

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105632V · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304209

**HIGHLY FREQUENCY-STABILIZED LASER
FOR SPACE GRAVITATIONAL WAVE DETECTOR DECIGO/DPF**

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ABSTRACT

Direct detections of gravitational wave (GW) by using a long-baseline laser interferometer have been tried in many countries. In Japan, a space-GW detector named DECIGO (Deci-hertz interferometer Gravitational wave detector), and its milestone mission DPF (DECIGO pathfinder) has been promoted. We have developed a space-borne highly frequency-stabilized light source for DECIGO and DPF with high mechanical stability, long-term stable operation, high-efficiency and compactness. The frequency of an Yb doped fiber DFB laser at 1030 nm was locked to the saturated absorption signal of the iodine molecule (I_2) at 515 nm. We have developed the breadboard model 1 (BBM1) of the I_2 stabilized Yb: fiber laser, which was installed on a 550x300x20-mm aluminum plate. The frequency noise of the laser was suppressed down to $0.4 \text{ Hz/Hz}^{1/2}$ at 1 Hz which was evaluated from the frequency error signal. In the present paper, we will report the details and performance of the BBM1 of the light source for DECIGO and DPF.

I. INTRODUCTION

Gravitational wave (GW), predicted in the general theory of relativity by A.Einstein, is temporal variations of spatial distortion caused from the motion and 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, which propagates as a transverse wave with quadrupole motion. The strain generated from GW is so small, $dL/L < 10^{-23}$, that no one has detected GW before. If direct detection of GW will be achieved, the creation of gravitational-wave astronomy would be expected such as investigation of very early universe and verification of general theory of relativity. Therefore, direct detections of gravitational wave (GW) by using a long-baseline laser interferometer have been tried in many countries. In Japan, two detection projects are promoted, one is a ground-base GW detector, KAGRA [1], and the other is a space GW detector, DECIGO (Deci-hertz interferometer Gravitational wave detector) [2]. The conceptual design of both detectors is a long-baseline Fabry-Perot (F.P.) Michelson laser interferometer with a highly frequency-stabilized laser. KAGRA, which is now under construction in Kamioka mine, is a laser interferometer with 3-km baseline whose observation bandwidth is between 100 and 1kHz. DECIGO is a triangle-shaped laser interferometer consisted of three satellites with 1000-km separation whose designed strain sensitivity is 10^{-24} at the frequency bandwidth between 0.1 and 1 Hz, and is planned to be launched in 2030. Before launching DECIGO, we plan two milestone missions. The first mission is DECIGO Pathfinder named DPF [3] and the following mission is pre-DECIGO. DPF is a small satellite with the weight of 400-kg, and the mission part consists of a single drag-free Fabry-Perot cavity with two test-mass mirrors and a highly frequency-stabilized laser, which will be launched after 2019 (see Fig.1). DPF has two purposes.

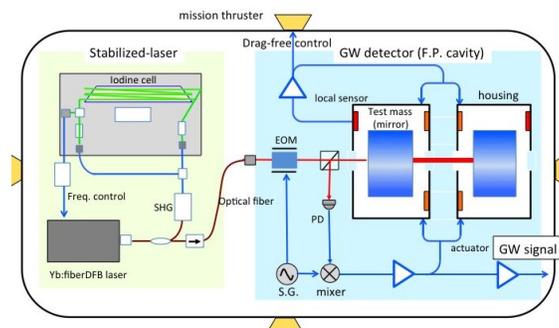


Fig.1 Conceptual design of DPF

Table 1 Requirements of the light source for DECIGO/DPF

project	wavelength [nm]	power [W]	frequency noise [Hz/ $\sqrt{\text{Hz}}$]@1Hz	intensity noise [$\sqrt{\text{Hz}}$]@1Hz
DPF	1030	0.02	0.5	1×10^{-8}
DECIGO	515	10	1	1×10^{-8}

One is a feasibility test of key technologies for DECIGO such as a space-borne frequency-stabilized laser and drag-free control of the test masses. The other is scientific target such as the observation of GW with minimum specification and the distribution of the earth's gravitational field. We have developed the frequency-stabilized light source for DECIGO and DPF, and in the present paper we explain the details and current status of our laser.

II. LIGHT SOURCE FOR DECIGO AND DPF

In order to realize its extremely high strain sensitivity, the light source for GW detector requires high frequency- and high intensity-stability, and also requires high power to suppress shot-noise-limited level. For example, 180-W output power is required for KAGRA. In addition, high-efficiency, compactness, high mechanical stability and long-term stable operation are also required as a light source for space GW detectors. The requirements of the light source for DECIGO and DPF are listed in Table 1. To obtain highly frequency stability of the laser, the choice of the frequency reference is critical. There are two kinds of frequency references. One is the absorption of molecules and the other is the resonance of a F.P. optical cavity. As an optical frequency reference, the resonance of a F.P. optical cavity has higher stability than the absorption of molecules at the frequency bandwidth around 1 Hz. The stability of F.P. cavity is, however, very sensitive to the external perturbations such as mechanical vibrations or temperature and pressure fluctuations. Therefore, we chose the iodine (I_2) absorption as our frequency references for the light source of DECIGO and DPF because the frequency stability of I_2 absorption is insensitive to the external perturbations and is more suitable for the space-borne laser.

High frequency-stability of $0.5 \text{ Hz}/\sqrt{\text{Hz}}$ at the frequency bandwidth around 1 Hz is required as a light source for DPF, which corresponds to the laser linewidth of 1 Hz. As the optical frequency standards, iodine-stabilized Nd:YAG lasers have long been studied whose second harmonics is locked to the iodine absorption at 532 nm [4], which is also used for the light source of the space GW detector in Europe (eLISA) [5].

Frequency stability level of these lasers are, however, worse than that of the requirements of DPF. Therefore, the iodine absorption at 515 nm is chosen for the light source of DPF, which is much narrower than that at 532 nm [6], and which would result in higher frequency stability of the laser. In the following section, the schematic of our highly frequency-stabilized laser is described.

III. I_2 -STABILIZED LASER

We had started developing the light source for DPF with a prototype desktop model (DTM). DTM is an I_2 -stabilized LD-pumped monolithic Yb:YAG laser called Yb:NPRO (Mephisto, InnoLight GmbH) with the wavelength of 1030 nm and the output power of 120 mW, which was presented in the previous conference (ICSO 2012) [7]. As the next step, DTM was improved into breadboard model 1 (BBM1).

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 and the wavelength turning range is 0.4 nm. The precision frequency control is obtained by a piezo-electric transducer (PZT) attached to the fiber, whose control bandwidth is 10 kHz. Compared with Yb:NPRO used in DTM, Yb: fiber DFB laser has smaller size and wide turning range without mode hopping, whose output is delivered from a single mode fiber. 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 from the amplified output by using an WG-PPLN crystal, and 47 mW of green light is obtained. Green light is separated into pump and signal beams by using an inline polarization controller (PC) and a polarized beam splitter (PBS). This light source part is based on all-fiber components, which improves robustness of the system.

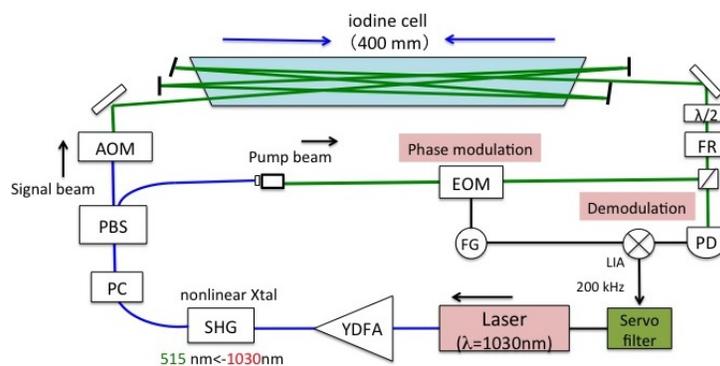


Fig.2 Schematic diagram of I₂-stabilized laser
YDFA; Yb doped fiber amplifier, SHG; second harmonics generation

Both signal and pump beams are introduced into the signal acquisition part through fiber collimators. Signal beam is passing through an I₂ cell in 5-fold configuration. The length of the I₂ cell is 400 mm and the total interaction length is 2000 mm. Signal and pump beams are collinearly counter-propagated in the I₂ cell to obtain saturated absorption signal. The pump beam is phase modulated by an electro-optic modulator (EOM) at 200 kHz, and the detected signal beam by a photo detector (PD) is demodulated at 200 kHz into offset-free frequency discrimination signal (Pound-Drever-Hall [8] and modulation transfer technique [9]). Pressure broadening effect is suppressed by cooling a finger of the I₂ cell. An acousto-optic modulator (AOM) located at pump beam eliminates interference noise. By using the differential detection method, the effect of the intensity noise of the laser on the frequency discrimination signal is decreased, and, in the consequences, the frequency discrimination signal with high signal-to-noise ratio (SNR) is obtained, which is used as the frequency error signal. Compared with DTM, the number of adjustable optical components is reduced and the height of optical axis becomes lower to 5 cm, which improves mechanical stability of BBM1. The signal acquisition part is mounted on a 35x50x2 cm aluminum breadboard. After amplified and filtered, obtained frequency error signal is fed back to the frequency actuator of the laser (PZT) to suppress its frequency noise. Auto-looking-acquisition system based on the field programmable gate array (FPGA) is applied to the system for frequency stabilization control.

IV. RESULTS AND FUTURE PROSPECTS

We found 70 linear absorption lines of I₂ in the laser tuning range of 0.4 nm, and about 20 saturated absorption lines stay in each linear absorption lines (see Fig.3). We developed a precision spectroscopy system, and linewidth, signal strength and pressure broadening effect of saturated absorption signal were investigated to determine the highest SNR signal as a frequency reference. The frequency of the laser was stabilized in reference to a hyperfine component of I₂. We preliminary selected a hyperfine component of P29 (43-0) a₁₁ as a frequency reference, and the frequency of the laser is locked to this line whose servo bandwidth and servo gain at 1Hz were 2 kHz and 150 dB, respectively. The frequency noise spectrum evaluated from error signal is shown in Fig.4. Blue trace indicates the frequency noise of the laser, and after activating the servo, the frequency noise was suppressed down to 0.4 Hz/√Hz at 1 Hz indicated by red trace, which satisfies the requirement level of DPF. Since the frequency stability level mention above was evaluated from the error signal, the absolute frequency stability should be precisely estimated. The first estimation of the absolute frequency noise was acquired from the SNR of the frequency discrimination signal, which was 10 Hz/√Hz in our previous experiments.

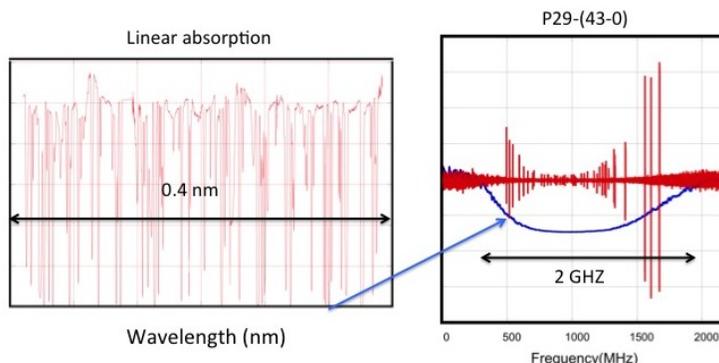


Fig.3 Linear absorption (left) and saturated absorption (right) of the iodine molecules at 515 nm

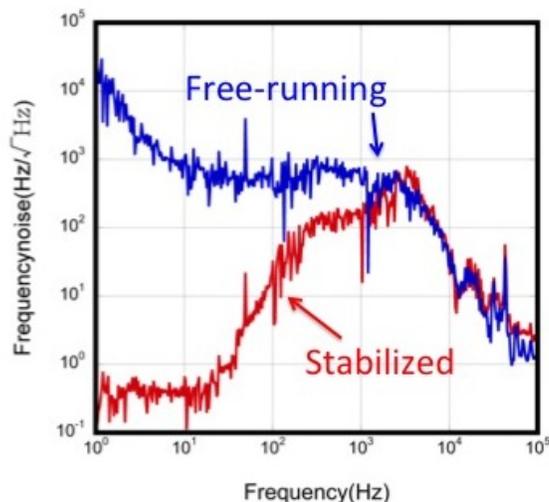


Fig.4 Frequency noise spectrum of the laser in free-running state (blue trace) and stabilized (red trace)

The frequency stability level should be improved by optimizing interaction length in the I_2 cell, pressure of I_2 and the choice of saturated absorption line. After the requirements of the light source for DPF is fully satisfied, the output power will be amplified by a high-power Yb-doped fiber amplifier to obtain 10 W of green light with keeping its frequency stability. It would be the light source for DECIGO.

The following light source (BBM2) is now underdevelopment, whose basic configuration of the signal detection is almost the same as that of BBM1. For BBM2, we plan to apply such improvements as modularization of the light source or saving of consumption power, which becomes more suitable for the space-borne laser. BBM2 will be also utilized for frequency comparison with BBM1 to evaluate the absolute frequency noise of the light sources.

ACKNOWLEDGEMENT

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

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