Spectral purity transfer between optical wavelengths at the $10^{-18}$ level

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Ultrastable lasers and optical frequency combs have been the enabling technologies for the tremendous progress made in precise optical spectroscopy over the last ten years. Recently, to improve the laser frequency stabilization beyond the thermal noise fundamental limit of traditional room-temperature high-finesse optical cavities, new solutions have been developed. These are complex and often wavelength-specific, so the capability to transfer their spectral purity to any optical wavelength is therefore highly desirable. Here, we present an optical frequency comb-based scheme that transfers $4.5 \times 10^{-16}$ fractional frequency stability from a 1,062 nm wavelength laser to a 1,542 nm laser. We demonstrate that this scheme does not hinder the transfer down to $4 \times 10^{-18}$ at 1 s, one order of magnitude below previously reported work with comparable systems. This exceeds, by more than one order of magnitude, the stability of any optical oscillator demonstrated to date, and satisfies the stability requirement for quantum projection noise-limited optical lattice clocks.

Optical frequency combs provide a phase-coherent link across the optical and microwave frequency domains. For instance, they have been used for the generation of ultralow-phase-noise microwave signals that allow the interrogation of atomic fountain clocks at the quantum projection noise limit. Here, we present a solution exploiting an optical frequency comb (OFC) based on an erbium-doped fibre femtosecond oscillator centred at 1,560 nm for the phase-locking of two optical oscillators. We demonstrate spectral purity transfer without frequency stability degradation from a 1,062 nm master laser stabilized by a high-finesse optical cavity (independently characterized at the $4.5 \times 10^{-16}$ stability level) to a 1,542 nm slave laser.

Bridging the large wavelength difference between the slave and master lasers requires spectral broadening of the femtosecond laser output to obtain a sufficiently wide frequency comb. In fibre-based optical frequency comb systems, the femtosecond oscillator output is usually amplified and spectrally broadened in dedicated branches to obtain a phase-coherent OFC output centred in the spectral region of each continuous-wave (c.w.) laser. The relative phase between the c.w. lasers is then obtained by beating each of them to the output of the dedicated branch. The amplification and spectral broadening of the comb’s output in dedicated branches introduces differential phase noise that degrades the phase comparison and thus the frequency stability transfer. Typically, differential phase noise prevents frequency comparison of the master and slave lasers with a fractional resolution better than $\sim 1 \times 10^{-16}$ near 1 s integration time.

To overcome this limitation, we beat both c.w. lasers with a single spectrally broadened comb output obtained from a $f$–$2f$ interferometer unit used for the detection of the carrier–envelope offset frequency $f_c$. Spreading the available optical power over a broadband spectrum results in a low intensity for the comb teeth, so the optical beaon notes for each c.w. laser have relative low signal-to-noise ratios (SNRs). Because of the low SNR, narrow bandwidth detection of the beatnotes is required. This is made possible by operating the comb in the ‘narrow-linewidth regime’, in which each tooth has nearly the same spectral purity as the c.w. laser to which the comb is locked. The experimental set-up is presented in Fig. 1.

The comb’s repetition rate $f_{\text{rep}}$ is phase-locked by directly beating a fraction of the non-amplified femtosecond oscillator output with the 1,542 nm c.w. laser. The high SNR of the resulting optical beatnote and a fast intracavity electro-optic modulator (EOM) actuator allow to realize a phase-locked loop with a bandwidth exceeding 1 MHz, permitting the comb to operate in the narrow-linewidth regime. In the case where neither the master nor the slave laser has a wavelength contained in the spectrum of the femtosecond oscillator output, an auxiliary stable c.w. laser oscillator is required to lock the comb’s repetition rate. Another fraction of the femtosecond oscillator output is amplified in an erbium-doped fibre amplifier (EDFA) and spectrally broadened by a highly nonlinear fibre (HNLF) to obtain an octave-spanning spectrum from 1 µm to 2 µm. The comb’s EDFA–HNLF output is brought to a beat detection unit, where it is separated with a fibre dichroic splitter into the spectral components near 1,062 nm and 1,542 nm. Those are then combined with the light from the master and slave lasers, respectively, brought to the beat detection unit via actively noise-cancelled fibres. The resulting beatnotes are photodetected and mixed with the carrier–envelope offset frequency to obtain the $f_c$-free signals $f_m = f_m - N_1 f_{\text{rep}}$ and $f_s = f_s - N_2 f_{\text{rep}}$, related respectively to the instantaneous frequencies of the master laser ($v_m$) and the slave laser ($v_s$). $N_1$ and $N_2$ are integers addressing the comb teeth. The $f_s$ and $f_m$ signals are filtered through tracking oscillators with a bandwidth of $\sim 5$ kHz and used to clock two direct digital synthesizers (DDS) implementing frequency division, resulting in $f_{\text{out}} = f_m/M_1$ and $f_{\text{rep}} = f_s/M_2$ signals. The $M_1$ and $M_2$ divisors are chosen such that $M_1/M_2 = N_1/N_2$. This allows the generation of a $f_{s}^{*} = f_m - f_s$ signal independent of the repetition rate $f_{\text{rep}}$, and therefore immune to phase fluctuations, as in the ‘transfer oscillator technique’. Because $N_1/N_2 \approx v_m/v_s$, the signal at frequency $f_{s}^{*}$ properly implements the heterodyne phase comparison between the 1,542 nm and 1,062 nm wavelength lasers. By comparing $f_{s}^{*}$ with a fixed frequency reference, we derive a phase error that is used to correct the frequency of the slave laser, thereby implementing a phase-locked loop of the 1,542 nm slave laser on the 1,062 nm master.
From the 1,062 nm master laser to the 1,542 nm slave laser with frequency noise, this demonstrates the transfer of spectral purity between 0.1 s and 1.0 s. In the assumption of uncorrelated white phase noise level is defined by the SNR of the phase difference between the two lasers. The two set-ups differ only in minute quasi-identical set-ups measuring the phase difference between the same master and slave lasers, as measured by two independent optical frequency comb-based systems (set-up illustrated by dashed lines). To characterize the full transfer scheme, we replace the reference laser by a separate slave, independently locked to the master via an independent optical frequency comb-based system. EDFA, erbium-doped fibre amplifier; HNLF, highly nonlinear fibre; synth, radiofrequency synthesizer; DDS, direct digital synthesizer.

To evaluate the optical frequency measurement capability of our system, we compare the $f_s^*$ signals obtained from two independent quasi-identical set-ups measuring the phase difference between the same master and slave laser. The two set-ups differ only in minute details of the comb’s repetition rate phase-locked loop. From the phase difference between the two $f_s^*$ signals, assuming that each system contributes equal and uncorrelated phase noise, we assess the phase noise added by the OFC set-up in the frequency stability transfer process. Figures 3 and 4 present the phase noise power spectral density (PSD) and the corresponding fractional frequency stability, respectively.

The measured additive phase noise exhibits a white noise plateau at $-72$ dBc Hz$^{-1}$ that extends down to 2 Hz Fourier frequency. This white phase noise level is defined by the SNR of the $f_m$ and $f_p$ beatnotes, which are limited by the low available comb light power in the 1,062 nm and 1,542 nm spectral regions. Possible improvements of the phase noise in this Fourier frequency region requires a higher SNR, which may be obtained with amplification of the relevant regions of the EDFA–HNLF output spectrum using semiconductor amplifiers$^{23}$, and/or using a sub-shot-noise gated detection scheme$^{25}$.

On longer timescales, the system exhibits excess noise that limits the fractional frequency stability to $3 \times 10^{-18}$ at 1 s. This lower limit is one order of magnitude below that in any previously reported work$^{8-13}$. The $2 \times 10^{-20}$ stability at 1,000 s is the lowest reported long-term stability for OFC systems$^8$. Possible residual sources of low-frequency excess noise include incomplete noise suppression in the optical fibre links and laser power fluctuations. Additionally, despite the fact that the beatnote detection is performed in a carefully designed vacuum set-up, which provides good isolation from acoustic and thermal disturbances, we cannot completely rule these out as
sources of phase noise. The detection of $f_{\text{m}} \cdot f_s$ and $f_0$ from the same spectrally broadened comb output is effective in suppressing the phase fluctuations introduced in the EDFA and HNLF when those are wavelength-independent or scale linearly with optical frequency. Higher-order terms are, however, not cancelled and may contribute to the measured excess phase noise.

To fully characterize the optical frequency stability transfer, we used two independent set-ups to phase-lock two slave lasers to the same master laser. We assessed the phase noise of the transfer process from that of the beatnote between the two slave lasers, assuming an equal and uncorrelated contribution from each system. Figures 3 and 4 present the phase noise PSD and the corresponding fractional frequency stability.

For technical reasons, in this configuration, the SNR of the $f_{\text{m}}$ and $f_s$ beatnote is degraded, which increases the white noise plateau to $-65 \text{ dBc Hz}^{-1}$ and limits the fractional frequency stability to $4 \times 10^{-18}$ at 1 s. Long-term stability is affected by the noise contribution of the interferometer beating the two slave lasers, as the set-up includes a few metres of non-noise-cancelled fibre. However, we still demonstrate a fractional frequency stability of $1 \times 10^{-17}$ at 1,000 s.

These results were obtained with a reliable fibre-based system, compatible with long-term continuous and autonomous operation, which makes it suitable for use in metrology experiments. We routinely operated the system in a research laboratory environment to obtain unsupervised, continuous, phase-slip-free operation limited only by anthropogenic disturbances. No fundamental limitations that might prevent the system from operating continuously were identified.

The presented technique is readily applicable to phase-locking any laser oscillator in the spectral region between 1 µm and 2 µm where the comb’s EDFA–HNLF output provides non-negligible optical power. It can be extended to the visible spectral region via second-harmonic generation. The proposed scheme is therefore directly applicable to most existing experiments.

Identifying unequivocally the dominant sources of low-frequency noise and developing strategies to circumvent them will require further work. Nonetheless, the current $3 \times 10^{-18}$ level exceeds, by more than one order of magnitude, the performance of any oscillator demonstrated to date and is compatible with the requirements of quantum projection noise-limited optical lattice atomic clocks. Transferring frequency stability from an optical oscillator at arbitrary wavelength to a laser with wavelength centred in the femtosecond oscillator output spectrum (and thus compatible with wide-bandwidth phase-locking of the comb’s repetition rate), the proposed technique can also benefit OFC-based low-phase-noise microwave signal generation, which is limited, close to the carrier, by the phase noise of the reference optical oscillator.

By demonstrating the capability to transfer spectral purity to any frequency comb-accessible wavelengths, this work strengthens the quest for lasers with extremely high stability at implementation-specific wavelengths.

Methods

Laser systems. The master laser was an ultrastable 1,062.5 nm Yb-doped fibre laser locked via the Pound–Drever–Hall (PDH) scheme to an ultrastable Fabry–Pérot cavity, providing a fractional frequency stability of $4.5 \times 10^{-16}$ at 1 s (ref. 20). The slave laser was a 1,542.5 nm diode laser prestabilized by offset phase-locking to an erbium-doped fibre laser that was itself stabilized by PDH locking to a Fabry–Pérot cavity. To demonstrate our set-up capability, we voluntarily degraded the fractional frequency stability of the slave laser to $\sim 1 \times 10^{-15}$ at 1 s, transmitting it through a section of non-noise-cancelled optical fibre. We stress that such a level of prestabilization is not required; the phase-locked loop locking the slave to the master laser has a bandwidth of $\sim 5 \text{ kHz}$, so prestabilization of the slave laser to a linewidth narrower than $\sim 100 \text{ Hz}$ is sufficient. This requirement can be met easily by locking the slave laser to a simple optical cavity or to an optical fibre delay line, obtaining a significant reduction in the complexity of the set-up. The reference laser was a 1,542.5 nm erbium-doped fibre laser locked via the PDH scheme to an ultrastable Fabry–Pérot cavity, providing a fractional frequency stability of $5.0 \times 10^{-16}$ at 1 s (ref. 23).

Fibre-based optical frequency comb. The optical frequency comb was a commercial core fibre-based optical frequency comb based on a femtosecond erbium-doped fibre laser equipped with an intracavity EOM. The EOM provided feedback on the comb’s repetition rate $f_{\text{rep}}$ with a bandwidth of $\sim 1 \text{ MHz}$, and allowed the comb to be locked to the slave laser in the narrow-linewidth region...
Teeth should not be wider than \( \approx 1,560 \text{ nm} \), where it is possible to obtain a beatnote with a large SNR, the effect of both frequency fluctuations on the master and slave laser phase range of a few megahertz. The transfer oscillator technique effectively suppressed offset frequency bandwidth-limited servo loop. The carrier-envelope offset frequency \( f_{\text{ENO}} \) integer addressing the comb tooth closer to the optical frequency oscillation of the system. This can be realized via tight locking of the repetition rate to an \( f_{\text{rep}} \) signal. We note, however, that higher-order \( f_m \) signals presented SNR values smaller than 10 dB in a 100 Hz bandwidth, limited by the white noise floor of the detection chain. Even though the comb’s repetition rate \( f_{\text{rep}} \) was tightly phase-locked to the \( f_{\text{rep}} = 1,542 \text{ nm} \) slave laser, it could exhibit residual noise due to an imperfect and bandwidth-limited servo loop. The carrier-envelope offset frequency \( f_{\text{c}} \) was not locked and, in a well-controlled laboratory environment, it could evolve over a range of a few megahertz. The transfer oscillator technique effectively suppressed the effect of both frequency fluctuations on the master and slave laser phase comparison. We note, however, that the spectral phase evolution produced in the femtosecond laser, scaling with the optical frequency of order higher than linear, is not cancelled. We observe that, if neither the master nor the slave laser happen to have a wavelength within the spectrum of the femtosecond oscillator output (\( \approx 30 \text{ nm} \) wide around 1,560 nm), where it is possible to obtain a beatnote with a large SNR, compatible with the wide phase-locking bandwidth of the comb), an auxiliary stable c.w. laser oscillator is required to lock the optical frequency comb in the narrow-linewidth regime. Because of the bandwidth limitations expressed above, the comb’s teeth should not be wider than \( \approx 100 \text{ Hz} \), so as not to impact the performance of the system. This can be realized via tight locking of the repetition rate to an auxiliary c.w. laser with the same linewidth, which can be obtained with laser stabilization on fibre spool delay lines, significantly reducing the complexity of the set-up.

Phase noise added by the EDFA–HNLF system. The optical phase noise introduced in the EDFA–HNLF system is wavelength dependent. For example, optical path length fluctuations introduce phase noise linear in optical frequency, while optical amplifier gain fluctuations and refraction index changes may introduce phase noise with a more complex dependency on the wavelength. Measuring the comb–c.w. laser beatnote \( f_{\text{c-w}} \) and \( f_{\text{c}} \), and the carrier-envelope offset frequency \( f_{\text{c}} \) in the same EDFA–HNLF branch, phase noise components with up to linear dependency on the optical frequency cancel out when the \( f_{\text{c-w}} \) and \( f_{\text{c}} \) signals are combined to generate the \( f_{\text{c-w}} \) signal. Note, however, that higher-order spectral phase evolution produced in the EDFA–HNLF is not cancelled.

The effect of the transfer oscillator technique applied to the \( f_{\text{c-w}} \) and \( f_{\text{c}} \) beatnotes measured from a single EDFA–HNLF branch is therefore twofold: it removes the effect of residual \( f_{\text{c-w}} \) and \( f_{\text{c}} \) fluctuations, and provides a comparison insensitive to the EDFA–HNLF added spectral phase noise up to linear order in optical frequency.

Beatnote detection. Beatnote detection was realized in independent, carefully designed, all-fibre beat detection units that were enclosed in separate vacuum chambers (one for each optical frequency comb set-up), providing thermal and vibration isolation. Light from the slave laser, the master laser, and the comb’s EDFA–HNLF output were sent to the beat detection units via single-mode optical fibres and manual polarization controllers (used to match light polarization and maximize the interferometer contrast). Optical fibres transmitting the light from the c.w. laser sources were equipped with fibre-noise cancellers, exhibiting feedback bandwidth greater than 100 kHz. Great care was taken to keep short the length of optical fibres that were neither noise cancelled, nor common path for the 1,542 nm and 1,062 nm spectral components. The beatnote detection unit was evacuated to \( \approx 100 \text{ mbar} \) for acoustic noise and thermal fluctuation isolation. No improvement was observed on further lowering the residual pressure.

Received 26 April 2013; accepted 9 December 2013; published online 19 January 2014

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Acknowledgements

This work was partly funded by the Ville de Paris’ Emergence(s) 2012 programme, and CNRS-D.N. and W.Z. acknowledge funding from the EMRP IND14 project, which is jointly funded by EMRP participating countries within EUROMET and the European Union. The authors thank S. Bize and the mercury optical clock team for the use of the ultrastable 1.062 nm laser, and M. Lours, J. Pinto and F. Cornu for technical support.

222

LETTERS

DOI: 10.1038/NPHOTON.2013.361
Author contributions
D.N., B.A., W.Z., G.S. and Y.L.C. conceived and realized the components necessary for the realization of the final experiments. D.N., B.A. and W.Z. acquired preliminary data. D.N. realized the final experiments, and acquired and analysed the presented data. D.N., B.A., W.Z., R.L.T., G.S. and Y.L.C. all took part in the conception of one or several of the final three experiments and in the preparation of the manuscript. G.S. and Y.L.C. planned and managed the project.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y.L.C.

Competing financial interests
The authors declare no competing financial interests.