Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 2-2, Ajaccio, Corsica, France, October 9-12 (2012)

Developments of a space-borne stabilized laser for DECIGO and DPF

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***Abstract*—As a light source for the space gravitational wave detector DECIGO/DPF, we have developed space-borne frequency-stabilized lasers. The light source was an Yb-doped fiber laser with the wavelength of 1030nm. The frequency of the Yb-fiber laser was stabilized in reference to the saturated absorption of iodine molecules so as to suppress the frequency noise down to 1 Hz/rtHz at 1s. We will report the second version of breadboard model of the frequency–stabilized laser for DPF.**

Keywords-component; frequency-stabilized laser, gravitational wave detection, space-borne laser

I. INTRODUCTION

The gravitational wave (GW) is the temporal space distortion propagating as a wave, which is caused by coalescence of neutron-star or black hole binaries. Since direct observation of GW is expected to reveal new aspect of the universe, laser interferometric gravitational wave detectors have been constructed in many countries such as TAMA300, GEO500, LIGO and VIRGO [1-3]. No one, however, succeeds in direct detection of the GW signal due to its extremely high required strain sensitivity, $\delta l/l < 10^{-23}$. In Japan, two next generation gravitational wave detection projects are now promoted. KAGRA is a ground-base 3-km laser interferometric gravitational wave detector with cryogenic mirrors, which is now under constructed in the Kamioka mine in Japan [4]. The other is a space gravitational wave detector DECIGO that is planed to be launched in 2024 [5]. DECIGO consists of three satellites, each of which contains two mirrors, and are formation-flighted with 1000-km separation, forming a triangle-shape Fabry-Perot Michelson laser interferometer (See Fig.1). Compared with the ground-base GW detectors, the space GW detector has following advantages that the arm length of the interferometer can be much longer, and the mirrors are free from seismic noise. These advantages lead to higher strain sensitivity of the detector at lower frequency range. The designed signal detection frequency range of DECIGO (arm length is 1000 km) is 0.1 Hz to 10 Hz, which is between that of LISA [6], a gravitational wave detector promoted by NASA and ESA, and that of next generation ground-base GW detectors, KAGRA, adv.LIGO and advVIRGO. As DECIGO is an extremely large mission and has many technical difficulties to be overcome, two milestone missions, DECIGO path finder (DPF) and pre-DECIGO are planned before launching DECIGO. DPF is a small satellite orbiting Earth, which is planed to be launched in 2015 [7].

DPF is composed of a short Fabry-Perot optical cavity and frequency-stabilized laser, and main target of the DPF is feasibility test of the key technologies of DECIGO: drag-free control of the mirrors in Fabry-Perot cavity, and the stable-operation of the frequency-stabilized laser, both of which have never been operated in the space. In this paper, we report the developments of a highly-stabilized light source for DECIGO and DPF.

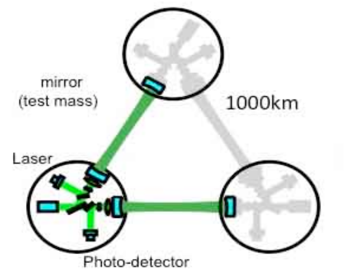

Fig.1 Configuration of the space gravitational wave detector DECIGO

II. LIGHTSOURCE FOR DECIGO

The space gravitational wave detector, DECIGO, is a Fabry-Perot Michelson laser interferometer with the arm length of 1000 km, and is designed to detects the space distortion with the strain sensitivity of higher than $\delta l/l, < 10^{-23}$ at the Fourier frequency between 0.1 Hz and 10Hz. Since the strain sensitivity of the laser interferometer is limited by the frequency noise of the light source and shot-noise, the high frequency stability and high output power are necessary for the laser. The required frequency stability is $\delta f/f < 10^{-15}$ at the observation frequency range around 1 Hz, which corresponds to the laser linewidth of narrower than 1Hz, and output power of 10W. In order to suppress the frequency noise of the laser, the laser frequency is stabilized to the optical frequency references, whose stability is essential to the frequency noise level of the laser. There are two candidates for the optical frequency reference, resonance frequency of a Fabry-Perot cavity and absorption frequency of atoms or molecules. Though the resonant frequency of the Fabry-Perot cavity shows the high frequency stability [8,9], the stability level is very sensitive to the external perturbations such as mechanical vibrations or thermal fluctuations. Therefore we choose the molecular absorption as a frequency reference that is suit to the space-borne frequency-stabilized laser. The iodine molecule (I_2) has strong absorption around 532 nm, which corresponds to the second harmonics of the Nd doped YAG laser with the wavelength of 1064 nm, and the I_2-stabilized Nd:YAG laser has long been developed as the optical frequency standards. Though the I_2-stabilized laser shows the high long-term stability, the frequency stability level around 1Hz is one order of magnitude worse than that of the required level of DECIGO/DPF. The frequency stability of the absorption line is limited by the signal to noise ratio (SNR) of the absorption signal, which is improved by choosing absorption line with narrower linewidth. The absorption line at 515 nm is narrower than that at 532 nm[10], whose wavelength is corresponds to the second harmonics of Yb doped YAG laser at 1030 nm. Therefore we have developed the I_2-stabilized Yb:YAG laser as a light source for DECIGO/DPF, which will show the better frequency stability than that of the I_2-stabilized Nd:YAG laser, and satisfy the requirement level of the DECIGO/DPF.

III. EXPERIMENTAL SETUP

As the first step, we have developed the desktop model of the iodine (I_2) stabilized Nd:YAG laser. The schematic diagram of the I_2-stabilized laser is shown in Fig.2. The light source was a continuous wave (cw) laser diode(LD)-pumped monolithic Yb:YAG laser called NPRO (Innolight Mephisto) with the wavelength of 1030nm and the output power of 100 mW. The second harmonics of the Yb:NPRO was generated by using a waveguide periodically-polled LiNbO3 crystals (WG-PPLN), and 10 mW of the second harmonics light (λ=515nm) is generated with the fundamental input power of 100 mW. The saturated absorption signal was obtained by using modulation transfer technique [11]. The 10mW of the green light is separated by using a polarization beam splitter (PBS) into signal and pump beam. After frequency shifted at 55 MHz by using an acousto-optic modulator (AOM) and phase modulated with 200 kHz by using an electro-optic modulator (EOM), the pump beam was introduced into the iodine cell. The length of the iodine cell is 400mm, and a 4-fold configuration resulted in the total interaction length of 1600 mm. The beam diameters of signal and pump beam was expanded to 1.5 mm in order to avoid time-of-flight (TOF) broadening of the absorption signal, and the finger of the iodine cell was cooled down to -10 C to decrease pressure broadening of the signal. The pump and signal beams were collinearly counter propagated in the iodine cell, and the detected signal beam by a photo detector (PD) was demodulated at 200 kHz to obtain a first derivative of the saturated absorption signal of I_2. Fig.3 shows the obtained saturated absorption signal around 515 nm. In the inset of Fig.3, the narrower saturated absorption signal of I_2 at 515nm (red trace) is compared to that at 532 nm (black trace).

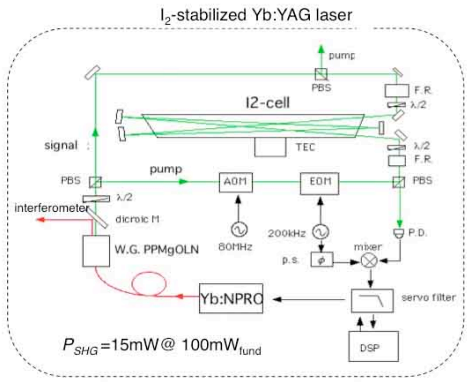

Fig.2 Schematic diagram of the I_2-tabilized Yb:YAG laser

IV. RESULTS AND DISCUSSIONS

The frequency fluctuation of the laser obtained from the first derivative of the saturated absorption signal (error signal) was filtered into the control signal by the servo circuit, and was applied to a PZT-driven frequency actuator of the Yb:NPRO to stabilize the laser frequency at the center of the saturated absorption frequency. Red trace in Fig.4 shows the frequency noise spectrum of the I_2-stabilized laser estimated by the error signal. The frequency noise was suppressed down to $2x10^{-1}$ Hz/rtHz at 1Hz. The frequency noise of the laser obtained from error signal is 'in-loop' signal that indicates the differentials between the frequency of the laser and that of the frequency reference. The frequency stability level of the I_2 absorption signal is estimated from the SNR of the signal, which is indicated by the blue trace in Fig.4. Seen from Fig.4, it is concluded that the frequency noise level of the I_2-stabilized Yb:NPRO between 1Hz and 100 Hz is dominated by that of the frequency reference (I_2 saturated absorption), which is higher than 1Hz/rtHz, and reaches the required frequency noise level of DECIGO/DPF. In the next step, the frequency noise level of the I_2-stabilized laser should be evaluated more precisely by using a CSO (cryogenic sapphire oscillator)-stabilized Ti-sapphire optical frequency comb developed by NICT whose frequency stability level reaches lower than 1Hz/rtHz around 1Hz.

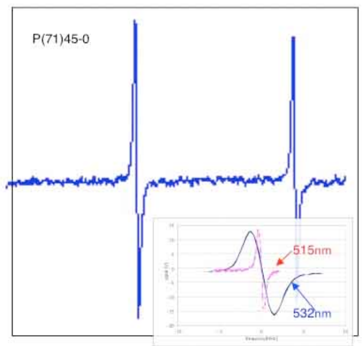

Fig.3 Saturated absorptin signal of I_2 at 515nm

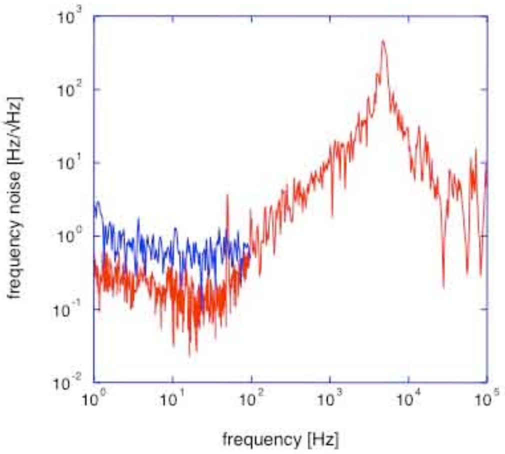

Fig.4 Frequency noise spectra of the I2-stabilized Yb:NPRO

V. BREADBOARD MODEL

After evaluating the frequency and intensity noise of the desktop model I_2-stabilized Yb:YAG laser, we have developed the breadboard model(BBM) of the I_2-stabilized laser. The schematic diagram of the BBM is shown in Fig.5. The light source was replaced with an Yb doped DFB fiber laser with the wavelength of 1030 nm. The output power of the Yb:DFB fiber laser was 10 mW, and was amplified by using an Yb fiber amplifier up to 200mW. The 20-mW of the second harmonics was generated by using a fiber-coupled ridge-waveguide PPLN crystal (NTT electronics). The green light was divided into signal and pump beam by an in-line PBS, and the pump beam was frequency shifted by using an in-line AOM, and introduced into a signal detection block. Before introducing into the signal detection block, the laser light was transmitted through the optical fibers, and the current all-fiber laser source system improves the robustness of the system. The signal detection block is assembled on the 300x550x20 [mm] aluminum plate, and most steering mirrors were fixed on the plate to improve mechanical stability (only two kinematic mirror mounts were used). The length of the I_2 cell was the same as that used in the desktop model (400mm), and 5-fold configuration expanded the interaction length up to 2000mm. The BBM of I_2-stabilized laser was automatically controlled by using one-chip microcomputer (Hitachi H8) which included lock and re-lock system. The auto lock system will be changed to FPGA based system which is suited to the spacewire system developed by JAXA.

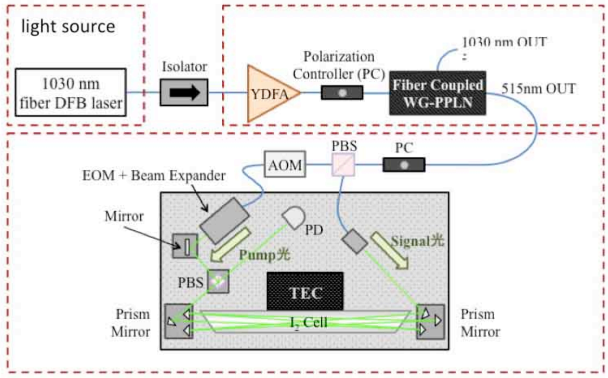

Fig.5 Configurations of breadboard model of I2-stabilized laser

VI. CONCLUSIONS

We have developed a space-borne frequency-stabilized laser for DECIGO and DPF. The frequency of the Yb:YAG laser was stabilized in reference to the saturated absorption of the iodine molecules to suppress frequency noise down to 1 Hz/rtHz, which satisfies the requirement level of DECIGO and DPF. As the next step, the breadboard model (BBM) of the frequency-stabilized laser has been developed, in which the light source was Yb doped DFB fiber laser. Compared with the desktop model, the BBM becomes compact, and the fiber based light source and semi-rigid signal detection block improved the mechanical stability and robustness.

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ACKNOWLEDGMENT

This research was supported by the Japan Aerospace Exploration Agency (JAXA), and by the Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research.

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