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LINEWIDTH NARROWING OF A DFB DIODE LASER USING A FIBER MACH-ZEHNDER INTERFEROMETER

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Abstract: The linewidth reduction from 3 MHz to 15 kHz was achieved with an 1156 nm DFB diode laser in a simple setup using an all-fiber Mach-Zehnder interferometer (MZI) with 5-m-long path imbalance. This result was achieved with no acoustic and vibration isolations. In addition, this result can be applied to any wavelength due to the commercial availability of DFB diode lasers and fiber-optic components in a wide wavelength range. The frequency lock was so robust that it could be maintained over weeks. Since a short fiber patch cord was adopted, optical power loss during the fiber transmission and bandwidth limitation due to the fiber delay were negligible.

Keywords: Linewidth, DFB diode laser, Fiber interferometer, Path imbalance.

1. INTRODUCTION

Narrow linewidth lasers are essential tools for numerous applications, including high-resolution spectroscopy, high-precision interferometric measurements, coherent optical communications systems, and local oscillators for atomic clocks. Although the linewidth of lasers can be reduced to 1 Hz level, limited by the thermal noise of an ultra-stable optical cavity using the Pound-Drever-Hall (PDH) method, other experimental methods have also been developed with their respective advantages. For example, the linewidth of lasers can be narrowed to kHz level through optical feedback from an off-axis confocal cavity or from a single-mode fiber resonator. The electrical feedback methods have also been developed, converting the frequency fluctuation of lasers into intensity variations by a frequency discriminator, such as a narrow optical filter and a fiber interferometer. Although the method using a fiber interferometer cannot compete with the PDH method in terms of ultimate performance, it can serve as a reliable, simple, compact, and cheap alternative for short-term linewidth reduction. By using an optical fiber as a delay line, large path imbalance becomes possible and experimental setup is insensitive to alignment errors. The history of the linewidth reduction using a fiber interferometer has been summarized in [1].

In this paper, we present the result of linewidth reduction of a DFB diode laser using an all-fiber interferometer with short path imbalance reducing the linewidth from 3 MHz to 15 kHz. No acoustic and vibration isolations were applied to maximize the simplicity and practicality of this technique. DFB diode lasers have many experimental advantages; they have wide mode-hop-free frequency tuning range up to more than 1000 GHz, and they are available at almost any wavelength between 760 nm and 2800 nm with output power up to 150 mW. Considering that all the fiber-optic components used in our experiment are easily available and off-the-shelf at any wavelength, this technique can be widely applicable.

2. THEORETICAL BACKGROUND

The laser frequency stabilization using a fiber interferometer can be interpreted as a self-stabilization by use of the laser's past output as a reference. We assume the electric fields of the radiation in two arms of the interferometer to be $E_1 = E_0 \exp[i2\pi\nu t]$ and $E_2 = E_0 \exp[i2\pi\nu(t+\tau)]$, where ν is the optical frequency and $\tau = nL/c_0$ is the time delay between the two arms, where n is the refractive index of the optical fiber, L is the length imbalance, and c_0 is the speed of light in vacuum. After these two beams are combined, provided the polarizations of the beams are kept, the intensity detected by a photodetector can be given as follows:

$$I \propto \left|E_1 + E_2\right|^2 \propto 1 + \cos[2\pi\nu\tau]. \tag{1}$$

Using this signal as a frequency discriminator, the laser frequency can be stabilized at the quadrature condition ($I/2$) to a discrete set of frequency values of

$$\nu_k = \left(k + \frac{1}{4}\right)\frac{c_0}{nL}, \tag{2}$$

where k is an integer. The frequency spacing between the stabilized frequencies is c_0/nL. When a 5-m-long fiber is used, as is in our experiment, this frequency spacing is about 40 MHz, which is inversely proportional to the optical path imbalance. The slope of the frequency discriminator at the quadrature point is given by

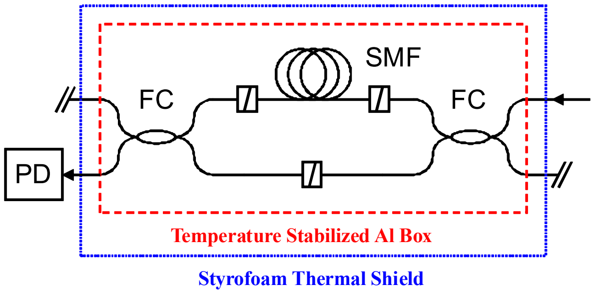

Fig. 1. Experimental setup for the all-fiber Mach-Zehnder interferometer with short arm imbalance. FC; 2x2 fiber coupler, SMF; 5-m-long single mode fiber, PD; photodiode.

$$\left.\frac{dI}{d\nu}\right|_{\nu=\nu_k} \propto \frac{2\pi nL}{c_0}. \qquad (3)$$

As the frequency discrimination slope is proportional to the optical path imbalance, a sharp discrimination slope can be obtained using a long fiber delay. However, the choice of the fiber delay line length is trade-off between the sharp frequency discrimination signal and optical power loss during the fiber transmission. The feedback control bandwidth limit by the fiber delay should also be considered in choosing the fiber length. It is noted that the relative fluctuation of the stabilized frequency ($\delta\nu/\nu$) is linearly proportional to the relative fluctuation of the optical path length ($\delta(nL)/nL$) of the fiber interferometer. Thus, the drift of the frequency of the stabilized laser is dependent on the environmental temperature variation irrespective of the fiber length.

3. EXPERIMENTAL SETUP

The linewidth of a DFB diode laser was reduced using a fiber MZI. The emission wavelength of this laser was around 1156 nm with the maximum output power of 10 mW. An optical isolator with the isolation of more than 30 dB was used to prevent optical feedback to the DFB diode laser. An anamorphic prism pair was inserted after ISO adjusting the laser beam aspect ratio to enhance the fiber coupling efficiency. The laser beam was focused into a single-mode fiber using a fiber collimation lens.

The main component of the setup is the all-fiber MZI, which is shown in Fig. 1. The MZI consists of two single-mode 2×2 fiber couplers (FCs) and a 5-m-long single-mode fiber patch cord for the interferometer path imbalance. All the fiber components were connectorized on all ends with angled physical contact type (FC/APC) connectors to prevent back-reflections. The MZI part of the experimental setup was placed into a compact aluminium box. This aluminium box has a dimension of $90\times150\times25$ mm^3 with the wall thickness of 4 mm. The temperature of this box was stabilized using a thermo-electric cooler (TEC) at 25℃. A Styrofoam box surrounded the aluminium box as a thermal shield for better temperature stability. The interference signal was detected by an InGaAs photodiode (PD) with the bandwidth of 50 MHz. The peak-to-peak voltage difference

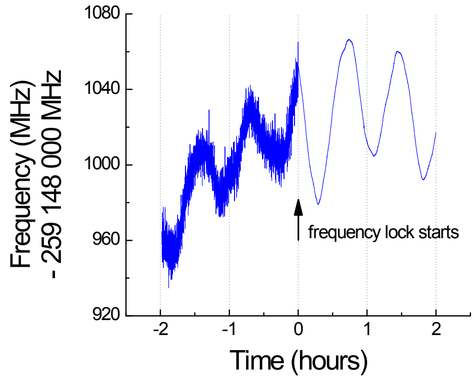

Fig. 2. Frequency of DFB diode laser before and after the frequency stabilization started at time of 0 hour, which was measured by a high resolution wavelength meter.

of the interference signal at PD was about 100 mV with visibility of interference near unity, when the optical power in both arms of the MZI was about 5 μW. The sum of the output signal of PD and the appropriate dc offset voltage was used as an error signal for a high-bandwidth feedback to the current of the DFB diode laser based on a proportional-integral-derivative (PID) controller to lock the laser frequency to the MZI quadrature point.

4. RESULTS AND DISCUSSION

The laser frequency variations before and after the stabilization, measured by a high-resolution wavelength meter with the sampling time of about 1 s, are shown in Fig. 2. The frequency stabilization started at time of 0 hour in Fig. 2. As can be clearly seen in Fig. 2, the short-term frequency fluctuation was suppressed significantly with the stabilization on, indicating the linewidth of the laser was substantially reduced. The long-term frequency drift is attributed to the room temperature variation due to the imperfect thermal shield. From the peak-to-peak frequency fluctuation of the stabilized laser in Fig. 2 (about 100 MHz) and the typical dependence of the optical path length of optical fiber on temperature (1×10-5/K) [15], the effective long-term temperature stability of the MZI setup can be estimated to be about 40 mK. The frequency instability in terms of Allan deviation can be calculated using the data in Fig. 2. The Allan deviation at 1 s was reduced from 9×10^{-9} to 2×10^{-10} by a factor of 45 after the frequency stabilization.

Fig. 3 shows the frequency noise power spectral density versus Fourier frequency of the free-running DFB diode laser (open circles), the stabilized DFB diode laser (out-of-loop, black line). These were obtained by measuring the power spectrum of the PD signal after the MZI with a fast Fourier transform spectrum analyzer, and were converted to the frequency noise spectrum by using the measured discrimination slope of 190 MHz/V. The frequency noise of the free-running DFB diode laser approximately shows a 1/f frequency noise behaviour. The out-of-loop frequency noise power spectral density was obtained using another independent temperature-stabilized fiber MZI with the same path imbalance (5 m) as a frequency discriminator. When

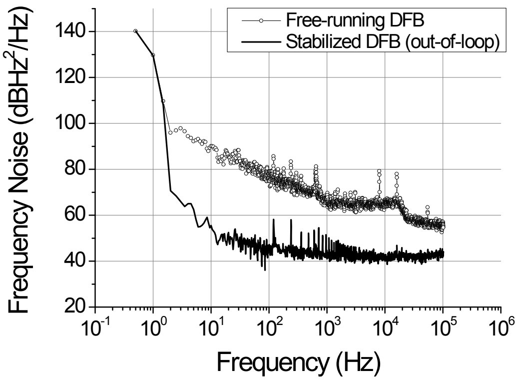

Fig. 3. Frequency noise power spectral density versus Fourier frequency of the free-running DFB diode laser (open circles), the stabilized DFB diode laser (out-of-loop with black line).

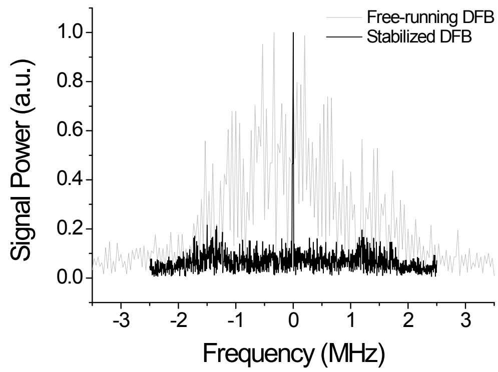

Fig. 4. The beat note between the DFB diode laser and the ECDL stabilized by an optical cavity when the DFB diode laser is free-running (gray line) and stabilized by a fiber MZI (black line).

we stabilized the laser frequency by the fiber interferometer, the frequency noise was reduced by about 40 dB at lower frequencies. The out-of-loop white frequency noise level of the stabilized DFB diode laser was approximately $S(f) = 41\, dBHz^2 / Hz$, from which the reduced linewidth can be estimated to be $\pi S(f)/\sqrt{2} = 28\, kHz$.

The actual linewidth was also measured using a heterodyne beat with another frequency-stabilized laser. Fig. 4 shows the beat note between the DFB diode laser and an ECDL stabilized by an optical cavity. The resolution bandwidth of the spectrum analyzer was 10 kHz and the sweep time was 60 ms. The stabilized ECDL was previously known to have the linewidth of about 1.6 kHz. When the DFB diode laser was free-running (gray line), its linewidth was about 3 MHz at the full width at half maximum (FWHM). When the frequency of the DFB diode laser was stabilized by a fiber MZI (black line), its linewidth at FWHM was reduced to 15 kHz, which is consistent with the result estimated from the frequency noise power spectrum (28 kHz). We can see a servo bump around 1.2 MHz, which represents the feedback control bandwidth. This was not limited by the fiber delay time, which is 25 ns for a 5-m-long fiber patch cord.

Finally, the long-term frequency measurement of the DFB diode laser stabilized by a fiber MZI was investigated. This was measured by a high-resolution wavelength meter for more than 40 hours. A diurnal change of the frequency of the stabilized laser can be seen, which is attributed to the variation of the room temperature and the imperfect thermal shield. The frequency drift was less than 30 MHz when the room temperature is relatively stable (daytime) and not more than 100 MHz even when the room temperature variation is relatively large (nighttime). It should be noted that the frequency lock was very robust so that it could be maintained for more than several weeks.

The frequency lock using a fiber interferometer can be a simple alternative to the high finesse optical cavity as optical fiber is relatively immune to an abrupt air pressure change. Furthermore, it has many advantages in that it is simple, compact, and cheap and the frequency lock is more robust. We expect that this technique can be utilized in many applications, where high degree of coherence is necessary, including long baseline interferometers such as gravitational wave detectors, formation-flying satellites, length-stabilized fiber distribution systems, fiber sensors such as hydrophonic or seismic detector arrays, distributed temperature and pressure sensors, or structural monitoring.

5. REFERENCES

[1] W.-K. Lee, C. Y. Park, J. Mun, and D.-H. Yu, "Linewidth reduction of a distributed-feedback diode laser using an all-fiber interferometer with short path imbalance", Review of Scientific Instruments, vol. 82, no. 7, pp. 073105, July 2011.