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Precise frequency transfer through a fiber network by use of 1.5-μm mode-locked sources

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We report the precise transfer of radio-frequency signals by use of the pulse repetition frequency of mode-locked laser sources at 1.5 μm transmitting through a fiber network. The passive transfer instability through a 6.9-km fiber is below 3×10^{-14} at 1 s, which is comparable with the optical carrier-frequency transfer of a narrow-linewidth cw laser. The instability of the measurement system is below 7×10^{-15} at 1 s. It is noted that the pulsed mode of operation offers almost an order-of-magnitude improvement in stability at 1 s over that with a sinusoidal amplitude modulation on an optical carrier. © 2004 Optical Society of America

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With the advent of optical atomic clocks and the associated superior short-term frequency stability,[1,2] the transfer of signals linked to such clock or frequency standards over an appreciable distance with a minimal loss of stability has become an active subject for research. In prior work the instability of the transfer of the optical carrier of a cw laser was demonstrated to be a few parts in 10^{14} at a 1-s averaging time over a 6.9-km-long fiber.[3] A femtosecond laser located at the remote end can be phase locked to this incoming cw laser carrier, essentially redistributing the optical frequency to the microwave domain by means of the mode-locked laser's repetition frequency. For simplicity, an alternative approach is to amplitude modulate the optical carrier at a desired rf at the local end of the fiber and recover the modulation frequency at the remote end as the transferred reference signal. However, the instability of this rf modulation-based frequency transfer protocol seems to increase to a few parts in 10^{13} at 1 s, which is significantly higher than that of the cw laser-based direct optical transfer.[3]

In this Letter we report the transfer of optical frequency standards by use of mode-locked laser sources at 1.5 μm that are transmitted through an optical fiber network. The motivation is to explore the dual-transfer process for both the optical carrier frequency and the rf signal represented by the laser's repetition frequency, as well as to compare the transfer of such a rf signal with that of a modulated optical carrier. When the 1.5-μm mode-locked laser is phase coherently connected to a Ti:sapphire mode-locked laser[4] serving as the clockwork for an optical atomic clock,[2] both the optical carrier frequency and the repetition frequency of the 1.5-μm mode-locked laser are connected to a single optical frequency standard. Therefore a single fiber link allows a user at the remote end to either use a fast photodiode to recover the rf reference signal or establish a more elaborate, direct connection to the optical carrier. The simultaneous existence of both the optical phase and the pulse repetition rate information would also permit novel measurement capabilities on material dispersion and length determination. The experimental results confirm that the instability of the transfer process for the repetition frequency (rf reference) over a fiber network is nearly the same as that of the optical carrier transfer of a cw laser and is almost an order of magnitude better than that of the transfer of a modulated carrier. Furthermore, it is clear that a pulsed transfer process preserves the stability of the optical carrier as in the cw optical transfer process.

To study the instability of the transfer of the repetition frequency, the output of a mode-locked fiber laser is sent through two dark fibers installed in the Boulder Research and Administrative Network (BRAN), with a 6.9-km-long round trip and nine breakout panels. The experimental setup for this analysis is shown in Fig. 1(a). Before being sent through the BRAN fiber, the output of the laser is split, and both a local portion and the transmitted portion are detected. The optical power incident on each detector is crucial in minimizing the noise level of the measurement system and is controlled with a fiber-pigtailed variable optical attenuator. The eighth harmonic of each signal is detected and mixed. To analyze the time-dependent transfer instability, the signal detected before the fiber is shifted in frequency by 10 kHz with a single-sideband generator,[5] producing a 10-kHz signal after mixing, which is then counted with sufficient

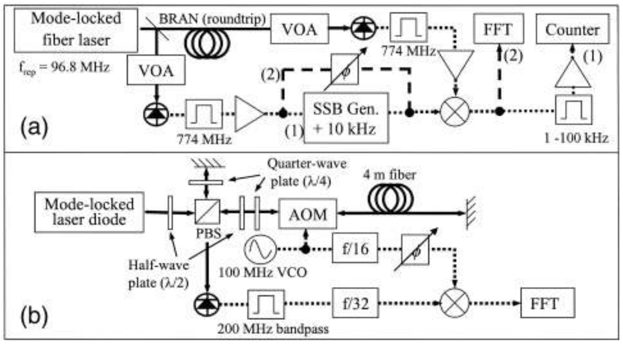

Fig. 1. (a) Experimental setup for measurement of the rf transfer instability for the fiber laser's repetition frequency, allowing time-domain analysis through frequency counting and the use of path (1) or frequency-domain analysis through jitter spectral density and the use of path (2). (b) Setup for measurement of the phase noise spectral density for transfer of the optical carrier of a mode-locked (ML) laser diode. VOA, variable optical attenuator; SSB, single-sideband; FFT, fast Fourier transform; PBS, polarizing beam splitter; VCO, voltage-controlled oscillator.

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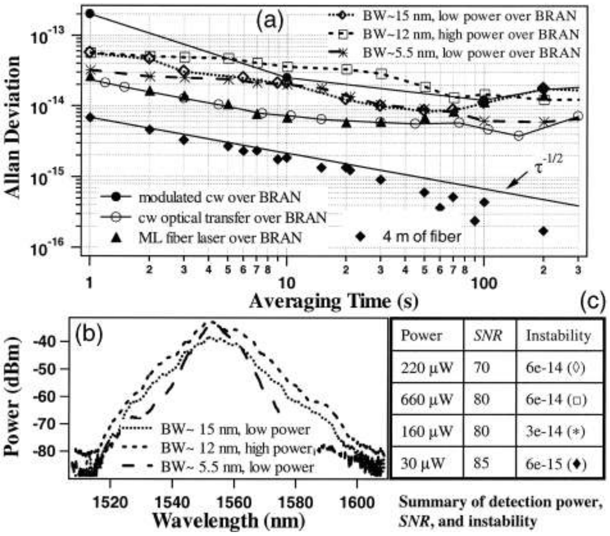
resolution [path (1)]. For analysis in the frequency domain the fast Fourier transform of the mixer output at the base band measures the spectral density of the rms timing jitter introduced by the fiber transmission [path (2)].

The transfer stability of the optical carrier of a mode-locked source is measured with the setup shown in Fig. 1(b). A portion of the output of a mode-locked laser diode[4] is sent through an acousto-optic modulator (AOM), and the first-order output is sent through 4 m of fiber and retroreflected. With appropriate polarization optics it is then combined with a portion of the original light stored in a reference arm, whose length is adjusted such that the reference pulse and the transmitted pulse overlap in time. The heterodyne beat is then detected on a photodiode, which has a frequency twice that of the AOM driving frequency. The phase noise introduced by the one-way transmission can then be determined by dividing the beat signal by 2 and mixing with the AOM driving frequency, which is set to quadrature with a phase shifter.

The transfer instability (Allan deviation[4]) of the repetition frequency of the mode-locked fiber laser is shown in Fig. 2(a). The instability at 1 s is as low as $<3 \times 10^{-14}$, shown as filled triangles, and is in close agreement with the instability for the optical carrier transfer of a narrow-linewidth cw laser discussed in Ref. 3 and shown here as open circles. In addition, the instability is almost an order of magnitude lower than that for the rf transfer of a sinusoidal amplitude-modulated optical carrier, also discussed in Ref. 3 and shown as filled circles.

We have identified two critically coupled parameters that profoundly affect the detected transfer instabilities. They are the signal-to-noise ratio (SNR) of the detected rf harmonic and the average power on the photodiode. The best result is achieved when a sufficiently high SNR is obtained with the lowest possible detection power. The noise floor of the measurement system is determined by use of a 4-m length of fiber as a transmission medium. For an average light power of $\sim 30\ \mu W$ on the detector, corresponding to a SNR of ~85 dB for a 1-kHz-resolution bandwidth, the instability at 1 s is below 7×10^{-15} [Fig. 2(a), filled diamonds]. This result is the same for different operating states of the fiber laser shown in Fig. 2(b). The solid line in Fig. 2(a) shows that the instability averages down as $\tau^{-1/2}$ for white frequency noise. When the pulses go through the much longer BRAN fiber, they broaden substantially, resulting in a smaller SNR given the same detection light power. For the best result we therefore employ the narrowest bandwidth pulses from the fiber laser, leading to the smallest temporal stretching of the transmitted pulses and the highest SNR for harmonic detection. We control the pulse bandwidth and operating power by adjusting the pump power and polarization state of the fiber laser, thus modifying the mode-locking condition. For example, when the fiber laser has a relatively large pulse bandwidth (~15 nm), the SNR of the detected eighth harmonic of the repetition frequency is only ~70 dB after the BRAN transmission, even though the average light power on the photodiode is increased to $\sim 220\ \mu W$. The detected instability increases to 6×10^{-14} at 1 s [Fig. 2(a), open diamonds]. Under a different mode-locking condition, a similar bandwidth (~12 nm) is achieved with more optical power ($\sim 600\ \mu W$) available for detection such that the SNR is enhanced to ~80 dB, leading to a similar level of instability at 1 s, 6×10^{-14} [Fig. 2(a), open squares]. It is likely that the nonlinear noise processes in the photodetection coupled with the increased light power lead to the relatively high instability. By using the narrowest pulse bandwidth (~5.5 nm) we obtain a sufficient SNR (~80 dB) for detection of the eighth harmonic with only $\sim 160\ \mu W$ of power on the photodiode, leading to the lowest instability of $\sim 3 \times 10^{-14}$ at 1 s [Fig. 2(a), asterisks]. These results are summarized in Fig. 2(c).

The effect of an erbium-doped fiber amplifier (EDFA) on the instability of the transfer of the fiber laser's repetition frequency is shown in Fig. 3. For this analysis an EDFA is inserted immediately before the BRAN fiber in Fig. 1(a), and it provides a factor of ~4 of optical gain. The instability at 1 s with the EDFA is $\sim 6 \times 10^{-14}$ [Fig. 3(a), filled squares] and is slightly greater than the instability at 1 s obtained without the EDFA (open squares). The increased instability is due to noise introduced by the EDFA itself and not to the issues involved in the discussion of Fig. 2, since the average light power incident on the photodiode after the BRAN is less and the SNR of the rf signal is greater with the EDFA in place. The spectral density of the rms timing jitter introduced by the EDFA is shown on the left axis of Fig. 3(b). At low frequencies the EDFA introduces more jitter. Because high frequency noise is averaged out for the Allan deviation and only low frequency noise is revealed, the Allan deviation is higher with the



Power	SNR	Instability
220 µW	70	6e-14 (◊)
660 µW	80	6e-14 (□)
160 µW	80	3e-14 (*)
30 µW	85	6e-15 (◆)

Fig. 2. (a) Allan deviation of the rf transfer of the fiber laser's repetition frequency for several different mode-locking conditions, (b) with the corresponding optical spectrum. Also included are modulated optical carrier and cw optical carrier transfers. Measurement with a 4-m fiber represents the measurement system's noise floor. (c) Summary of detected instabilities versus power and SNR. BW, bandwidth.

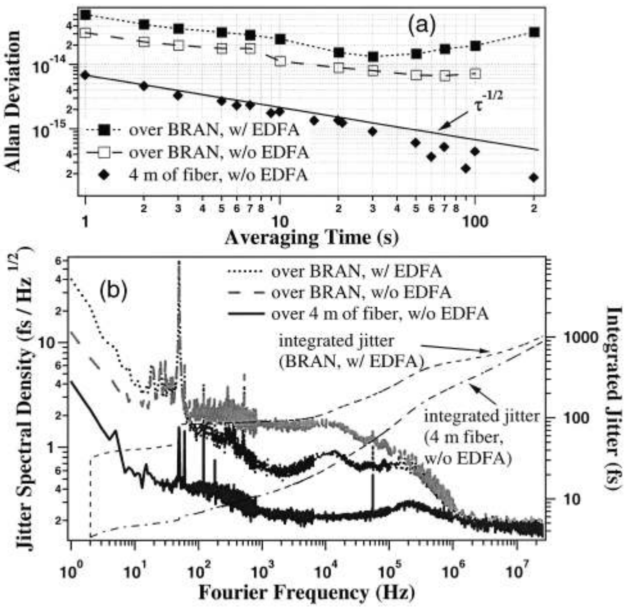


Fig. 3. (a) Instability of the rf transfer of the fiber laser's repetition frequency with (filled squares) and without (open squares) an EDFA. Measurement noise floor (filled diamonds). (b) Jitter spectral density on the left axis with (dotted curve) and without (dashed curve) an EDFA and the measurement noise floor (solid curve). Integrated jitter displayed on the right axis with the EDFA (dashed curve) and for the noise floor (dashed–dotted curve).

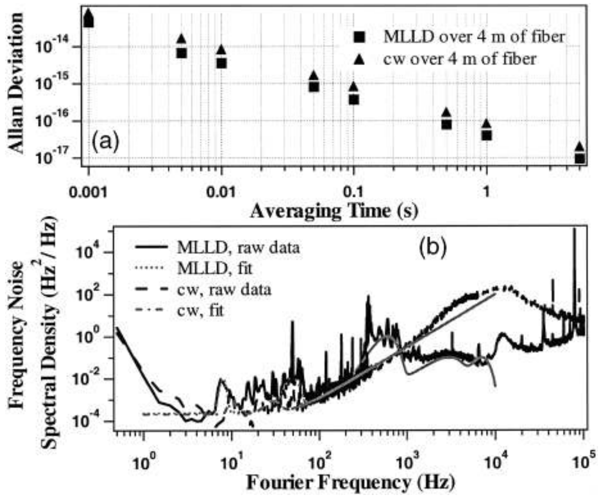


Fig. 4. (a) Allan deviation of optical carrier transfer of a mode-locked laser diode (MLLD) (squares) and cw laser (triangles), computed from (b) fits to the frequency noise spectral density for the MLLD and cw laser.

use of the EDFA for averaging times greater than 1 s. However, the jitter spectral density shows that for frequencies >100 Hz the EDFA suppresses the jitter as expected because of the long time constant of the EDFA's gain dynamics. On the right axis of Fig. 3(b) is the integrated rms jitter of the noise floor and the system with the EDFA in place. Although the jitter of the noise floor is dominated by noise introduced by the rf amplifiers, it is interesting to note that with the EDFA, the jitter does not exceed 1 ps for integration from 1 Hz to 25 MHz.

To verify that the optical carrier of a mode-locked source can be transferred as reliably as that of a cw laser, the instability of the transfer of the optical carrier of a mode-locked laser diode over 4 m of fiber is measured. The spectral density of the rms frequency noise introduced by the transfer is determined as described in Fig. 1(b) and is shown in Fig. 4(b). Also shown is the spectral density of the frequency noise introduced when transferring a cw laser. From the phase noise spectral densities the Allan deviations can be determined[4]; they are shown in the upper panel of Fig. 4. They are obtained after curve fitting of the frequency noise spectral densities (shown in the bottom panel) to increase the frequency resolution for the integration. It is clear from Fig. 4 that the optical carrier of a mode-locked source can be transferred as reliably as a cw source.

In summary, a mode-locked fiber laser has permitted the transfer of a rf signal over an installed fiber network with the same level of stability as is seen for a cw optical carrier transfer. The level of instability ($<3 \times 10^{-14}$ at 1 s) is approximately ten times better than that for rf transfer with a modulated optical carrier. Because of the temporal stretching experienced by the pulse during transmission resulting in a reduced SNR of the detected rf signal for a given optical power, it is desirable to maintain a small bandwidth of the launched pulses to reduce the effect of this stretching. It will be interesting to recompress the pulse by use of dispersion-compensation fiber to study the effect on the SNR of the rf signal and the stability of the rf transfer. A recompressed pulse is also useful for performing a cross correlation with prelaunch pulses, allowing highly precise jitter measurements and feedback control to be performed. This will permit future time-domain experiments such as the synchronization of two remotely located mode-locked lasers.

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