Parallel Transfer of Time and Frequency Signals Over Single Optical Carrier via Fiber Link

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***Abstract*—We present parallel transfer of optical frequency, radio frequency, and time reference over single optical carrier. This method makes full use of both coherent optical detection and pseudo-coded spread spectrum modulation, which benefits with simultaneous detection of the multiple time and frequency signals, effectively reducing the dispersion and non-reciprocal effect of WDM-based fiber link. UTC (BIRM) is precisely regenerated through parallel transfer and feedback control at the remote site. Preliminary experiments over a 120 km single fiber channel indicate that the fractional optical frequency instability reaches 7.27 $\times 10^{-16}$ and 3.25$\times 10^{-18}$ at 1 s and 10^4 s averaging time, respectively. Meanwhile, the fractional time instability and radio frequency instability reach 0.02 ps and 7.81$\times 10^{-17}$ at 10^5 s averaging time, respectively. This approach has a potential in extending to free-space simultaneous transfer of time and frequency to support satellite-to-ground/inter-satellite precise time-frequency comparisons and high-speed laser communications.**

Keywords—metrological instrumentation, fiber optics links and subsystems, lasers and laser optics, phase measurement

I. Introduction

In recent years, the rapid development of optical frequency standards has driven an increasing demand for ultra-stable frequency distribution [1-3]. Accurate regeneration of the optical frequency standards over the link is crucial for scientific research and advanced applications [4-7]. Additionally, high-stability time-frequency transfer and synchronization is of great significance to tests of fundamental physics and precise interferometric measurement [3, 7-9].

Here we present parallel transfer of time and frequency signals over a single fiber channel, which incrementally utilizes electro-optic modulation and acousto-optic modulation. Time and radio frequency transfer is achieved by two-way comparison and feedback control. Meanwhile, the stability of frequency is improved through low-noise frequency conversion. Furthermore, the coherent optical frequency transfer is simultaneously realized based on the principle of Doppler noise suppression. The dispersion and inconsistent delays of WDM-based fiber link are eliminated by single optical carrier. This method also supports code division multiplexing by employing pseudo-code spread spectrum modulation, which enables multi-node time and frequency transfer network.

II. Methods

Figure 1 demonstrates the main schematic diagram of parallel transfer. The local site generates time-frequency references, including coherent optical frequency reference output by an ultra-stable narrow linewidth master laser, 1PPS time reference and 10MHz reference output by a maser clock, which is directly traceable to UTC (BIRM). At the remote site, the slave laser and slave clock are locked to achieve stable regeneration of the time-frequency reference signals through the transfer fiber link. At the local site, the modem generates pseudo-code spread spectrum modulation signals based on the interactive data and intermediate frequency carrier, which is referenced by the maser clock.

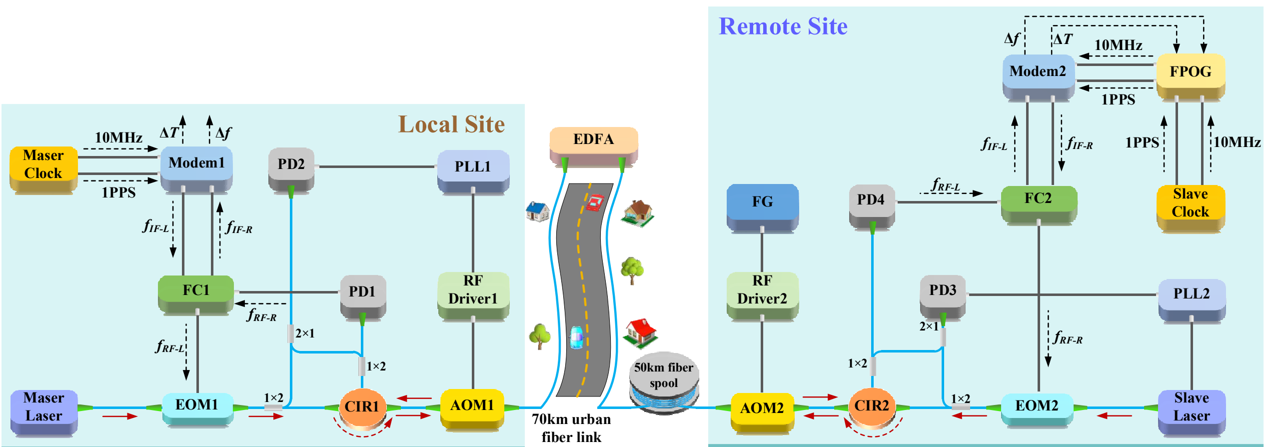

Fig. 1. Principle of parallel transfer of time, radio frequency and optical frequency over single optical carrier via fiber link. FC: frequency converter, EOM: electro-optic modulator, PD: photodetector, CIR: circulator, PLL: phase locked loop, AOM: Acousto-optic modulator, EDFA: Erbium-Doped Fiber Amplifier, FG: function generator, FPOG: frequency and phase offset generator.

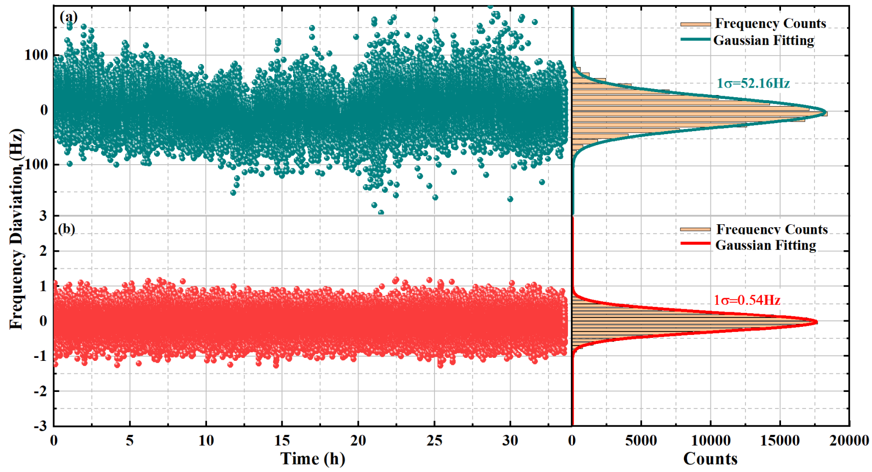

Fig. 2. Beat frequency data contrast (a) Free-running link (b) Stabilized link.

The time-frequency signal is up-converted to the microwave frequency for increasing the measured frequency difference of the RF references between the two sites. After electro-optic amplitude modulation, one part is used as a local optical frequency reference. And the other part is transferred to the remote site through acousto-optic frequency shift and 120 km fiber link, which consists of 70 km of urban fiber and 50 km spooled fiber in a laboratory environment. The signals after the transfer link is divided into two parts. One part is used for heterodyne locking to achieve coherent optical frequency transfer. And the other part is transmitted through down-conversion and demodulation for radio frequency and time transfer. The optical frequency noise over the fiber can be compensated in real time by Doppler noise suppression. On this basis, a stable coherent optical carrier is formed over the full link. The modems between the two sites receive the incoming spread spectrum pseudo-code modulation signals, which contain time and frequency information under each reference. High-precision time-frequency transfer is achieved, according to the principle of two-way transfer. At the remote site, the time-frequency differences output by the modem are used to regulate the 10MHz signal and 1PPS signal output by the frequency and phase offset generator, forming a closed-loop feedback control to achieve remote reproduction of the RF reference.

III. Results

A loopback arrangement is used to verified the fractional instability. We firstly evaluate the performance of the coherent optical frequency transfer by measuring the out-of-loop beat frequency between the maser laser and the slave laser. A Π-type frequency counter (K+K FXE) is used to record the frequency data. As shown in Fig.2, the peak-to-peak frequency jitter is improved from 400 Hz to 2.5 Hz during 34 h measurement duration with the noise suppression. Meanwhile, 1σ of frequency counts obtained by Gaussian fitting is apparently improved from 52.16 Hz to 0.54 Hz.

Fig.3 shows the fractional optical frequency instability. At an averaging time of 1 s, 10^2 s, and 10^4 s, the fractional optical frequency instability is improved to 7.27×10^{-16}, 8.12×10^{-17}, and 3.25×10^{-18}, respectively. Within the integration time of 1-10 s, the deviation from 1/τ slope of the stabilized link may be caused by out-of-loop residual noise. Fiber length reduction and temperature control will be further adopted to optimize the transfer performance.

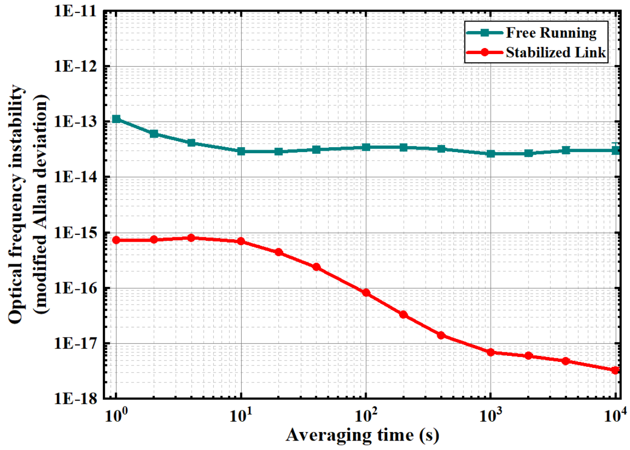

Fig. 3. Fractional coherent optical frequency transfer instability comparison.

At the remote site, time reference and radio frequency are synchronized to the local site by the continuously measured time-frequency differences and the feedback to the frequency and phase offset generator, as shown in Fig.4.

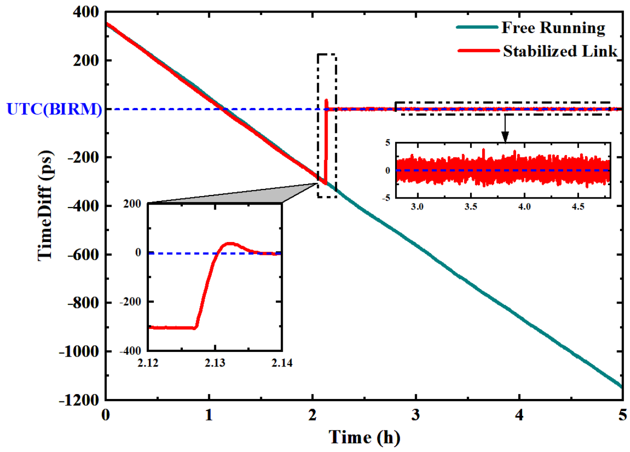

Fig. 4. Time difference curves between two sites measured by modems.

There is a linear drift of about 78.4 fs/s of the time difference between the two sites for an inherent frequency difference of about 0.8 μHz between the 10 MHz frequency output by the clocks. During the time-frequency adjustment, the synchronization rate of the frequency and phase offset generator is controlled within 1 mHz for ensuring enough carrier-to-noise ratio of the modem and the transfer accuracy, that is, the fastest rate of time-frequency adjustment is 100 ps/s. In the stable state of time-frequency synchronization, the peak-to-peak of the time difference between the two sites can be controlled within 7 ps.

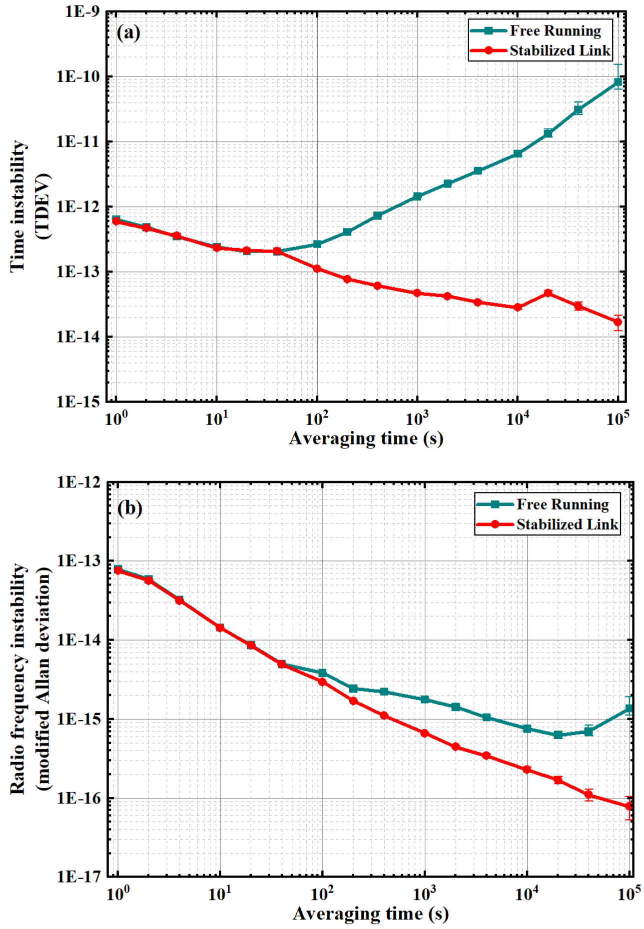

Fig. 5. Comparison of curves before and after synchronization. (a) Time instability. (b) Radio frequency instability.

The comparison of time and radio frequency instability curves before and after synchronization are shown in Fig.5. The instability between the two sites is significantly improved by adjustment of the frequency and phase offset generator at the remote site. The time stability is improved to 0.11 ps, 0.03 ps, and 0.02 ps at an averaging time of 10^2 s ,10^4 s, and 10^5 s, respectively. And the radio frequency is improved to 2.95×10^{-15}, 2.23×10^{-16}, and 7.81×10^{-17} at an averaging time of 10^2 s ,10^4 s, and 10^5 s, respectively.

IV. Conclusions

We demonstrate a time-frequency parallel transfer method to realize remote synchronization of coherent optical frequency, radio frequency and time reference. Over 120 km single fiber channel verification, the results show that at an averaging time of 1 s, 10^2 s, and 10^4 s, the fractional instability of optical frequency transfer reaches 7.27×10^{-16}, 8.12×10^{-17}, and 3.25×10^{-18}, respectively. UTC (BIRM) is precisely regenerated through parallel transfer and feedback control at the remote site. At an averaging time of 10^2 s, 10^4 s, and 10^5 s, the fractional instability of radio frequency transfer reaches 2.95×10^{-15}, 2.23×10^{-16}, and 7.81×10^{-17}, respectively, and the fractional instability of time transfer reaches 0.11 ps, 0.03 ps, and 0.02 ps, respectively. This scheme provides a feasible solution for simultaneous transfer of hybrid time-frequency signals through a single channel, effectively improving the channel utilization of time-frequency networks. It can be further applied to achieve remote precise traceability for the next generation of optical time and frequency metrology.

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