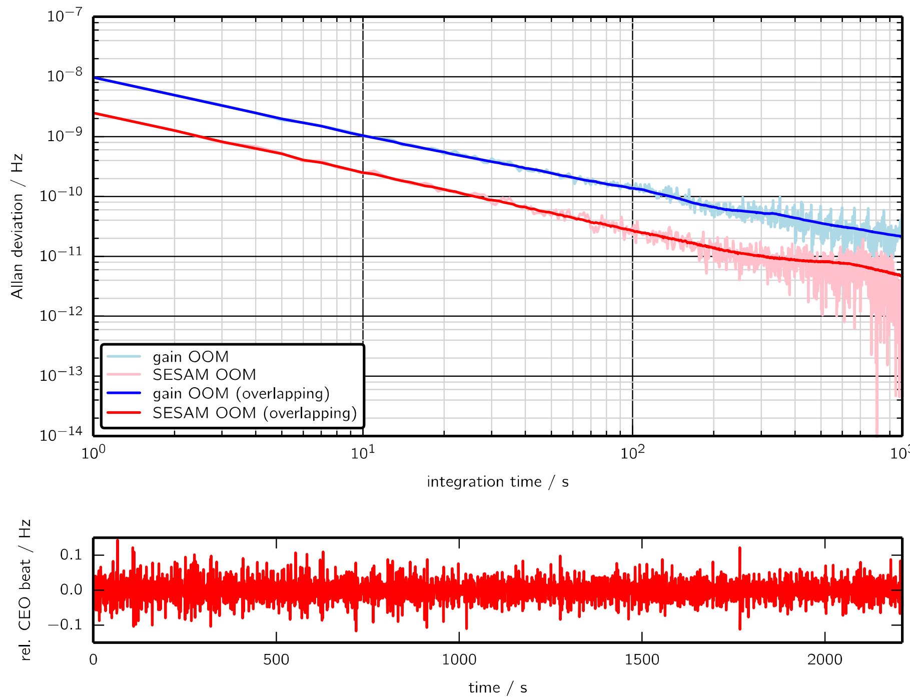

Fig. 6. In the top panel, we plot the standard (light colors) and overlapping (normal colors) Allan deviation for the standard gain-modulation (blue), and for SESAM-modulation (red). The lower panel shows the frequency fluctuations of the CEO beat recorded over around 40 minutes.

5. Conclusion and outlook

We present the first CEO control of an ultrafast laser based on an optically-pumped SESAM as OOM. In this first proof-of-principle demonstration, the SESAM is simultaneously used for the modelocking of the 1.55-µm Er:Yb:glass laser and as intracavtiy OOM. We used a multimode 812-nm laser diode as SESAM pump source. Since the frequency comb used for these experiments was already self-referenced using the standard technique of feedback to the optical pump of the gain medium [11], we were able to directly show the benefits of the new stabilization scheme in terms of CEO modulation bandwidth, frequency noise performance and long-term frequency stability. Hence, the residual integrated phase noise (1 Hz–100 kHz) was improved by more than an order of magnitude (from 720 mrad to less than 65 mrad), and the fractional frequency stability by a factor of 4 (from $1 \cdot 10^{-8}$ to $2.5 \cdot 10^{-9}$ at 1 s).

During these experiments, as pointed out in Section 3, we used a standard SESAM optimized only for modelocking, in which most of the optical power was absorbed in the DBR region. Optimizing the SESAM structure for use as OOM should significantly improve the achieved performance.

The experimental results presented here show that OOM using a SESAM is a very promising method for fast frequency comb stabilization. This very simple technique only uses a low-cost multi-mode pump and it leaves the overall laser performance undisturbed since no additional element is introduced in the laser cavity. Nevertheless, this approach is also applicable for modelocked lasers that do not make use of a SESAM to start modelocking, such as Kerr-lens modelocked lasers. This could be realized by using an intra-cavity SESAM with a low modulation depth, which should not influence modelocking significantly, but should provide the same feedback to the CEO when modulated.

The demonstrated CEO stabilization technique is built on the very mature and very well-know SESAM technology [31]. Together with the highly suitable properties for ultrafast laser operation such as very low values for nonlinearity, dispersion, thermal lens, and losses, we believe that modulation bandwidths even in the GHz regime can be obtained by fully exploiting the absorber properties of SESAMs (absorber recombination time in the picosecond regime [32,33]. This should allow stabilizing lasers with broad CEO beats, such as lasers pumped by highly multi-mode pump lasers, high repetition-rate lasers and fiber lasers [34–37]. Additionally, in contrast to previously demonstrated electrically-driven graphene modulators [21], the extremely low losses of the SESAM makes this technology compatible with high-power and high-energy lasers such as thin disk lasers that operate in the kW intra-cavity power range. Very recently, the first CEO-stabilized SESAM modelocked thin disk laser was demonstrated using pump current modulation [13]. It is based on Yb:CALGO, uses standard pump modulation for the CEO-lock and achieves a residual in-loop integrated phase noise of 120 mrad (1 Hz–1 MHz). While this proof-of-principle experiment clearly shows that the highly-multimode pumping scheme supports stable CEO-locked operation, implementing a sufficiently fast current control for multi-kW pump sources might be challenging. In contrast, CEO stabilization using OOM of the SESAM should be easy to implement even for oscillators with several hundred watts of output power. Such performance will be highly attractive for applications such as intra-cavity multi-MHz high-harmonic generation (HHG) providing coherent and frequency-stabilized VUV/XUV radiation [38,39].

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