Stabilization of Laser Intensity and Frequency Using Optical Fiber

Kakeru Takahashi, Masaki Ando and Kimio Tsubono
Department of Physics, Faculty of Science, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
E-mail: kakeru@granite.phys.s.u-tokyo.ac.jp

Abstract. We developed a laser stabilization system composed of optical fibers. In this system all optical devices used for stabilization are connected with optical fibers. This system has advantages for space use and for low-frequency (<10 Hz) stabilization. We suppressed the intensity noise to $6 \times 10^{-7} \sqrt{\text{Hz}}$ at 1 Hz, and to $4 \times 10^{-8} \sqrt{\text{Hz}}$ at 1 kHz. We also suppressed the frequency noise to $20 \text{Hz} \sqrt{\text{Hz}}$ at 1 Hz, and to $2 \text{Hz} \sqrt{\text{Hz}}$ at 80 Hz. This system is one of the candidates for the laser stabilization system of DECIGO.

1. Introduction
Recently, the importance of laser stabilization has become higher, because many experiments use a laser for high-precision measurements. One example of such measurements is the detection of gravitational waves (GWs). In an interferometrical detector, the frequency of the laser used in the interferometer is a standard of the arm length, which is fluctuated by GWs. Since the typical amplitude of GWs is very small (a strain of about $10^{-21} \sqrt{\text{Hz}}$), we need a highly frequency-stabilized laser. We also need intensity stability, because the fluctuation of the input laser power disturbs the output of the interferometer. Large interferometric GW detectors on the Earth have arms of 300 m - 4 km long [1][2][3][4]. Their sensitivity is becoming sufficient to detect GWs of about 100 Hz - 1 kHz. The frequency of GWs depends on the timescale of motion of the source mass; in other words, the size of the mass. A small mass that has a short timescale emits high-frequency GWs. A large mass that has a long timescale emits low-frequency GWs. For example, a coalescence of a supermassive blackhole binary is one candidate of low-frequency GWs [5].

There are some problems to detect low-frequency GWs on the Earth. Though we need a larger interferometer having 1000 km, or longer arms to detect this, it is too large to build on the Earth. Moreover, in the low-frequency band (< 10 Hz), seismic noises limit the sensitivity of a GW detector. A space GW detector is one promising way to avoid these problems. Now, there are two big space GW detector projects: DECIGO [6] (Japan) and LISA [7] (NASA and ESA).

In this paper, we consider a laser-stabilization system as a candidate for the system of DECIGO. The requirement of the laser intensity and frequency stability of DECIGO is $1 \times 10^{-8} \sqrt{\text{Hz}}$ for intensity and 1 Hz/\sqrt{\text{Hz}} for frequency [8].

© 2008 IOP Publishing Ltd
Though the laser stabilization systems of large interferometers that have already started working have good performance for their detection band, they are not sufficient at the low-frequency band ($< 1$ Hz). At this band, any alignment noise caused by the vibration of optical devices or the jitter of a laser beam disturbs the stability. One way to suppress low-frequency noise is to use a highly symmetrical optical system [9]. Though this system achieved $0.1 \text{ Hz/} \sqrt{\text{Hz}}$ (at 1 Hz) stability, it is too complex for space use.

In this paper, we demonstrate a new low-frequency stabilization system. In this system, we compose all optical paths with optical fibers, and use fiber-coupled optical devices. Because this system is insensitive to alignment noise or jitter, we can compose a low-frequency laser stabilization system. Besides, the alignment-insensitivity of a fiber optical system makes the system tough for shock, which the system will suffer when a spacecraft is launched, or it bursts its thrusters. High flexibility of the position of optical devices is also an advantage of fiber optical system. This enable us to use the restricted space in a spacecraft efficiently. Thus, our system may help in a future high-precision measurements in space, like DECIGO.

Our system also has advantages for a laser source on Earth. Because it is not sensitive to an alignment error, it suppress the effect of seismic noises. Usually, the difficulty of low-frequency stabilization comes from fluctuations of optical devices, because of seismic noises. By suppressing this problem, we can stabilize a laser at the lower-frequency band. This will make a contribution for a future on-Earth low-frequency GW detector.

One very similar frequency stabilization experiment was reported in [10]. In our system, we stabilize both the frequency and the intensity. Moreover, our result of frequency stabilization is better than theirs.

2. Experimental setup

![Figure 1](image-url)  
**Figure 1.** Experimental setup. AOM, Acousto-Optic Modulator; PD, Photo Detector; IES, Intensity Error Signal; IMS, Intensity Monitor Signal; FES, Frequency Error Signal; FMS, Frequency Monitor Signal;
went into the FSM. Intensity and frequency stabilities were evaluated in each module separately. The laser source, the Acousto-Optic Modulator (AOM) and electrical circuits were put in air, and the other was put in a vacuum tank at a pressure of 10 Pa (shown in Figure 1). The laser source was a DFB fiber laser with a wavelength of 1550 nm. The laser power was 10 mW.

2.1. Intensity stabilization
In the ISM, we detect any fluctuation of the laser intensity by a photo detector (called intensity error signal) and feedback the difference between the signal and a voltage reference IC (AD587) to the AOM. An AOM is a device that changes its transmittance to compensate for any intensity fluctuation. To evaluate the resultant stability correctly, we picked up laser light from a feedback loop and detected another signal (intensity monitor signal). The stabilization band was 80 kHz, which was restricted by the phase delay of the AOM.

In our setup, the shot noise was $3.7 \times 10^{-8}/\sqrt{\text{Hz}}$. Though we did not reach the requirement of DECIGO ($1 \times 10^{-8}/\sqrt{\text{Hz}}$), it is important to ensure that we can suppress the intensity noise to the shot noise of this laser source before we use a higher-power laser.

2.2. Frequency stabilization
2.2.1. Frequency fluctuation detector We used an asymmetric Michelson interferometer (AMI) as a detector of frequency fluctuation. The length difference of two arms of the AMI was 110 m. We chose an AMI, not same other devices, like a ring cavity or a Fabry-Perot cavity, because of its simplicity, which is an important feature for space use. Though the larger asymmetry of AMI makes the detector sensitive, a too-sensitive detector needs pre-stabilization, which makes the system complex. To construct a simple and sensitive system, the 110 m asymmetricity is good for our laser source. The optical fiber used in an AMI was coiled around a metal core and packed in an aluminum case. This makes the AMI solid and insensitive to external noises.

![AMI suspension](image)

**Figure 2.** Suspension of the AMI. The AMI is suspended by double pendulum. The middle mass is made of copper surrounded by the damping mass. Each mass is suspended by a coil spring, not by wire, so as to avoid vertical vibration. Usually, these suspension used in optical system become complex and difficult to operate because alignment setting is hard. Our system does not need such effort because of fiber.

To suppress the effect of seismic noise, we suspended the AMI with a double pendulum. Each mass was suspended with a coil spring to suppress any vertical seismic noise, not only the
horizontal one. This suspension has resonances at about 1 Hz. To damp this resonance, we used eddy-current damping. The whole suspension was about 50 cm height, 15 cm × 15 cm dimension. The spring suspension, not wire suspension, makes the suspension tough for shock or vibration, and easy to handle.

2.2.2. The FSM We picked up laser light and detected frequency fluctuation with an AMI. The signal from the AMI (frequency error signal) was fed back to the laser’s PZT frequency control system. This PZT has a resonance at 22.64 kHz, which restricts the band of stabilization. We set the control band to 3.2 kHz in this experiment.

To suppress acoustic noise, we put the suspension in a vacuum tank at a pressure of 10 Pa. Some other devices, including devices for intensity stabilization, were put in the same chamber (shown in Figure 1).

To evaluate the resultant stability correctly, we picked up laser light from a feedback loop and detected another signal (frequency monitor signal). Although the AMI for frequency monitor signal has almost the same structure as that for the frequency error signal, we coiled a part of 110 m fiber of AMI for a frequency monitor signal around a cylindrical PZT to lock the AMI at the operating point.

3. Result and discussion

3.1. Intensity stabilization

![Figure 3](image-url)

**Figure 3.** Intensity noise spectrum. (a) Free-run noise. (b) (solid curve) Stabilized noise (intensity monitor signal). (c) Shot noise. (d) $6 \times 10^{-7} f^{-1/2}/\sqrt{\text{Hz}}$. (e) (dashed curve) Root sum square of (c) and (d).

Figure 3 shows the result of intensity stabilization. The stability at 1 Hz was $6 \times 10^{-7}/\sqrt{\text{Hz}}$. We could stabilize the laser intensity noise by 20 dB.
In our setup, the shot noise limit was $3.7 \times 10^{-8}/\sqrt{\text{Hz}}$. Though the stabilized noise (line (b)) was close to the shot noise at 1 kHz, it was noisier at lower frequency. It is well fitted by the summation of shot noise and $6 \times 10^{-7} f^{-1/2}/\sqrt{\text{Hz}}$ noise.

The source of $6 \times 10^{-7} f^{-1/2}/\sqrt{\text{Hz}}$ noise has not yet been identified. One possibility for the source of this noise is the AOM driver. Though the shape of line (d) seems to be electric noise of the control circuits, the noise of all circuits used in intensity stabilization loop, except for AOM driver, is 1/20 smaller than line (d). Moreover, this noise level did not change with the input laser power. This is one feature of intensity noise from transmittance fluctuation.

### 3.2. Frequency stabilization

![Figure 4](image-url)

Figure 4. Frequency noise spectrum. (a): Free-run noise. (b): Stabilized noise (frequency monitor signal ). (c): Expected stabilized noise calculated from free-run noise and feedback transfer function.

Figure 4 shows the result of frequency stabilization. The stability at 1 Hz was $20 \text{ Hz}/\sqrt{\text{Hz}}$, covered with resonance of suspension. We stabilized the laser frequency noise by 40 dB. The best stability was $2 \text{ Hz}/\sqrt{\text{Hz}}$ at 80 Hz.

The effect of shot noise was $2.1 \times 10^{-2} \text{ Hz}/\sqrt{\text{Hz}}$. The effect of thermal noise of the fiber, calculated from pessimistic parameters, was about $10^{-4} \text{ Hz}/\sqrt{\text{Hz}} [11]$.

At the higher frequency band than 100 Hz, the stabilized noise fits to the expected noise (line (c); calculated from free-run noise and feedback transfer function). At a band lower than 100 Hz, the stabilized noise was worse than expected. Peaks around 1 Hz - 2 Hz, 3.6 Hz and 9 Hz - 10 Hz came from resonance of suspension. This means that our frequency-stabilization system is never free from mechanical vibration. Thus, at a lower frequency band than the suspension’s resonant frequency, we can not avoid seismic noise. To achieve DECIGO’s requirement, we need better suspension, or to make the system more tough against vibration.
4. Conclusion
In this experiment, we developed a laser-stabilization system composed of optical fibers. We suppressed noises of the laser source to $6 \times 10^{-7} \sqrt{\text{Hz}}$ for intensity and $20 \text{Hz}/\sqrt{\text{Hz}}$ for frequency at 1 Hz. The best stability was $4 \times 10^{-8} \sqrt{\text{Hz}}$ at 1 kHz for intensity and $2 \text{Hz}/\sqrt{\text{Hz}}$ at 80 Hz for frequency.

It looks like the main noise source was the AOM driver for intensity and the resonance of suspension for frequency. The seismic noise will be the next main noise for frequency.

Since the optical system with optical fiber has some advantages that do not depend on the frequency band, we can say that this method can be a new stabilizing tool. The requirement of frequency stabilization of LISA is $30 \text{Hz}/\sqrt{\text{Hz}}$ at $10^{-3} \text{Hz} - 1 \text{Hz}$ [12]. Though the stability of our system becomes bad in the lower-frequency band, considering that the noise of the lower frequency band is usually caused by a seismic noise, our method is a promising stabilizing method for space use.

References
[1] Ando M et. al. 2001 Phys. Rev. Lett. 86 3950
[2] Willke B et. al. 2002 Class. Quant. Grav. 19 1377
[3] Acernese F et. al. 2002 Class. Quant. Grav. 19 1421
[4] Abbott B et. al. 2004 Nucl. inst. and meth. A 517 154
[5] Haehnelt M G 1994 Mon. Not. R. Astron. Soc. 269 199
[6] Seto N, Kawamura S and Nakamura T et. al. 2001 Phys. Rev. Lett. 87 221103
[7] Meshkov S 2000 Gravitational Waves Proc. of the 3rd E. Amaldi Conference(New York: AIP Conf. Proc.) p 523
[8] Kawamura S et. al. 2006 Class. Quantum Grav. 23 S125
[9] Ludlow A D, Huang H, Notcutt M, Zanon-Willette T, Foreman S M, Boyd M M, Blatt S and Ye J 2007 Opt. Lett. 32 641
[10] Cliche J F, Allard M and Têtu M 2006 Proc. of SPIE 6216 62160C
[11] Kräkenes K and Bløtekjær K 1995 J. of Light. Tech 13 682
[12] The LISA Study Team 1998 Laser Interferometer Space Antenna for the Detection and Observation of Gravitational Waves: Pre-Phase A Report 2nd edn (MPQ233) Max-Plank-Institut für Quantenoptik