Delivery of Optical Frequency References through Atmosphere using a Frequency Comb

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Abstract: Optical frequency references are transferred in the atmosphere over a 60-m round-trip propagation distance. Fractional instability ~10^{-14}–10^{-13} at 1s is observed and large phase modulation caused by air fluctuation leads to sizeable linewidth broadening.

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1. Introduction

Highly precise frequency/timing references have a wide range of applications such as tight timing synchronization among network components and the study of ultrafast phenomena in physics, biology, chemistry and materials sciences. Among several frequency reference remote-delivery schemes, recently using frequency combs (FCs) as the clock carrier for transmission has gained more favorable momentum. Many experiments related to optical frequency transfer via optical fiber networks over distances of km scale have been reported [1], [2]. However, for frequency reference transfer over short distances or between mobile objects, fiber optic transmission may not be economical or even possible. Therefore, alternative reference delivery routes are needed.

We have recently reported our experiment results on free-space transfer of *microwave* clocks using a femtosecond-laser FC, first under controlled lab conditions [3] and then through uncontrolled open atmosphere [4]. Compared to the microwave clock transfer scheme, FC-based optical frequency transfer is more advantageous not only because of the much higher clock frequencies but also because a FC can simultaneously carry thousands of frequency references over a wide spectral range. The latter gives the FC-based scheme a much higher capacity compared to the conventional scheme based on single-frequency lasers. In this presentation, we report our latest experimental results on *optical* frequency reference transfer via atmospheric transmission of a FC across an outdoor transmission link. The result may provide useful numerical references for the design of practical atmospheric clock delivery links. It may also render a resolution limitation on some of the FC-based probing schemes such as long-distance ranging and coherent LIDAR.

2. Experimental Setup

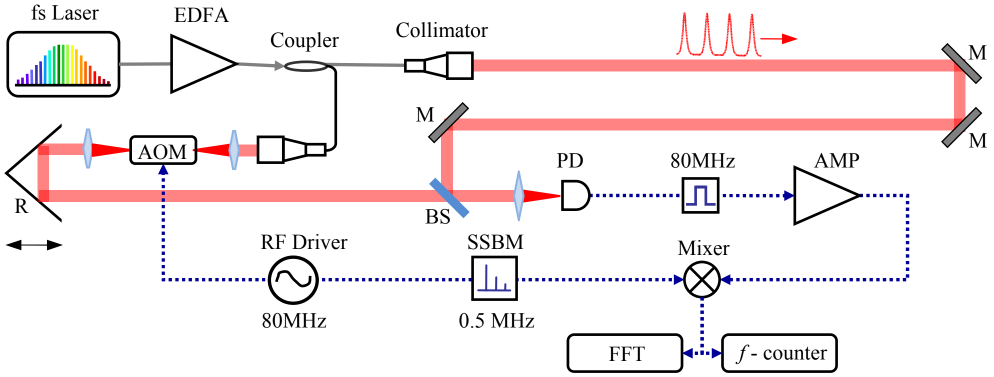

Fig. 1. Schematic of the outdoor optical frequency transmission test system. AMP: microwave amplifiers, AOM: acousto-optic modulator, BS: beam splitter, EDFA: erbium-doped fiber amplifier, M: silver mirrors, PD: photodetector, R: retro-reflector, and SSBM: single-side band modulator

Fig.1 shows the schematic of the experimental system used to measure the frequency transfer instability. The entire setup is located on the rooftop of our laboratory building on the campus of the University of Alabama in Huntsville. A commercial fiber laser (Precision Photonics FFL-1560) acts as the laser source generating a near-infrared femtosecond pulse train with 4-mW average power and a 90-MHz pulse repetition rate. A highly-doped erbium-doped fiber amplifier is used to amplify the pulse train to 100mW average power with the pulsewidth shortened to less than 100fs. A fiber coupler splits 30% of the power to the reference arm and the remaining power is used for the transmission. For the purpose of optical heterodyning detection, the reference beam is frequency-shifted by passing it through an acousto-optic modulator (AOM) driven at 80 MHz and selecting the first order deflection. It then goes through a tunable delay line, which ensures temporal overlapping of the femtosecond pulses from the reference and the transmission paths. The transmission pulse train is collimated into a 7-mm diameter beam at a fiber collimator and launched into the atmospheric transmission link. The beam is reflected back to the experimental setup by a 2-inch gold mirror housed in a sturdy fixture mounted on the rooftop platform at a distance of 30 m (i.e. 60 m round-trip distance). The collected transmitted beam is resized through a telescope before being collinearly combined with the reference beam at a beam-splitter. When optical pulses in both beams temporally overlap, an 80-MHz beat signal is generated. The beat signal is picked up by a photodiode and then sent to a double-balanced mixer, where it is compared to a local oscillator drawn from the original 80MHz signal driving the AOM. The local signal acquires a slight frequency offset (500 kHz) from 80 MHz at a single-sideband modulator (SSBM). As a result, a 500-kHz beat note is generated by the mixer. It is then sent to a fast Fourier transform (FFT) analyzer (SRS SR785) for a direct measurement of the noise spectrum and a frequency counter for the measurement of the Allan deviation.

3. Result and Discussion

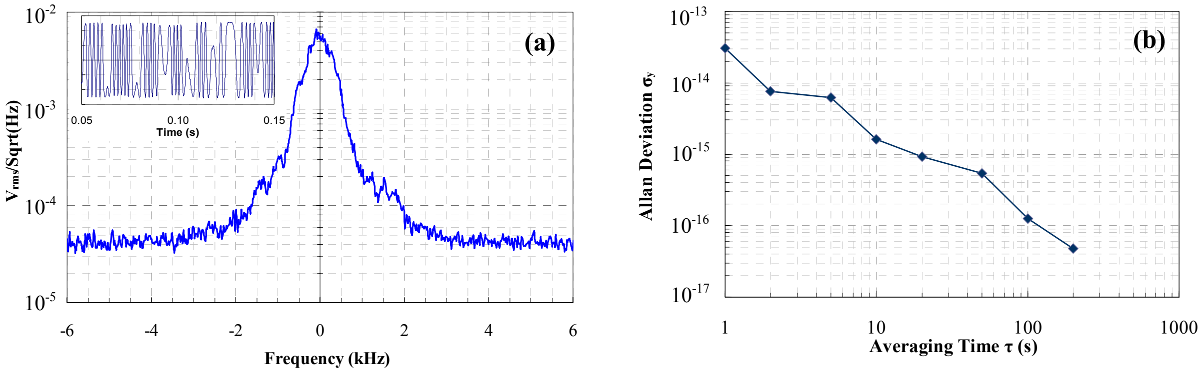

Fig. 2. (a) A typical spectrum of the transmission-broadened optical clock signal. **Inset**: a time-domain trace of the beat note between the recovered clock and the original clock. **(b)** A typical Allan deviation measurement result.

The transmission test has been performed at different times of the day and under various weather conditions. Except very windy days, where the laser beam suffers strong beam wander, the noise measurement has given consistent results. Compared to microwave clock transfer [3], the magnitude of the excess phase noise for optical clock transfer is much greater. This fact can be clearly seen by turning off the SSBM and compare the recovered 80-MHz beat signal directly with the original 80-MHz clock signal driving the AOM. Fig. 2 (a) inset shows a time-domain trace of the IF output of the mixer (upon low-pass filtering). It is apparent that the phase fluctuation due to atmospheric propagation is much greater than 2π for optical frequency transfer. This is attributed to the much shorter wavelength of the optical clock. For such large phase modulations, the direct phase noise measurement scheme used in Ref. 3 and 4 is no longer valid. Instead, one has to look at the entire noise sideband of the clock signal to gain a proper evaluation of the phase noise. For this purpose, we directly measured the spectrum of the 500-kHz beat note. Fig. 2 (a) shows a typical spectral trace centered at the nominal frequency. The trace is averaged over 1 s. It shows that the optical clock signal is broadened to the scale of hundreds of Hz through the 60-m atmospheric transmission. Such a significant line broadening is believed to be caused by the fluctuation of the refractive index of the air over the transmission path due to wind and turbulence, which works effectively as a phase modulator.

A typical result of the Allan deviation measurement is shown in Fig. 2 (b). The fractional frequency instability due to transmission is about 10^{-14} – 10^{-13} at 1 s. Considering the difference of the total transmission distance, our results approximately agree with a recent report on optical frequency transfer over a 100-m atmospheric link using a single-frequency laser [5]. The power law of the Allan deviation appears to be close to τ^{-1}, showing possible influence from a white phase or Flicker phase modulation.

4. Reference

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