Experimental demonstration of a low repetition rate optical frequency comb

Francesco Canella[1,2,3,*], *Johannes* Weitenberg[2,4], *Paras* Dwivedi[2,5], *Fabian* Schmid[2], *Gianluca* Galzerano[3], *Theodor W.* Hänsch[2,5], *Thomas* Udem[2,5], and *Akira* Ozawa[2]

[1]Dipartimento di Fisica, Politecnico di Milano, 20133 Milan, Italy
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
[3]Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche, 20133 Milan, Italy
[4]Fraunhofer-Institut für Lasertechnik ILT, Steinbachstraße 15, 52074 Aachen, Germany
[5]Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München, Germany

Abstract. Optical frequency combs operating at low repetition rate exhibit high pulse energy for a given average power. Therefore, low repetition rate frequency combs may efficiently drive nonlinear frequency conversion into the mid-infrared or extreme ultraviolet region to extend frequency metrology to such exotic wavelengths. In this work, we have experimentally demonstrated a low-noise optical frequency comb operating at 40 kHz repetition rate using a Yb:KYW mode-locked laser (center wavelength at 1030 nm, repetition rate 40 MHz) and an acousto-optic modulator-based pulse picker. We have stabilized a single comb mode to an ultra-stable continuous wave laser operating at 1033 nm. The integral rms phase noise (in the range 10 Hz - 20 kHz) was measured to be 167.2 mrad.

1 Introduction

Since their early development, optical frequency combs (OFCs) have revolutionized frequency metrology and are nowadays a key tool for high-precision spectroscopy and optical frequency standards [1]. In the frequency domain, OFCs consist of several hundred thousand spectral modes equally spaced by the pulse repetition rate. Typically, this lies in the MHz-GHz range for conventional fiber and solid-state laser-based oscillators. A pulse train with a relatively low repetition rate below 10 MHz can have correspondingly higher pulse energy and is therefore beneficial for driving nonlinear frequency conversion processes of OFCs, which are particularly important for precision spectroscopy. For instance, our planned experiment of precision spectroscopy of the 1S-2S transition in He^+ ions requires an OFC in the extreme ultraviolet region (XUV), at 60.8 nm [2].

XUV combs suitable for spectroscopy can be generated by Intracavity High-order Harmonics Generation (ICHHG), where high-average power laser pulses are accumulated inside an enhancement cavity, and the HHG takes place at the intracavity focus [3]. This scheme requires special care to manage undesirable effects due to high power and intensity, like thermal drift and damage to optical elements.

Alternatively, by operating the OFCs at a lower repetition rate, a similarly high pulse energy could be achieved without using a high-average power laser. Although lower repetition rates result in OFC with smaller mode spacings, OFCs at kHz repetition rate should have sufficiently large mode spacing for precision spectroscopy of transitions that have narrow natural linewidths. e.g. the afore-mentioned 1S-2S transition in He^+ (expected linewidth of ~1 kHz) or the nuclear transition in ^{229m}Th at ~150 nm (natural linewidth of ~100 μHz) [4]. High-intensity ultrafast lasers at such low repetition rates are conventionally developed using the chirped pulse amplification (CPA) scheme. Moreover, by actively controlling the round-trip phase at the oscillator, it was demonstrated that each pulse has an identical carrier-envelope phase (CEP), allowing applications in the study of field-sensitive phenomena driven by few-cycle pulses [5]. However, even if such CEP-stabilized low-repetition-rate laser systems have been shown to be suitable for observing ultrafast phenomena in the time domain, the existence of a fine-comb structure in the frequency domain remains to be demonstrated.

In this work, we present a frequency comb with a repetition rate as low as 40 kHz by pulse picking of a 40-MHz repetition rate OFC. We characterized its phase noise with respect to an ultra-stable continuous-wave (cw) reference laser, showing a small phase noise and linewidth, suitable for exciting Hz-level narrow transitions.

2 Experiment

To demonstrate the low repetition rate OFC, we have designed an experimental setup based on a 40 MHz OFC. This consists of a Kerr-lens mode-locked Yb:KYW oscillator, followed by a solid-state amplifier whose gain

* Corresponding author: francesco.canella@polimi.it

medium is Yb:LuAG, and an acousto-optic modulator (AOM) frequency shifter for fast control of the CEO frequency. The laser repetition rate is controlled by PZT-actuated cavity mirrors. The output of the Yb:KYW oscillator is about 25 mW and is centered at 1030 nm, with a spectral bandwidth of approximately 14 nm. The comb is phase-stabilized exploiting error signals obtained from the beat note between the OFC and an ultra-stable cw laser emitting at 1033 nm. At the comb output, an AOM-based pulse picker reduces the comb's repetition rate to 40 kHz. The pulse picker also allows the selection of intermediate repetition rates at other sub-multiples of 40 MHz. After the pulse picker, the optical pulses are amplified again by a second Yb:LuAG amplifier. A feedback loop finely controls a PZT-actuated mirror positioned in the beamline to reduce the phase noise induced by fluctuations in the beam path length.

3 Results and discussion

Fig. 1 shows the spectrum of heterodyne beat note between the low repetition rate comb and the cw reference, acquired from the path length feedback loop. In Fig. 1, the 17^{th} and 18^{th} harmonics (chosen to avoid low-frequency flicker noise) of the repetition rate are visible with four peaks corresponding to the beat frequencies. The signal-to-noise ratio of the beat peak exceeds 30 dB, clearly confirming the comb-like structure of the pulse-picked comb at 40 kHz. The beat linewidth is limited by the resolution of the spectrum analyzer (RBW = 10 Hz).

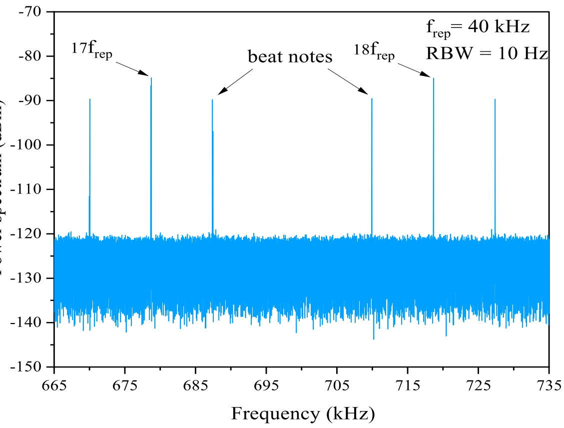

Figure 1 RF spectrum of the heterodyne beat note between the 40 kHz comb and the ultrastable cw reference.

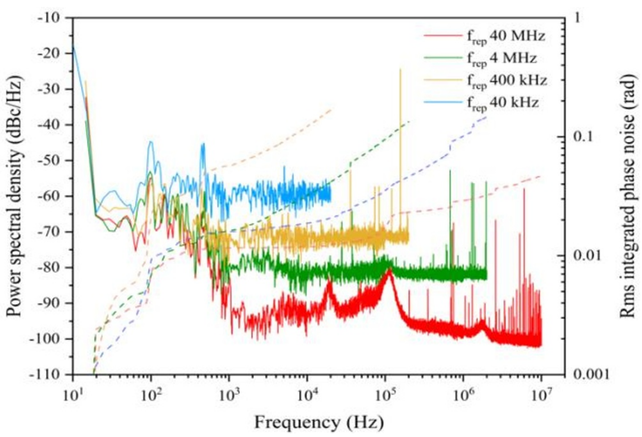

Figure 2 Phase noise PSD (solid) and integrated noise (dashed) for repetition rates of 40 MHz, 4 MHz, 400 kHz, and 40 kHz.

We computed the power spectral density (PSD) of the phase noise and the rms of integrated phase noise of this beat note signal. In Fig. 2, the PSD and integrated noise of the original comb (repetition rate 40 MHz) and the 40 kHz comb are shown together with traces at 4 MHz and 400 kHz repetition frequencies for comparison. The PSD is derived from recorded temporal traces of the beat note and applying the Fast Fourier Transform (FFT). Before applying the FFT, we applied the Blackman window. In addition, we applied the gated optical noise reduction technique (GATOR) [6], which corresponds to averaging the spectrum of multiple-beat contribution from several comb modes and allows revealing technical noise below the shot-noise floor of single comb mode. Integrated phase noise is calculated from 10 Hz to half of the repetition rate (except for the 40 MHz comb, where integration stops at 10 MHz). For the 40 kHz trace, rms integrated phase noise in the 10 Hz-20 kHz range is 167.2 mrad. From Fig. 2 we observe that pulse picking does not add noticeable noise contributions to the comb phase noise above the noise floor. It should be noted that the phase noise evaluation is essentially limited by the measurement noise floor and overestimates the real comb noise.

4 Conclusions

In conclusion, we demonstrated an OFC at 40 kHz repetition rate using an AOM pulse-picker. Results confirm the narrow-linewidth comb structure at low repetition rate, while phase noise measurements show an integrated rms phase noise of 167 mrad. The pulse picking process does not add significant noise contribution at this level. These results are promising for future developments in low-noise XUV frequency combs for high-precision spectroscopy.

References

1. S. Diddams, K. Vahala, T. Udem, Science **369**, 6501 (2020)
2. M. Herrmann, M. Haas, U. D. Jentschura, F. Kottmann, D. Leibfried, G. Saathoff, C. Gohle, A. Ozawa, V. Batteiger, S. Knünz, N. Kolachevsky, H. A. Schüssler, T. W. Hänsch, and T. Udem, Phys. Rev, A **79**, 052505 (2009)
3. I. Pupeza, C. Zhang, M. Högner, and J. Ye, Nat. Photonics **15**, 175 (2021)
4. L. von der Wense and C. Zhang, The Eur. Phys. J. D **74**, 146 (2020)
5. A. Baltuška, T. Udem, M. Uiberacker, M. 362 Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hänsch, and F. Krausz, Nature **421**, 611 (2003)
6. J. D. Deschênes and J Genest, Phys. Rev. A **87**, 1 (2013)