Optical frequency comb with submillihertz linewidth and more than 10 W average power

T. R. SCHIBLI[1]*, I. HARTL[2], D. C. YOST[1], M. J. MARTIN[1], A. MARCINKEVIČIUS[2], M. E. FERMANN[2] AND J. YE[1]

[1]JILA, National Institute of Standards and Technology and University of Colorado, Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA
[2]IMRA America, 1044 Woodridge Avenue, Ann Arbor, Michigan 48105, USA
*e-mail: t.schibli@osa.org

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Growing demands for high average and peak powers in extreme nonlinear optics[1], attosecond-pulse[2,3] and extreme ultraviolet comb generation experiments[4,5] can find a powerful solution in fibre-based mode-locked lasers. Using passive enhancement cavities[6], fibre lasers have produced high-repetition-rate femtosecond pulse trains with multikilowatt average powers and peak powers reaching hundreds of megawatts[7]. One major challenge for novel high-resolution spectroscopy and precision measurement in suboptical wavelength regions[8–10] is to transfer the state-of-the-art optical phase coherence into the extreme ultraviolet domain through the extreme nonlinear optics enabled by these high-power systems. We demonstrate here that optical frequency combs produced by high-power fibre lasers reach unprecedented levels of performance in both precision and average power. We achieve a record low relative linewidth of <1 mHz between a traditional Ti:sapphire frequency comb and a novel 10 W average power fibre comb, at the same time demonstrating all the necessary elements for power scaling precision comb technology to beyond 10 kW.

Optical atomic clocks have now surpassed the best caesium frequency standards in both stability and systematic uncertainty[11,12]. An important element in these optical clocks is mode-locked laser-based optical frequency combs for the distribution of the clock's optical frequency to other optical or radio-frequency (RF) spectral domains. Such clockwork has usually been based on Kerr–Lens mode-locked femtosecond (fs) Ti:sapphire lasers. The bulky nature and critical alignment of such lasers required stable environmental conditions and periodic realignment of the laser system. Frequency combs based on mode-locked fibre lasers have already shown stable, long-term operation[13,14]. Early experiments indicated that fibre oscillators sometimes suffered from larger optical phase noise than traditional bulk lasers[15], but it has recently been demonstrated[13,14,16–18] that all-fibre systems could produce high-quality optical frequency combs with average powers of ~100 mW. However, power scaling such sources beyond a few 100 mW unavoidably introduced a prohibitively large amount of phase noise due to the substantial amplitude-to-phase noise conversions in typical fibre amplifiers.

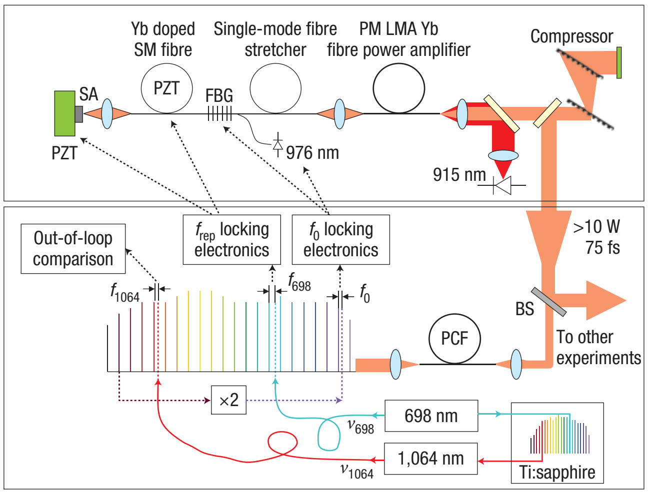

Figure 1 **Experimental set-up of the fibre comb.** The elements of the fibre comb are a saturable absorber (SA), a piezo actuator (PZT), a fibre Bragg grating (FBG), a polarization-maintaining, large-mode-area fibre (PM LMA), a beamsplitter (BS), a photonic-crystal fibre (PCF), a subhertz linewidth c.w. laser used for repetition-rate locking (698 nm) and a stabilized c.w. Nd:YAG laser used for the out-of-loop phase characterization (1,064 nm). The 1,064 nm laser is phase-locked to the subhertz-linewidth 698 nm laser using a self-referenced Ti:sapphire comb. $\nu_{698,1064}$ denote the optical frequencies of the 698 nm and 1,064 nm c.w. lasers, respectively. $f_{698,1064}$ denote the heterodyne beat note frequencies in the RF domain between the corresponding c.w. lasers and the nearest mode in the fs comb. Most of the fibre comb power can be directed to other experiments, such as cavity-enhanced high-harmonic generation.

Developments in large-mode-area Yb:fibres have enabled chirped-pulse amplification of fs pulse trains to very high average powers[19]. We recently succeeded in combining a high-power fibre system with a passive enhancement cavity[6], leading to fs pulse trains with record high average powers of several thousand watts

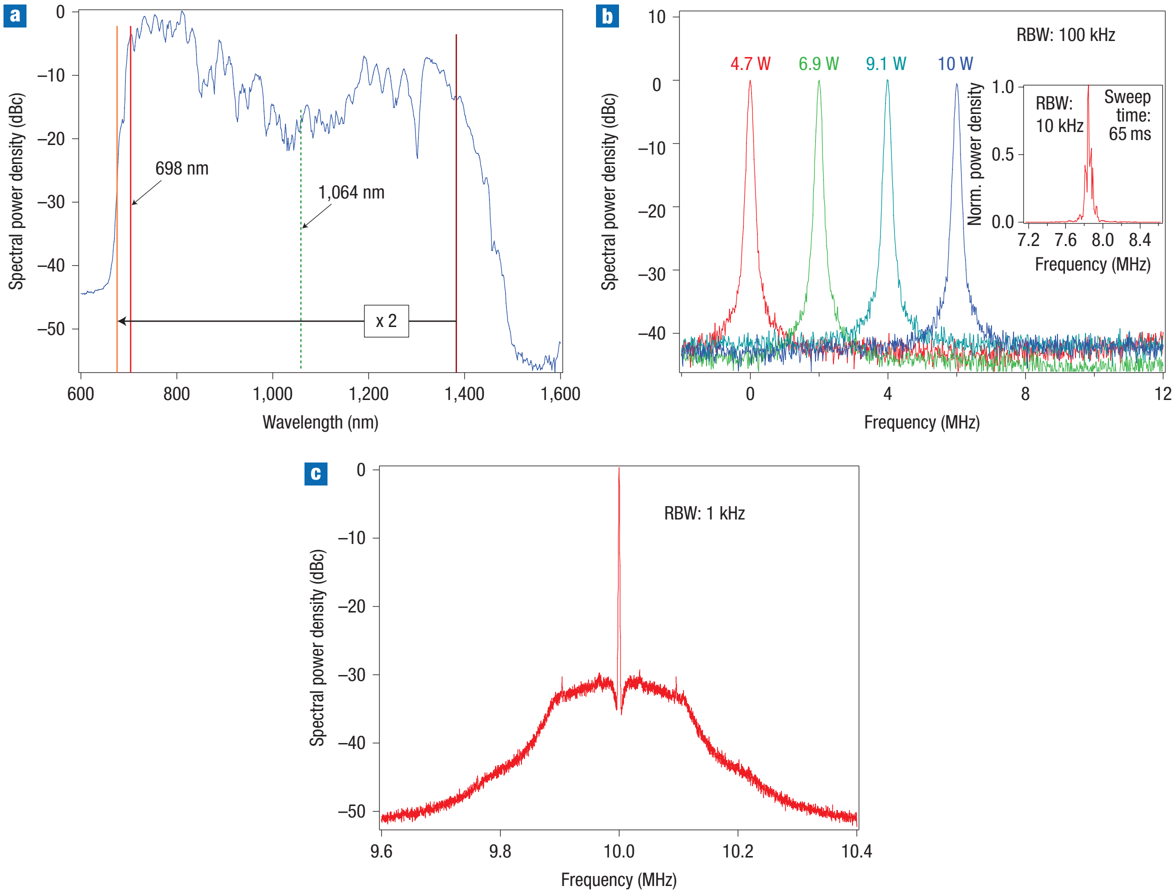

Figure 2 Optical spectrum of the frequency comb and carrier-envelope offset frequency. a, Optical spectrum after the photonic-crystal fibre. The two outermost vertical lines indicate the spectral components used for generating the f_0 beat note. **b**, Free-running f_0 beat note obtained from a nonlinear f–$2f$ interferometer at four different levels of average output powers (4.7 W, 6.9 W, 9.1 W and 10 W) from the comb system. Each trace shows an average of 25 single scans at 100 kHz RBW. The 25 scans are accumulated within a 20 s period during which the free-running f_0 beat note remains within a few kilohertz, a result unparalleled by traditional Ti:sapphire oscillators. The four traces are offset in the *x* direction for clarity. The inset shows the free-running beat note on a linear scale with a resolution bandwidth (RBW) of 10 kHz and a sweep time of 65 ms. **c**, Phase-locked f_0 beat note at 1 kHz RBW. Of the power, 90% is within the coherent carrier.

and hundreds of megawatts peak power[7]. The laser operated in the similariton regime[20,21], where the dispersion of the oscillator is slightly positive and the resulting pulse peak power is reduced to limit the nonlinear amplitude-phase coupling. Here, we demonstrate a high power Yb:fibre system with >10W average power that is passively more stable than any previously reported comb systems. Furthermore, with precision phase control and out-of-loop comparison—enabled by ultrastable continuous-wave (c.w.) lasers and an independent optical frequency comb—we experimentally demonstrate an optical frequency comb system with phase stability (displayed in the optical linewidth of comb modes) surpassing any reported systems based on bulk or fibre. This result is particularly important considering that the power of the frequency comb is at a record level of >10W. These attributes are necessary for producing highly phase-stable frequency combs in wavelength regions below the optical domain.

The fibre system shown in Fig. 1 consists of a 136 MHz Fabry–Pérot-type fs fibre oscillator that operates in the similariton regime[20,21], using an apodized fibre Bragg grating for dispersion compensation. The pulse train from this oscillator is amplified in a chirped-pulse amplifier (CPA). The pulses are first stretched to ~70 ps to avoid nonlinear phase shifts in the amplifier. The power amplifier consists of 8 m of large-mode-area, polarization-maintaining, double-clad Yb:fibre. After amplification, the pulses are recompressed using two fused-silica transmission gratings. The compressed pulses, measured by frequency-resolved optical gating, show a pulse duration of 75 fs at an average output power of >10 W.

A part of the compressed pulse train (~1 W) is launched into a 15 cm long, dispersion-flattened photonic-crystal fibre (PCF) with a zero-dispersion point around 1,060 nm. After broadening in the PCF, the optical spectrum spans more than one octave—from 675 nm to 1,450 nm (Fig. 2a). Some of this continuum is sent into a nonlinear f–$2f$ interferometer, where part of the long-wavelength side of the continuum (~1,350 nm) is doubled and made to interfere with light at the short wavelength end of the continuum at ~675 nm. We determine the carrier-envelope offset frequency f_0 of the Yb:fibre oscillator from this heterodyne beat signal. Owing to the extremely low amplitude and phase noise of the similariton oscillator paired with the linear amplification process in the CPA, the free-running fast linewidth of the f_0 beat note is <10 kHz (inset in Fig. 2b), a record for fibre laser systems. The centre frequency of f_0 is stable to within a 100 kHz window for minutes. Such stable operations of f_0 have never previously been observed. Ti:sapphire-based oscillators can display a narrow linewidth for f_0, but f_0 usually drifts many

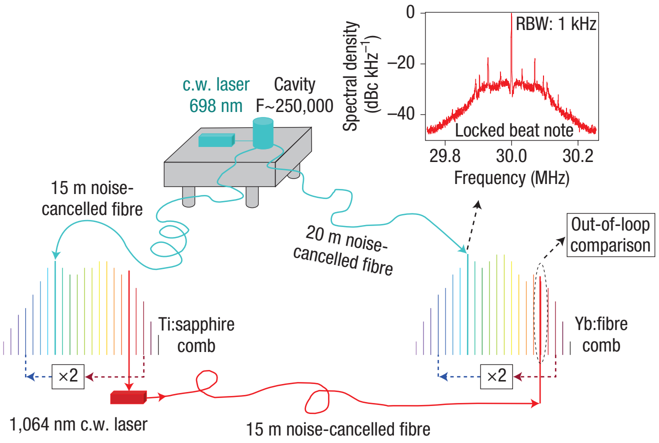

Figure 3 Experimental set-up for precise phase comparison of combs. The carrier-envelope offset frequency of each of the two combs is individually stabilized using $f-2f$ interferometers. Each comb is stabilized to a common, subhertz linewidth cavity-stabilized c.w. laser at 698 nm, accomplished by phase-locking the heterodyne beat note between one of the comb modes and the c.w. laser to a common caesium clock. The inset shows this locked beat-note for the case of the fibre laser. The 698 nm light is delivered through two noise-cancelled fibre links. A second c.w. laser is phase-locked to the Ti:sapphire comb at 1,064 nm and a fraction of its power is transferred to the Yb:fibre comb through a third noise-cancelled fibre link. The heterodyne beat note between the 1,064 nm laser and the Yb:fibre comb is then recorded with an FFT analyser for linewidth measurement and a frequency counter to determine the relative stability between the two fs combs. This out-of-loop beat note is shown in Fig. 4, which includes phase noise contributions from all relevant phase-locked loops and unbalanced differential air paths for optical beats. The arrows in the figure indicate the flow of phase coherence.

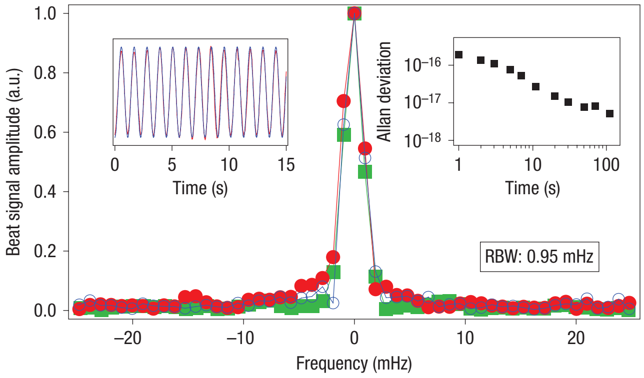

Figure 4 Out-of-loop comb comparison. Out-of-loop beat note between the stabilized Nd:YAG laser and the fibre frequency comb from two independent runs (open blue and filled red circles) showing a RBW-limited linewidth of 950 μHz at 1.05 ks sampling time. The green filled squares show a direct beat between the outputs of the two noise-cancelled fibres (15 m and 20 m, respectively) that deliver the subhertz linewidth 698 nm laser to the two fs combs. The left inset shows a 15 s record of the out-of-loop beat note (red) with a sinusoidal fit (blue), demonstrating perfect coherence between the two fs combs. The right inset displays the Allan deviation of the out-of-loop beat note scaled to the frequency of the transfer-oscillator at 281 THz. The stability data below 10 s was calculated from a series of 430 samples taken with 1 s gate time. The data above 10 s was calculated from ∼100 samples with 10 s gate time.

megahertz over a minute. On the other hand, fibre frequency combs generally show little drift in f_0, but so far show free-running f_0 linewidths above 50 kHz (refs 22 and 23).

Most fibre frequency combs use amplifiers that operate in a nonlinear regime; that is, the pulses are not only amplified but are also spectrally broadened due to self-phase modulation inside the amplifying fibre. This nonlinearity adds phase and amplitude noise to the original pulse train and restricts the achievable pulse energy to a few nanojoules. In our current system, we use a CPA that not only enables substantially higher pulse energies (currently ∼100 nJ) but also eliminates the amplitude-to-phase noise conversion from the amplification process. Therefore, the amplifier's output power has no observable effect on the linewidth or signal-to-noise ratio of the frequency comb, as shown in Fig. 2b. This also demonstrates that the cladding pumping scheme, an essential ingredient for scaling the average power beyond 1 W, is compatible with low phase noise operation, opening an avenue towards precision nonlinear optics experiments at unprecedented high average powers.

To phase-stabilize the frequency comb, we phase-lock the f_0 beat signal to a caesium atomic clock using a digital phase detector followed by two servo actuators, one of which controls the pump power for the fibre oscillator and the other the temperature of the fibre Bragg grating. Figure 2c shows the f_0 beat note when locked to a caesium clock at 10 MHz. Of the RF power, 90% is within the coherent carrier, showing excellent control over the fibre carrier-envelope offset frequency. This coherent carrier is further analysed with a fast Fourier transform (FFT) analyser, displaying a resolution bandwidth (RBW) limited linewidth <1 mHz.

To transfer the phase coherence of a 698-nm subhertz linewidth optical local oscillator[24] used in the JILA strontium optical lattice clock[12] to the fibre frequency comb, we stabilize the repetition rate f_{rep} of the fibre oscillator relative to this c.w. laser. This is accomplished by phase-locking the heterodyne beat note between one of the comb teeth at ∼698 nm and the c.w. laser to the same caesium clock (Fig. 2a). This subhertz c.w. laser provides a much better short-term stability than any commercially available microwave source. Again, two servo actuators are used, one controlling a fast and the other a slow piezoelectric transducer (PZT) inside the fibre oscillator (Fig. 1). The phase-locked heterodyne beat note contains ∼85% of the RF power within the coherent carrier (inset of Fig. 3).

To evaluate the performance of this novel, high-power fibre comb, we directly compare it with a well-established frequency comb produced by an octave-spanning Ti:sapphire laser[25]. We use two highly stable c.w. lasers to accomplish phase-coherent transfer and comparison across spectral gaps of several hundreds of nanometres and over distances of tens of metres. Figure 3 shows the basic idea of this comparison. The Ti:sapphire laser and the Yb:fibre laser are both phase-locked to the same subhertz linewidth reference laser at 698 nm. The offset frequency f_0 of each of the combs is independently stabilized using $f-2f$ interferometers. Using the 698 nm c.w. laser as a common optical reference allows us to compare the two combs without being limited by the reference stability. As the 698 nm reference and the two combs are each separated by tens of metres, it is crucial to actively stabilize the fibre link path lengths between the three set-ups to a small fraction of an optical cycle[26,27]. We use a Nd:YAG laser as a transfer laser for comparison between the two combs. The Nd:YAG laser is first phase-locked to one of the Ti:sapphire comb teeth at 1,064 nm (ref. 26). Some light of this transfer laser is then delivered through a third, noise-cancelled fibre link to the fibre comb. The heterodyne beat note between the stabilized Nd:YAG laser and the fibre comb was recorded with an FFT analyser and a frequency counter. From the FFT analyser we find RBW-limited linewidths of <1 mHz (1.05 ks accumulation time), as shown in Fig. 4 (red and blue circles). This requires that both combs and the transfer laser provide submillihertz relative linewidths. The left inset shows a 15 s record of this out-of-loop beat note in the time domain (red) with a sinusoidal fit (blue). This time record demonstrates perfect phase coherence between the two combs maintained over many seconds. The right inset in Fig. 4 shows the Allan deviation of the out-of-loop beat note measured by a frequency counter (Agilent 53131A in time-arming mode[28]), reaching low 10^{-18} at 281 THz over just 100 s.

In conclusion, we have demonstrated that a Yb:fibre-based similariton oscillator followed by a cladding-pumped fibre CPA produces an unprecedented high-average-power, ultraprecise, optical frequency comb with $\sim$125 μW power per mode ($\sim$600 nW per mode in the supercontinuum for 1 W in the PCF). Despite the large average power, we obtain the narrowest relative linewidth between two independent fs combs. Furthermore, we observe the narrowest free-running f_0 signal for fibre systems to date. We expect that the unparalleled power scalability of fibre systems and the ability to produce precise phase-stabilized, high-repetition-rate, high-average-power, optical frequency combs will have an important impact in many areas of ultrafast science and technology.

METHODS

The key elements of the fibre system are the fibre oscillator, the pulse stretcher, the pulse amplifier and the pulse compressor. The oscillator was mode-locked with a subpicosecond-lifetime, saturable absorber and the dispersion was compensated with a linearly chirped fibre Bragg grating with a dispersion of -0.028 ps^2, a reflectivity of 10% and a bandwidth of 60 nm centred at 1,050 nm. The dispersion of the oscillator was slightly positive ($\sim+4{,}000$ fs^2) for operation in the similariton regime[7,17,18], producing strongly chirped pulses within the oscillator. The oscillator output spectrum was centred at 1,065 nm with $\sim$40 nm of bandwidth. The pulses were compressible to 60 fs. The average output power of the oscillator was $\sim$160 mW. Operating the oscillator in the similariton regime helped to avoid the problem of soliton–continuum interaction[29] and minimized the contribution of optical wavebreaking to the carrier phase noise. Moreover, for small values of positive cavity dispersion, contributions to the timing jitter from frequency fluctuations were minimized and the timing jitter was dominated by direct timing fluctuations from the amplified spontaneous emission (ASE). This was further confirmed by a timing noise model of the similariton laser[30]. From the model the quantum-limited timing jitter was estimated to be $\sim$12 fs ms^{-1} r.m.s. in the present system. The quantum-limited timing jitter of ytterbium similariton fibre lasers can indeed be smaller than that of comparable erbium fibre lasers due to the higher intracavity pulse energies, minimizing the impact of ASE. Hence Yb systems should potentially be the optimum choice for ultralow-noise fibre comb systems. Further phase noise reduction can be expected with the implementation of large core ytterbium oscillator fibres, where power levels up to several watts can be reached for pulsewidths of the order of 30–50 fs.

The pulse stretcher consisted of $\sim$30 m of anomalous third-order dispersion, single-mode fibre. The length of the anomalous third-order stretcher fibre and the normal single-mode fibre output pigtail of the oscillator were carefully adjusted to compensate for the third-order and $\sim$95% of the fourth-order dispersions of the grating compressor. At the output of the stretcher fibre the pulses were $\sim$70 ps in duration.

The power amplifier consisted of 8 m of 700 μm^2 mode area polarization-maintaining double-clad Yb:fibre that was end-pumped by four fibre-coupled 915 nm diode bars. The pump wavelength overlapped with the wide absorption band of the Yb:fibre to avoid pump-wavelength jitter-induced amplitude noise in the amplified pulse train.

After amplification the pulses were recompressed using two fused-silica transmission gratings. The overall transmission efficiency of the compressor was $\sim$70%, resulting in a compressed output power of $>$13W at 40 W pump power. The compressed pulses were of 75 fs duration (characterized by frequency resolved optical gating, FROG). The central peak of the pulses contained $\sim$94% of the total energy of the pulse[7].

POWER SCALING

The B-integral—a measure for the nonlinear phase shift—in the current fibre amplifier was estimated as 0.6, based on the nonlinearity parameter of the power amplifier of $\gamma \approx 2.2 \times 10^{-4}$ W^{-1} m^{-1}. The experiments confirmed that the comb linewidth in CPA systems is not compromised across the pulse spectrum as long as linear amplification is used. The absence of amplitude to phase conversion was also observed from the inherently noisy pump diodes as implemented here. We therefore conclude that further power and energy scaling of high-power fibre comb systems is possible. Assuming state-of-the-art fibre amplifiers with mode areas of 4,000 μm^2 and a stretched pulse width of 1 ns, pulse energies of 50 μJ should be reachable for pulses in the 50–100 fs range with a linear CPA system with a B-integral of <1. Hence average powers <1 kW can be reached at repetition rates of 20 MHz. After focusing, peak intensities $>5 \times 10^{14}$ W cm^{-2} should be reachable in free space, which is more than enough for the generation of sub-100 nm wavelength light by means of high-harmonic generation in noble gases. In conjunction with optical enhancement cavities, even higher peak intensities may be produced, potentially opening the door to high-average-power extreme ultraviolet combs.

OPTICAL PHASE COHERENCE

In the out-of-loop characterization of the fibre frequency comb linewidth, it is crucial to minimize the out-of-loop path lengths in the set-up. In particular, all non-common beam paths must be either actively stabilized, such as for the case of the noise-cancelled fibre links, or kept as short as possible. In the fibre comb set-up shown in Fig. 1, the sum of all of the out-of-loop path lengths was kept within $\sim$10 cm. All of the out-of-loop paths were located within a near-airtight box to reduce the influence of acoustic noise and airflow. The temporal delay between the short and long wavelength parts in the f–$2f$ interferometer was realized with a Fabry–Perot-like arrangement, in which the input coupler was a dichroic mirror with high reflectivity for the short-wavelength side and high transmission for the long-wavelength side of the supercontinuum. The second mirror has a high reflectivity for both wavelengths. The length of the delay line is <1 mm, and therefore, does not affect the stability of f_0.

Using the 698 nm laser as a common reference in the comb comparison experiment greatly reduced the influence of drifts and the finite linewidth of the reference laser. This enabled measurements of relative linewidths of the order of 1 mHz, although the reference laser's linewidth was several hundreds of millihertz. Normally, as one is interested in the relative stability between two systems, the noise of a common reference can be cancelled perfectly. For example, two RF signals can be phase-locked to a common RF standard. Then, a direct comparison between the two RF signals will reveal the performance of the phase-locked loops, ideally without any influence from the common reference. However, our experimental situation is slightly more complicated. As the two frequency combs have different repetition rates (95 MHz and 136 MHz), we need to analyse the influence of the reference clock (that is, the 698 nm c.w. laser) on the out-of-loop phase comparison due to possibly unbalanced phase noise propagations between these two systems. For this purpose, we assumed that the drift of the reference laser was approximately linear (first-order approximation). We could then write the absolute optical frequency of the 698 nm reference laser as $\nu_{698} + \Delta T \cdot \mathrm{d}\nu_{698}/\mathrm{d}t$, where ΔT is the measurement time and ν_{698} the absolute optical frequency of the reference laser at the beginning of the measurement. We can express the reference laser frequency in terms of both fs combs as

$$\nu_{698} + \Delta T \frac{\mathrm{d}\nu_{698}}{\mathrm{d}t} = f_{0,i} + n_i f_{\mathrm{rep},i} + f_{698,i},\ i \in [1,2],$$

where $f_{0,i}$ and $f_{\mathrm{rep},i}$ denote the carrier envelope offset frequency and the pulse repetition rate of each comb, respectively. $f_{698,i}$ is the heterodyne beat frequency between the 698 nm reference laser and the n_i-th mode in the respective comb. Here, we distinguish between radio frequencies denoted by the symbol f and optical frequencies denoted by the symbol ν. A similar expression can be written for each beat notes $f_{1064,i}$ between the 1,064 nm laser and the m_ith mode in each comb. If we are only interested in the influence of the reference laser to the out-of-loop beat note $f_{1064,\mathrm{ol}}$ (assuming perfect phaselocks for $f_{\mathrm{rep},i}$ and $f_{0,i}$) we can derive the following simple expression:

$$\frac{\mathrm{d}f_{1064,\mathrm{ol}}}{\mathrm{d}t} = \left(\frac{m_2}{n_2} - \frac{m_1}{n_1}\right)\frac{\mathrm{d}\nu_{698}}{\mathrm{d}t}.$$

Again, m_i and n_i denote the mode in the ith comb ($i \in [1,2]$) with which the heterodyne beat note between the 1,064 nm and the 698 nm are generated. In the best case, we find the ratios m_i/n_i to be identical, resulting in perfect immunity against drifts of the reference laser. However, the two combs could be locked in such a way that $f_{698,i}$ tunes in the same direction as $f_{\mathrm{rep},i}$, although it is the opposite for the other comb. In the worst case, the same could apply simultaneously for the $f_{1064,i}$ beat notes with the 1,064 nm laser. In this case, we find

$$\left(\frac{m_2 \pm 1}{n_2} - \frac{m_1}{n_1 \pm 1}\right) \le 10^{-6}.$$

This is due to the fact that the mode numbers m_i and n_i are of the order of a few million. We conclude that the subhertz linewidth and ~1 Hz s^{-1} drift of the 698 nm laser are sufficient to measure millihertz linewidths at 1,000 s acquisition times.

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Author contributions

T.R.S. is responsible for the design and the overall execution of the experiment; T.R.S. and D.C.Y. for the stabilization of the Yb:fibre comb; M.J.M. for stabilization of the octave spanning Ti:sapphire comb and the 1,064 nm Nd:YAG laser; J.Y. for the overall laboratory infrastructure and concept development in precision measurement and phase control of fs combs; and I.H., A.M. and M.E.F. for the design and construction of the Yb:fibre laser.

Author information

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