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Coherence transfer of subhertz-linewidth laser light via an 82-km fiber link

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We demonstrate optical coherence transfer of subhertz-linewidth laser light through fiber links by actively compensating random fiber phase noise induced by environmental perturbations. The relative linewidth of laser light after transferring through a 32-km urban fiber link is suppressed within 1 mHz (resolution bandwidth limited), and the absolute linewidth of the transferred laser light is less than 0.36 Hz. For an 82-km fiber link, a repeater station is constructed between a 32-km urban fiber and a 50-km spooled fiber to recover the spectral purity. A relative linewidth of 1 mHz is also demonstrated for light transferring through the 82-km cascaded fiber. Such an optical signal distribution network based on repeater stations allows optical coherence and synchronization available over spatially separated places. © *2015 AIP Publishing LLC*.
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Nowadays, transfer of ultrastable optical frequency references between distant sites allows remote comparisons between optical atomic clocks,[1,2] tests of fundamental physics,[3,4] and precision timing control of astronomical antennas.[5] Fiber link, as a ubiquitous communication network established all over the world, is a candidate for frequency transfer. In recent years, many groups have made efforts to directly transfer optical frequencies through fiber links with achieved frequency transfer instabilities of 10^{-19}.[6–9] In most of them, much attention has been paid to the relative frequency instability and accuracy, and little has been paid to the linewidth of the transferred light. Transfer of laser light with hertz-level-linewidth to remote locations while maintaining its high spectral purity and low phase noise is significant for high resolution spectroscopy, precision detection and measurements.[10,11] Combining with an optical frequency comb at remote sites to transfer the coherence of light at the fiber-optic communication wavelength to other optical wavelength or the microwave region, it enables distribution and correlation of spatially and spectrally separated coherent signals, permitting a variety of applications.[12–15]

Several groups have transferred laser light through fiber links with an absolute linewidth at the hertz level or a resolution-bandwidth (RBW)-limited relative linewidth. Foreman *et al*. transferred laser light at 1064 nm through a 7-km fiber with a relative linewidth of 1 mHz. They tested the absolute linewidth of the beat signal between two lasers separated by 3.5 km to be 1 Hz.[7] Williams *et al.* achieved a relative linewidth of RBW-limited 1 Hz after dissemination of laser light at 1535 nm through a 38-km fiber.[8] Coddington *et al*. measured the absolute linewidth of the beat signal between laser light at 1535 nm separated by 200 m to be 3 Hz.[12] A quantum cascade laser at 10.3 μm is phase-locked to the light transferred through a 43-km fiber link with an achieved absolute linewidth of less than 10 Hz.[15]

However, it is not straightforward to obtain spectrally narrow laser light at the output of fiber links beyond 50 km even using active fiber noise compensation (FNC) techniques.[16] The acquisition time of the error signal for FNC depends on the fiber length, which determines the servo bandwidth of FNC. A long-distance fiber link makes the servo sidebands close to the carrier, posing a challenge to filter out the carrier. To address this problem, one may divide the long-distance fiber link into several fiber segments.[17] A repeater station is constructed to connect every two fiber segments. The length of each fiber segment is chosen for suitable servo bandwidth and enough power remaining in the carrier for phase-locking a transceiver laser to copy the spectral purity from the original light.

In this paper, we first transfer subhertz-linewidth laser light through a 32-km urban fiber link. With FNC technique, the relative linewidth of laser light when transferring through the fiber link is suppressed within 1 mHz (RBW-limited), and the absolute linewidth of the transferred light at the remote end is less than 0.36 Hz, limited by the performance of the local light. Furthermore, we establish a repeater station following the idea of Lopez *et al.*[17] to transfer the light for additional 50-km spooled fiber link. The relative linewidth of the light transferred through an 82-km cascaded fiber is also reduced to RBW-limited 1 mHz.

We use two diode lasers operating at 1557 nm with a free-running linewidth of ∼10 kHz. By using the Pound-Drever-Hall (PDH) technique,[18] each laser is independently stabilized to a 10-cm-long ultrastable optical cavity made of ultra-low expansion glass. The beat signal between two similar lasers (Laser_1 and Laser_2) is measured for 1000 times on a spectrum analyzer with RBW of 0.12 Hz. According to the linewidth distribution, the most probable linewidth[19] of the beat signal is 0.36 Hz.

The fiber link consists of a pair of 16-km urban telecommunication fiber between East China Normal University (ECNU) and Shanghai South Railway Station (SSRS). To test the performance of the FNC system conveniently, two ends of the fiber pair at SSRS are connected, forming a 32-km fiber link. The total loss of the fiber link is 25 dB, bigger than a normal value set by a spooled fiber, which arises from dirty connectors and poor fiber components in the link.

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A bi-EDFA (bi-directional Erbium doped fiber amplifier) with a single-pass gain of 15 dB is implemented at the remote end to make up the loss.

When the subhertz-linewidth laser light ($Laser_1$) transfers through the fiber link, environmental disturbances, such as temperature variation, acoustic noise, and vibration, modulate the laser light via the fiber link, resulting in a broadened linewidth. We measured the relative linewidth of the transferred light on a spectrum analyzer by beating the transferred light at the remote site with that at the local end on a photodiode (PD). Figure 1(a) shows the spectrum by averaging over 50 measurements with center-overlapped. It indicates that the relative linewidth of the light transferred through the 32-km urban fiber link has been broadened to nearly 1 kHz.

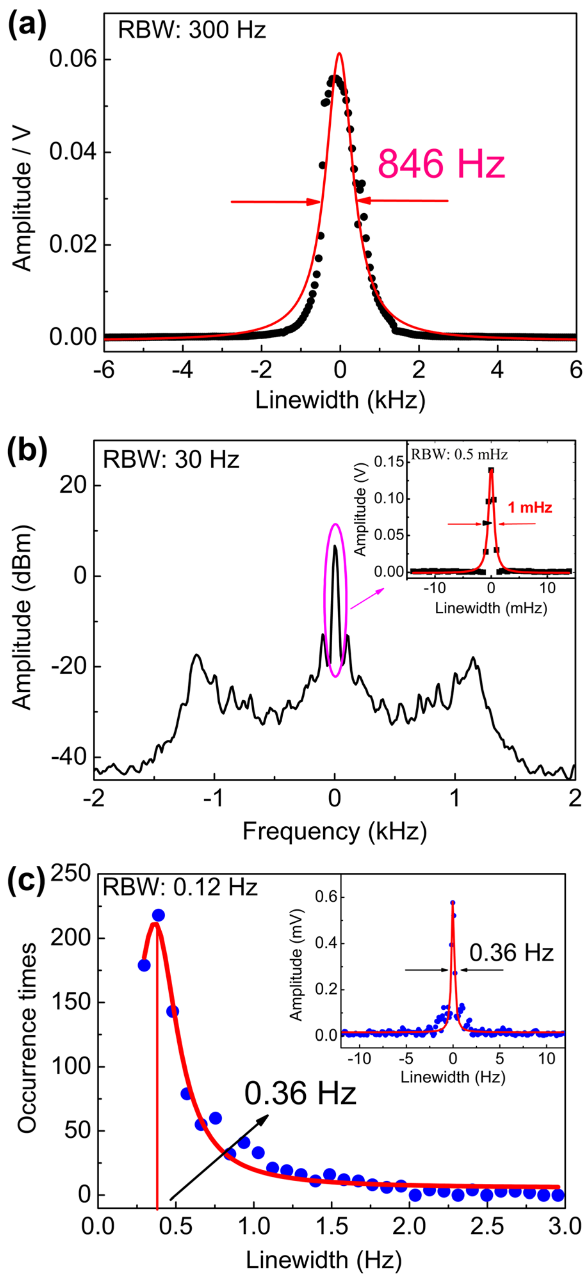

FIG. 1. Linewidth measurements. (a) Spectrum of the beat signal between the light transferred through a 32-km urban fiber and the local light when FNC is off (RBW = 300 Hz, measurement time 3.3 ms). (b) Spectrum of the beat signal when FNC is on. The inset shows a spectrum in linear scale with a finer resolution of 0.5 mHz and measurement time of 2000 s. (c) The linewidth distribution of the beat signal when FNC is on (blue dots). The red line is a Lorentzian fitting of the distribution with a most probable value of 0.36 Hz. The inset shows an example of the spectrum of the beat signal with RBW = 0.12 Hz and measurement time of 8.2 s.

To maintain spectral purity and coherence of the laser light after transferring through the fiber link, a FNC system is implemented. In the FNC system, the random phase noise is measured by beating the round-trip light transferred through the fiber link with that from the local end on a photo detector. The beat signal is mixed with a stable radio frequency (RF) source on a double balance mixer (DBM) to obtain an error signal. Since DBM can only distinguish phase variation in range of $\pm\pi$, we divide the frequency of the beat signal by 64 to improve dynamic range and robustness of the compensation system. The error signal is sent to a servo control system to adjust the driving frequency of an acoustic-optic modulator (AOM) at the input of the fiber link, for example, AOM_1 and AOM_3 in Fig. 3, to compensate the fiber phase noise. Another AOM with shift frequency of -110 MHz is employed at the output of the fiber link to ensure that the beat signal is derived from the light reflected back from the remote end instead of other sites in any position of the fiber.

To protect the interferometer in the FNC system from the disturbance of air flow, we made an acrylic box to cover the optics. All the connectors for cables and fibers are installed in the box to guarantee the sealability. Consequently, the acrylic box improves the relative frequency instability noise floor of the compensation system by more than one magnitude.

As long as the fiber noise is compensated (FNC is on), the relative linewidth of the beat signal between the transferred light and the local light is suppressed. Figure 1(b) shows the spectral distribution of the beat signal. The carrier of the beat signal has an RBW-limited linewidth of 1 mHz, as shown in the inset of Fig. 1(b). Two sidebands beside the carrier at Fourier frequency of 1.2 kHz are set by the servo bandwidth of the FNC system, resulting from the time delay due to the length of the fiber.[8] More than 90% of the power remains in the carrier.

Since the light has a relative linewidth of 1 mHz after transferring through the fiber, which is much smaller compared with the laser linewidth, the transferred light is likely to have a comparable linewidth as the input light. And the spectrum measurements of the beat note between the transferred light at the remote site and $Laser_2$ confirms this point, as shown in Fig. 1(c). The inset of Fig. 1(c) shows an example of the spectral distribution of the beat signal. In 1000 groups of measurements, the most probable linewidth of the beat signal between the transferred light and $Laser_2$ is 0.36 Hz, the same as the measurement between the input light and $Laser_2$. The probability of the measured linewidth of 0.36 ± 0.10 Hz is about 54%. The results show that as long as FNC is on, the coherence of the light that transferred through the 32-km urban fiber remains.

Besides the linewidth measurement, we also measured the phase noise power spectral density (PSD) of the transferred light on a fast Fourier transformer. As shown in Fig. 2(a), when FNC is off, the relative phase noise PSD follows the power-law[20] as $S_{\rm fiber}(f) = h/f^2$ below 200 Hz,

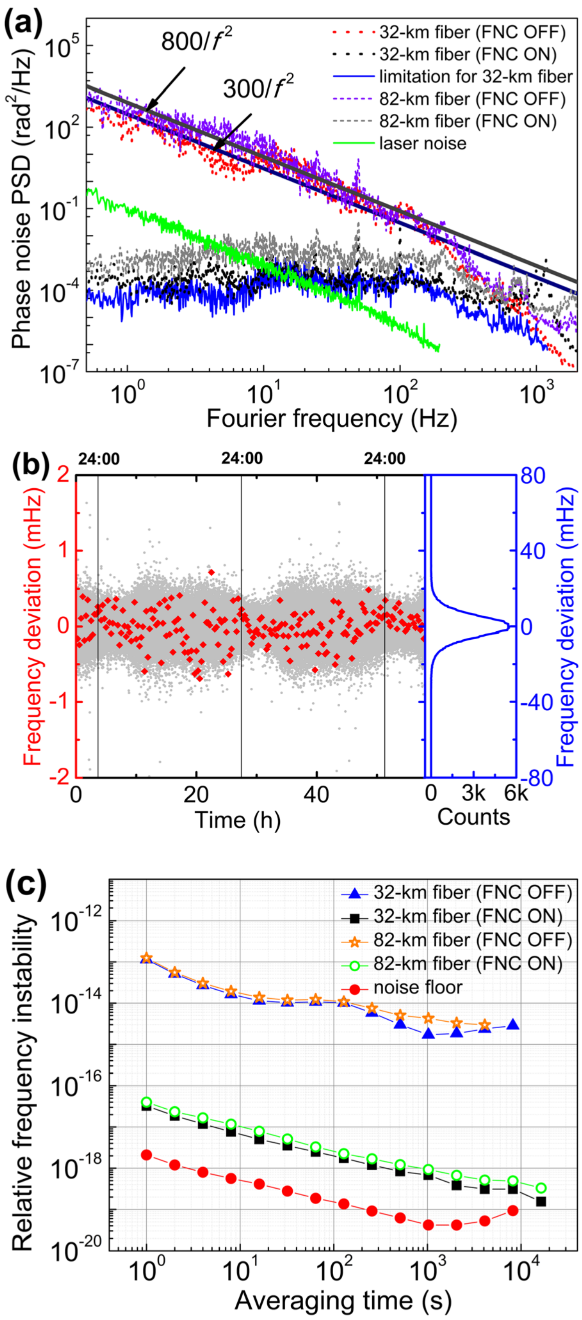

FIG. 2. Performance measurement of optical frequency transfer. (a) Phase noise PSD of light transferred through an uncompensated 32-km urban fiber link (red dotted line), compensated 32-km fiber link (black dotted line), calculated phase noise PSD limitation of the 32-km urban fiber link (blue line), uncompensated 82-km cascaded fiber link (violet short dashed line), compensated 82-km fiber link (grey short dashed line) and phase noise PSD of Laser$_1$ (green line). (b) Frequency deviation of the transferred light from the expected value when transferring through 32-km fiber link. The fractional relative frequency deviation is calculated as $(-6.6 \pm 8.3) \times 10^{-20}$. (c) Relative frequency instability induced during transferring through the 32-km fiber link when FNC is off (blue triangles), FNC is on (black squares), and through the 82-km fiber link when FNCs are off (orange stars), FNCs are on (green circles), and noise floor of the FNC (red dots).

where f is the Fourier frequency, and h is a coefficient which varies for different fiber links and equals to 300 in this work. When FNC is on, the relative phase noise is suppressed to the calculated limitation with a perfect FNC.[8,20] The peaks at 1.2 kHz are set by the servo bandwidth of the FNC system. Compared with the laser phase noise shown in the figure, the relative phase noise added to the light when transferring through the fiber is much smaller at low Fourier frequencies, maintaining high spectral purity at the light carrier, while those at high frequencies contribute to small modulation sidebands besides the carrier. The integrated phase noise from 0.5 Hz to 10 kHz is equal to 0.48 rad, corresponding to 0.39 fs (rms) timing jitter.[7] The phase noise at Fourier frequencies larger than 10 kHz is about four orders of magnitude smaller than those at low frequencies, giving negligible contributes to the integrated timing jitter.

Moreover, we record the beating frequency on a frequency counter (Agilent 53132A) with a gate time of 1 s for more than 57 h. Figure 2(b) displays the frequency deviation of the transferred light from the expected value. Based on the recorded data, the relative frequency instability of transferred light with noise compensated is given in terms of modified Allan deviation to be 3.5×10^{-17} at 1 s averaging time, reaching 3×10^{-19} at 10^4 s averaging time, as shown in Fig. 2(c).

The distribution of the frequency deviation over counts follows a Gaussian function. After taking out two cycle slips, we divided the remaining data into 209 subsets with a length of continuous 1000 s time period. The mean value of each subset is calculated, as shown with red filled diamonds in Fig. 2(b). The 209 data points have an arithmetic mean of $-12.8\,\mu$Hz (-6.6×10^{-20}) and a standard deviation of 0.23 mHz. Consequently, the statistical fractional uncertainty of the 209 data points is calculated to be 16.0 μHz (8.3×10^{-20}). These results indicate that the system meets the requirements of remote comparisons of optical atomic clocks.[1,21–23]

When extending the transfer length, the loss of light power results in a degraded signal-to-noise ratio (SNR) of the beat signal used for noise compensation, thereby deteriorating the performance of the FNC system. To make up the power loss, bi-EDFAs and FBAs (fiber Brillouin amplifiers) are usually employed.[6,20,24] However, due to the time delay of light while transferring in a long-distance fiber link, the servo bandwidth of FNC systems reduces. This set difficulties to resolve a carrier. Cascaded fiber link based on repeater stations could overcome this limitation.[17] The servo can have enough bandwidth to make the carrier unburied in the noise by dividing a whole fiber link into multiple segments with optimized length. In each repeater station between two fiber segments, a transceiver laser is employed to re-generate a spectrally narrow laser light for seeding to the next fiber segment.

Figure 3 shows our experimental setup for optical coherence transfer through an 82-km cascaded fiber link. In the repeater station, part of light from the previous 32-km urban telecommunication fiber beats against a portion of the light from a transceiver laser operating at 1557 nm. A phase lock loop (PLL) is employed to track the heterodyne beat signal to a stable RF reference by adjusting the current of the transceiver laser. The tracking precision is measured to be 3×10^{-19} at 1 s. And the in-loop signal of the PLL has an RBW-limited linewidth of 1 mHz, which indicates that the transceiver laser accurately inherits the characteristics of the transferred light. As long as the transceiver laser is tightly phase-locked to the transferred light from the previous fiber segment, the left of the laser light is sent to the next 50-km spooled fiber segment with a FNC system. The RF signals

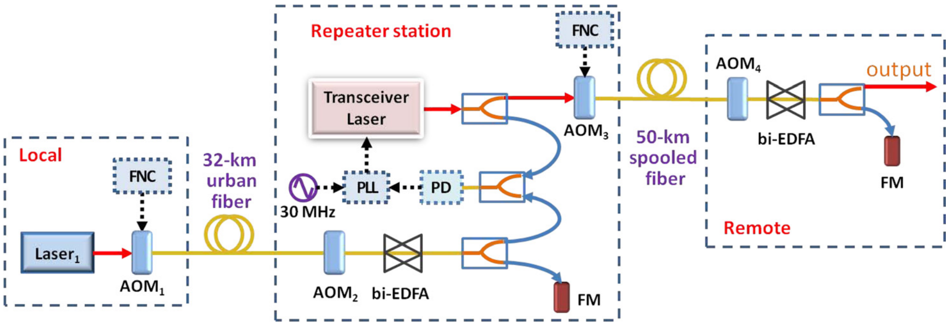

FIG. 3. Schematic of the experimental setup of an 82-km cascaded fiber link with a repeater station. The 82-km cascaded fiber link consists of a 32-km urban fiber and a 50-km spooled fiber. Each part employs an FNC system to suppress the phase noise induced by environmental disturbance via the fiber. FM: Faraday mirror.

for all the AOMs and the RF reference for PLL in the repeater station are synthesized from a single RF time base, which is independent of that in the local or remote end. The frequency drift of the time-base in the repeater station has no effect on the transferred light by setting the total frequency shift added to the light to zero.[17] In our system, the frequencies of AOM$_2$, AOM$_3$, and the RF reference for PLL are -110 MHz, 80 MHz, and 30 MHz, respectively.

When PLL and FNCs work, the relative linewidth of the transferred light is suppressed to be RBW-limited 1 mHz, which indicates that the coherence of the light source is precisely transferred via the cascaded 82-km fiber link. Furthermore, we measure the relative phase noise PSD of the transferred light, as shown in Fig. 2(a). When FNCs are off, the phase noise PSD follows $S_{\text{fiber}}(f) = 800/f^2$ at Fourier frequencies below 200 Hz. While FNCs are on, the phase noise PSD is suppressed, approaching to the limitation of the compensation system. According to 35 hours' record of the frequency deviation of the transferred light, the relative frequency instability is 4×10^{-17} (1 s), falling down to 3×10^{-19} at about 5 h, as shown in Fig. 2(c). Meanwhile, the fractional frequency deviation from the expected frequency is calculated as $(-1.2 \pm 1.3) \times 10^{-19}$.

In summary, by using FNC systems to compensate the fiber phase noise induced by environmental disturbance, we demonstrate coherence transfer of subhertz-linewidth laser light through a 32-km urban fiber link and an 82-km cascaded fiber link. The relative linewidth of the transferred light is reduced to a RBW-limited 1 mHz, an order of magnitude smaller than the purest optical oscillators.[25,26] With repeater stations installed between fiber segments with a length of tens of kilometers, the laser light could recover the power as well as spectral purity. The length for transferring a narrow-linewidth laser light could be potentially extended to thousands of kilometers by employing cascaded fiber links connected with repeater stations.

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