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# COMPACT MODE-LOCKED DIODE LASER SYSTEM FOR HIGH PRECISION FREQUENCY COMPARISONS IN MICROGRAVITY

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## I. INTRODUCTION:

Nowadays cold atom-based quantum sensors such as atom interferometers start leaving optical labs [1],[2] to put e.g. fundamental physics under test in space. One of such intriguing applications is the test of the Weak Equivalence Principle, the Universality of Free Fall (UFF), using different quantum objects such as rubidium (Rb) and potassium (K) ultra-cold quantum gases [1]–[4]. The corresponding atom interferometers are implemented with light pulses from narrow linewidth lasers emitting near 767 nm (K) and 780 nm (Rb). To determine any relative acceleration of the K and Rb quantum ensembles during free fall, the frequency difference between the K and Rb lasers has to be measured very accurately by means of an optical frequency comb. Micro-gravity applications not only require good electro-optical characteristics but are also stringent in their demand for compactness, robustness and efficiency. For frequency comparison experiments the rather complex fiber laser-based frequency comb system may be replaced by one semiconductor laser chip and some passive components. Here we present an important step towards this direction, i.e. we report on the development of a compact mode-locked diode laser system designed to generate a highly stable frequency comb in the wavelength range of 780 nm.

## II. COMPACT MODE-LOCKED DIODE LASER SYSTEM:

In the following we present the laser setup as well as mode-locking results.

### *A. Concept and components*

The mode-locked diode laser system which is specifically designed for micro-integration is configured as an extended-cavity diode laser (ML-ECDL) setup, depicted in Fig. 1. The ML-ECDL consists of an 1 mm long AlGaAs double quantum well ridge-waveguide laser diode, collimation optics, and a plane dielectric mirror. The two-section diode chip features a 100 µm long saturable absorber and a 900 µm long gain section. The front facet of the diode located at the absorber section is coated to 10 % reflection while the resonator-side facet is anti-reflection (AR) coated. Collimation of the diode's output on both sides is realized by aspheric micro-lenses. Additional intra-cavity beam correction is realized with a cylindrical lens. The optical resonator formed by the front facet of the diode laser and the nearly zero group velocity dispersion (GVD) dielectric mirror is approx. 40 mm long. For the measurements a dc current is applied to the gain section. Fundamental passive mode-locking is realized by reverse biasing the saturable absorber section of the diode.

### *B. Mode-locking performance*

For the results presented here the gain section dc injection current (DCI) was set to 260.00 mA and the saturable absorber bias (SAB) to about -1.16 V. The mount temperature ($T_{Mount}$) was stabilized to the room temperature, i.e. $T_{Mount}$ is 20.00 °C.

To analyze the optical and RF spectral characteristics the light is coupled into single-mode optical fibers after passing through an optical isolator (Qioptic (Gsänger) DLI-I).

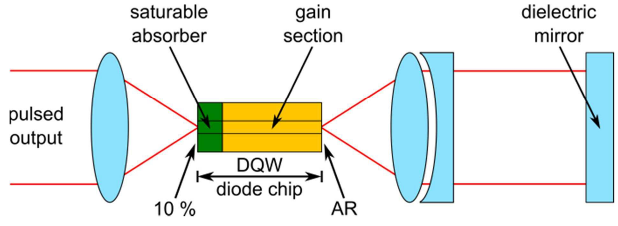
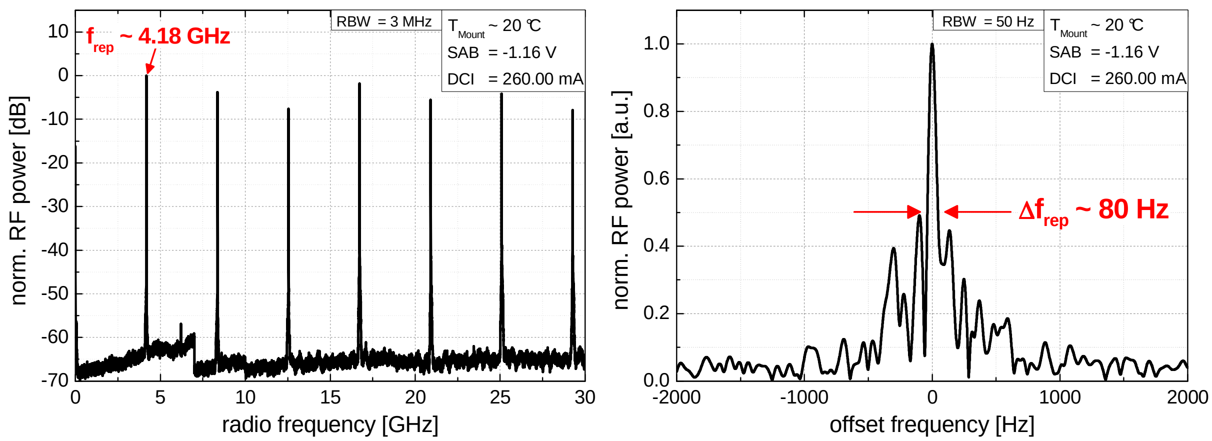



**Fig. 1.** Schematic of the mode-locked diode laser system. The optical resonator is formed by the front facet of the diode and the dielectric mirror.




**(a)** **(b)**

**Fig. 2. (a)** Normalized (norm.) RF spectrum of the mode-locked pulses up to 30 GHz. **(b)** Zoom into the RF spectrum near the pulse repetition frequency $f_{rep}$.

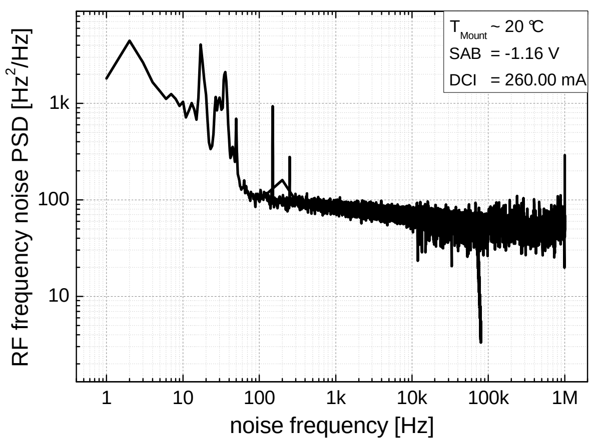



**Fig. 3.** RF frequency noise PSD versus noise frequency for pulse repetition rate. Data is derived from frequency noise PSD measurements based on IQ de-modulation of the beat note signal [5] (bandwidth 1 Hz to 80 kHz and 100 Hz to 12.8 MHz) and from phase noise measurements carried out with the ESA PN tool (Option FSV-K40 for R&S FSV-30) (bandwidth 10 kHz to 1 MHz). At noise frequencies above 1 MHz the measurement is limited by the analyzer.

We characterize the RF performance of the mode-locked pulse train using a combination of a fast photodiode (NewFocus 1434), a broadband RF amplifier (Centellax TA0L30VA) and an electrical spectrum analyzer (R&S FSV-30). Fig. 2 shows a typical RF spectrum of our ML-ECDL in its fundamental mode-locking regime. The pulse repetition rate is approx. 4.2 GHz corresponding to the resonator length of the ML-ECDL. A signal-to-noise-ratio (SNR) of more than 60 dB (resolution bandwidth (RBW) = 3 MHz) can be observed for the fundamental RF peak, and still more than 50 dB for its seventh harmonic, indicating high quality mode-locking.

A RF linewidth of the pulse repetition rate at full-width-at-half-maximum (FWHM) of about 80 Hz (RBW = 50 Hz) is reached (limited by the analyzer's resolution bandwidth and low frequency jitter), as shown in Fig. 2(b). Measurement of the frequency noise power spectral density (PSD), as depicted in Fig. 3, allows for a more detailed analysis of the mode-locking stability. Frequency noise PSD spectra are determined for a wide bandwidth, from very low noise frequencies (1 Hz) all the way up to 3 GHz. This is accomplished by combining phase noise data derived from a time series measurement with the IQ (in-phase/quadrature) tool of the RF analyzer [5], which provides access to noise frequencies up to 12.8 MHz, and from the RF phase noise data measured with the phase noise measurement tool (PN tool; option FSV-K40 for R&S FSV-30), which provides access to noise frequencies above 12 MHz. At low noise frequencies (below 1 kHz) increased noise can be observed, which may be attributed to residual thermal and mechanical instabilities of the setup. The white noise floor of the fundamental beat corresponds to about 56 $Hz^2/Hz$ (IQ data, 500 ms integration time) while the corresponding RMS integrated timing jitter amounts to ~ 2 ps (PN tool, bandwidth 20 kHz to 1 MHz).

The optical characteristics are analyzed using an optical spectrum analyzer (Yokogawa AQ6373). Fig. 4 shows the optical spectrum corresponding to the RF characteristics described above. The mode-locked pulses feature a peak wavelength of approx. 788 nm, an optical bandwidth exceeding 2.5 nm at -3 dB and 7 nm at -20 dB.

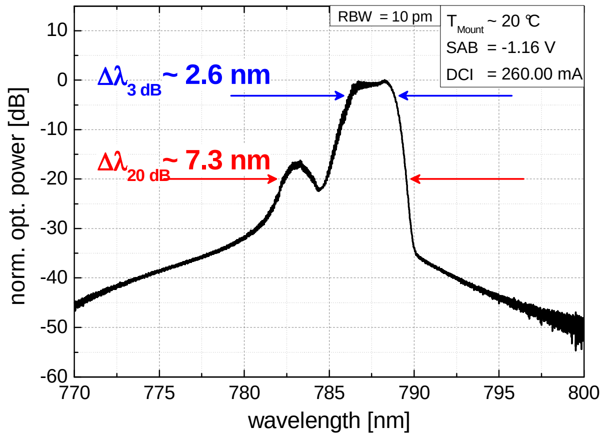



**Fig. 4.** Optical spectrum

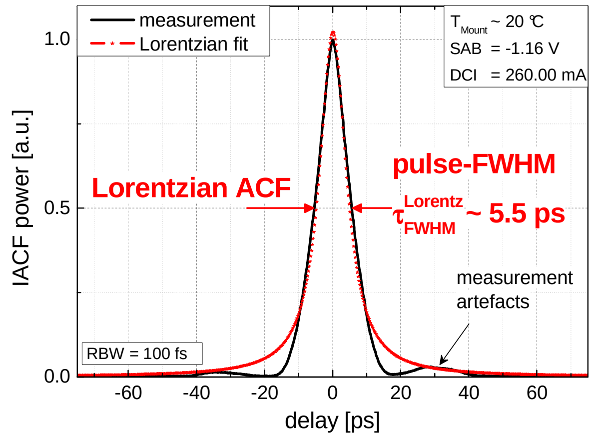



**Fig. 5.** Intensity autocorrelation function

Pulse shape and width of the mode-locked pulses are evaluated by measuring their intensity autocorrelation function (IACF). The IACF corresponding to the data shown above is depicted in Fig. 5. Assuming a Lorentzian pulse shape of the ICAF a FWHM pulse width of 5.5 ps is reached.

From the optical and temporal characteristics a time-bandwidth-product of approx. 7 can be calculated, which indicates strongly chirped mode-locked pulses well above the Fourier-limit. Moreover the mode-locked pulses feature an average optical power of about 90 mW, measured with a calibrated photodetector. This corresponds to a peak power of approx. 2.5 W. Hence optimal pulse compression would allow for pulses as short as about 170 fs with a peak power of more than 80 W.

## III. SUMMARY AND CONCLUSION:

We presented a mode-locked diode laser system realized as a compact extended-cavity that is specifically designed for micro-integration on an AlN ceramic bench with a footprint of about 20 cm$^2$. This ML-ECDL emits stable fundamentally mode-locked optical pulses at 4 GHz repetition rate with a RF linewidth of about 80 Hz (RBW = 50 Hz). The strongly chirped pulses feature an optical bandwidth of more than 7 nm at -20 dB and a pulse width of less than 6 ps.

For frequency comparison experiments the pulse repetition rate will be further stabilized by e.g. applying a feedback control signal to the saturable absorber. For K and Rb precision experiments as described above the optical spectrum will be adjusted to the appropriate wavelength range by adapting the quantum well composition. Extending the wavelength range will be realized by e.g. modification of diode chip properties such as quantum well number. Currently we are working on the micro-optical integration of all the components onto an AlN ceramic bench similar to those we developed at the FBH for continuous wave ECDLs [6], see Fig. 6.

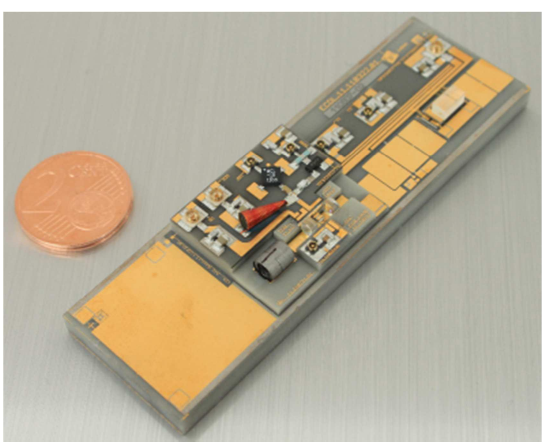


**Fig. 6.** Micro-integrated continuous wave ECDL @ FBH [6].

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