

Optics Letters

Coherence transfer of subhertz-linewidth laser light via an optical fiber noise compensated by remote users

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Received 14 July 2016; revised 18 August 2016; accepted 21 August 2016; posted 25 August 2016 (Doc. ID 270315); published 14 September 2016

We present a technique for the coherence transfer of laser light through a fiber link, where the optical phase noise induced by environmental perturbation via the fiber link is compensated by remote users. When compensating the fiber noise by remote users, the time base at the remote site independent from that at the local site does not destroy the performance of the fiber output light. Using this technique, we demonstrate the transfer of subhertz-linewidth laser light through a 25-km-long, lab-based spooled fiber. After being compensated, the relative linewidth between the fiber input and output light is 1 mHz, and the relative frequency instability is 4×10^{-17} at 1 s averaging time and scales down to 2×10^{-19} at 800 s averaging time. The frequency uncertainty of the light after transferring through the fiber relative to that of the input light is 3.0×10^{-19}. This system is suitable for the simultaneous transfer of an optical signal to a number of end users within a city.

OCIS codes: (060.4510) Optical communications; (120.4820) Optical systems; (120.5050) Phase measurement.

http://dx.doi.org/10.1364/OL.41.004368

In recent years, optical frequencies have been transferred via fiber links in different continents all over the world, aiming at frequency comparisons between optical atomic clocks at two distant sites [1–3], tests of fundamental physics [4], and precision timing control of astronomical antennas [5]. Compared with frequency transfer through satellite, it has the advantage of higher frequency stability when transferring through a noise-compensated fiber link [6]. Optical frequencies have been successfully transferred through public fiber networks in different countries [7–15]. The length of an optical fiber link for optical frequency transfer has been successfully extended to 1840 km in Germany [16]. Frequency comparison between two separated Sr optical clocks located at PTB (Germany) and SYRTE (France) has been demonstrated with a 1415-km-long optical fiber link [3]. International fiber links for frequency transfer are under construction in Europe.

So far, the most popular scheme is based on optical frequency transfer from one place to another, where the error signal for fiber noise compensation (FNC) is obtained at the local site. Those schemes are well suited between two cities far apart, for example, from city A to city B in Fig. 1. Multi-access at any arbitrary points along the fiber link has been demonstrated [17,18]. While inside a city, it is likely to transfer the optical frequency from a central station to multiple remote users, as shown in Fig. 1. To meet this application, Schediwy *et al.* proposed a scheme for FNC at the remote site [19]. The error signal for FNC is obtained at the remote site by heterodyne beating the fiber output light against the light that transfers through the fiber for three times. They tested the frequency of the output light from a 6-km-long, noise-compensated spooled optical fiber against that of the input light in the same laboratory with the same time base. However, for a practical application, the time base at the remote site is independent of that at the local site.

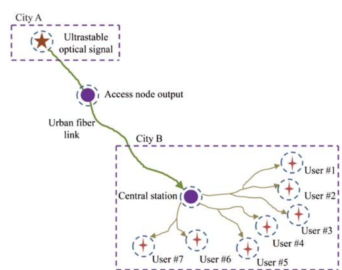

Fig. 1. Example of optical fiber networks between two cities and those inside a city. Optical frequency signal can be transferred between two distant cities (e.g., city A and B) linked with an optical fiber, where the optical phase noise is compensated at the input of the fiber (city A). While using the scheme discussed in this Letter, it will be convenient to simultaneously transfer an optical frequency from a central station to multiple end users inside a city. The fiber-induced optical phase noise is compensated by remote users. The stars denote where the FNC systems are located.

0146-9592/16/184368-04 Journal

When remote users phase-lock the detected beat note containing the fiber-induced noise to radio frequency (RF) signals synthesized from their time bases, it may destroy the performance of the fiber output light. In their latest work, they have realized optical frequency transfer through an optical fiber whose noise is controlled by remote receivers owning to first transferring a microwave frequency reference signal to the sender of optical signals to share a same time base at both places [20].

In this Letter, we present a technique for the simultaneous transfer of laser frequencies via fiber links, where the fiber-induced noise is compensated by remote users. The frequency of the fiber output light is independent of the time base at the remote site by specially choosing the frequencies of all the RF signals at the remote site [7]. We demonstrate this technique by coherently transferring a subhertz-linewidth laser light via a 25-km-long fiber link inside a lab. By comparing the fiber output light against the input light, a relative linewidth between the input and the output of the noise-compensated fiber link is measured to be as narrow as 1 mHz (resolution bandwidth [RBW] limited), and the relative frequency instability is 4×10^{-17} at 1 s averaging time and scales down to 2×10^{-19} at 800 s averaging time. The frequency uncertainty of the light after transferring through the fiber relative to that of the input light is 3.0×10^{-19}.

The light for transferring through the optical fiber in this experiment is from a planar external cavity laser operating at 1557 nm. By using the Pound–Drever–Hall (PDH) technique [21], the laser is frequency stabilized to the resonance of a 10-cm-long, ultrastable Fabry–Pérot optical cavity made of ultra-low expansion glass. The laser linewidth is measured to be 0.3 Hz by comparing against another similar narrow-linewidth laser system at 1557 nm [22]. The frequency instability for each laser is about 8×10^{-16} at 1 s averaging time.

Figure 2 shows the diagram of the experimental setup for light transfer through the optical fiber. The electric field of the light from the subhertz-linewidth ultrastable laser mentioned above is $E_s = A_s \cos(\Omega_s t + \varphi_s)$, where A_s, Ω_s, and φ_s are the amplitude, angular frequency, and phase of the light. The light is first frequency shifted on AOM_1 (acousto-optic modulator). Then the diffracted light (+1st order) with power of 2.6 mW is coupled into a 25-km-long spooled fiber link. The single-way loss of the 25-km-long fiber is 5 dB, and other loss from the AOMs and fiber couplers is about 10 dB. To compensate the losses, a bidirectional erbium-doped fiber amplifier (bi-EDFA) is installed at the remote site.

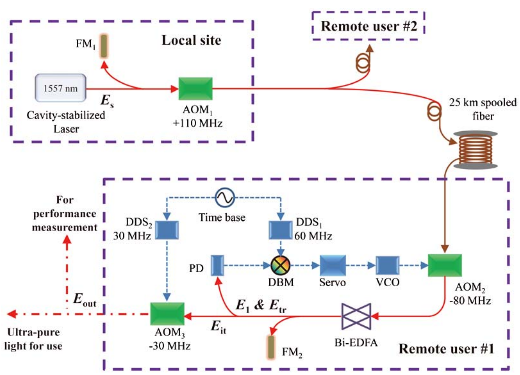

Fig. 2. Experimental setup. The optical signal is transferred via a 25-km-long spooled fiber. The optical phase noise induced by environmental perturbation via the fiber is compensated at the remote site. The frequency of the −1st order diffracted light after AOM_3 (the output light for use) is independent of the time base at the remote end. FM, Faraday mirror; AOM, acousto-optic modulator; PD, photo-detector; Bi-EDFA, bidirectional erbium-doped fiber amplifier; DBM, double-balanced mixer; DDS, direct digital synthesizer; VCO, voltage controlled oscillator.

At the remote site, the fiber output light is first frequency shifted by nearly −80 MHz on AOM_2, which is also used as the executor of the FNC. The electric field of the one-way light incident onto the PD (photo-detector) is

$$E_1 = A_1 \cos[(\Omega_s + \omega_{\mathrm{LO}} - \omega_{\mathrm{RE1}})t + \varphi_s + \varphi_{\mathrm{LO}} - \varphi_{\mathrm{RE1}} + \varphi_p], \quad (1)$$

in which ω_{LO} of $2\pi \times 110$ MHz and φ_{LO} are the driving angular frequency and phase of AOM_1, ω_{RE1} of $2\pi \times 80$ MHz and φ_{RE1} are the driving angular frequency and phase of AOM_2, and φ_p is the added optical phase noise after transferring through the fiber.

Assuming the optical phase noise induced by environmental perturbation on the fiber link in either direction is equal, the electric field of the light after transferring through the fiber between two Faraday mirrors (FM_1 and FM_2) for another round-trip is

$$E_{\mathrm{tr}} = A_{\mathrm{tr}} \cos[(\Omega_s + 3\omega_{\mathrm{LO}} - 3\omega_{\mathrm{RE1}})t + \varphi_s + 3\varphi_{\mathrm{LO}} - 3\varphi_{\mathrm{RE1}} + 3\varphi_p]. \quad (2)$$

E_{tr} heterodyne beats against E_1 on PD. Then the ac term of the heterodyne beat note is

$$i_{\mathrm{ac}} \propto 2A_1 A_{\mathrm{tr}} \cos[(2\omega_{\mathrm{LO}} - 2\omega_{\mathrm{RE1}})t + 2\varphi_{\mathrm{LO}} - 2\varphi_{\mathrm{RE1}} + 2\varphi_p]. \quad (3)$$

A RF signal from a direct digital synthesizer (DDS_1) with the angular frequency of $2\omega_{\mathrm{RE2}} = 2\pi \times 60$ MHz and the phase of $2\varphi_{\mathrm{RE2}}$ is mixed with i_{ac}. The mixed down signal is filtered and sent to a servo system. Then the servo system makes $\omega_{\mathrm{LO}} - \omega_{\mathrm{RE1}} = \omega_{\mathrm{RE2}}$ and $\varphi_{\mathrm{LO}} - \varphi_{\mathrm{RE1}} + \varphi_p = \varphi_{\mathrm{RE2}}$ by tuning the driving frequency of AOM_2.

After being compensated, the single-way light at the remote is expressed as

$$E_{\mathrm{it}} = A_{\mathrm{it}} \cos[(\Omega_s + \omega_{\mathrm{RE2}})t + \varphi_s + \varphi_{\mathrm{RE2}}]. \quad (4)$$

We can see that E_{it} depends on ω_{RE2}, which is referenced to the time base at the remote end. To remove the effect of the time base at the remote end, another AOM_3 operating at ω_{RE2} of $2\pi \times 30$ MHz with the phase of φ_{RE2} is employed. This RF signal is also referenced to the time base at the remote site. As a result, the electric field of the −1st order diffracted light after AOM_3 (the output light of this scheme for use) is

$$E_{\mathrm{out}} = A_{\mathrm{out}} \cos(\Omega_s t + \varphi_s), \quad (5)$$

which is independent of the time base at the remote site.

To measure the relative frequency instability of the light after transferring through the fiber link, we use a π-type frequency counter, which is referenced to the time base at the local site, to record the beating frequency between the fiber input light E_s and the output light E_{out}. As shown in Fig. 3(a), the relative frequency instability of the light after the transferred noise-compensated fiber link is 4×10^{-17} at 1 s averaging time and scales down to 2×10^{-19} at 800 s averaging time (red filled triangles). The black dots show the noise floor of the

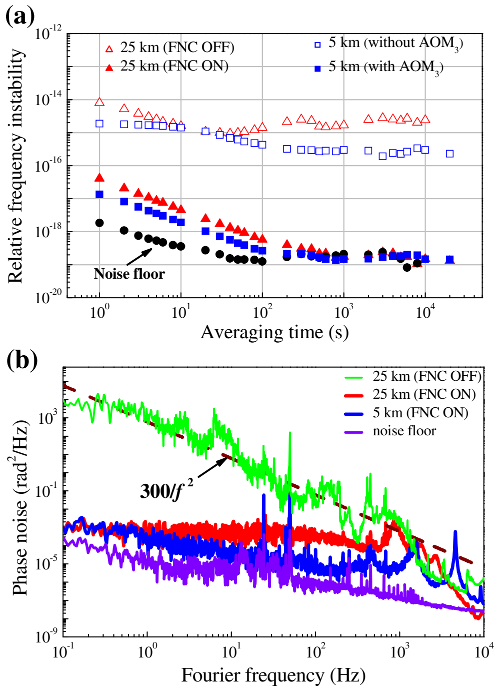

Fig. 3. (a) Relative frequency instability of the light after transferring through the 25-km-long spooled fiber when FNC is off (red open triangles), and when FNC is on (red filled triangles), through the 5-km-long fiber link when FNC is on but without AOM_3 (blue open squares), and with AOM_3 (blue filled squares), and through a 2-m-long fiber (noise floor of the system, black dots). (b) Relative phase noise PSD of the light transferred through an uncompensated 25-km-long fiber link (green line), a compensated 25-km-long fiber link (red line), a compensated 5-km-long fiber link (blue line), and a compensated 2-m-long fiber (noise floor, violet line).

compensated system by replacing the 25-km-long fiber link with a 2-m-long fiber. As we can see, at the averaging times longer than 10^3 s, the relative frequency instability is limited at the 10^{-19} level by the temperature fluctuation-induced length fluctuation of a piece of fiber in the measurement system but outside the FNC system. The room temperature fluctuates within 1 K over a day.

The frequency of the beat signal was measured in 57,000 s on a counter with a gate time of 1 s. We divide all the data into 57 groups, and calculate a mean value for each group. Based on those mean values, we calculate the frequency of the transferred light deviated from that of the input by -2.2×10^{-19} on average with an uncertainty of 3.0×10^{-19}.

We used a fast Fourier transform spectrum analyzer to measure the phase noise power spectral density (PSD) added to the light after it is transferred through the 25-km-long fiber link. As shown in Fig. 3(b), when the FNC system is off, the relative phase noise PSD (green line) follows the power law as $S_{\text{fiber}}(f) = h/f^2$ at the Fourier frequencies f below 1 kHz; here h is a coefficient that varies for different fiber links and equals to 300 in this experiment. Once the FNC system at the remote end is activated by the remote user, the relative phase noise is remarkably suppressed down to 10^{-3} rad^2/Hz in the frequency range of 0.1–1 kHz. The integrated phase noise from 0.5 Hz to 10 kHz is equal to 1.1 rad, corresponding to 0.9 fs root mean square (rms) timing jitter. The peak at ~1 kHz is the servo bandwidth of the FNC system for the 25-km-long fiber link. It is nearly two thirds of the servo bandwidth of 1.5 kHz in a traditional FNC system operated at the local site, because in our system the error signal for FNC is obtained at the remote end after the light is transferred through the fiber three times. We also use a 5-km-long spooled fiber to make the same measurement. The relative phase noise PSD of the compensated 5-km-long fiber link is shown in Fig. 3(b) with a blue line. The servo bandwidth is 5 kHz, five times higher than that of the 25-km-long fiber link. It indicates that in both cases the servo bandwidth is determined by the fiber length.

As a contrast, if AOM_3 is not implemented in the system and even if FNC is on, the frequency of the fiber output light depends on the time base at the remote site, as shown with the blue open squares in Fig. 3(a). The time base at the remote site is from a quartz oscillator with a frequency instability of 4×10^{-9} at 1 s. This measurement is based on the 5-km-long fiber link. The frequency instability is 2×10^{-15} at 1 s averaging time, and is limited to the 10^{-16} level at longer averaging time due to the independent time base at the remote site. Once AOM_3 is employed, the relative frequency instability of the light after transferring through the same noise-compensated fiber link is 1×10^{-17} at 1 s averaging time and remarkably scales down to 3×10^{-19} at 100 s averaging time (blue filled squares), independent of the time base at the remote site.

We measured the linewidth of the beat signal between the input and output light of the 25-km-long fiber. As shown in Fig. 4(a), the relative linewidth of the beat signal for the uncompensated fiber link is as large as 560 Hz with a RBW of 100 Hz and a measurement time of 6.6 ms. As long as the FNC system at the remote site is on, the linewidth of the beat

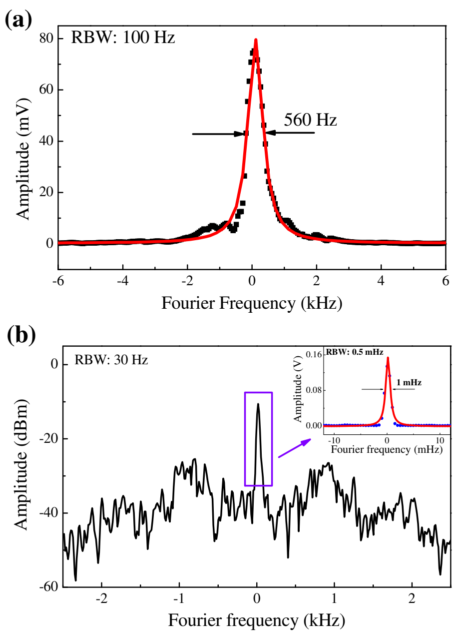

Fig. 4. Linewidth measurements. Spectrum of the beat signal between the input and output of the 25-km-long fiber link when (a) FNC is off with a RBW of 100 Hz and measurement time of 6.6 ms and (b) FNC is on. The inset shows a spectrum in a linear scale with a finer resolution of 0.5 mHz and a measurement time of 2000 s.

signal is suppressed to a RBW-limited linewidth of 1 mHz (0.5 mHz RBW and measurement time of 2000 s), as shown in the inset of Fig. 4(b). The bumps at nearly 1 kHz shown in Fig. 4(b) agree with the servo bandwidth shown in the noise PSD of the compensated 25-km-long spooled fiber in Fig. 3(b). The amplitude of the carrier is nearly 25 dB higher than that of the noise in a RBW of 30 Hz. About 93% of the optical power remains in the carrier.

In summary, by compensating the fiber-induced optical phase noise at the remote site, we demonstrate a coherence transfer of an optical frequency through a 25-km-long spooled fiber link inside a lab. The frequency of the fiber output light is independent of the time base at the remote site. The relative frequency transfer instability is 4×10^{-17} at 1 s averaging time and 2×10^{-19} at 800 s averaging time. The frequency uncertainty of the light after transferring through the fiber is 3.0×10^{-19}. The relative frequency transfer linewidth is a RBW-limited linewidth of 1 mHz. It supports a coherence transfer of the signal from the best optical clocks in the world.

For the FNC scheme described in this Letter, the light frequency can be simultaneously sent to a variety of outlets at different remote sites from arbitrary nodes. By shifting the light carrier frequencies in different channels by a few tens of gigahertz and using wavelength-division multiplexers to combine and to split the light apart, crosstalk between channels can be reduced. The complex for this scheme is to shift the light frequencies in different channels by a few tens of gigahertz without losing coherence. As an alternative method, crosstalk can be reduced by choosing different AOM-driving frequencies in different channels to make the beat notes at different remote users shift by a few megahertz. Then in each channel, the remote user uses a band pass filter with a bandwidth of nearly 1 MHz to filter out the signal for noise compensation. The number of remote users for this scheme will be determined by some technical problems such as the bandwidth of the band pass filters and light power attenuation. In the case of multiple remote users, the scheme discussed in this Letter simplifies the setup at the central station, and leaves the end users to independently control the FNC systems.

Funding. National Natural Science Foundation of China (NSFC) (11334002, 11374102); Shanghai Rising-Star Program (15QA1401900); Program of Introducing Talents of Discipline to Universities (B12024).

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