COHERENT OPTICAL FREQUENCY TRANSFER via 110-km URBAN FIBER NETWORK

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Abstract

Optical frequency at 1542 nm was coherently transferred over a 110-km optical fiber using an urban fiber network (JGN2) between Tsukuba and Kashiwa cities. The phase fluctuation induced by the fiber length fluctuation was actively reduced by stabilizing the fiber length using a fiber stretcher and an acousto-optic frequency shifter. Residual frequency instability of the transmitted light at the remote end was reduced down to 1.5×10^{-15} at an averaging time of 1 s.

Introduction

Transfer of the ultra-stable frequency references plays important roles for communication, metrology, fundamental physics and astronomy, in which radio frequency (rf) or optical frequency is distributed optically through low-loss optical fibers without degrading the original frequency stability. Since additional phase noise caused by the optical length fluctuation of the fiber degrades the stability of the signal, active phase noise cancellation in long-distance signal transmissions has been studied by many research groups. Recently, results on coherent optical frequency transfer with residual frequency instability of lower than 10^{-17} through 32-km [1] and 265-km [2] fibers were reported. One of the challenging applications of such a coherent frequency transfer is the precise frequency comparison between two ultra-stable atomic clocks in different laboratories separated more than 100 km. We are planning to compare the optical frequencies of the Sr optical lattice clock developed by Katori group at the University of Tokyo (UT) [3] and the microwave frequency standards in NMIJ at Tsukuba with an frequency uncertainty of smaller than 10^{-15}. The distance between Tokyo and Tsukuba cities is more than 50 km, and the fiber length between them exceeds more than 100 km. The frequency references should be delivered over 100 km with the residual uncertainty at a level of 10^{-15}.

In this paper, we report the coherent transfer of the optical frequency using a 1542-nm laser over 110 km via an urban optical fiber network between Tsukuba and Kashiwa cities. It is, to our knowledge, a first coherent optical carrier frequency transfer over 100-km with lossy and noise urban fiber networks.

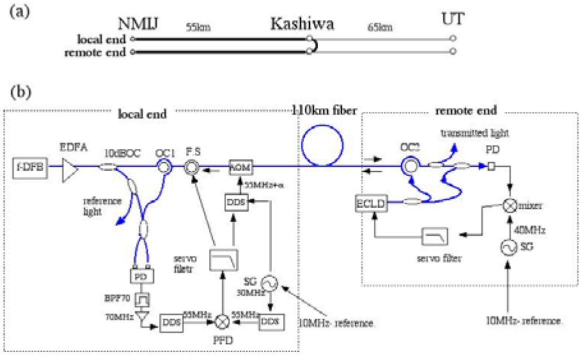

Fig.1 Schematic diagram of the optical fiber network (a) and the experimental set-up (b).

Experiments

Fig. 1(a) shows the optical fiber network used in our study. A pair of dark parallel fibers are installed between TU at Tokyo and NMIJ at Tsukuba, and most part of which was provided by Japan Gigabit Network 2 (JGN2) [5]. In our current study, parallel fibers were connected at Kashiwa relay station located at the middle point of the fiber network, and the optical carrier transmission test has been done by this 110-km round-trip fiber network (NMIJ-Kashiwa-NMIJ) in order to evaluate the uncertainty of the transmitted light. The loss and fluctuations of the fiber were more than – 45 dB and 500 mm/hour, respectively. The additional phase fluctuation of the transmitted light was optically measured, and suppressed for the precision transmission of the carrier frequency.

The experimental setup is shown in Fig. 1(b). The light from a commercial fiber DFB laser (Koheras Adjustek) with the wavelength of 1542 nm was amplified and entered into the local end of the fiber. The light was divided into two by a 10dB optical coupler, and the stronger part of the light was transmitted through the 110-km fiber network. A piezo-driven fiber stretcher and an acousto-optic modulator (AOM) whose center frequency was 55 MHz were used as phase actuators of the optical carrier. At the remote end, a home-made external-cavity laser diode (ECLD) was phase-locked to the transmitted light through the 110-km fiber with an offset frequency of 40 MHz, and the phase-locked light from the ECLD was entered into the remote end of the fiber by using an optical circulator, which is called an optical repeater. The offset frequency of 40MHz at the repeater distinguished the light returned at the remote end from the back-scatted light in the fiber. The returned light from the remote end was combined with the reference light from the 10-dB optical coupler at the local end. The heterodyne beat note at 70 MHz is detected from the combined light because the frequency of the returned light is doubly shifted by the AOM (55 MHz×2) and was also shifted –40MHz by the optical repeater. The beat note at 70 MHz was converted into 55 MHz by a direct digital synthesizer (DDS), and was mixed with the local oscillator at 55 MHz for detecting optical phase signal. In order to obtain the optical phase signal, a digital phase-frequency discriminator (DPFD) was used as a frequency mixer. The DPFD generates phase discrimination signal whose linear dynamic range is much larger than that obtained by an ordinary double-balanced mixer (DBM), which make it possible to measure the length of the optical fiber whose length is much longer than the coherent length of the light source, details of which is described in our previous paper [4]. The optical phase signal was fedback to the fiber stretcher to suppress the optical phase fluctuation of the transmitted light. The AOM used to expand the dynamic range of the phase actuator.

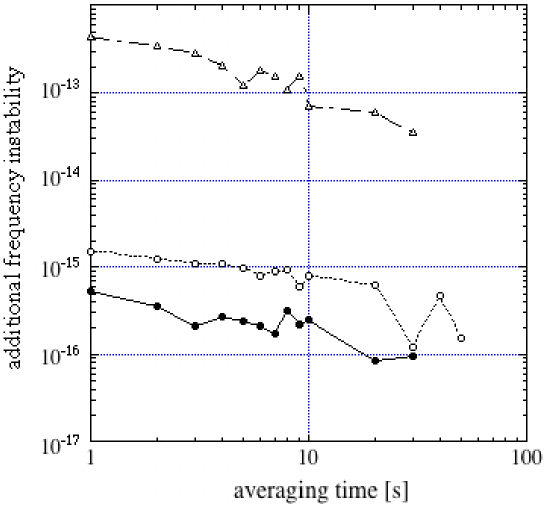

Fig. 2 Instability of the transmitted optical frequency: free-running (triangle); stabilized, out-of-loop signal (open circle); stabilized, in-loop signal (solid circles).

Results and discussions

For evaluating the additional frequency noise of the transmitted light, the transmitted light at the remote end was combined with the reference light. The heterodyne beat note from the combined light at 55 MHz was counted by the frequency counter, which means the out-of-loop signal of the servo system. Fig. 2 shows the measured Allan standard deviation. The additional frequency noise of the transmitted light (triangles) of 4×10^{-13} at 1s is suppressed down to 1.5×10^{-15} when the servo system was activated (open circles).

Solid circles in Fig. 2 indicate the frequency instability measured from the 70 MHz beat note obtained at the local end which is called in-loop signal. The discrepancy of the frequency instability between transmitted light (out-of-loop) and round-trip light (in-loop) is considered to be caused from the additional phase noise at the optical repeater or polarization mode dispersion (PMD). Our present results are worse than that reported in Ref.2 because of relatively large phase noise in the urban fiber environment. Obtained fractional frequency instability level satisfies the requirement of the 110-km optical link for evaluating the Sr lattice clock.

Acknowledgement

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[5] JGN 2 is operated by the National Institute for information and communications (NICT), Japan.