Multi-octave optical coherence spanning hundreds of meters

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Abstract: We demonstrate coherent transfer of optical signals with radian level noise (in a 3.5 MHz bandwidth) through a series of laser systems spanning from 657 nm to 1535 nm and several hundred meter distances.

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Erbium fiber (EF) frequency combs have become increasingly attractive to the optical frequency metrology and optical clock community. Their relative environmental stability and adaptability to telecom wavelengths have long made them attractive options. Additionally, fiber frequency combs have recently been demonstrated to have low noise characteristics comparable to even those of a Ti:Sapphire (TS) frequency comb [1,2]. Here we explore and exploit the noise characteristics of an erbium fiber frequency comb by developing a coherent network spanning hundreds of meters and incorporating an EF frequency comb, a TS comb [3] and with stability provided by two stable optical cavities [4,5], all connected by stabilized Doppler links [6,7]. This network is capable of transferring radian level phase stability over a significant distance and optical spectrum. Such a network is attractive in that it allows for the rapid characterization of the noise properties of our EF frequency comb without requiring it to be in the same physical location as either the other frequency comb or the stable optical cavities. More generally, by incorporating the erbium fiber comb into the network it becomes possible to quickly characterize additional optical sources anywhere in the 500 nm to 2000 nm range and located anywhere in the building.

In our demonstration system (figure 1) two independent coherent cavity-stabilized lasers, in the visible (657 nm) and IR (1126 nm) [4,5], provide the highly phase coherent light for the system. Two different optical frequency combs are stabilized to these lasers, allowing transfer of the coherence across a large range of the spectrum. One frequency comb is based on a mode-locked, 1 GHz, Ti:Sapphire (TS) laser and spans the visible to the near IR [3]. The second frequency comb is based on a mode-locked, 50 MHz, Erbium fiber (EF) laser and spans the near IR [1]. The cavity-stabilized lasers are used to stabilize one tooth of

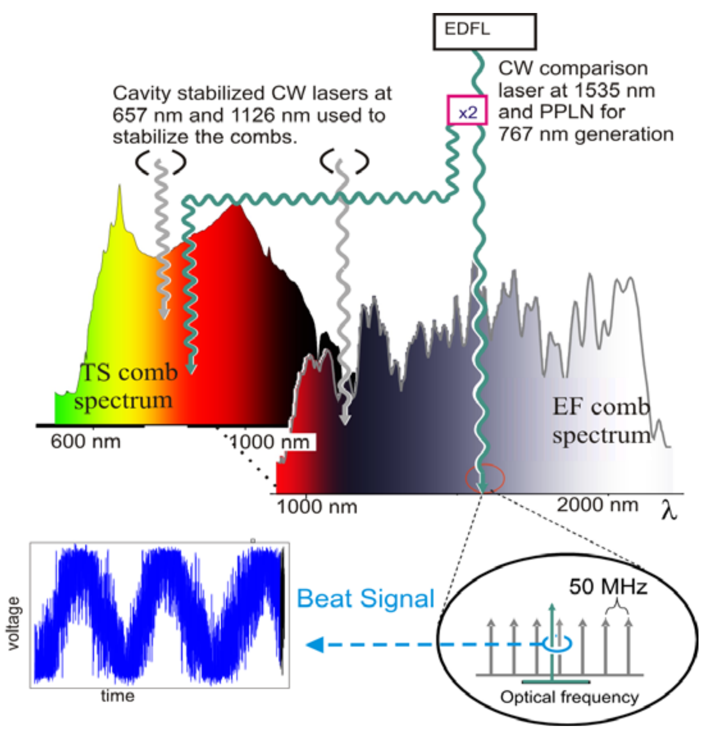

Fig. 1. Configuration for the measurement of optical coherence across the network of four laboratories. Two stable optical cavities existing in separate, isolated rooms are transferred over Doppler-stabilized fiber links and heterodyned with an optical tooth of each of the frequency combs. Both frequency 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 by phase locking to the cavity-stabilized CW lasers. With both combs locked, the low phase noise of the two cavities is effectively extended from 600 nm to 1200 nm for the Ti:Sapphire (TS) comb and from 1000 nm to 2100 nm for the Erbium fiber (EF) comb.

It should also be noted that these combs exist in separate laboratories as well. In order to measure phase noise around the network, a final CW fiber laser at 1535 nm is employed to bridge this distance. Frequency doubled light from this laser is locked to a tooth of the TS spectrum and the fundamental is transferred over a third fiber stabilized link and heterodyned with a single tooth of the EF comb for the coherence measurement (blue data is an actual beat mixed down to 1 Hz).

The TS comb can be stabilized to either the 1126 nm light or the 657 nm light. This allows for either a closed loop experiment, or two independent arms for cavity comparison.

each frequency comb by feeding back to the comb repetition rate [1,3]. The carrier-envelope offset frequency, f_0, for the frequency comb is measured in the standard f-to-2f fashion [8,9] and stabilized. It is interesting to note that while we use only a specific portion of either frequency comb spectrum, similar experiments have demonstrated that the low phase jitter can be seen along the entirety of either comb [1,2]. Thus we have access to highly coherent light anywhere from 500 nm to 2 μm. To perform the final frequency comparison, a third CW laser is used as transfer oscillator. This erbium doped fiber laser (EDFL) generates 1535 nm light that is doubled to 767 nm and locked to a tooth of the TS comb. The fundamental light is then heterodyned with a tooth of the EF comb to compare the two arms of the system.

It should be noted that the two cavity-stabilized lasers and the two fiber frequency combs are all in different laboratories, each physically separated by hundreds of meters. To deal with this separation the two cavity stabilized lasers and the 1535 nm light from the EDFL are transmitted through Doppler stabilized fiber links to maintain tight coherence across this distance [6,7]. In general the portion of the total system phase jitter contributed from a fiber link is negligible (see figure 2).

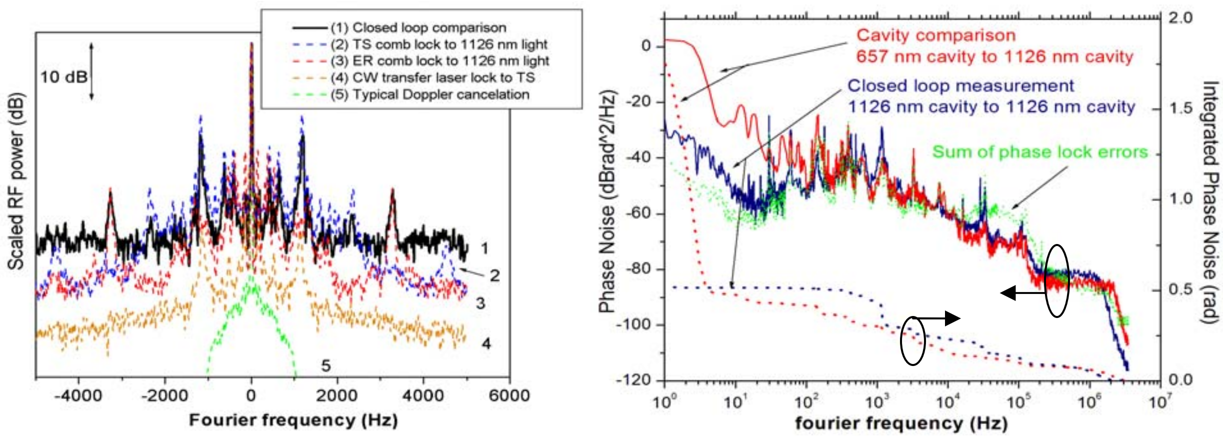

Fig. 2. (a) Heterodyned beat demonstrating the optical coherence between the two arms of the system (black). Also shown are the series of heterodyned beat measurements characterizing the more critical phase locks. For clarity the heterodyne beat frequencies have been centered at zero. (b) Corresponding optical phase noise measurements for closed and open loop experiments. The green trace represents the summed noise from all phase locks in the system. One can see noise contributions from the locks affecting the final phase noise measurement. Phase noise seen below 10 Hz is due to unstabilized optical path lengths and cavity-to-cavity drift. Dotted lines below give the integrated phase noise.

Two experiments were performed. The TS comb can be stabilized by either the 1126 nm light or the 657 nm light. By locking both combs to the 1126 nm light we did a closed-loop experiment that allowed us to characterize the phase noise in the system due to the phase locks and out-of-loop drift. As seen in figure 2, this system has 0.5 radian phase jitter at 1535 nm (integrated from 3.5 MHz to 1 Hz), corresponding to a 400 attosecond timing jitter. The primary limitations above 10 Hz were the phase locks of the combs to the cavity-stabilized lasers. It is interesting to note that the performance of the EF comb was very comparable to the TS comb here, although even higher phase coherence has been demonstrated for TS combs. Below 10 Hz the noise spectrum was dominated by out-of-loop drift accounting for less than 0.1 radian phase jitter.

In the second experiment, the TS comb was locked to the 657 nm cavity so that the two arms of the system became completely independent. Under these conditions the phase noise spectrum was nearly identical except that relative drift of the two cavities now dominated below 10 Hz. Again, above 10 Hz the noise spectrum is really a measure of the phase noise of the optical locks for the EF and TS frequency combs.

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