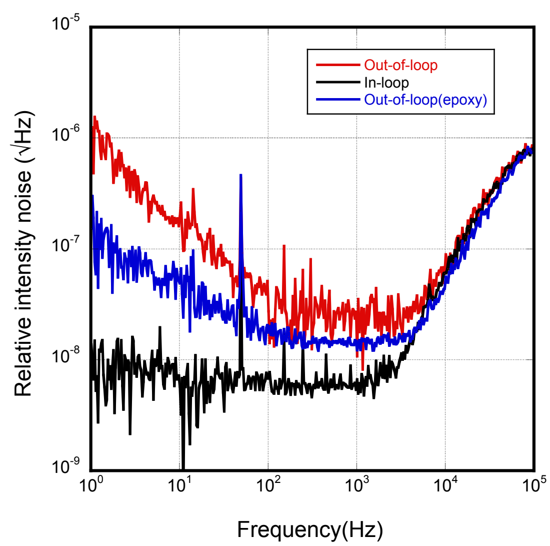

Fig.10. RIN spectra of fiber components experiment. Black: stabilized (in-loop), red: stabilized (out-of-loop), blue: stabilized (out-of-loop) whose fiber coupler is fixed

C. Intensity Stabilization at 200 kHz

The intensity stabilization at modulation band of 200 kHz is realized by controlling an acousto-optic modulator (AOM) as a power actuator. The schematic diagram of experimental setup is shown in fig.11. Signal beam is diffracted by an AOM. 1st order diffraction beam is detected by PD, and the detected signal is compared with voltage reference, and the error signal is fedback to the power of RF signal applied to AOM.

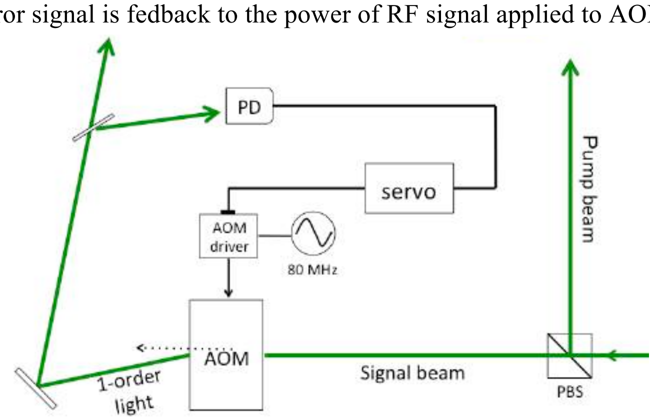

Fig.11. The experimental setup of intensity stabilization at 200 kHz. AOM: accost-optical modulator, PBS: polarized beam splitter

D. Result of Intensity Stabilization at 200 kHz

RIN evaluated from error signal is shown in fig.12. Blue trace indicates the RIN at the free-running state and green trace indicates that at the stabilized state. The control servo bandwidth and servo gain at 1 Hz were 500 kHz and 10 dB, respectively. RIN of dI/I=3x10^{-7} /√Hz was obtained at 200 kHz. In order to improve the stability, the control bandwidth of the servo should be expanded more than 1 MHz.

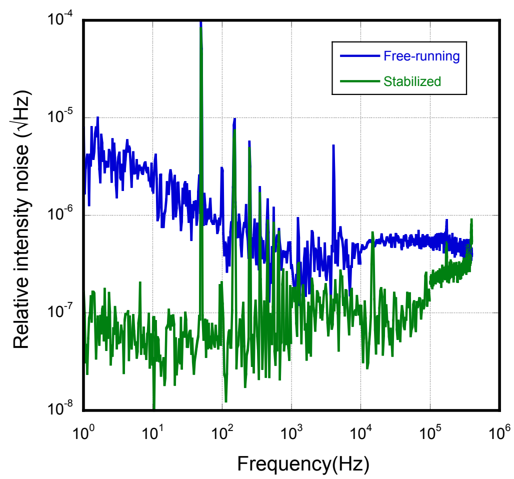

Fig.12. Relative intensity noise, which is controlled by AOM (evaluated by error signal) blue trace indicates free-running state and green trace indicates stabilized.

IV. FUTURE PROSPECTS

The absolute frequency stability should be evaluated by beat signal of 2 BBMs, and short- and long- term frequency stability should be df/f=10^{-15}(df=1 Hz). In order to improve the frequency stability at 1 Hz, we should suppress the intensity noise of the laser down to 10^{-8} /√Hz at 200 kHz, and obtain high SNR of the frequency reference.

We are also planning to obtain 10 W of green light by combination of high-power Yb-doped fiber amplifiers and coherent power combining with keeping the frequency and intensity stability of the master laser.

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