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Integrated optical frequency transfer and optical physical layer key distribution with enhanced link reciprocity detection

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Optical fiber transmission has been widely used in communications and metrology, wherein optical frequency transfer (OFT) and optical physical layer secure key distribution (OKD) have become research hotspots [1,2]. Moreover, OFT can perform a comparison between state-of-the-art optical atomic clocks and implement coherent optical phase transfer over long distances to support geodesy [1,3]. Meanwhile, OKD based on optical feature fluctuations can offer advanced security for secure communication, deriving from the uniqueness of the fiber channel feature fluctuations [2,4]. To date, OFT and OKD have been researched and demonstrated, respectively. In OFT-based applications involving security, however, OFT and OKD are required [3], and combining OFT and OKD can provide the technology base to improve the transmission performance and security of communication systems simultaneously [5, 6].

In this article, an integrated OFT and OKD scheme using the common lasers over a single fiber is proposed, as shown in Figure 1(a). The transferred light fluctuates in multiple optical dimensions, such as optical phase noise and orthogonal polarization mode (OPM) since the transmission features of optical fiber are changing constantly with external thermal and vibrational fluctuations. In the proposed integrated scheme, the fluctuations of the single transferred light in multiple optical dimensions are extracted simultaneously by bidirectional transmission over a fiber link for OFT and OKD. Specifically, the detected optical phase noise is canceled to achieve stable OFT, and the multidimensional fiber feature information fluctuations are employed to generate highly correlated random waveforms as the entropy source of OKD. Compared to the individual OFT and OKD systems, the integrated scheme has the potential to improve the performance and security of communication systems while promoting the integration of the optical clock network and telecommunication network while saving the light source and fiber resources. Furthermore, since both the stable OFT and credible OKD rely on the bidirectional reciprocity of the transmission link, detection of a transmission link reciprocity can be introduced for secure time and frequency transfer [7], for example, link reciprocity detection is realized by monitoring the stability of OFT and the decoding accuracy (DA) of the OKD-based communication. Experimentally, an integrated OFT and OKD system is demonstrated over a 20-km fiber link. The stability in terms of Allan's variance (ADEV) of 1.82×10^{-16} at 1 s and 5.98×10^{-20} at 10000 s for OFT is obtained. Moreover, the correlation of the random waveforms between two legal users for OKD is better than 0.98.

Experimental setup. Figure 1(b) presents the experimental setup over a 20-km single-mode fiber (SMF), which is placed in an air-conditioned lab with peak-to-peak temperature fluctuations of approximately 3°C. A narrow-linewidth laser (NKT X15) with an optical frequency of approximately 193 THz and a linewidth of less than 100 Hz is used as the light source for the experiment system under the common clock condition. The stable OFT is implemented by a two-way comparison, and the OKD is implemented based on the random phase fluctuation between two OPMs [4]. The light at the Alice side is split into two parts. One part is reflected by a Faraday mirror and remains in the Alice side as the reference light. Meanwhile, the other part is sent to the optical fiber after passing through the acousto-optic modulator and the polarizer (POL). The polarization transmission direction of the POL is set parallel to the polarization direction of the output light from the laser. The optical phase noise and polarization of the light are constantly changing with external factors on SMF. On the Bob side, the light intensity received is changed with polarization after passing the POL. The light received is split into two parts, one of which is sent to a photodetector and an analog-to-digital converter to record the fluctuation of light intensity. The recorded fluctuation is employed as the entropy source for key generation. The other part is used for optical heterodyne detection with the local reference light to extract phase noise and realize stable OFT. Since the polarization transmission direction of the POL is set parallel to the polarization direction of the output light from the laser, the fluctuation of received light intensity will not exert additional influence on the extraction of phase noise. After the bandpass filters and amplification, the beat notes are measured by a high-resolution frequency counter (K + K FXE) operating in Π-type, illustrating the detected optical phase noise of the transmission link. Alice can obtain a random waveform highly correlated with Bob, and the fiber introduces optical phase noise through a

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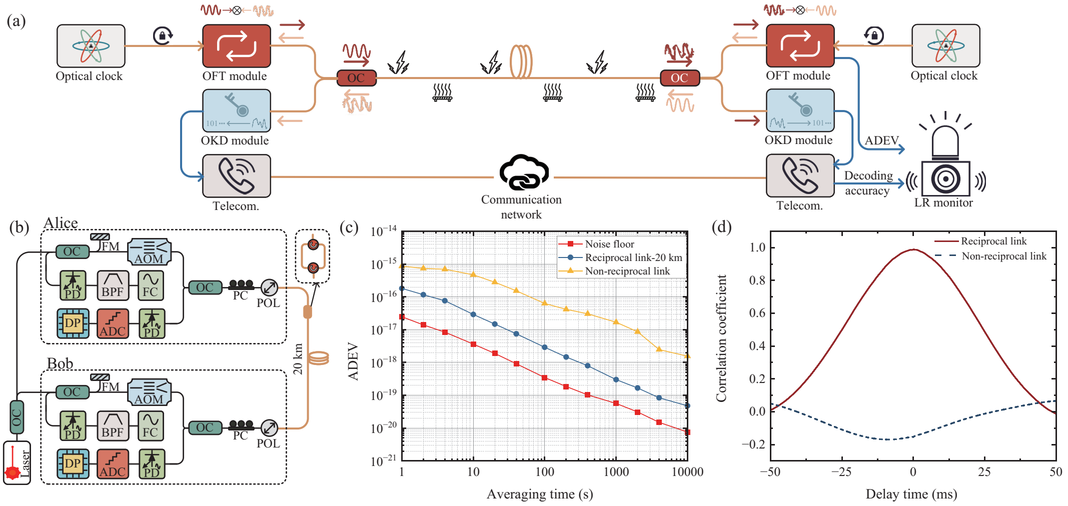

Figure 1 (Color online) Principle, experimental setup, and results. (a) Principle of an integrated OFT and OKD scheme. OFT: optical frequency transfer; OKD: optical physical layer secure key distribution; ADEV: Allan's variance; LR: link reciprocity. (b) Experimental setup. OC: optical coupler; AOM: acousto-optic modulator; PC: polarization controller; POL: polarizer; PD: photodetector; BPF: bandpass filter; FC: frequency counter; ADC: analog-to-digital converter; DP: data processor; FM: Faraday mirror. (c) Measured stability in terms of ADEV over back-to-back links (noise floor), 20-km reciprocal links, and non-reciprocal links. (d) Cross-correlation functions of the signals obtained by Alice and Bob over the reciprocal and non-reciprocal links.

similar process.

Non-reciprocity detection is also demonstrated by inserting a non-reciprocal part, which is realized by employing two optical circulators with a 30-cm pigtail for each port, as shown in the inset of Figure 1(b).

Results and discussion. Figure 1(c) shows frequency stability in terms of ADEV for the experimental OFT. Based on the proposed integrated scheme, the noise floor of the system is better than 2.49×10^{-17} at 1 s and 7.59×10^{-21} at 10000 s over 1-m fiber. Over the 20-km reciprocal link, the measured ADEV can be better than 1.82×10^{-16} at 1 s and 5.98×10^{-20} at 10000 s, indicating that the stable OFT is achieved.

Figure 1(d) shows the cross-correlation function between the two random waveforms. The results reveal that the cross-correlation coefficient peak is better than 0.98 over the reciprocal link, validating the feasibility of the OKD based on the proposed integrated OFT and OKD scheme. The waveforms recorded in Alice and Bob and the calculation of the key rate are shown in Appendixes A and B.

Over the non-reciprocal link, the stability of OFT in terms of ADEV is better than 8.63×10^{-16} at 1 s and 1.56×10^{-18} at 10000 s, and the correlation coefficient between the random waveforms obtained in Alice and Bob with any time delay is less than 0.1, as shown in Figures 1(c) and (d). The waveforms recorded over the non-reciprocal link by the legal users are presented in Appendix A. Compared with the results obtained over the reciprocal link, the short- and long-term stability of OFT are both deteriorated, and the random waveforms recorded by Alice and Bob are completely uncorrelated with each other. Furthermore, the DA of the secure communication based on the key generated by the recorded random waveforms will deteriorate significantly. Although the deterioration of the stability of the OFT and the DA of the secure communication based on OKD may rely on multiple factors, by checking the two parameters in the integrated system simultaneously, the presence of non-reciprocal links can be detected correctly.

Conclusion. In summary, an integrated scheme using common lasers over a single fiber is proposed, which can advance the convergence of optical clock and optical communication networks while saving laser and fiber resources. Moreover, the integrated OFT and OKD scheme can be used to detect the link reciprocity for secure time and frequency transfer. The proposed scheme is demonstrated experimentally based on two-way comparison and OPM fluctuation over a 20-km fiber link. The stability in terms of ADEV of 1.82×10^{-16} at 1 s for OFT and the correlation of random waveforms between two legal users better than 0.98 for OKD are obtained.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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