Optical clock distribution over stable fiber links in noisy environments

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Abstract: We demonstrate a 190-km-long optical fiber link that achieves high-stability frequency transfer in noisy environments. A four-stage cascaded link with ultralow-noise laser repeater stations connects distant optical lattice clocks without deteriorating their stabilities. © 2022 The Authors

1. Introduction

In anticipation of the redefinition of the second in the near future, there is a demand for the establishment of technology to distribute optical clock signals on a nationwide scale with a precision of 10^{-18} levels. In addition, novel applications such as relativistic geodesy are expected by comparing frequencies between distant optical clocks [1]. Optical fiber networks that have been used for optical information communication can be applied to high-precision network optical clocks, which will provide a new space-time infrastructure above that of traditional microwave clocks and GNSS links. Light propagating through an optical fiber suffers from frequency noise caused by environmental perturbations such as vibration, acoustics, temperature changes, and atmospheric pressure fluctuations, which degrades the frequency stability of the transfer signal. To overcome this problem, fiber noise compensation (FNC) techniques have been developed [2].

In quantum projection noise limit measurements, the frequency instability of an optical clock scales as $Q^{-1}N_a^{-1/2}\tau^{-1/2}$, where Q is the Q factor of observed clock spectrum, N_a is the number of atoms observed in unit time, and τ is the averaging time. Optical lattice clocks (OLCs) have the advantage of increasing N_a while maintaining high precision [3], and the clock instabilities of less than 2×10^{-16} $(\tau/\mathrm{s})^{-1/2}$ have been demonstrated [4,5]. The fiber links connecting such OLCs require even higher stabilities. The FNC technique reduces the fiber noise at frequencies below a feedback bandwidth $f_{BW} \approx 50/(L/\mathrm{km})$ kHz, where L is the fiber length, and link instability scales as $h_L^{1/2}L^{3/2}\tau^{-3/2}$, where h_L is the fiber noise coefficient [6]. In quiet environments such as rural areas, as $h_L \approx 0.5$ Hz^2/Hz/km level has been reported in European links [7], where link instabilities lower than 1×10^{-16} $(\tau/\mathrm{s})^{-3/2}$ can be achieved over 100-km-long fiber. On the other hand, the noise level in Japanese links in noisy environments in metropolitan areas is as high as $h_L \approx 70$ Hz^2/Hz/km [8], which increases the link instability by a factor of more than ten.

In such noisy environments, it is effective to increase the feedback bandwidth of FNC by means of a multistage cascaded link [8], which divides a long fiber into N spans and applies FNC for each span. By connecting them with laser repeater stations (LRSs), an improvement of link stability up to N times can be expected. As the interferometric noise from the LRSs accumulates in the cascaded link, it is necessary to develop interferometers with sufficiently low noise. Here, we demonstrate a 190-km-long four-stage cascaded fiber link, where LRSs incorporate ultralow-noise optical interferometers based on planar lightwave circuits (PLCs). The link instability of 3×10^{-16} $(\tau/\mathrm{s})^{-3/2}$ makes it possible to connect distant OLCs without deteriorating long-term clock stability.

2. Experiments

Figure 1 shows a schematic of the experimental configuration for frequency comparison between distant OLCs via a multistage cascaded fiber link. The OLCs are based on strontium (Sr) atoms and operated with the clock wavelength of 698 nm. We adopt 1397 nm, a subharmonic of the Sr clock frequency, for the clock lasers, transfer laser, and repeater lasers. At a local site, the clock laser is pre-stabilized to a reference cavity to narrow the linewidth and improve short-term stability. A part of the clock laser is converted to 698 nm by second-harmonic generation (SHG) to probe the clock transition of Sr atoms in an optical lattice, and the laser frequency is stabilized to the atomic resonance by using a frequency shifter. The transfer laser is heterodyne-locked to the clock laser at a transfer laser station and sent to the first LRS. As 1397 nm is in the E-band and fiber loss, including the water-peak attenuation, is as large as 0.4 to 0.5 dB/km, one span of the cascaded link can be up to 100 km. For longer span links, the C-band around 1550 nm with the lowest fiber loss of ~0.2 dB/km is typically used, which requires optical frequency combs for frequency links between the optical clocks and fiber links.

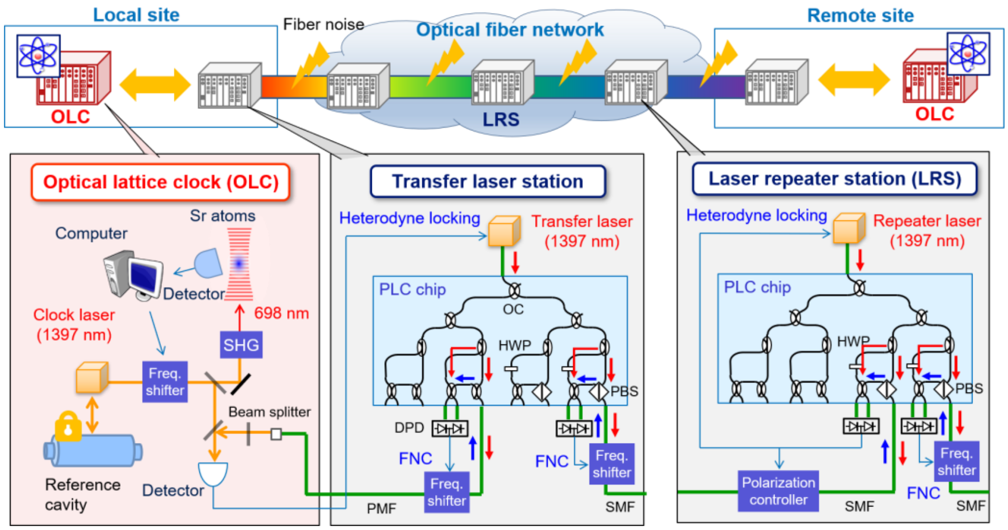

Fig. 1. Experimental configuration for frequency comparison between distant optical lattice clocks (OLCs) via a cascaded fiber link. LRS: laser repeater station. SHG: second-harmonic generation. PLC: planar lightwave circuit. OC: optical coupler. HWP: half-wave plate. PBS: polarizing beamsplitter. DPD: differential photodetector. PMF: polarization-maintaining fiber. SMF: single-mode fiber.

The configuration of the transfer laser station and the LRS are similar, consisting of the transfer (or repeater) laser, a PLC chip, differential photodetectors (DPDs), a polarization controller, a heterodyne locking system, and FNC systems with frequency shifters. Four optical interferometers are fabricated in the 44 × 42 mm^2 PLC chip [8]. Two are composed of optical couplers (OCs) and used to detect beat signals between transmitted light (red arrows) and received light (blue arrows) with the same polarization. They are used for distribution ports with short fiber links, where the transmitted light is retro-reflected by a beam splitter. The other two interferometers are composed of OCs, half-wave plates (HWPs), and polarizing beamsplitters (PBSs), and used to detect beat signals between orthogonally polarized transmitted light and received light. They act like Faraday mirrors and are used for long fiber links. Each interferometer has an arm-balanced design, in which the frequency noise induced in the transmitted light and received light is cancelled as a common mode. In addition, non-common paths from the laser input to each interferometer are designed to be of equal length, which minimizes relative noise between interferometers. The repeater laser is heterodyne-locked to the received light using the beat signal and sent to the next station and back to the previous station. A round-trip beat signal is detected in the previous station, which is used for FNC of the span. At a remote site, the repeater laser is sent to the OLC using the distribution port, like it is at the local site, and a beat measurement with the clock laser performs the distant clock comparison.

3. Results and conclusion

Figure 2(a) shows a schematic of a 190-km-long cascaded fiber link connecting OLCs operating at RIKEN (Wako) and NTT (Atsugi). The clock frequency generated at RIKEN is sent to NTT via the four-stage cascaded link, where LRSs are operating at two telecommunications offices and the University of Tokyo (UTokyo), and is compared with the clock frequency at NTT. The frequency difference between the two clocks is measured as shown in Fig. 2(b), where the frequency data are obtained with a gate time of 1 s. The measured differential frequency is mainly due to the height difference Δh between the two clocks, which is given by $\Delta\nu / \nu_0 \approx g\Delta h/c^2$, where $\Delta\nu$ is the clock frequency difference, ν_0 is the clock frequency, g is the gravitational acceleration, and c is the speed of light. Figure 2(c) shows the frequency instability of the differential frequency, evaluated by modified Allan deviation. Blue squares represent the case when the clock lasers are not stabilized to the atomic resonance, and the short-term instability follows with 3×10^{-16} $(\tau/\mathrm{s})^{-3/2}$ (light blue dashed line). This is consistent with the instability of a 240-km-long five-stage cascaded fiber link demonstrated for a UTokyo-NTT-UTokyo fiber loop [8], where the instability reaches 1×10^{-18} at 2,600 s.

Unlike the loop fiber link, the instability of the distant clock laser comparisons reaches 3×10^{-16} and increases with τ due to the noise floor and frequency drift of the reference cavities (black dashed line). Operating the OLCs by stabilizing the clock lasers to the atomic resonance improves the long-term instability to 1×10^{-15} $(\tau/\mathrm{s})^{-1/2}$ (light red dashed line) as shown by red circles. Therefore, the link instability becomes lower than the clock instability at averaging times longer than 1 s.

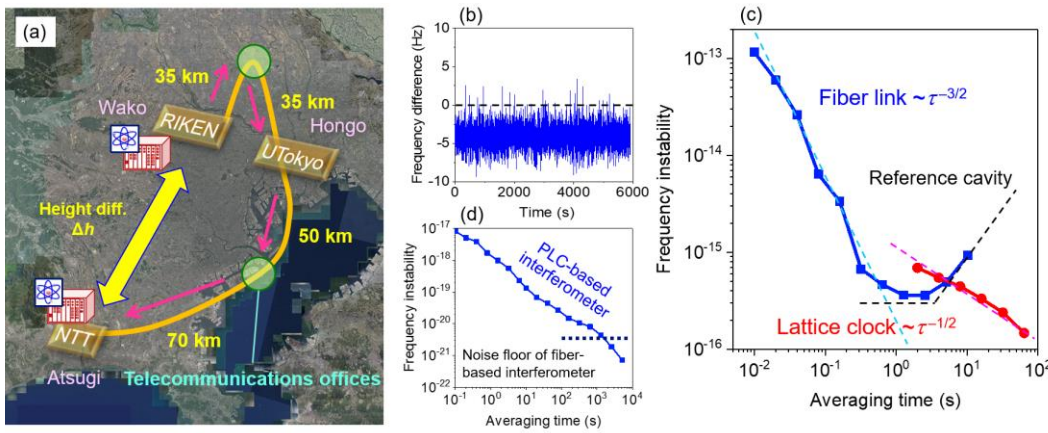

Fig. 2. (a) 190-km-long cascaded fiber link connecting two distant OLCs operating in RIKEN (Wako) and NTT (Atsugi). (b) Frequency difference between the two distant OLCs measured with a gate time of 1 s. (c) Frequency instability of comparison between two reference cavities (blue) and OLCs (red). (d) Frequency instability of the PLC-based interferometer.

As a comparison, the frequency instability of the PLC-based interferometer is shown in Fig. 2(d). It represents 2×10^{-18} at 1 s and 7×10^{-22} at 5,000 s, and is expected to improve further in the long term. Therefore, interferometric noise of LRSs in the four-stage cascade link does not degrade the stability of the clock comparison. In particular, the instability of 7×10^{-22} is difficult to achieve in commonly used fiber-based interferometers even with temperature control [9], as shown by a black dotted line in Fig. 2(d). This indicates that the PLC-based interferometers almost completely suppress temperature sensitivity.

In conclusion, we have demonstrated a 190-km-long fiber link connecting distant optical lattice clocks. Both the clock and fiber link are based on 1397 nm, which is advantageous for networking multiple distant clocks. The link instability of 3×10^{-16} at an averaging time of 1 s is obtained by the multistage cascaded link technique with ultralow-noise laser repeater stations, which will support clock comparisons at the 10^{-18} level.

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