Evaluation of Fiber Noise Induced in Ultrastable Environments

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***Abstract*— Phase noise induced by environmental disturbance was greatly reduced when the optical fiber was installed in an ultrastable environment. In this paper, the optical fiber length was 10 m, and the reduction in the phase noise power spectral density was approximately 70 and 30 dB at Fourier frequencies of 10 mHz and 10 Hz, respectively. To evaluate faint fiber noise, we developed a modified Mach–Zehnder heterodyne interferometer with reduced optical path length fluctuation. The Allan deviation calculated from the phase noise was 7×10^{-20} at a 1-s averaging time and reached 2×10^{-21} at a 10 000-s averaging time (measurement bandwidth: 500 Hz). In addition, we revealed the frequency bands in which fiber noise is reduced by selectively removing the environmental stabilization measures of evacuation, vibration isolation, acoustic shielding, and temperature stabilization from an ultrastable environment.**

***Index Terms*— Environmental factors, frequency stability, laser interferometer, laser noise, metrology, noise cancelation, noise measurement, optical fiber interference, phase measurement, phase noise.**

I. Introduction

In recent years, the frequency uncertainty of optical clocks has been greatly reduced [1]–[3]. One of the factors limiting the uncertainty is the frequency fluctuation of the laser used to observe clock transitions (clock laser); its improvements have been successively reported [4]–[8]. The use of a cesium-based time scale as a reference in a frequency measurement has already become insufficient for evaluating such a highly precise frequency, and frequency ratio measurement between optical clocks [9] has become important.

To meet this requirement, transfer of frequency stability, spectral linewidth, and purity using a fiber-based frequency comb (fiber comb) has been attracting attention [2], [10]–[13]. This technique can precisely compare optical frequencies in different wavelengths and can significantly suppress the influence of the frequency fluctuation of the clock laser on the frequency ratio [2].

In such precise frequency comparisons, "fiber noise" occurs in the transmission lines of the fiber comb and often limits the frequency precision [14]. Fiber noise is a phase noise induced in the signal light of a laser passing through an optical fiber. The noise is induced by environmental disturbance along the optical path length. In particular, the fiber noise strongly affects the frequency precision of a fiber comb with a multibranch configuration (multibranch fiber comb) since the fiber paths in the respective branches suffer different fiber noises [15]. Thus, a single-branch configuration has been proposed to avoid the fiber-noise difference [12], [16]–[18].

However, we believe that multibranch fiber combs still have various advantages including spectral tailoring of a nonlinearly broadened spectrum and a high signal-to-noise ratio of the beat note with a continuous-wave (CW) laser output. Recently, we proposed and demonstrated a method to actively cancel the interbranch phase noise difference of a multibranch comb and improve the relative frequency precision of a multibranch fiber comb [19].

In this paper, we demonstrate a simple fiber noise reduction technique with the aim of improving the frequency precision of the multibranch fiber comb. Specifically, we stabilized the environment surrounding the optical fiber and investigated the extent to which a highly stabilized environment reduces fiber noise. We investigated the frequency band of fiber noise induced by certain environmental factors by selectively removing the environment stabilization measures. Furthermore, we designed and constructed a modified Mach–Zehnder heterodyne interferometer for the precise measurement of such faint fiber noise.

II. Interferometer for Faint Fiber Noise Measurement

This section describes an interferometer for detecting fiber noise with high sensitivity. In [21] and [22], a highly stable environment was introduced to realize a frequency reference with low-frequency instability using a fiber delay line interferometer [20], [21]. In contrast, in this paper, we investigate the relative phase noise and frequency stability of optical fiber in highly stable environments. Fig. 1 shows a diagram of an interferometer for the detection and measurement of fiber noise induced in a fiber under test (FUT). The detection is based on a self-heterodyne technique with a Mach–Zehnder interferometer. One arm of the interferometer has an

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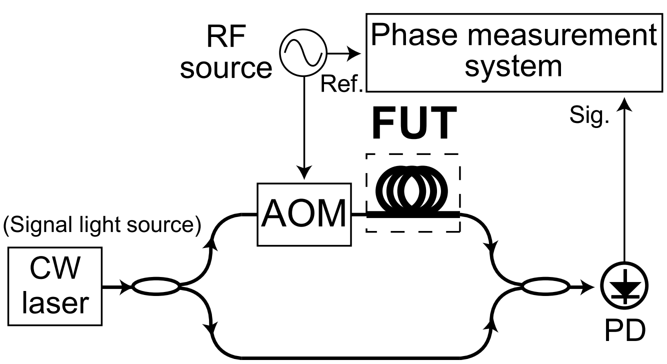

Fig. 1. Diagram of a Mach–Zehnder-type self-heterodyne interferometer for measuring fiber noise induced in an FUT. FUT: fiber under test; AOM: acousto-optic modulator; and PD: photodetector.

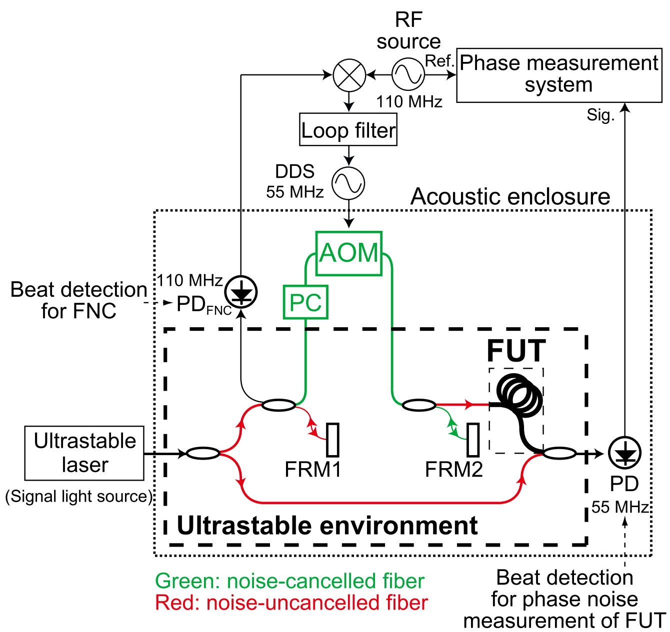

Fig. 2. Experimental setup for a modified Mach–Zehnder interferometer for the highly sensitive measurement of fiber noise accumulated in an FUT. PC: polarization controller; FRM: Faraday rotator mirror; PD: photodetector; DDS: direct digital synthesizer; and FNC: fiber noise cancelation.

acousto-optic modulator (AOM) and an FUT. The AOM shifts the CW laser frequency for heterodyne detection. In this paper, we set the length of the FUT at 10 m, which is comparable to the length of one of the branches in a multibranch fiber comb. We used a phase measurement system to measure the fiber noise from a self-heterodyne signal detected by a photodetector (PD).

To selectively measure the faint fiber noise accumulated in an FUT in a stable environment, the fiber noise induced in the fibers composing the interferometer should be suppressed. In addition, heat from the AOM generated from an intense radio frequency driving signal disturbs the interferometer environment and neighboring fiber temperature.

To achieve highly sensitive measurement, we designed and constructed the interferometer shown in Fig. 2 [22]. We incorporated two techniques in the setup to selectively detect the fiber noise accumulated in an FUT while suppressing the fiber noise in the fibers composing the interferometer.

First, we placed an AOM outside the ultrastable environment. This makes it possible to avoid the heat release from the AOM that disturbs the neighboring fiber, the FUT, and the ultrastable environment itself. The fiber noise accumulated in the fiber path, which is shown by the green line in Fig. 2, was canceled by using a fiber noise cancelation (FNC) technique [14]. An error signal was demodulated by a mixer from a heterodyne beat detected at PD_{FNC}. The AOM was driven through a loop filter and a direct digital synthesizer (DDS). The AOM was used not only as a frequency shifter but also as an FNC actuator. The fiber path length for FNC is about 10 m, which is short enough to obtain sufficient FNC servo bandwidth and gain.

Second, we suppressed the fiber noise caused in the fiber composing the interferometer except for the FNC path [23], [24] by adjusting the fiber length difference between the two arms. We cannot distinguish the fiber noise induced in a path shown as a red line and the FUT from the detected phase noise signal. The fiber length adjustment can cancel out the fiber noise in a low-frequency region between the two arms [25]. By appropriately adjusting the fiber length shown by the red line in Fig. 4, we can selectively measure the fiber noise accumulated in the FUT.

To detect faint phase noise accumulated in the FUT, the frequency noise of the light source should be minimized. We used a 1535-nm ultrastable laser locked to the resonance of an ultralow expansion (ULE) glass cavity as the source; the configuration is similar to that described in [26]. Although the frequency noise of the laser is largely canceled out at the detection stage, residual noise is included in the measured phase noise. This is explained in Section III-B. The frequency noise of the ultrastable laser is currently in the lowest class and can minimize the laser noise to influence the phase noise measurement.

III. Ultrastable Environment

To prevent fiber noise from being induced in the interferometer and FUT, we placed them in an aluminum chamber. We employed the following six environment stabilization measures to realize an ultrastable environment inside the chamber.

1) *Hermetic Sealing:* We closed the valve of the vacuum chamber and blocked any air exchange with the outside air. The chamber and flange were sealed with O-rings. We used a hermetic feed-through attached to the flange to introduce an optical fiber into the chamber.
2) *Evacuation*: We evacuated the gas in the chamber with a turbomolecular pump. The pressure was pumped down to several Pascals. We stopped the pump before the measurement to avoid vibration and other noise. We were able to keep the pressure below 500 Pa for several days although it rose gradually once we stopped the pump. The 500 Pa is less than 1/100 the atmospheric pressure. We assume it to be sufficient for suppressing fiber noise.
3) *External Temperature Control:* We controlled the temperature of the outside surfaces of the aluminum chamber. A platinum resistance thermometer was fixed to the outer surface of the chamber lid as a temperature sensor. We attached large film-type heaters to the outside plane

TABLE I
COMBINATIONS OF ENVIRONMENT-STABILIZATION MEASURES DEMONSTRATED IN THIS PAPER

Measures→ / ↓Name of condition	Hermetic sealing	Evacuation	External temperature control	Internal temperature control	Acoustic shielding	Vibration isolation
(A) Ultrastable environment	✓	✓	✓	✓	✓	✓
(B) Vibration isolation removed	✓	✓	✓	✓	✓	
(C) Acoustic shielding removed	✓	✓	✓	✓		✓
(D) External temperature control removed	✓	✓	✓		✓	✓
(E) Both temperature controls removed	✓	✓			✓	✓
(F) Evacuation removed	✓		✓	✓	✓	✓
(G) Laboratory environment						

of the chamber to uniformly control the temperature of the entire chamber. We used a commercial temperature controller to control the temperature. We set the temperature slightly higher than the room temperature since we control the temperature solely by heating. As a result, the temperature fluctuation, measured with a platinum resistance thermometer in a control loop, was suppressed to within 10 mK.

4) *Internal Temperature Control:* We controlled the temperature of the copper box inside the chamber. The internal temperature can be more precisely stabilized by controlling the temperature of the inner copper box in addition to the use of external temperature control [26]. A thermistor was attached to the upper surface of the copper box as a temperature sensor and was used as one resistance of a Wheatstone bridge. This configuration produces highly precise temperature controllability. We applied an ac voltage across opposite corners of the Wheatstone bridge. A lock-in amplifier measured the voltage across the other two corners of the bridge, and its output was used as an error signal. Using the error signal, we fed back the output current via a loop filter to a heater attached across the entire surface of the copper box. The setting temperature was 25 °C, which was slightly higher than the external temperature control, since the temperature was controlled only by heating. We assume that the internal temperature was controlled to within a few mK based on fiber noise measurements as mentioned later.
5) *Acoustic Shielding:* We installed a vacuum chamber in an acoustic enclosure. The enclosure has a specification value of an acoustic transfer rate of lower than −20 dB from several hertz to several hundreds of hertz.
6) *Vibration Isolation:* Operate a vibration isolation platform where the chamber is placed. The specification as regards vibration suppression from the bottom to the top surface of the passive antivibration table used in the study was more than 20 dB for 3–10 Hz and more than 40 dB for more than 10 Hz.

In this paper, we demonstrated combinations of environment stabilization measures as shown in Table I. There are certain impossible combinations for the six environment stabilization measures. For example, evacuation must be accompanied by a hermetic seal and internal temperature control must be accompanied by external temperature control. We were able to investigate the influence of environmental factors related to these measures by excluding one or two of them. Here, we use the term "ultrastable environment" for an environment to which we applied all six environmental stabilization measures.

IV. RESULTS AND DISCUSSION

A. Propagation Delay Fluctuation

To confirm whether or not an ultrastable environment could suppress fiber noise, we measured the phase fluctuation of a beat signal at 55-MHz detected at a PD by a phase noise test set (Symmetricom 5125A). Fig. 3 shows the propagation delay time fluctuation of the signal light, which was calculated from the phase fluctuation. The ultrastable environment greatly improved the delay fluctuation accumulated in the FUT. This result indicates that fiber noise can be reduced by environmental stabilization.

B. Phase Noise

To analyze the fiber noise in detail, we measured the power spectral density (PSD) of the phase noise from 10 mHz to 1 MHz by using the phase noise test set. Fig. 4 shows the results obtained under the various environmental conditions.

The ultrastable environment greatly suppressed the fiber noise below a Fourier frequency of 1 kHz compared with our laboratory environment [24]. The fiber noise was suppressed by more than 70 and 30 dB at 10 mHz and 10 Hz, respectively. In 30-Hz–30-kHz range, the phase noise reached the shot noise limit, which can be lowered by increasing the power incident on the PD.

Table II summarizes the improved phase noise frequency band obtained with the various environmental stabilization measures. Vibration isolation reduced the fiber noise existing

TABLE II
IMPROVED PHASE NOISE FREQUENCY BAND AND ALLAN DEVIATION AVERAGING TIME RANGE WITH DIFFERENT ENVIRONMENTAL STABILIZATION MEASURES

	Evacuation	External temperature control	Internal temperature control	Acoustic shielding	Vibration isolation
Improved phase noise frequency band	around 20 Hz and below 4 Hz	below 1 mHz	below 10 mHz	below 10 Hz	6 − 100 Hz
Improved Allan deviation averaging time range	0.01 − 1000 s	more than 100 s	100 − 1000 s	0.02 − 1000 s	0.01 − 1 s

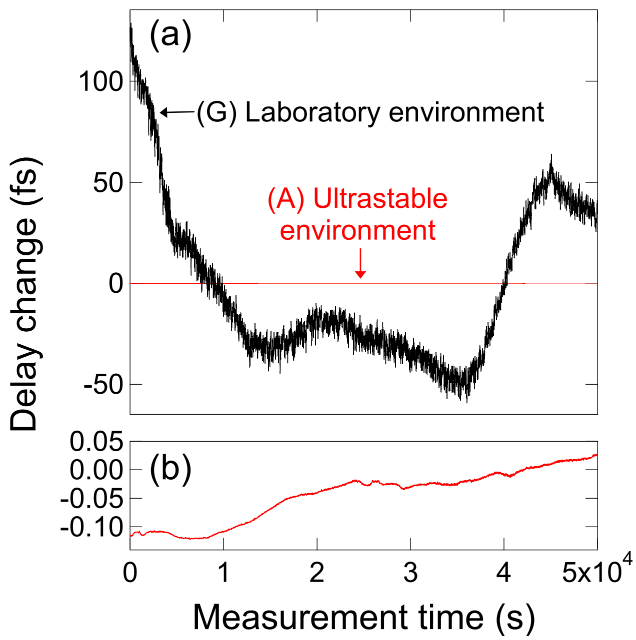

Fig. 3. Propagation delay fluctuation induced in a 10-m-long FUT. (a) Comparison of laboratory and ultrastable environments. (b) Magnified delay fluctuation in the ultrastable environment. (A) and (G) corresponding to the notation of the combinations shown in Table I.

in 6–100 Hz. This was assumed to be realized by isolating the interferometer from ground vibration. Acoustic shielding suppressed low-frequency phase noise to below 10 Hz. After the acoustic shielding, the power incident on the PD became stable. We assumed that the acoustic enclosure stabilized the temperature and suppressed the acoustic noise. The fiber connectors used in the FNC path might form a weak cavity and that resulted in faint fiber noise being converted to intensity noise by means of weak cavity resonance. We assume that this phase and intensity noise is simultaneously suppressed by the acoustic shielding. By evacuating the chamber, the fiber noise at Fourier frequencies of around 20 Hz and below 4 Hz was suppressed. We assume that the frequency components around 20 Hz and below 4 Hz were due to vibrational and thermal conduction through air to the fiber interferometer, respectively. The thermal controls suppressed the fiber noise in the low-frequency region. The external and internal temperature controls suppressed the fiber noise below 1 and 10 mHz, respectively.

Here, we consider the fiber noise measurement limit with our setup. The strong peak at 700 kHz in Fig. 4 in all cases originates from a modulation to stabilize the ultrastable laser to the ULE glass cavity. Although this modulation component was reduced by the self-heterodyne interferometer, the component remained because of the path length difference of the interferometer arms, and a residual component appeared in the frequency range. Thus, the measurement limit around the peak frequency is limited by the residual modulation component from the laser. The white phase noise floor ranging from 30 Hz to 30 kHz provided a good match with the shot noise level (magenta solid line in Fig. 4) calculated from the power incident on the PD. Thus, we assume that the frequency range measurement limit is determined by the shot noise.

We measured the background noise of the measurement setup by removing the FUT and measuring the fiber noise in an ultrastable environment (black dashed line in Fig. 4). In this measurement, we increased the power incident on the PDs to the PD saturation power to reduce the shot noise. Although the measured phase noise was reduced in 30-Hz–10-kHz frequency range, it was higher than some other results in the frequency region below 10 Hz. We assume that some measurement condition was not reproduced after we had removed the FUT. It is possible that the reflectivity at the fiber connectors, which were linked with a polarization controller, the AOM and the fiber feed through, changed when the FUT was removed. Further investigation is necessary to understand the difference.

C. Allan Deviation

We measured the Allan deviation (0.001–20 000 s) by using the phase noise test set to understand how the fiber noise degrades the frequency stability of the signal light of the laser. Fig. 5 shows the Allan deviation calculated from the PSD shown in Fig. 4 with a measurement bandwidth of 500 Hz. The measurement bandwidth is comparable to the fiber noise bandwidth. The Allan deviation is normalized by the carrier frequency of the laser (195.3 THz).

The Allan deviation in our laboratory environment (black circles in Fig. 4) is comparable to the relative frequency stability of recent multibranch combs [15], [27], [28]. This indicates that the frequency stabilities of the multibranch fiber combs are limited by the fiber noise differences between the branches.

In ultrastable environments, the frequency stability was improved over the entire averaging time range compared with our laboratory environment because of the fiber noise suppression. The Allan deviation was 7×10^{-20} at an averaging time of 1 s and improved down to 2×10^{-21} at an averaging time of 10 000 s. Specifically, it was improved by three orders

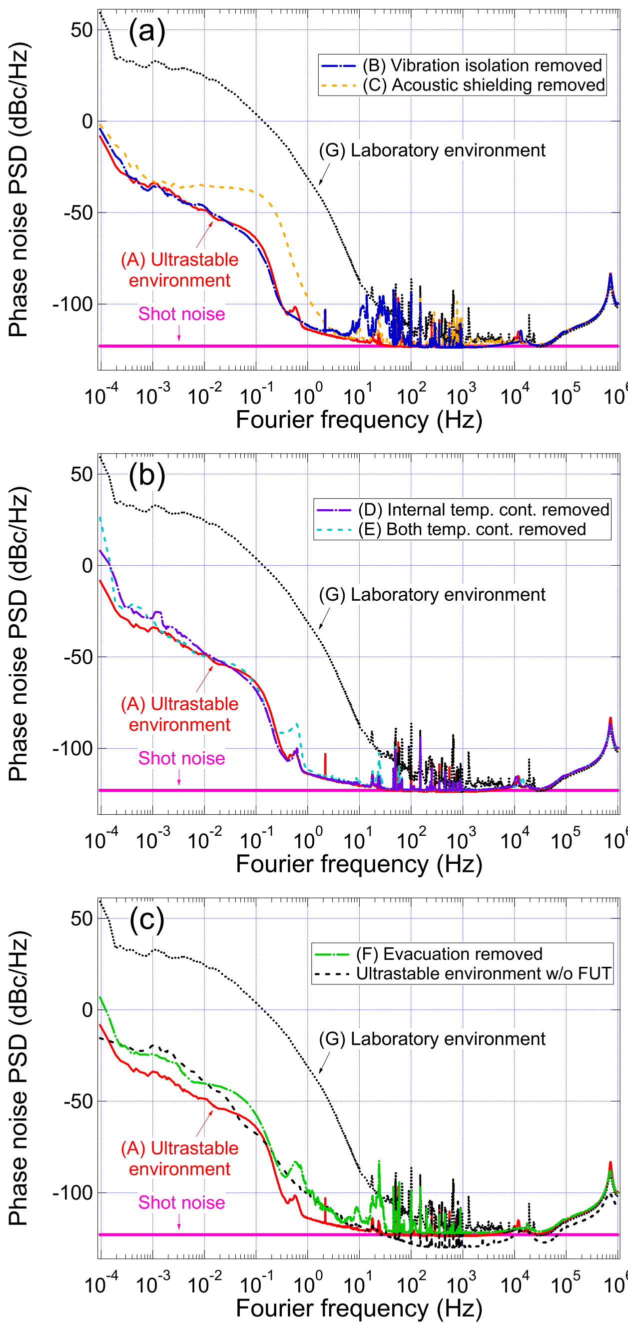

Fig. 4. PSD of phase noise accumulated in 10-m-long FUT under various environmental conditions. (a) Vibration isolation removed and acoustic shielding removed. (b) Internal temperature control removed and both temperature controls removed. (c) Evacuation removed and without an FUT. (The results for an ultrastable environment, our laboratory environment, and shot noise are shown in all figures.) temp. cont.: temperature control. (A)–(G) correspond to the notation of the combinations shown in Table I.

of magnitude for a 0.2–2000-s averaging time. Table II also summarizes the averaging time range of the Allan deviation improved by different environmental stabilization measures.

Here, we consider the measurement limit of the Allan deviation. The Allan deviation difference for long averaging times ranging from 2000 to 20 000 s in ultrastable environments, with the vibration isolation removed, and with the acoustic shielding removed is assumed to reflect the fluctuations in room temperature on the days of the experiments.

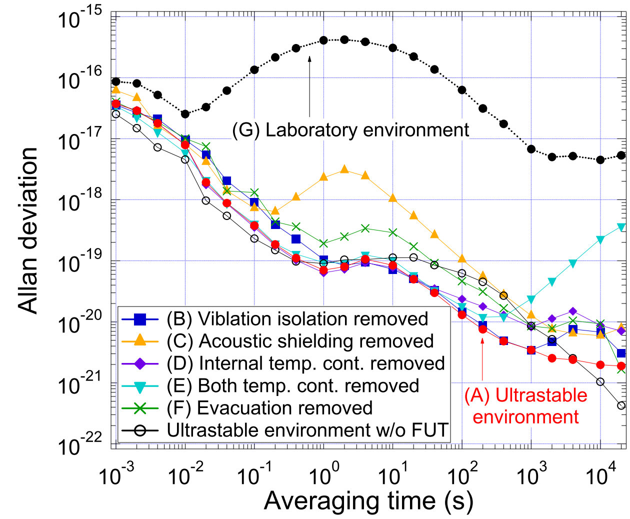

Fig. 5. Frequency instability depending on interferometer environment (measurement bandwidth 500 Hz), temp. cont.: temperature control. (A)–(G) correspond to the notation of the combinations shown in Table I.

With a short averaging time, all cases showed similar results. This indicates that the signal shot noise is dominant in the time range. We investigated the measurement limit of the setup by removing the FUT. As the result, for an averaging time exceeding 4000 s, Allan deviation was better than that measured using the interferometer with the FUT. This indicates that the fiber noise between the two interferometer arms was reduced by adjusting the path lengths of the arms. In contrast, some results were better than for an ultrastable environment without the FUT with shorter averaging times of less than 4000 s. This may indicate the presence of an unrecognized noise source as described in the phase noise analysis in Section IV-B.

D. Discussion

We revealed that highly stabilized environments greatly reduce fiber noise. With a 10-m-long fiber, the reduction in the phase noise PSD was as large as 30–70 dB in the low-frequency region, which corresponded to Allan deviations of 7×10^{-20} and 2×10^{-21} at averaging times of 1 and 10 000 s, respectively. These values are no worse than the frequency precisions of the best frequency combs.

We also revealed how each environmental stabilization measure works in terms of fiber noise reduction by applying appropriate combinations of stabilization measures. This constitutes a valuable guideline for designing an efficient system since we can select the measures depending on the target frequency precision.

Our final goal is to reduce the relative phase noise of a multibranch fiber-based frequency comb; this paper is part of a study toward this goal. As regards a frequency comb phase locked to an ultrastable laser with a broad servo bandwidth, we assume that the phase noise added in "out-of-loop" transmission lines is dominant in the phase noise of the comb output. In this paper, we found that the fiber noise induced in a 10-m-long fiber in our laboratory environment was similar to the relative frequency stability of multibranch combs obtained in [28]. This suggests that the dominant factor limiting the relative frequency stability of the multibranch fiber comb is the fiber noise induced at each branch. On the other hand, an erbium-doped fiber amplifier (EDFA) is also a possible noise source in the transmission lines. At the current stage, we have concluded that the noise generated in the EDFA is not much larger than the fiber noise induced by the laboratory environment.

V. Conclusion

We investigated the degree to which "fiber noise" is induced by surrounding environmental disturbance and added to signal light through optical fiber and can be reduced by suppressing environmental disturbance. For this purpose, we developed methods including a modified Mach–Zehnder heterodyne interferometer to measure such small fiber noise. Its measurement limit is of an unprecedented level both in terms of Allan deviation and phase noise spectral density; the method would prove useful for fiber noise measurement in many scenarios.

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