Large Doppler shift suppressed free space optical frequency comparison

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Free-space optical clock networks will enable applications such as navigation, gravitational sensing, precision spectroscopy and fundamental physics experiments, but have to cope with motion between the clock sites, resulting in significant Doppler shifts and disrupt the reciprocity of the two-way measurement. Here we demonstrated a novel Doppler shift suppressed method, namely, a time-delay-based Doppler shift suppression method for free space two-way optical frequency comparison (TWC). The effect of the Doppler shift on the instability of the optical frequency synchronization can be effectively improved by adding an extra delay before the measurement site. When the amplitude of the sinusoidal Doppler shift change is A and the period is T_0, τ_0 is the link delay and τ_d is the additional delay, the relative fractional frequency instability in terms of Allan deviation (ADEV) can be written as, $\sigma_{tw\_d}(\tau) = \frac{2AT_0}{\pi f_0 \tau}\left|\sin\left(\frac{\pi(\tau_0-\tau_d)}{T_0}\right)\right|\sin^2\left(\frac{\pi\tau}{T_0}\right)$. Consequently, when $\tau_d = \tau_0$, the effect of Doppler shift can be passively suppressed. As shown in Fig. 1(a), we build a 1.2 km round-trip free space link at Shanghai Jiao Tong University campus. We use a narrow-linewidth laser (NKT X15) at a frequency nearly 193 THz as the optical reference and the interferometer structure is implemented with a free space optical module to avoid precise temperature control. Without any Doppler shift, the TWC system can improve the ADEV result by four orders of magnitude compared with the free running link, achieving 9.4×10^{-20} at 1000 s. To simulate the Doppler shift, we use the arbitrary waveform generator (AWG) to modulate the driving frequency for one of the acousto-optic modulators (AOMs) with the sinusoidal amplitude of 1 MHz (the radial velocity is 0.78 m/s) and a period of 500 s. With the Doppler shift, the ADEV deteriorate to the to 1.8×10^{-18} at 1000 s as shown in Fig. 1(e). By adding a delay of about 4 μs, the fractional frequency instability can be corrected to 3.4×10^{-19}. We also calculate the effect of delay mismatch $\Delta\tau$ on the instability of the system by theoretical simulation as Fig. 1(f) shows. When $\Delta\tau$ is less than 5 ns, the effect of Doppler shift can be completely suppressed. In summary, we first propose a time-delay-based Doppler shift suppression method, which provides an effective solution for free space time and frequency synchronization under the motion platform.

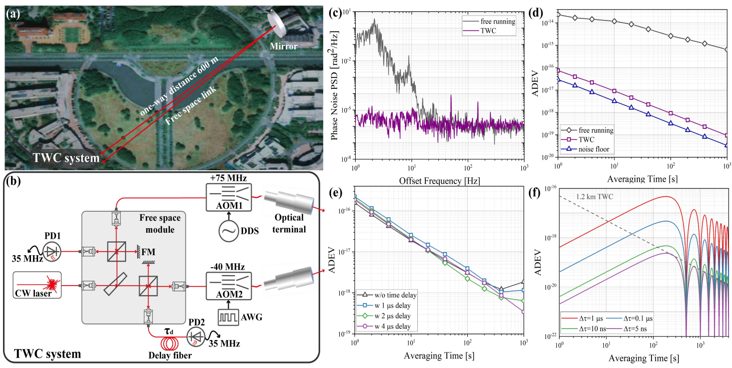

Fig. 1: (a) The 1.2 km round-trip free space link at Shanghai Jiaotong University. (b) Schematic diagram of the time-delay TWC system for the Doppler shift suppression. PD: photodetector, FM: Faraday mirror, AOM: acousto-optic modulator, DDS: direct digital synthesizer, AWG: arbitrary waveform generator. (c) Phase noise power spectral density (PSD) results. (d) ADEV results in absence of the Doppler shift. (e) Doppler suppression results using the time-delay method. (f) The ADEV deteriorates caused by the delay mismatch obtained from the theoretical calculation.