Femtosecond VECSELs with up to 1-W Average Output Power

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Since the first demonstration of passively modelocked VECSELs, their performance in terms of output power, repetition rate and pulse duration substantially improved. Recently, up to 6.4 W of average power in 28ps pulses were achieved from a modelocked VECSEL with an integrated saturable absorber (MIXSEL, [1]). The shortest pulse duration generated by a VECSEL was 60 fs at less than 35 mW average output power in harmonic modelocking [2]. To date, femtosecond VECSELs were based on quantum well (QW) gain structures and the average output power has been limited to <150 mW [3] (Fig. 1a). In contrast, so far modelocked VECSELs based on quantum dot (QD) gain structures have been restricted to 18 ps using QW-SESAMs [4].

Here we report on record-high average output power of a femtosecond VECSEL (Fig. 1a: 1 W, 784 fs) and present the first detailed study of femtosecond VECSELs modelocked by fast QD-SESAMs. We investigate the modelocking performance both for VECSELs with QD and QW gain structures. Based on our previous work on the influence of GDD on the pulse duration [5] we developed a top coating inspired by the work of Lumb et al. [6]. The top coating consists of 6 AlAs/AlGaAs pairs and a fused silica layer on top. The thicknesses are optimized using a Monte Carlo algorithm combined with a standard optimization. This provides a flat GDD with values between ±10 fs^2 over a range of 30 nm around the design wavelength (Fig. 1b) which is several orders of magnitude lower compared to previous designs. Furthermore, we used optimized positions of the gain layers in the standing wave pattern to broaden and flatten the spectral gain. The SESAM we used for the QW-based gain results has a standard resonant design with QD saturable absorber. This SESAM has a fast absorption recovery component in the order of 800 fs. However, for the QD-based gain results, the same SESAM was made antiresonant by depositing a quarter-wave layer of fused silica on top. This leads to a higher saturation energy of the SESAM, which allows higher power levels. Additionally, the GDD is lowered to ±100 fs^2 in a 30 nm range around the design wavelength. All these design improvements enabled the first operation of a QD-VECSEL in the femtosecond regime. We achieved for both QD- and QW-based gain structures a similar minimal pulse duration of 416 fs (QD) and 455 fs (QW) with 140 mW (QD) and 110 mW (QW) average output power (Fig. 1b). Direct soldering of the QD-based gain chip onto a CVD diamond heat spreader and subsequent substrate removal enabled power scaling to 1-W average power with a pulse duration of 784 fs and a pulse repetition rate of 5.4 GHz. The peak power of 200 W in combination with the high average power makes this source attractive for numerous applications such as biomedical multi-photon imaging.

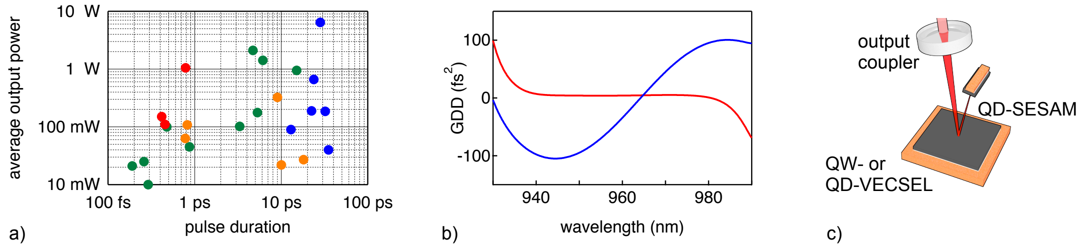

Fig. 1 a) Overview of ultrafast VECSEL results highlighting this paper's results (red). QW-VECSEL are indicated by green points, QD-VECSEL by orange points and the MIXSEL by blue points. b) GDD of the VECSEL structure (red) and of the antiresonant QD-SESAM (blue). c) Experimental setup consisting of the output coupler, the QW- or QD-VECSEL and the QD-SESAM.

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