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Phase-stabilized free-space link for optical frequency transfer

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ABSTRACT

Optical frequency transfer through the atmosphere is needed for diverse free-space applications, e.g. coherent communication, optical clock comparison and relativity experiments. The task requires an appropriate optical link system that provides the multimodal abilities of not only pointing, acquisition, and tracking (PAT) but also phase noise suppression in the presence of air turbulence. Here, we describe a free-space optical (FSO) link system built over a 1.4 km outdoor path to transmit optical frequencies with a fast beam tracking capability together with an active feedback compensation scheme of the atmospheric phase noise. The FSO link is able to offer a frequency transfer stability of 3.51×10^{-19} at 100 s averaging, which suffices to deliver the current state-of-the-art optical clock signals.

1. Introduction

High-accuracy optical clocks are being under intensive development and utilized for various scientific studies of remote timescale comparison, e.g. fundamental constants measurement [1,2], global navigation and geodesy [3,4], astronomical observation [5] and relativity testing [6,7]. These applications demand optical frequency transfer over a long distance, while the fiber-line-based method has been well established as demonstrated to transmit high-accuracy optical clock signals with phase stabilization for remote clock-to-clock comparison [8,9]. Meanwhile, the ability to transfer the optical clock signal via a free-space optical (FSO) link over a long distance becomes essential for inter-continental scale, ground-to-satellite, and space-borne applications. In response, quite a few FSO links have been demonstrated so far particularly for the open-air optical time and frequency transfer [10,11], comb-based optical frequency generation and transfer [12–14], and optical coherent and quantum communications [15–17].

Dynamic effects of air turbulence on the FSO link may be characterized in terms of the Fried parameter that is determined by taking into account the atmospheric condition, altitude, and path length [18,19]. Usually, for weak turbulence, the Fried parameter reaches a few tens of centimeters, comparable to the beam size widely used for the FSO link. In this situation, the wavefront distortion leading to the beam wander and fade is not significant, so a simple tilt-tip control scheme of light transmission suffices to satisfy the required pointing, acquisition, and tracking (PAT) functions [20]. If this is not the case due to either long path in higher altitude or severe atmospheric turbulence, the Fried parameter reduces to be smaller than the beam size of the FSO link with significant wavefront distortion. In this case, the FSO link needs not only PAT system but also the wavefront distortion in an adaptive way [21,22]. Under a harsh atmospheric condition or long-haul optical path, the adaptive approach might be served to compensate the wavefront distortion so that the coupling efficiency on to a single-mode fiber is improved.

In addition, an essential element to construct a reliable open-air FSO link is the capability of suppressing the phase noise induced by the atmospheric disturbance during light transmission. This requirement has preferably fulfilled by returning the transferred beam via the same optical link, with subsequent real-time feedback compensation of the Doppler shift caused by the accumulated phase noise [9,13,14,23]. Nonetheless, the overall path length of an FSO link is severely restricted by the deep fade of the transmitted light caused by the beam wander and scintillation without PAT control. Therefore, incorporating appropriate functional capabilities of PAT become important for long-distance delivery to be made without the loss of original optical frequency stability inherited from the optical clock even in the presence of atmospheric turbulence [14,20,24].

In this investigation, we present a phase-stabilized FSO link system built with enhanced PAT capabilities over a 1.4 km atmospheric path on the KAIST main campus in Daejeon, South Korea. The FSO link is intended to transmit the optical frequency comb of an ultrashort pulse laser, which will act as an airborne distributor of optical frequencies

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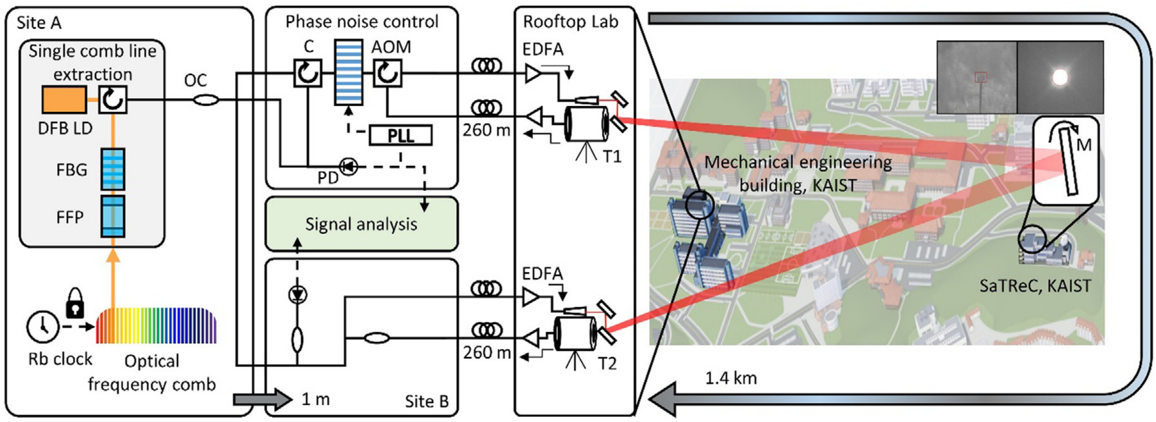

Fig. 1. Free-space optical (FSO) link constructed in this investigation for optical frequency transfer over a 1.4 km path with feedback compensation of atmospheric phase noise. Identical transceiver systems are used at Site A and Site B, each consisting of a Galileo-type refractive telescope and a Cassegrain-type reflective telescope. FFP: fiber Fabry–Perot filter, FBG: fiber Bragg grating, DFB LD: distributed feedback laser diode, OC: optical coupler, C: circulator, AOM: acousto-optic modulator, PD: photo-detector, PLL: phase locked loop, EDFA: erbium-doped fiber amplifier, T: transceiver.

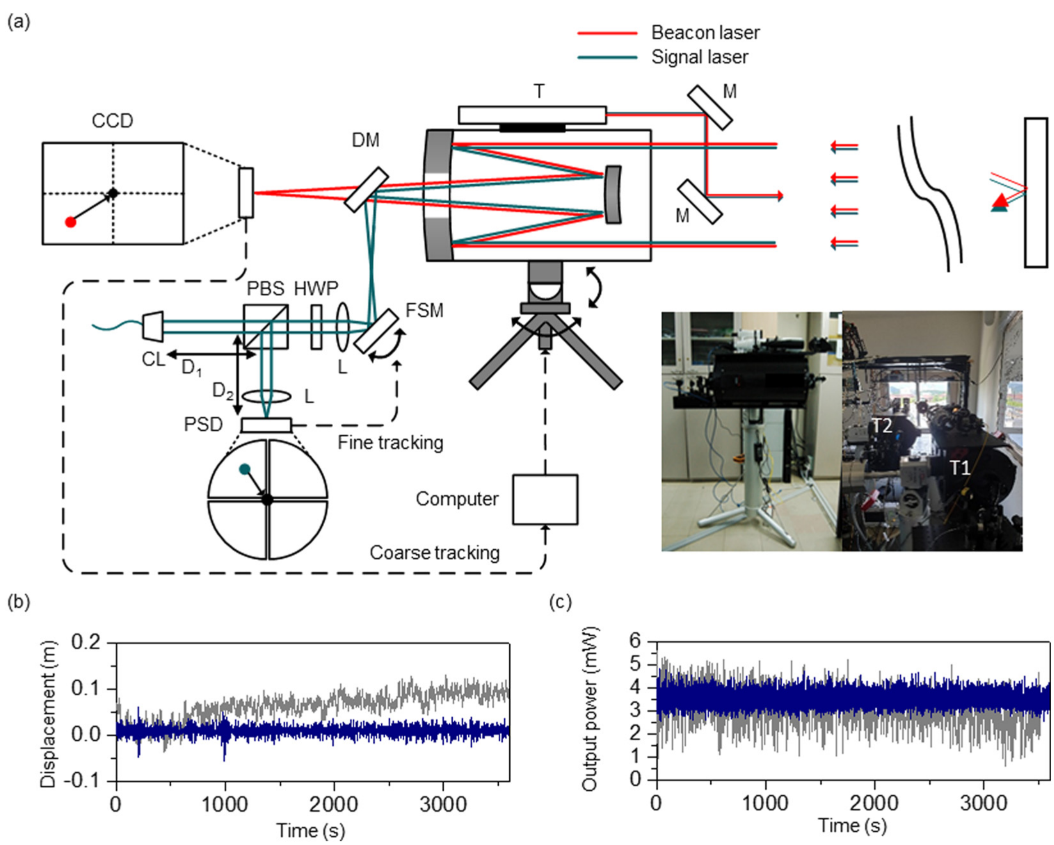

Fig. 2. Transceiver system with coarse and fine tracking capabilities. (a) System configuration. (Inset) Photos of two identical transceiver systems; one installed for Site A and the other for Site B. (b) Tilt-tip coarse tracking result in terms of the image displacement on the CCD; with control on (blue) and off (gray) (c) Fine tracking result in terms of the optical power at the inlet collimator to the receiving fiber; control on (blue), control off (gray) CCD: charge-coupled detector, DM: dichroic mirror, T: transceiver, M: mirror, FSM: fast steering mirror, HWP: half wave plate, PBS: polarization beam splitter, L: lens, CL: collimator lens, PSD: position sensitive detector.

of 1.0 Hz linewidth in stabilization to state-of-the-art optical clocks. The FSO link is equipped with a real-time feedback compensation scheme of the atmospheric phase noise. In addition, more importantly, a dual-step tip-tilt control system is incorporated to avoid the deep fade attributable to beam wander and scintillation. As a result, the optical frequency transfer can be made with a fractional stability of 10^{-18} at 100 s averaging, which is comparable to the stability level of state-of-the-art optical references. Further, the potential of the FSO link is discussed for long-distance terrestrial, airborne and ground-to-satellite applications.

2. Phase-stabilized free space link

Fig. 1 illustrates the overall system configuration of the FSO link constructed in this study. The total outdoor path between Site A and Site B has a length of 1.4 km folded in half using a flat mirror of a 127 mm diameter so that the two sites are located in closed proximity to facilitate back-to-back experimental work for direct comparative analysis. Two identical transceiver systems are installed; one at Site A, and the other at Site B. Each transceiver system is bi-directional, consisting of a Galileo-type refractive telescope for light signal transmission

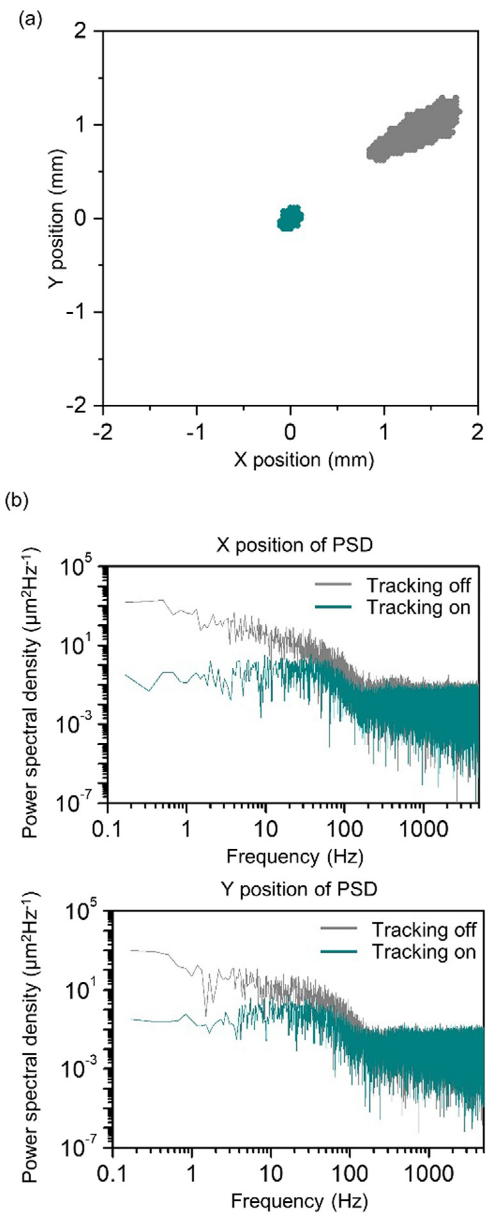

Fig. 3. Angle-of-arrival fluctuation induced by beam wander in terms of the detected X-Y positions on the PSD sensor used for fine tracking control. (a) PSD X-Y position instability; with fine tracking on (blue) and off (gray). (b) Power spectral density of time-dependent PSD X-Y position fluctuations; with fine tracking on (blue) and off (gray).

and a Cassegrain-type reflective telescope for light signal receiving. The light signal is carefully synthesized by extracting a single comb line by means of injection locking to a distributed-feedback diode without the loss of frequency accuracy and stability [25]. The frequency comb is based on an Er-doped fiber laser (C-fiber, Menlosystems GmbH) emitting ultrashort light pulses.

The frequency comb disseminates optical-clock-referenced optical frequencies through its come lines being stabilized with reference to a high finesse optical cavity as described in the authors' previous work [25], This optical stabilization scheme permits both the repetition rate and carrier-envelop offset frequency to be locked so that individual comb lines have a 1.0 Hz linewidth at a 1.0 s integration time. Further, this scheme for multiple wavelength generation will be crucial in the fields of coherent dense-wavelength-division-multiplexing (DWDM) communication, broadband atomic/molecular spectroscopy, and multi-wavelength distance measurement. The light signal synthesized from a single comb line by injection locking is amplified to 20 mW power prior to transmission through bi-directional Er-doped fiber amplifiers (EDFAs). The PAT performance of the tilt-tip control of the transceiver system is evaluated using a 633-nm HeNe laser of 5 mW power installed as a beacon beam. At the same time, the real-time compensation capability of the atmospheric phase noise is evaluated with the pulse repetition rate set at 100.0 MHz in stabilization to the Rb atomic clock by regulating the fiber cavity length with phase-locked loop (PLL) control using an acousto-optic modulator (AOM). This evaluation task performed in this work requires no strict control of the carrier-envelop offset frequency as a prerequisite.

The refractive transmitting telescope expands the light signal to a beam radius ($1/e^2$) of 20 mm, which is necessary to reduce light scintillation while minimizing the optical power loss during transmission from Site A over to the receiver telescope of a 250 mm aperture diameter at Site B. The transmitted light signal is collimated into a single-mode fiber delivery line of a 260 m length, which is necessary to lessen light scintillation by averaging out high-order beam wavefront distortions induced by atmospheric turbulence. Now, for active compensation of the atmospheric phase noise, half of the received optical power at Site B is split by an optical coupler and sent back to Site A through the same optical path in the reverse direction. It is assumed that in the return path the same amount of atmospheric phase noise is accumulated as the preceding one-way trip, i.e., the round-trip signal is supposed to carry twice the atmospheric phase noise of the one-way path. Subsequently, by employing an acousto-optic modulator (AOM) operating at a 40-MHz driving frequency, only half of the total phase noise can be compensated at Site A for the one-way light signal arriving at Site B [14].

Fig. 2 depicts the transceiver system adopted in this investigation. In response to the beam wander and scintillation caused by the atmospheric disturbance, the necessary tilt-tip control action takes place in two steps; one is the coarse control by motorizing the transceiver mount support, and the other is the fine control conducted by employing a fast steering mirror (FSM) in combination with a position sensing detector (PSD). The coarse control permits aligning the whole transceiver system continuously so as to track the beacon laser beam by activating the rotational and azimuthal motions of the telescope mount support. The beacon laser spot is captured using a digital CCD camera, with its X-Y coordinates with respect to the center position (Fig. 2a) are used as the position feedback signals to track the beacon laser with a 2 Hz bandwidth and a 5 arcsec angular resolution. Next, the fine control deals directly with the optical frequency signal so that it can be well coupled into the receiving optical fiber. For this purpose, the used FSM is equipped with a 2.54 mm aperture size, offering a 3-dB bandwidth of 0.87 kHz with an angular resolution of 2 μrad. At the same time, the PSD employed for X-Y position feedback signals provides a fast detection bandwidth of 150 kHz. The FSM and PSD are assembled in a confocal mode with the collimating lens to focus the transmitted light signal on the receiving optical fiber line.

The effect of the tilt-tip coarse control is well demonstrated by a long-term monitoring of the beacon laser spot, of which the X-Y positions tend to keep drifting due to the weight imbalance of the transceiver system itself (Fig. 2b). With the coarse control turned on, however, no notable deflection is detected continuously over an hour even in the presence of beam wander due to wind and structural vibration. In addition, the power fluctuation of the beacon beam measured at the inlet of the telescope remains near an average of 3.5 mW without significant drift or fluctuation for an hour (Fig. 2c). Further, with both the coarse and fine control on, the X-Y positions sensed on the PSD are located right at the conjugation point of the collimator lens of the receiving fiber (Fig. 3a). With the X-Y position data being taken Fourier-transform (Fig. 3b & c), it can be analyzed that the time-dependent atmospheric disturbance is mostly dominating within a few hundreds of Hz in frequency. The resulting beam wander and scintillation can be well suppressed, especially in lower frequencies by a factor of 30 dB.

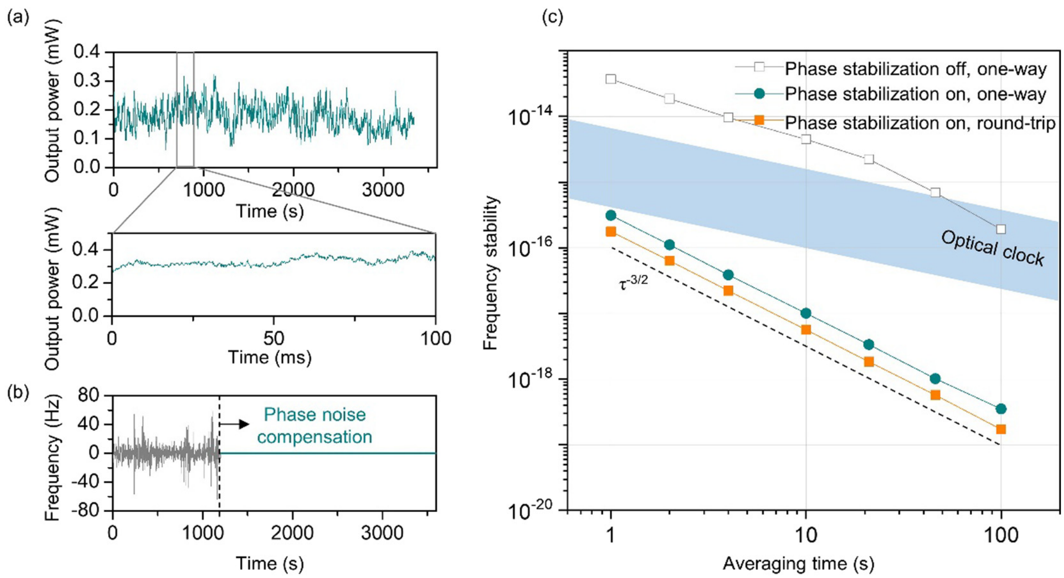

Fig. 4. Stability evaluation of optical frequency transfer with phase noise compensation. (a) Time-dependent optical power fluctuation received at Site B. (b) Doppler shift monitored before and after phase noise compensation. (c) Allan deviations of transferred optical signals for round and one-way trips. The blue band indicates the frequency stability level of state-of-the-art optical clocks, and the black dashed line of $\tau^{-3/2}$ is shown for guidance of the case of no delay-unsuppressed noise [9].

3. Optical frequency transfer

The dual-step control scheme devised in this study is able to provide only long-term but also short-term tilt-tip regulating capability, which is inevitable for reliable optical frequency transfer with active feedback compensation of the atmospheric phase noise. The overall performance index may be quantified in terms of the optical power that can be collected by the receiving fiber placed at the final stage at Site B. Our experimental result confirms that the optical power always exceeds 150 μW (Fig. 4a), which is the minimum level required to amplify the transmitted light signal without the loss of frequency stability. The frequency stability of the finally transmitted light signal is measured by back-to-back comparison, i.e., beating with its original comb line obtained from the original frequency comb at Site A (Fig. 1). When only the dual-step tracking control is operated, without active feedback phase noise compensation, the frequency instability reaches ± 20 Hz due to imperfect phase noise stabilization (Fig. 4b). With active phase noise cancellation on together with the dual-step tilt-tip tracking control, the resulting frequency fluctuation reduces to ± 10 mHz for an hour with a 1 s gate time. In terms of the Allan deviation (Fig. 4c), the frequency instability is found to be 10^{-16} at 1 s averaging time, which is 2 orders of magnitude lower than the raw level of phase noise encountered without feedback compensation at all. With increasing the average time to 100 s, the frequency stability improves to a level of 3.51×10^{-19}, which suffices to deliver state-of-the-art optical clock signals.

4. Conclusion

Our FSO link has been successfully demonstrated over a 1.4 km outdoor path. With coarse tilt-tip tracking, the telescope maintained its seeing position toward the flat mirror located in the middle of the link path. The fine tracking scheme specially devised in this study permitted the optical power level being collected through the receiving fiber to be not less than 150 μW, which is strong enough to be amplified without the loss of frequency stability. Finally, with active phase noise cancellation, the overall performance index of frequency transfer stability reached a 10^{-16} level at 1.0 s averaging, and a 10^{-19} level at 100 s averaging, which is deemed sufficient to deliver the state-of-the-art optical clock signals. With further improvement of our results, we intend to work toward the ground-to-satellite optical frequency transfer with increased beam aperture sizes while the accompanying scintillation is to be suppressed by means of adaptive optics. Furthermore, this optical link with dual-step two tracking systems is expected to cover not only static but also dynamic targets for various LIDAR and communication applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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