Coherent Optical Frequency Transfer over 100 km Fiber Link Using Bidirectional Active Optics

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***Summary*—Precise and stable coherent optical frequency transfer over long-haul fiber link is required by diverse scientific applications, such as large-scale optical clock networks, global positioning and timing, very-long baseline interferometry, and high-sensitivity tests of fundamental physics. To meet the needs of the above applications, active compensation schemes for cancelling fiber-induced phase noise has developed considerably over the past ten years. However, optical signal severely reduces across distant fiber-optic networks, which degrades optical beat signal and feedback control.**

Here, we adopt active phase compensation and bidirectional optical frequency locking to achieve ultra-stable optical carrier transfer. The phase noise of the fiber link is effectively suppressed, meanwhile, the ultra-stable optical frequency signal is regenerated accurately at the remote site.

Preliminary experiment over 100 km fiber link indicates that the additional frequency stability exhibits 1.9×10^{-16} and 2.5×10^{-17} at an averaging time of 1 s and 100 s, respectively. This approach has a capacity of extending to the parallel transfer of microwave and optical frequency, and free-space optical frequency transfer.

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

I. Introduction

The comparison and dissemination of ultra-stable optical-frequency references on large scales poses a major challenge for various ultra-precision experiments in metrology or fundamental physics [1-4]. The key lies in eliminating phase fluctuations due to thermal and acoustic changes in long-distance fibers during propagation. In the past decade, the high-sensitivity detection of optical phase through laser heterodyne has become a basic tool for low-noise optical frequency transfer [5]. Several research institutions have carried out theoretical research and prototype development, and telecommunication fiber link tests [6-9]. As the distance and complexity of long-haul fiber networks increase, the resulting attenuation may reduce the signal level and robustness of heterodyne interference. Optical amplifiers, such as EDFA and FBA, can be used to increase signal intensity. However, EDFA typically requires strict gain control to minimize backscattering. Furthermore, the link noise suppression bandwidth is directly related to the fiber length, which is critical for optical frequency transfer stability.

Here, we demonstrate a coherent optical frequency transfer based on the principle of Doppler noise suppression and bidirectional active optics. Over a 100 km fiber link in laboratory, the phase noise of the link is effectively suppressed, and the remote accurate reproduction of ultra-stable optical frequency signal is realized. In addition, we also compare and analyze the optical frequency signals before and after link noise compensation in the time and frequency domains, respectively.

II. Methods

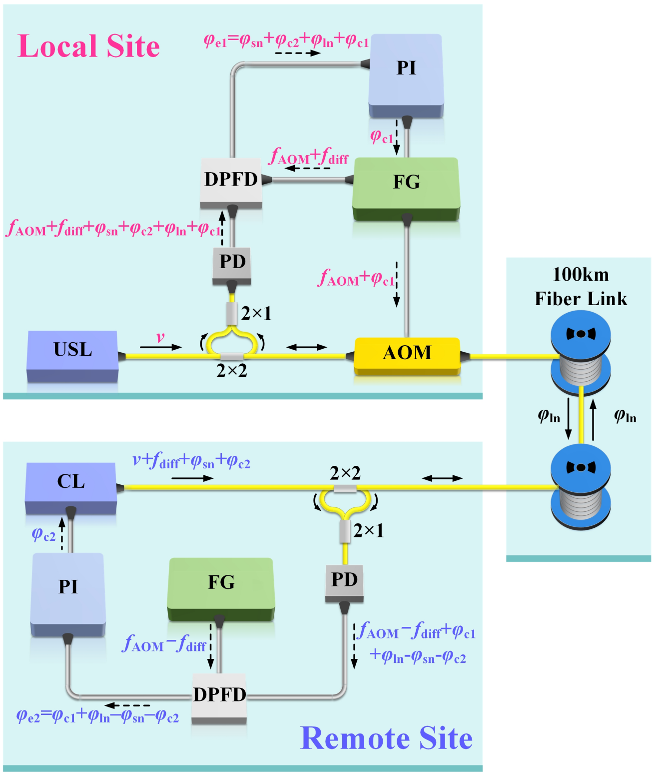


Fig.1 Principle of coherent optical frequency transfer over 100km fiber link. USL: ultra-stable laser, PD: photodetector, DPFD: digital phase-frequency discriminator, AOM: Acousto-optic modulator, FG: function generator, PI: proportional integral controller, CL: coherent laser, v: ultra-stable laser signal, f_{AOM}: AOM upshift frequency, φ_{c1}: fiber link noise compensation phase, f_{diff}: frequency deviation between USL and CL, φ_{sn}: frequency error between USL

and CL, φ_{c2}: frequency error compensation phase, φ_{ln}: fiber link noise, φ_{c1}: local site phase-locked error signal, φ_{e2}: remote site phase-locked error signal.

The system consists of two sites: the local site and the remote site. At both sites, an optical reference is generated by extracting part of the optical frequency signal through a fiber coupler. The other part of the optical frequency signal is transferred through long-haul fiber and up-shifted by the acousto-optic modulator (AOM), which performs laser heterodyne detection with the reference signal of the opposite site. At the local site, the phase-locked loop is used to compensate the link noise, meanwhile, the ultra-stable optical frequency signal is accurately regenerated by locking coherent laser to the incoming signal. The regenerated signal can be utilized on-site or transferred to the next site via the fiber link. Frequency deviation $f_{\rm diff}$ between the ultra-stable laser and coherent laser can be adjusted by temperature control or changing the reference RF frequency at the remote site. It is worth noting that the frequency deviation $f_{\rm diff}$ can be set to zero, that is, the same optical frequency locking is realized. In our system, the upshift frequency of AOM ($f_{\rm AOM}$) is 40 MHz, and the frequency deviation $f_{\rm diff}$ = 30 MHz.

III. RESULTS

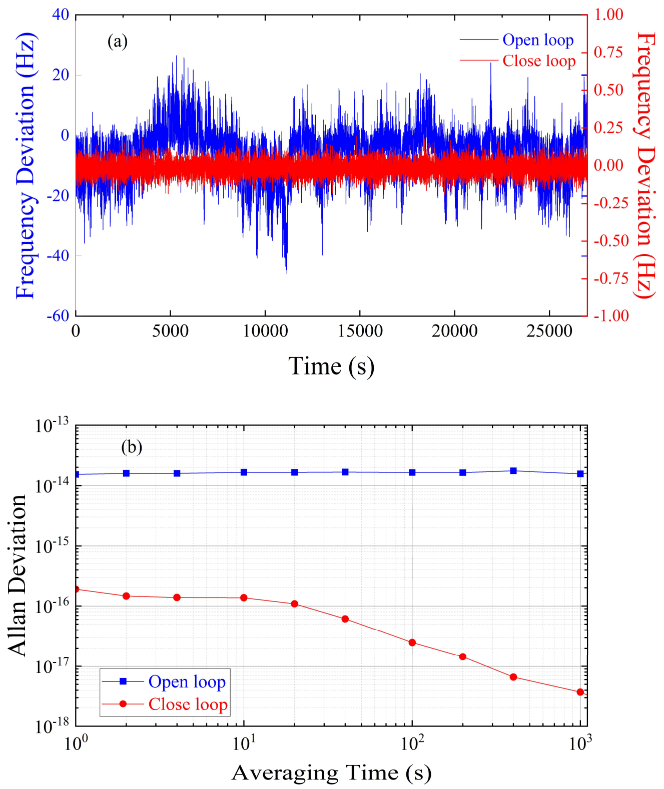


Fig.2 (a) Frequency deviation comparison in cases of open loop and closed loop. (b) Fractional frequency instability comparison.

We evaluate fiber link performance by measuring the beat note signal between the ultra-stable laser and the coherent laser. A Π-type frequency counter is used to record the frequency data, as shown in Fig.2. With the help of phase noise compensation, the peak-to-peak of the beat note signal frequency jitter is improved from 72.4 Hz to 0.4 Hz. The fractional frequency stability is improved to 1.9×10^{-16} and 2.5×10^{-17} at an averaging time of 1 s and 100 s, respectively. The deviation from 1/τ slope may be the interferometer floor noise caused by temperature variation and low-frequency mechanical vibration.

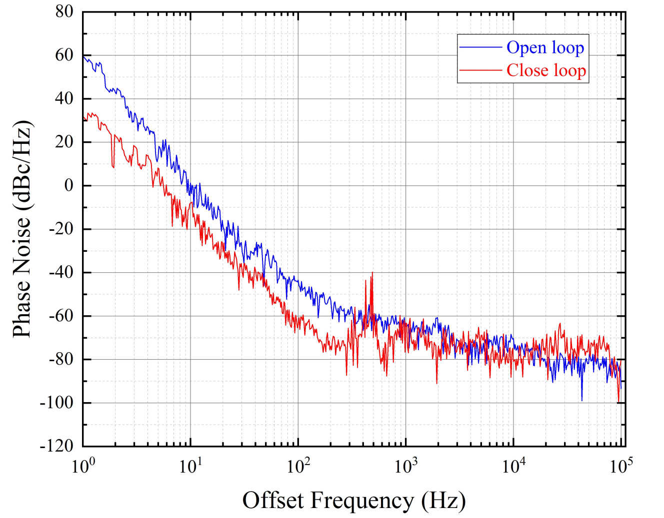
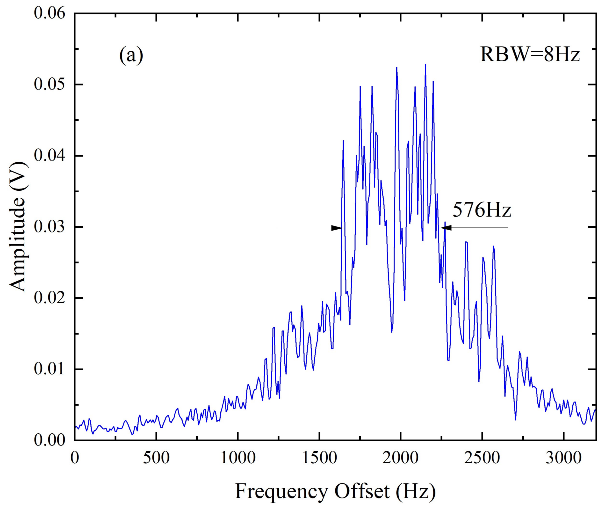


Fig.3 Phase noise power spectral density results

Fig.3 shows the phase noise results, in which the blue curve and the red curve corresponding to the free-running and active compensation phase noise, respectively. In the range of 1-200 Hz, the fiber link noise can be effectively suppressed. At 1 Hz frequency offset, the phase noise is suppressed about 30 dB. Due to the delay compensation limitation [6], the locking bandwidth f_c is limited to 1/4τ, where τ is the one-way link delay. In our system, considering the actual link length (L) is approximately101 km, the theoretical locking bandwidth (f_c) is about 505 Hz, and the actual locking bandwidth is 483 Hz.

We also utilize an FFT spectrum analyzer to measure the beat linewidth, which is illustrated in Fig. 4. When the link noise is adequately suppressed, the fractional linewidth of the Lorentz fit undergoes a substantial reduction, from 576 Hz down to 18.9 mHz.



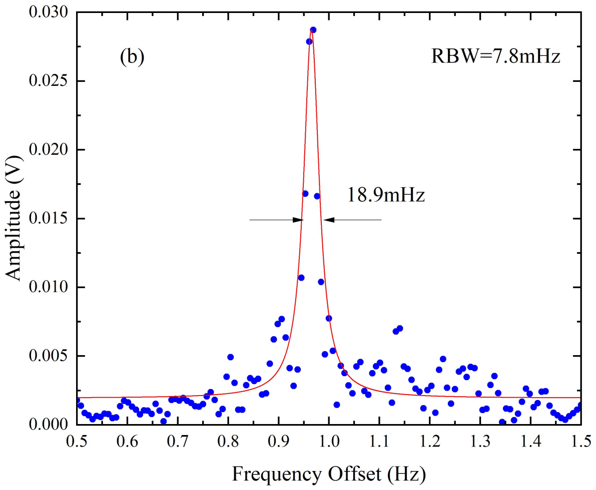


Fig.4 RF spectrum of the down-mixed beat note (a) Open loop (b) Closed loop

IV. CONCLUSIONS

In this paper, we utilize bidirectional active phase-locking to achieve a 100 km fiber link ultra-stable optical frequency transfer in a laboratory environment. The results demonstrate that the fractional frequency transfer stability reaches 1.9×10^{-16}/s and 2.5×10^{-17}/100s. The phase noise rejection ratio at 1Hz frequency offset reaches 30 dB, and the link locking bandwidth reaches 483 Hz, which is close to the theoretical limit. The system can serve as a regeneration device for large scale ultra-stable optical frequency transfer networks, and may fulfill the requirements of optical clock networks for the next-generation optical time-frequency metrology.

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