Radian-level coherent optical links over 100's of meters and 100's of terahertz

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Abstract: We demonstrate coherent transfer of optical signals with radian level noise (in a 25 MHz bandwidth) through a series of laser systems spanning from 657 nm to 1550 nm and over several hundred meter distances.

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Very coherent laser sources can be realized by locking lasers to stable optical cavities [1-4]. These coherent laser sources have been developed in the context of optical clocks, where they serve the role of a highly stable "flywheel". Depending on the specific application, these coherent laser systems are built for very different optical frequencies. Furthermore, they are not generally transportable and thus typically exist in physically separated locations. Fortunately, the basic tools for comparing coherent optical sources at different frequencies and over a distance have

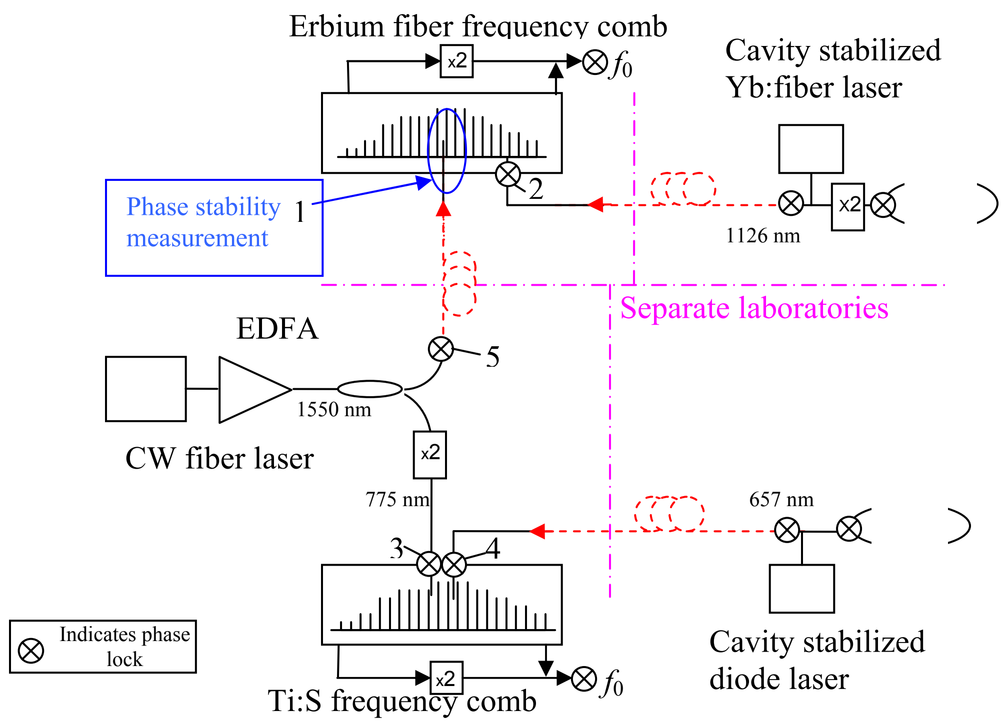

Fig. 1. Configuration for the measurement of optical coherence across the network of four laboratories. Dotted lines indicate Doppler-stabilized fiber links extending from lab to lab. Both frequency combs use the standard f to 2f technique to determine and stabilize the carrier-envelope offset frequency, f_0, while the repetition rate is stabilized to a cavity stabilized laser. The CW Erbium fiber laser is doubled in a PPLN crystal and phase stabilized to a comb tooth of the Ti:S frequency comb. The cavity stabilities are passed along two paths of sequential phase locks. The two paths of stability are as follows: (1) Cavity stabilized Yb:fiber laser => stabilized Doppler link => Erbium fiber frequency comb, (2) stabilized diode laser => stabilized Doppler link => Ti:S frequency comb => Erbium fiber laser=> additional stabilized Doppler link. Numbers 1-5 indicate the location where phase noise measurements are taken (figure 2).

been developed. These tools include low phase-noise optical combs for transfering the coherence across the optical spectrum [5-8] and Doppler-cancelled fiber links for transfering the coherence over a distance on optical fibers [9,10]. These technologies and optical clocks themselves have developed to a point where we can consider building coherent local fiber networks connecting various coherent sources at different locations and different optical frequencies. Here we explore the phase noise properties of such a coherent system. Our demonstration system (figure 1) comprises two independant coherent cavity-stabilized lasers in the visisble and IR, two different optical frequency combs, a CW transfer oscillator and three stabilized optical fiber links spanning four different locations. One frequency comb is based on a modelocked Ti:Sapphire laser and can span the visible to the near IR [7]. The second frequency comb is based on a modelocked fiber laser and can span the near IR [8]. The system is capable of comparing two different coherent sources that operate at wavelengths from 500 nm up to 2 microns at locations 100’s of meters apart.

As shown in figure 1, phase stability for the two arms of this experiment is provided by two cavity stabilized CW lasers, a Yb fiber laser at 1126 nm and a laser diode at 657 nm [3,4]. The 1126 nm light is used to stabilize one tooth of the frequency comb by feeding back to the repetition rate of an Erbium fiber (EF) frequency comb detailed in Ref. [8]. The carrier-envelope offset frequency, f_0, for the EF frequency comb is measured in the standard f-to-2f fashion [5,6] and stabilized. The Ti:Sapphire (TS) frequency comb (described in Ref. [7]) is similarly stabilized to the 657 nm light. It is interesting to note that while we use only a specific portion of either frequency comb spectrum, similar experiments have demonstrated that the phase stability can be seen along the entirety of either comb [7,8]. Thus we could in principle generate stabilized light anywhere from 500 nm to 2 μm.

The EF frequency comb is connected by fiber to the cavity-stabilized 1126 laser that serves as its optical reference, and the TS frequency comb is similarly connected by fiber to the cavity-stabilized 657 nm laser. In order to avoid phase-noise induced on these fiber links, we use the Doppler cancellation technique for optical fiber

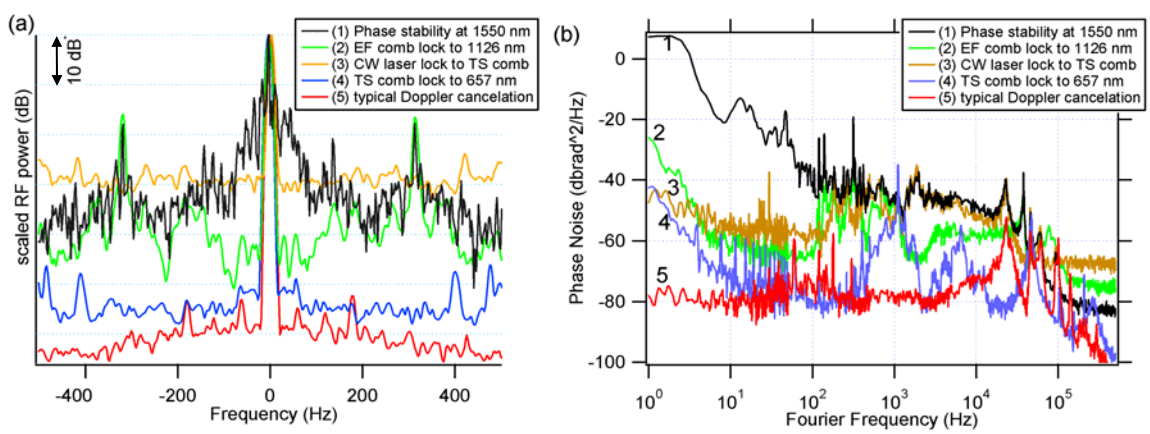

Fig. 2. (a) Heterodyned beat demonstrating the optical coherence between the two arms of the system (black). Also shown are the series of heterodyned beat measurements characterizing the more critical phase locks. For clarity the heterodyne beat frequencies have been centered at zero. Numbers 1-5 correspond to measurement points on figure 1. (b) Corresponding optical phase noise measurements. One can see noise contributions from the locks affecting the final phase noise measurement; however, the significant 1/f phase noise seen below 100 Hz is due to an unstabilized path length. Note, all measured phase noises have been scaled to correspond to 1550 nm.

detailed in Refs. [9,10]. In this technique light is frequency up-shifted by an acousto-optic modulator (AOM) before entering the transmission fiber. At the end of the transmission fiber a small part of the signal is reflected back down the fiber and back through the AOM where it is compared to the original light by mixing on a photodiode. This mixing generates an RF frequency that is phase locked to a synthesizer to cancel out fiber induced noise. In general the portion of the total system phase instability contributed from a fiber link is negligible (see figure 2).

The frequency combs have some overlap (although small) in the 1 μm wavelength range, so a phase instability measurement could be performed directly in principle. However, such a comparison over fiber is awkward in part because dispersion makes it difficult to stabilize comb light in a fiber using an AOM, so one additional stage is added. This stage uses a CW, Erbium fiber laser to generate 1550 nm light that is frequency doubled to 775 nm and locked to a tooth of the TS frequency comb. A small portion of the 1550 nm light is sent over a third stabilized fiber link and compared to a tooth of the EF frequency comb to complete the phase noise measurement. In addition to being easily transferred over a fiber, this CW laser has the additional advantage of generating light in the centers of both the TS and the EF frequency comb optical spectra.

We track the phase stability of the system by observing the RF heterodyned beat signals at the intersection of the two stability arms and at all phase locked points. From the phase noise spectrum, figure 2b., it is apparent that at Fourier frequencies greater than 100 Hz we are limited by the quality of the phase locks. An integration of the phase noise (figure 2b, plot 1) out to 500 kHz yields 0.93 radian phase instability. To extrapolate out to the 25 MHz Nyquist frequency (set by the 50 MHz EF frequency comb) we take the phase noise floor from the EFFC lock to the 1126 nm light (dominate noise source at that point) and integrate out to 25 MHz yielding a 1.52 radian phase instability in a 100 Hz to 25 MHz bandwidth. Below 100 Hz it is our belief that the noise is dominated by a single out of loop path that generates a 1/f noise spectrum, rather than the phase noise between the 657 nm and 1126 nm lasers. Incorporating this spectrum into the phase instability calculation yields a 3.5 radian phase instability. However, this path can be stabilized as well and an integration of the phase noise from the phase locks suggests that doing so will improve the phase instability to the 1.6 radian level even without the further improvements to the phase locks currently underway.

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