Coherent Regeneration of Optical Frequency with 1-s instability at 10^{-17}

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Abstract*—The remote regeneration of coherent optical frequency technique finds increasing applications in the fields of large-scale optical clock networks, precision spectroscopy, very-long baseline interferometry, and high-sensitivity tests of fundamental physics. Meanwhile, with the improvements of coherent optical frequency generation, the requirement of stable transfer is more and more demanding. Here, we demonstrate a regeneration system of coherent optical frequency based on bidirectional phase locking, in which the locking loop at the local site is for eliminating optical phase noise over the link, and the locking loop at the remote site is for locking to the incoming coherent optical frequency. Preliminary experiment over a 1.5 km fiber link indicates that the additional frequency stability can reach 5.9×10^{-17} and 7.0×10^{-19} at an averaging time of 1 s and 10^3 s, respectively. This method can be further extended to remote optical frequency comparisons for multiple users.

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

I. Introduction

With the rapid development and performance improvement of ultra-stable laser and optical clocks, accurate and stable optical frequency transfer links are constantly upgrading to accommodate the increasing demand in fundamental physics applications [1-3]. At present, optical frequency transfer through fiber is the only effective method to achieve remote optical frequency comparison and measurement [4-6]. Optical amplifications are usually required to ensure the interferometric signal-to-noise ratio of long-haul fiber links, hence additional link noise is inevitably introduced [7, 8]. Meanwhile, the placement and gain of the amplifier need to be optimized according to the link attenuation and bidirectional incident laser power. Here, accurate and stable coherent regeneration of optical frequency is achieved based on bidirectional laser heterodyne detection loop. Only the incoming laser power needs to be considered, since no optical amplifier is used at the remote site. Over 1.5 km urban fiber link, the fractional instability can reach the level of 10^{-17}/s.

II. Methods

Figure 1 shows the bidirectional optical frequency locking loop principle scheme. A laser heterodyne phase-locked loop is formed by the incoming light and the local light at the local site and the remote site, respectively. The additional noise over the link is eliminated by means of acousto-optic modulation frequency stabilization. At the remote site, the output frequency of the narrow linewidth coherent laser is controlled by adjusting the pump current to follow the incident laser signal.

During the locking state, the coherent optical frequency can be precisely regenerated at the remote site, serving either as the local reference or being transferred to the subsequent site. The laser heterodyne frequency denoted as f_L and f_R, of the two sites are both determined by the laser frequency difference and the acousto-optic shift frequency:

$$\begin{cases} f_L = f_{AOM1} + f_{AOM2} + \Delta v \\ f_R = f_{AOM1} + f_{AOM2} - \Delta v \end{cases} \quad (1)$$

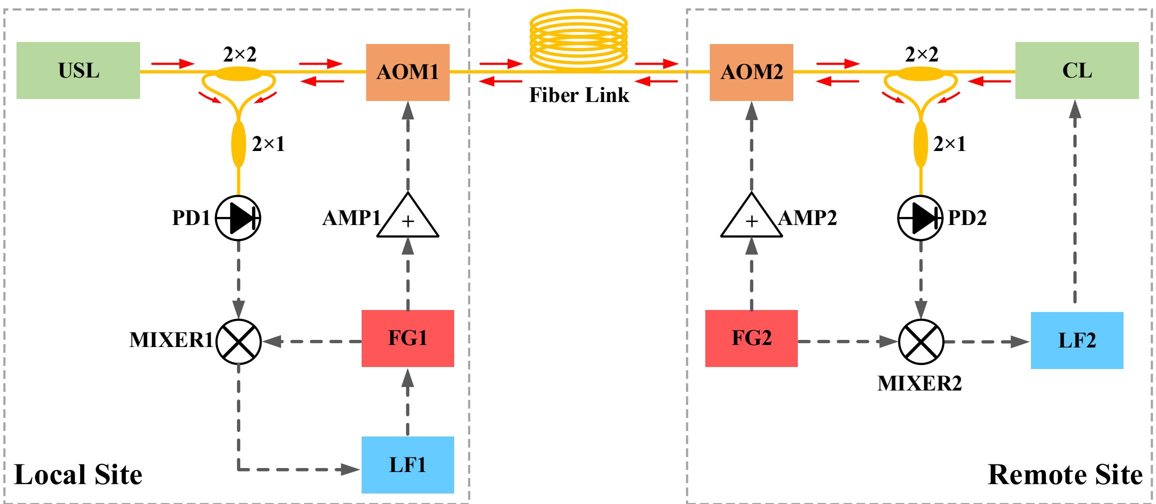

Fig. 1. Principle of regeneration of coherent optical frequency over fiber link. USL: ultra-stable laser, PD: photodetector, AOM: Acousto-optic modulator, AMP: amplifier, FG: function generator, LF: loop filter, CL: coherent laser.

III. Results

We evaluate the regeneration performance of coherent optical frequency by measuring the out-of-loop beat frequency between the ultra-stable laser and the coherent laser. A Π-type frequency counter is used to record the frequency data. And the fractional optical frequency instability comparison is shown in Fig.2. With the phase noise compensation, the fractional frequency instability is improved to 5.9×10^{-17} and 7.02×10^{-19} at an averaging time of 1 s and 10^3 s, respectively.

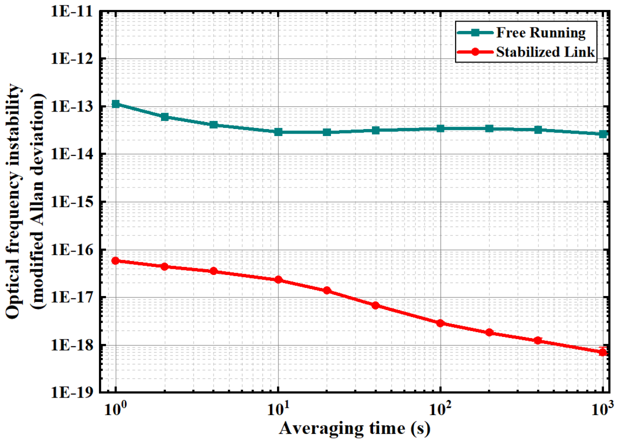

Fig. 2. Fractional optical frequency instability comparison.

An FFT spectrum analyzer is used to measure the beat linewidth, as illustrated in Fig. 4. With adequate suppression of the fiber link, the fractional linewidth of the Lorentz fit significantly decreases to 26.7 mHz.

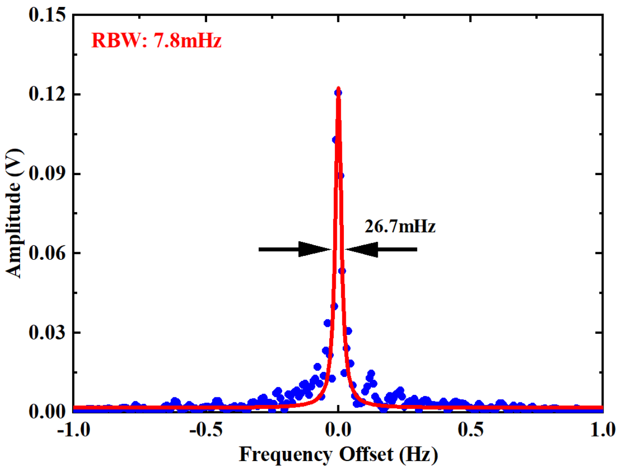

Fig. 3. RF spectrum of the optical beat frequency.

IV. Conclusions

In this paper, we achieve regeneration and subsequent amplification of coherent optical by employing a bidirectional locking method without optical amplifier. The laser frequency difference and link noise are precisely compensated. The results indicate that the fractional coherent optical frequency transfer instability reaches 5.9×10^{-17} and 7.0×10^{-19} at an averaging time of 1 s and 10^3 s, respectively. The measured fractional linewidth is 26.7 mHz. This approach provides a powerful ultra-stable optical frequency regeneration solution for future large-scale optical clock network and optical frequency reference applications.

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