Precision optical carrier transmission over 110km through urban fiber network

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Abstract

Optical carrier frequency at 1.5μm was transmitted over 110km through round-trip fiber network (JGNII) between Tsukuba and Kashiwa, in which all the delivering fibers were installed in urban environment. Additional phase noise of the optical carrier caused by the fiber length fluctuations was detected by using phase-frequency discriminator (PFD), and was suppressed by controlling fiber stretcher and acousto-optic modulator (AOM). The residual frequency instability due to the fiber length fluctuation was reduced down to 1.5×10^{-15} at the averaging time of 1s.

1 Introduction

The distributions of radio frequency (rf) and optical frequency references have, recently, become more important in communications, metrologies, fundamental physics, and astronomy. In long-distance fiber-optic signal transmissions, the optical length fluctuations of the fiber caused by the acoustic noise, vibration, and thermal expansion degrade the stability of the rf and optical carrier frequency after transmitted through long optical fibers. Therefore precision long-distance signal distributions with active phase noise cancellation have been studied in many research groups [1-6], and, recently, precision optical carrier transmissions with residual frequency instability of lower than10^{-17} through 35-km [5] and 265-km [6] fiber were reported. In these studies, most parts of the fiber were wound around fiber spools in the laboratory condition.

In this presentation, precision optical carrier frequency transmission over 110 km is reported. To our knowledge, precision carrier transmission over 100km using lossy and noisy fiber networks in urban environmental installation has never reported before.

Our initial motivation for precision signal transmission study is to develop reference rf signal distribution system for ALMA (Atakama large mm sub-mm array) project. Photonic method called 'photonicLO' was proposed in which the reference signals up 900 GHz were distributed as heterodyning beat signal of two lasers through optical fibers. In ALMA project, the length fluctuations of the 25-km fibers should be suppressed down to 3μm. In order to measure length fluctuations of the long fiber precisely by using optical interference, we developed multi-bit digital phase-frequency discriminator (PFD), which made it possible to measure the length of the long optical fiber whose length is much longer than the coherent length of the laser used for optical interference [7]. Then we have applied our photonic LO technique to the precision optical carrier transmission.

The final goal of the present study is to transmit optical carrier frequency from Tokyo University (TU) at Tokyo to National Metrology Institute of Japan (NMIJ) at Tsukuba for evaluating the frequency stability of the Sr optical lattice clock, which has been developed by Prof. Katori [8]. In this study the optical carrier should be transmitted over 120km with keeping the residual frequency uncertainty at a level of 10^{-15} at 1s or below.

2 Experiments

The optical fiber network used in our study consists of a pair of dark parallel fibers from TU to NMIJ (see fig.1(a)), most part of which is Japan Gigabit Network II (JGNII). In the present study, we use NMIJ – Kashiwa – NMIJ fiber network which consists of parallel fibers connected at Kashiwa station, which is the relay station located at the middle point of this network, because the length and loss of the fiber is almost the same as that between NMIJ and TU. In this setup, the frequency stability of the transmitted light can be evaluated (the local and remote end of the fibers are located at the same place).

For stable signal distribution, the additional phase noise of the round-trip light is optically measured, and the

error signal is fedback to the fiber length and optical carrier frequency to compensate the additional phase noise of the transmitted carrier signal. The schematic diagram of our precision optical carrier transmission system is shown in fig.1 (b). The light source is a commercial fiberDFB laser (Koheras ADJUSTEK: λ=1543nm). The 10-mW laser light is entered into the local end of the fiber, and is divided into two (reference and traveling light) by a 10dB optical fiber coupler. After passing through an optical circulator (OC1), acousto-optic modulator (AOM) and a piezo-electric-transducer (PZT) -driven fiber stretcher,

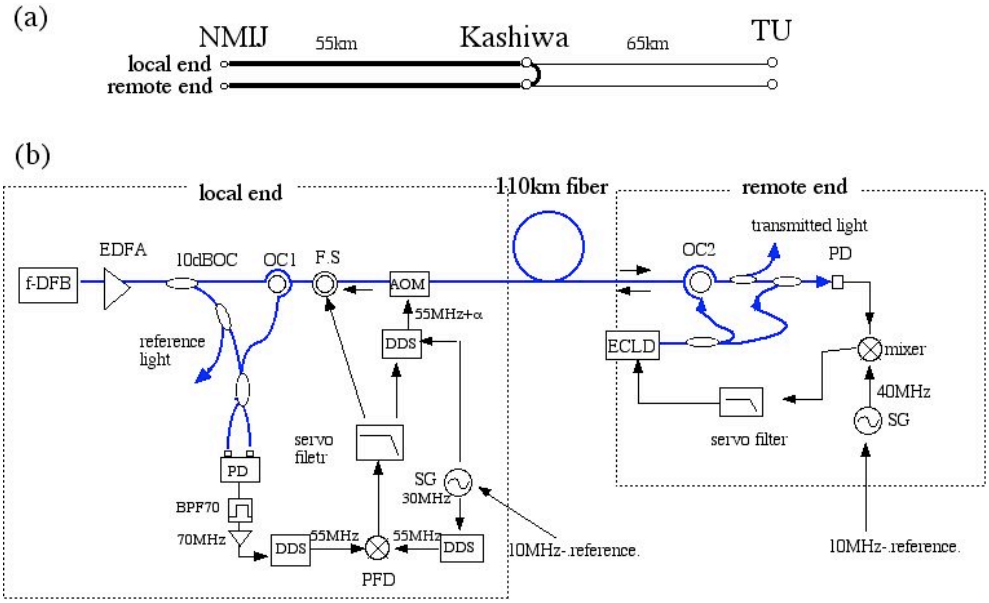

fig.1 Schematic diagram of (a) optical fiber network, and (b) experimental set-up
OC: optical circulator, SG: signal generator, DDS: direct digital synthesizer,
f-DFB: fiber-DFB laser, ECLD: external-cavity laser diode

the traveling light is transmitted through a long delivering fiber. The length and loss of the delivering fiber are 110km and –47dB, respectively. At the remote end of the delivering optical fiber, an extended-cavity laser diode (ECLD) is phase locked to the transmitted light with the offset frequency of 40 MHz, and this phase-locked laser light is entered into the optical circulator (OC2), and goes back to the same delivering optical fiber, which is called as 'optical repeater'. At the local end of the fiber, the offset frequency of 40 MHz is utilized for distinguishing the returned light from the back-scattered light in the delivering fiber. After passing through delivering fiber and the optical circulator (OC1), the returned light is combined with the reference light by 3dB optical coupler at the local end. Heterodyne beat note at 70 MHz is detected by photo detectors from the combined light because the round-trip light is frequency-shifted twice by the AOM driven at 55MHz, and are also shifted at the optical repeater by 40MHz (55+55-40=70). The frequency of the heterodyne beat note at 70MHz is converted into 55 MHz by using a direct digital synthesizer (DDS), which keeps the phase of the signal, and is mixed with the local oscillator at 55 MHz by using the PFD. The phase signal of the carrier light obtained from the PFD is filtered, and fed back to the fiber stretcher to suppress the phase fluctuations of the round-trip light. 10-MHz reference signals from H-maser (AIST HM2) are supplied to all the signal

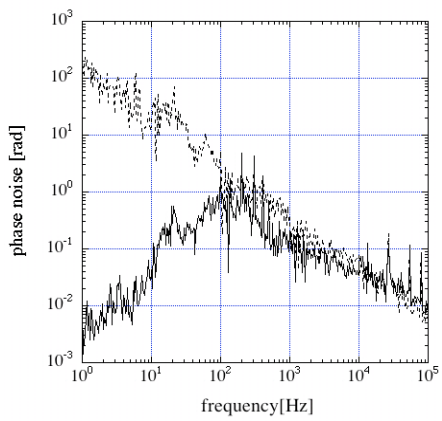

fig.2 the phase noise spectrum of the round-trip light at free-running (dotted) and stabilized (solid)

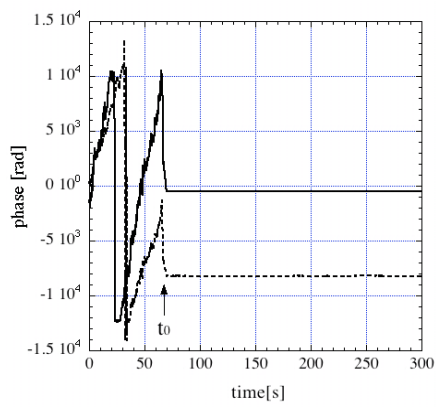

fig.3 phase of the round-trip light (solid) and transmitted light (dotted)

generators used in this system and frequency counters, whose frequency stability is $6x10^{-13}$ at 1s.

The length fluctuation of the 110-km fiber (typically 500mm/hour) in urban-environment installation is much larger than that of the fiber in the laboratory condition, which is much larger than the dynamic range of the fiber stretcher. Therefore phase control signal at the lower frequency range is also added to the AOM, which is used as the phase actuator of the carrier signal. With the help of AOM, the phase of the carrier frequency is stably stabilized for more than 1 hour without cycle slip. The servo bandwidth is 300 Hz, which is limited by the optical delay time of the round-trip light. The phase noise spectrum of the round trip light is shown in fig.2, which indicates the in-loop error signal of the servo system, and the phase noise of the round trip light is suppressed down to $2x10^{-3}$ rad/Hz$^{1/2}$ at 1Hz (solid trace in fig.2)

3 Results and discussions

In order to evaluate the additional phase fluctuation of the transmitted light, the transmitted light at the remote end is combined with the reference light at the local end, and obtained heterodyne beat signal at 55 MHz is mixed with the local oscillator by another PFD, which means the out-of-loop error signal of the servo system. Fig.3 shows the temporal behavior of the phase of the round-trip light (solid trace) and the transmitted light (dotted trace). When servo circuit is activated at time t_0, the fluctuations of both traces are suppressed, which shows that in this system, the phase fluctuations of the transmitted light at the remote end of the fiber is suppressed when the round-trip phase is stabilized at the local end. Fig.4 shows the root Allan variance of the fractional frequency uncertainty of the transmitted light, which means the additional frequency noise on the optical carrier in transmitting through optical fibers. Triangles in fig.4 indicate the fractional frequency uncertainty of the transmitted light through 110-km fiber, which is evaluated from 55 MHz beat signal at remote end. When the servo system is activated, the residual frequency uncertainty of the transmitted light is suppressed down to $1.5x10^{-15}$ at averaging time of 1s, which is indicated by white circles. Our present results are worse than that reported in ref.5 by 20dB due to relatively large phase noise in the urban fiber environment (larger than that in ref.5 by 16dB). Solid circles in fig.4 indicate the frequency uncertainty of the round-trip light in activating servo system, which is evaluated from the 70 MHz beat note at the local end.

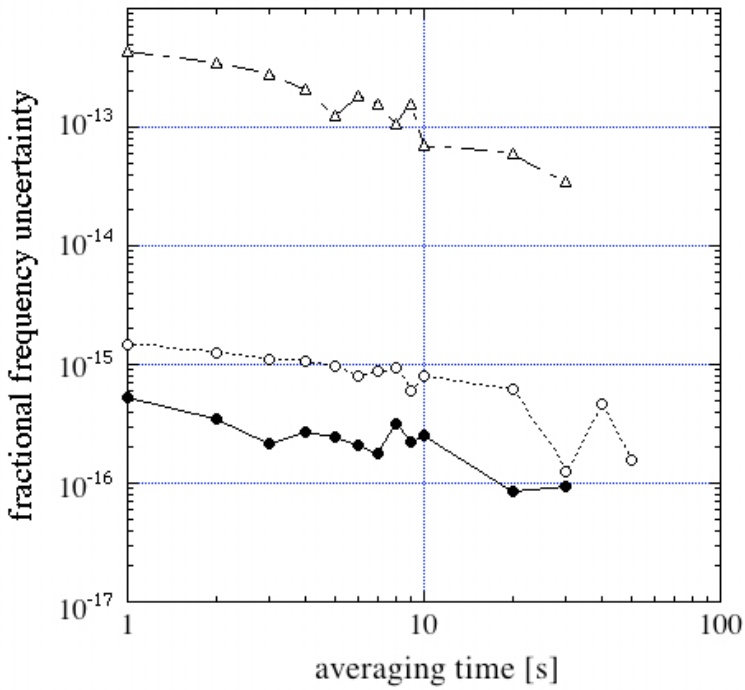

fig.4 Uncertainties of optical carrier frequency of transmitted light in free-running (triangle) stabilized (white circles), and stabilized round-trip light (solid circles)

The residual frequency uncertainty of the transmitted light should be equal to that of the round-trip light in the present system. Discrepancy between two signals is considered to be caused from the residual phase noise of the phase locking servo at the remote end.

4 Conclusions

The optical carrier frequency at 1.5μm is transmitted through the 110-km optical fiber in urban environment installation, which gives larger additional phase noise to the transmitted light. Our phase noise stabilize system suppresses the additional frequency noise of the transmitted light down to 1.5×10^{-15}. Obtained fractional frequency uncertainty level satisfies the requirement of the long-distance optical carrier distribution for evaluating the frequency stability of the optical lattice clock, and will be improved by increasing servo gain of the phase noise stabilizing system and that of the phase-locking servo of the optical repeater.

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6 References

[1] L.-S.Ma, P.Jungner, J.Ye, J.L.Hall,"Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path",Opt.Lett.,**19**, 1994, pp.1777

[2] K.Sato, H.Hara,S.Kuji, K.Asari, M.Nishino, N.Kawano, "Development of an ultrastable fiber optic frequency distribution system using an optical delay control module for frequency standard and VLBI", IEEE Trans.Instrum.Meas., **49**, 2000, pp.19

[3] F.Narbonneau, et.al, "High resolution frequency standard dissemination via optical fiber metropolitan network", Rev.Sci.Instrum., **77**, 2006, 064701

[4] C.Daussy et.al,"Long-distance frequency dissemination with a resolution of 10^{-17}", Phys.Rev.Lett, **94**, 2005, pp.203904

[5] S.M.Foreman, et.al, "Coherent optical phase transfer over a 32-km fiber with 1-s instability at 10^{-17}", Phys.Rev.Lett., **99**, 2007, pp.153601

[6] N.R.Newbury, P.A.Williams, W.C.Swann,"Coherent transfer an optical carrier over 251 km", Opt.Lett., **32**, 2007, pp.3056

[7] M.Musha, Y.Sato, K.Nakagawa, K.Ueda, M.Ishiguro, A.Ueda"Robust and precise length stabilization of a 25-km long optical fiber using an optical interferometric method with a digital phase-frequency discriminator". Appl. Phys. **B82**, 2006, pp.555

[8] M.Takamoto, F-L.Hong, R.Higashi, H.Katori, "An Optical Lattice Clock", Nature **432**, 2005, pp.321