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Portable Atmospheric Transfer of Microwave Signal Using Diode Laser with Timing Fluctuation Suppression

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Abstract

We demonstrate an atmospheric transfer of microwave signal over a 120 m outdoor free-space link using a compact diode laser with a timing fluctuation suppression technique. Timing fluctuation and Allan Deviation are both measured to characterize the instability of transferred frequency incurred during the transfer process. By transferring a 100 MHz microwave signal within 4500 s, the total root-mean-square (RMS) timing fluctuation was measured to be about 6 ps, with a fractional frequency instability on the order of 1×10^{-12} at 1 s, and order of 7×10^{-15} at 1000 s. This portable atmospheric frequency transfer scheme with timing fluctuation suppression can be used to distribute an atomic clock-based frequency over a free-space link.

Keywords

atmospheric communication; frequency transfer; diode laser; timing fluctuation suppression

1 Introduction

Timing and frequency transfer is important to precision scientific and engineering applications, such as frequency standards, optical communication, radar, and navigation [1]–[4]. Over the past decades, many studies of highly stable frequency distribution were focused on the transfer technique via fiber link [5]–[10]. Recently, timing and frequency transfer based on free-space links has begun to attract a remarkable attention as it can provide higher flexibility than fiber links [11]. This free-space frequency transfer can benefit the application for high-fidelity optical links in the future space-terrestrial networks [12] and alternative navigating schemes independent of the global positioning system [13]. In the last few years, there have been several important works in free-space transfer of optical and microwave frequency information. Sprenger et al. studied the frequency transmission of both optical-frequency and radio-frequency (RF) clock signals over 100 m atmospheric link using a continuous wave (CW) laser [14]. Gollapalli and Duan used a pulsed laser to achieve an atmospheric transfer of both RF and optical clock signals over 60 m free-space link [15], [16]. With two cavity stabilized optical frequency combs (OFC), Giorgetta et al. demonstrated an optical time-frequency transfer over 2 km free-space link via two-way exchange between the coherent OFCs with the femtosecond-level resolution of [17]. Furthermore, they improved their experimental setup and achieved a highly precision timing-frequency transfer over a 10 km free-space link in a city environment [18]. Recently, Kang et al. reported a technique of timing jitter suppression for indoor atmospheric frequency comb transfer, which achieved a few femtoseconds timing fluctuation [19].

Although these experiments have demonstrated that the current atmospheric frequency transfers achieved synchronizations between two sites over free-space links, some of them did not suppress the timing fluctuations affected by air turbulence [14]–[16]. In this case, the extra timing fluctuation limits the applications of laser-based atmospheric frequency transfer in areas where sub-picosecond synchronization systems should be constructed. However, the experimental systems for suppressing the timing fluctuations were not concise and robust. For example, the two-way time and frequency transfer (TWTFT) technique used two cavity-stabilized frequency comb to bidirectionally transfer timing signals, which increased the difficulty of some portable applications [17], [18]. The balanced optical cross-correlators (BOC) technique [19] used a crystal to generate optical harmonics, which could result in the difficulty of collimation and focus in the outdoor use. Therefore, it is a big challenge to build a simple and portable sub-picosecond frequency transfer system in outdoor environment.

In this paper, we demonstrate an outdoor atmospheric transfer of microwave signals over free-space link using a compact diode laser with a timing fluctuation suppression technique.

2 Schematic of Timing Fluctuation Suppression in Frequency Transfer

In order to transfer a microwave signal from a transmitter to a receiver via an optical carrier, the most convenient scheme has three steps: directly loading the microwave signal onto the

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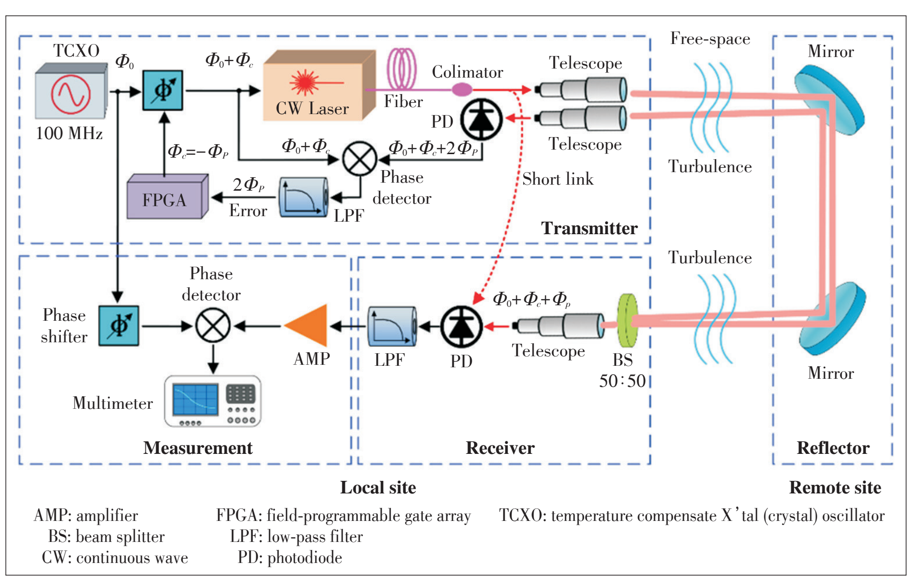
optical carrier; transferring the light to remote receiver via an optical link; recovering this microwave signal with a photo-detection scheme [20]–[22]. However, in an actual frequency transfer system, the three steps introduce excess phase noise or timing jitter into the signal, and result in the degradation of stability of the original microwave signal. On the transmitter, the intense noise of the optical light, primarily introduced by the instability of the laser's current driver, determines the quality of the local modulated optical carrier. Over the transmission link, the air turbulence and temperature drift may introduce excess strong timing jitter and drift into the transmitted optical light in the atmosphere. On the receiver, the photodetection electronics, including photodiode, amplifier, and filter, may also introduce electronic excess noise in the recovered signal. Altogether, these noise sources contribute to the total timing fluctuations in the microwave transmission system. For an atmospheric microwave transfer over a long distance transmission link, the timing fluctuations and frequency instability are mainly caused by the air turbulence and temperature drift. Literatures reveal that the air turbulence induces fluctuations of the refractive index [23], [24], which could directly lead to excess phase noise in the transmitted frequency signal. Therefore, in order to improve the stability of the frequency transfer significantly, the timing fluctuation should be suppressed by a phase compensation technique. Here, based on the three-step scheme mentioned above, we use an upgraded atmospheric frequency transfer with phase compensation.

Fig. 1 shows the schematic of the frequency transfer with a timing fluctuation suppression technique. At the local site, an optical carrier is provided by a commercial distributed feedback laser (DFB) diode which has a center wavelength of 1550 nm. A 100 MHz microwave signal generated from a temperature compensate X'tal oscillator (TCXO) is phase shifted first, and is then loaded onto the optical carrier via a direct current amplitude modulation (AM) scheme. The modulated laser beam is coupled to a telescope via an optical collimator, and is then launched into the free-space transmission link. At the remote site, the beam is sent back to the receiver by a golden-coated reflector. At the receiver, half of the transmitted beam is reflected to the transmitter along the same optical path by a 50:50 beam splitter. The reflected beam is collected by another telescope and is tightly focused onto a high-speed photodiode at the transmitter. The detected microwave signal with twice timing fluctuations is amplified and then mixed with the phase-shifted microwave signal to generate a phase error signal. This error signal is filtered to eliminate the harmonic components and fed back to a digital field-programmable gate array (FPGA) processor, to calculate out the one-way timing fluctuation. Based on the calculation, the FPGA processor produces a controlling signal to adjust the phase shifter, to compensate the timing fluctuation (Fig. 1). At the receiver, with another high-speed photodiode, the remaining beam is also converted to a microwave signal which is used to compare with the RF reference source, to estimating the performance of the frequency transmission.

The mechanism of the timing suppression is explained below. As shown in Fig. 1, we assume that the microwave signal has an initial phase. At the transmitter, this signal is phase-shifted with Φ_c, and then delivered to the receiver over a free-space transmission link. Assuming the air turbulence introduces a phase fluctuation Φ_p to the transmitted signal over the one-trip free-space link, the total phase delay of the recovered microwave signal at the receiver is given by $\Phi_{total}=\Phi_0+\Phi_c+\Phi_p$. With a 50:50 beam splitter, half of beam is reflected to the transmitter along the almost same optical path, which will introduce a same turbulence-affected phase fluctuation Φ_p. In this case, the round-trip returned microwave signal detected by the photodiode has a phase delay $\Phi_0+\Phi_c+2\Phi_p$ due to the twice turbulence effect. After eliminating the fixed phase $\Phi_0+\Phi_c$ by comparing to the phase-shifted reference signal, we get an error signal with the phase error information $2\Phi_p$. Here, this error signal is fed back to the FPGA processor to calculate out the one-way timing fluctuations Φ_p, and the processor also produces a controlling signal to adjust the phase shifter as the following equation $\Phi_c=-\Phi_p$, to compensate the turbulence-affected phase fluctuation. When the FPGA is active, the phase error Φ_p will be compensated, and consequently, the timing fluctuation affected by air turbulence for the recovered microwave signal on the receiver will be corrected. Based on the schematic and analysis of the timing fluctuation suppression above, we built up an actual atmospheric frequency transfer experiment,



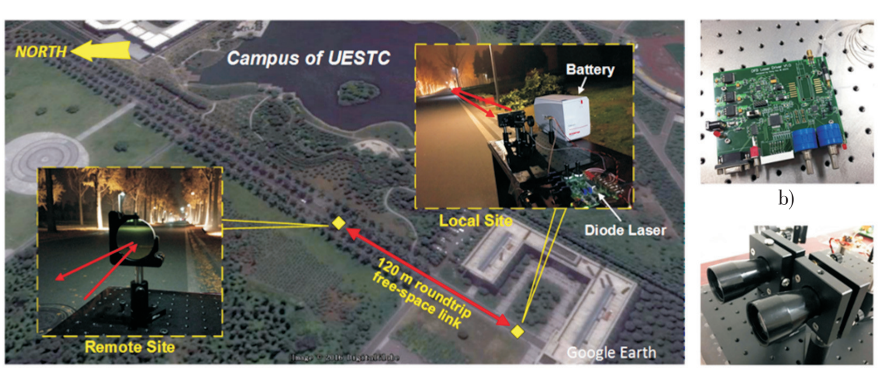
▲**Figure 1. Schematic of atmospheric frequency transfer with timing fluctuation suppression.**

which is shown in **Fig. 2**.

3 Experimental Setup of Frequency Transfer

The atmospheric frequency transmission link was located on a long avenue in the campus of the University of Electronic Science and Technology of China (UESTC) (Fig. 2a). The local site included a transmitter and a receiver, and the remote site included a mirror as beam reflector. The distance between local and remote sites was 60 m. On the local site, a modulated laser beam generated from a diode laser with 1550 nm center wavelength, 3 MHz linewidth, and 18 mW output power, was launched from the transmitter via a 1550 nm AR-coated telescope, and the beam size over free-space was about 20 mm. On the remote site, a golden-coated 2 inch mirror was mounted on a sturdy mount which was anchored on a platform along the avenue. The beam was sent back to the receiver's telescope on the local site, and collected by a fast photodetector to recovery a microwave signal. Here, the telescopes on local site were anchored on another platform along the same avenue (Fig. 2c). The forward and backward transfer formed a total 120 m roundtrip transmission link. Note that, our experimental setup was in an open-air environment and far from the laboratory rooms. This was attributed to a UPS-based battery which supported all electronic components in our system.

Our experiment was conducted in our campus at a normal night. In this experiment, we measured the timing fluctuations and frequency instability of the transferred microwave signal caused by air turbulence. In this case, a 100 MHz microwave signal with a power of 20 mW generated from the TCXO was loaded onto the DFB laser. In our experiment, we launched the laser beam with 18 mW output power, and detected 2 mW round-trip returned beam on the transmitter's photodetector. The great optical power loss is mainly due to the bad air quality in our city. Here, the photo-detection of the retro-reflected signal can introduce additional phase-error due to limited optical power as well as photo-detection nonlinearity. To minimize the residual timing error, the beam must be focused on the center of the photodiode (PD)'s detection area to obtain the best signal to noise ratio (SNR). In addition, the collected 2 mW optical beam is enough to produce the electronic signal for the next stage. In this case, the residual timing error can be ignored since it is far less than the timing fluctuation affected by air turbulence. We extracted and amplified the round-trip returned microwave signal by a band-pass filter and RF amplifier, to obtain a 7 dBm microwave signal. This signal was compared to the local reference signal to produce an error signal. By sending the error signal into the FPGA processor, a controlling signal was produced to drive the phase shifter, so that the timing fluctuation caused by the air turbulence could be compensated. In this servo loop, the compensation bandwidth of the FPGA processor is about 10 kHz. Therefore, we believe the most of fluctuations affected by air turbulence can be suppressed in this bandwidth. To evaluate the quality of the transmitted signal with the proposed timing fluctuation suppression technique, we collected the transmitted beam on the receiver, converted it to a 100 MHz microwave signal on the photodiode, and amplified it with a high-gain low-noise RF amplifier. The amplified 7 dBm microwave signal was mixed with the reference signal to produce a DC output. After low pass filtering, the DC signal was recorded by a high-resolution voltage meter. Our transfer experiment started at 1 a.m. and ended at 5:30 a.m. roughly. Since the wind was not very strong during the measuring time, the beam sway caused by the amplitude noise was not very significant in this case.



a) b) c)

UESTC: University of Electronic Science and Technology of China

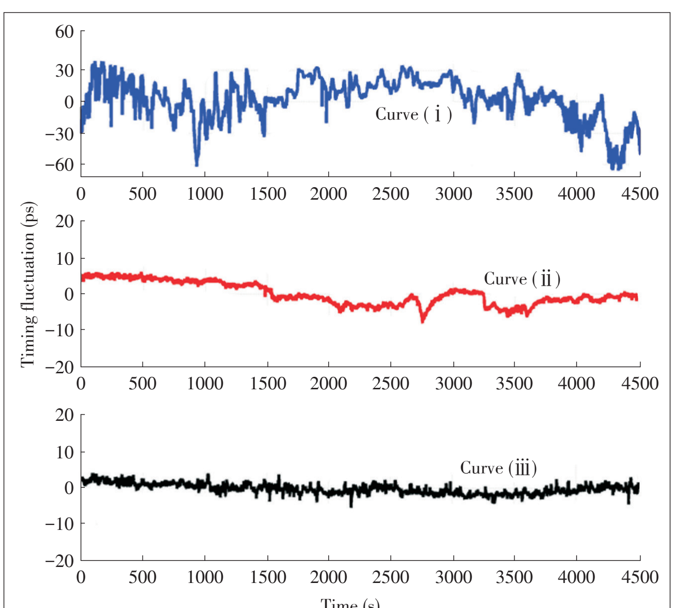
▲Figure 2. a) The actual experimental setup for portable atmospheric frequency transfer with the timing fluctuation suppression. The local and remote sites are located on a long avenue in UESTC. The distance between them is 60 m and the total free-space transmission distance is 120 m; b) the diode laser with a low-power current driver; c) the telescopes for launching and receiving beams.

4 Experimental Results and Discussion

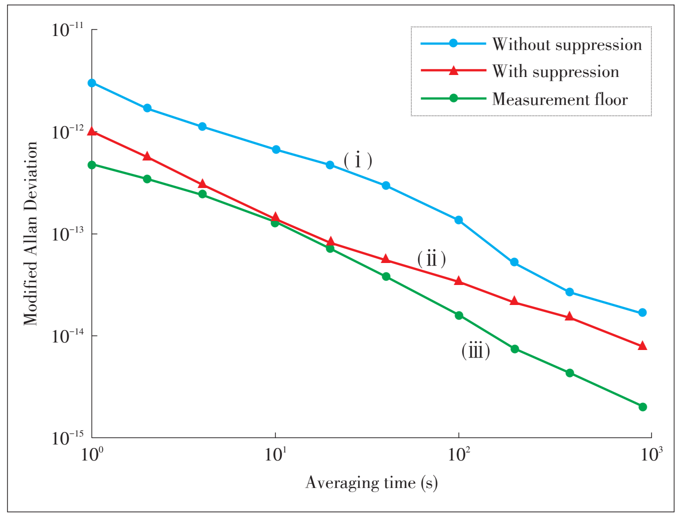
In this experiment, the two telescopes were put as close as possible at the transmitter side, to get the identical turbulence effect over the bidirectional transmission links. Since the phase compensation can suppress the extra timing fluctuations affected by turbulence, we believe the quality of the frequency transfer could be improved distinctly, compared to the direct link. Here, we measured the timing fluctuations and frequency instabilities of the transferred microwave signals with and without the timing suppression, respectively. The timing fluctuation results are shown in **Fig. 3**. Curve (i) shows the timing fluctuation of the transmitted 100 MHz microwave signal without timing fluctuation suppression, and its calculated RMS timing fluctuation is about 22 ps within 4500 s.

Curve (ii) shows the timing fluctuation of transmitted microwave signal with timing fluctuation suppression, and the RMS timing fluctuation is reduced to about 6 ps within 4500 s. Here, we also measured the timing fluctuations of frequency transfer with a short link as the measurement floor (Fig. 1), which is just attributed by the electronic noise of our photonic system. For this short link, its timing fluctuation is shown as Curve (iii) and the RMS timing fluctuation is calculated about 1.3 ps within 4500 s. By comparing the transmission links with and without timing fluctuation suppression, we believe that the phase compensation technique could suppress the timing fluctuation effectively.

Fig. 4 demonstrates the instability results of the transferred microwave signal. Curve (i) is the relative Allan Deviation result of the transferred signal without phase compensation, which is calculated from the sampled data in Fig. 3. It shows the 120 m free-space frequency transmission without timing fluctuation suppression has a instability of 3×10^{-12} for 1 s and 2×10^{-14} for 1000 s. Curve (ii) is the relative Allan Deviation result for the transferred signal with timing fluctuation suppression, and it shows the 120 m free-space frequency transmission with timing fluctuation suppression has a instability of 1×10^{-12} for 1 s and 7×10^{-15} for 1000 s. Curve (iii) shows the measurement floor, which was obtained via a short link (Fig. 1). With the comparison of these curves, we can find that the instability of the free-space transmission link with timing fluctuation suppression is improved distinctly. Note that, curve (iii) is merely the lower bound of the instability incurred during atmospheric transfer of microwave signals. This is because it was measured only with the short link, and most of the turbulence effect was cancelled. This Allan Deviation measurement floor in our case is limited by the stability of the frequency source and the electronic noise on local site. The accuracy achieved by our atmospheric frequency transfer system with phase compensation may be quite adequate with some short distance free-space applications. With comparison with instability of our transfer results and a commercial Cs clock (5071A) [25], we can find that the instability of our transmission link is lower. Therefore, we believe that disseminating a Cs or Rb clock signal over free-space link by using the proposed portable atmospheric frequency transfer scheme in this paper is feasible. The compensation bandwidth of our loop is about 10 kHz, and most of the timing fluctuation with the frequency below 10 kHz can be suppressed. However, this also limits the distance of the transmission link, because the short compensation time (100 μs, corresponding to 10 kHz) limits the round-trip travel time of optical beam. In this case, the distance will be limited to tens km (by multiplying compensation time and light velocity). Therefore, our technique for atmosphere transfer of microwave can be used in the application of short distance synchronization between two or more stations.



▲ **Figure 3. Timing fluctuation results for the atmospheric microwave transfer. Curve (i) is the result for 120 m free-space transmission link without timing fluctuation suppression; Curve (ii) is the result for 120 m free-space transmission link with timing fluctuation suppression; Curve (iii) is the result for a short link at local site as a measurement floor.**



▲ **Figure 4. Instability results for the atmospheric microwave transfer: (i) relative Allan Deviation between the transferred microwave and reference signal without timing fluctuation suppression; (ii) relative Allan Deviation with timing fluctuation suppression; (iii) Allan Deviation for a short link as the measurement floor.**

5 Conclusions

We demonstrate an outdoor atmospheric frequency transfer technique using a compact diode laser with a timing fluctuation suppression. The RMS timing fluctuation for 120 m transmission of a 100 MHz clock frequency was measured to be approximately 6 ps within 4500 s, with fractional frequency instability on the order of 1×10^{-12} at 1 s and the order of 7×10^{-15} at 1000 s. Comparing the instability of transfer results of the proposed system and a commercial Cs clock (5071A), we find that the instability of our transmission link is lower than the Cs clock. We believe that disseminating a Cs or Rb clock signal over free-space link by using the proposed atmospheric frequency transfer scheme is feasible. We will challenge in building a femtosecond portable atmospheric frequency transmission link with longer distance. There will be some improvement to achieve this. For example, we will use higher frequency microwave to increase the resolution of phase discrimination and higher power laser to increase the SNR on the photodetection. In addition, a fast steering mirror will be used to cancel the beam vibration.

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