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Frequency Comb Stabilization of Ultrafast Lasers by Opto-Optical Modulation of Semiconductors

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***Abstract*—In this paper, we review the current state and discuss new developments in opto-optical modulation (OOM) of semiconductor elements for frequency comb self-referenced stabilization of ultrafast lasers. This method has been successfully used for carrier-envelope offset (CEO) frequency stabilization of diode-pumped solid-state lasers operating in 1-μm and 1.5-μm regimes, providing high feedback bandwidth and resulting in low noise performance. We compare the achieved results for Er- and Yb-based laser materials and in different regimes of repetition rates up to 1 GHz. In addition, we present the first semiconductor OOM for CEO stabilization in an ultrafast fiber laser. Moreover, we discuss requirements and design guidelines for OOM chips. In most demonstrations, semiconductor saturable absorber mirrors have been used for OOM, which in parallel were also responsible for pulse formation. By separating the OOM functionality from the pulse formation, we expect that it will enable low-noise CEO stabilization in other types of ultrafast lasers, such as, for example, high-power Kerr-lens mode-locked thin disk lasers.**

***Index Terms*—Mode-locked lasers, optical frequency comb, stabilization, metrology.**

I. INTRODUCTION

OPTO-OPTICAL control and modulation methods constitute a powerful tool to alter the properties of a laser source by another laser beam, in other words by controlling light by light. Especially when using fast recombination processes in semiconductors, this method enables overcoming limitations in modulation bandwidth of standard modulator technologies. In this article, we discuss the use of opto-optical modulation (OOM) of a semiconductor chip in mode-locked solid-state and fiber lasers for fast frequency control and stabilization of the carrier-envelope offset (CEO) beat in optical frequency combs.

For several decades, opto-optical control has been exploited in a wide range of research areas. Cross-gain modulation was developed in the mid-1990s for all-optical wavelength conversion in semiconductor optical amplifiers (SOA) as a simple method to exchange optical frequencies in telecommunication networks and as a fast optical switch [1], [2]. In this case, a continuous-wave (CW) laser signal at a desired wavelength is injected into an SOA along with the optical data signal. The saturated SOA allocates the gain between the two signals and transfers the data stream to the CW signal with bit inversion. The original data signal is then filtered out. In a different area, fast optical modulation of a mid-infrared quantum cascade laser (QCL) has been realized by front facet illumination with 100-fs light pulses from a Ti:Sapphire laser, resulting in a modulation of the QCL output power at the ~90-MHz repetition rate of the illuminating laser [3]. Implementing an optical feedback loop acting indirectly on the optical frequency of a CW QCL via refractive index change induced by a near-infrared laser beam illuminating the top surface of the QCL (thus not by facet injection as in the aforementioned case) reduced its frequency noise power spectral density (FN-PSD) by a factor of ten and the associated laser linewidth by a factor of ~3 [4]. The error signal for this noise reduction method was derived from the voltage noise measured between the QCL terminals. Very recently, simultaneous front facet illumination by two CW laser sources of different wavelengths was also used to produce pure frequency modulation in a QCL [5].

Opto-optical control based on semiconductor chips inside ultrafast solid-state lasers has been pioneered in 2010 by Savitski *et al.* [6]. The authors optically pumped a saturable Bragg reflector (SBR) inside a Ti:Sapphire laser with a CW laser beam, which enabled rapid switching between CW and mode-locked operation. The thermally-induced change in the nonlinear response of the SBR allowed for a switching time of ~75 μs between both regimes. Instead of addressing thermal changes, it is also possible to directly control the saturation level in quantum wells or quantum dots. This enables response times in the ns to ps regime, which makes OOM in semiconductor chips highly attractive for areas such as frequency comb stabilization.

Optical frequency combs from mode-locked lasers [7]–[9] have revolutionized and opened up a variety of research fields

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such as optical frequency metrology, optical clocks, the generation of ultra-low-noise microwave signals, the calibration of astronomical spectrometers and high-resolution broadband spectroscopy to cite just a few relevant examples [10]. Most of these applications require a fully-stabilized frequency comb, i.e., in which the two degrees of freedom, the CEO frequency f_{CEO} and the repetition rate f_{rep} are phase-locked to a radio-frequency (RF) reference signal. The standard method for CEO stabilization is based on self-referencing using nonlinear interferometry such as *f*-to-2*f* [7] or 2*f*-to-3*f* [11]. The control and stabilization of f_{CEO} is usually realized by feedback to the pump power of the mode-locked laser, which can conveniently be directly applied to the current of the pump laser in mode-locked oscillators that are pumped by semiconductor laser diodes, such as fiber lasers, diode-pumped solid-state lasers (DPSSLs) or thin disk lasers (TDLs). While being reliable and relatively simple to implement with the use of low-power single-mode pump diodes used in fiber oscillators, the method is less straightforward in DPSSLs and TDLs, which usually require high power pump diodes that are highly transverse-multimode and need to be driven at high currents and/or voltages. Dedicated driving electronics is often required to modulate these pump diodes [12], [13].

Furthermore, pump current modulation results in a modulation of the laser gain that is limited in bandwidth by the cavity dynamics of the ultrafast laser, which depends in particular on the gain lifetime. This parameter is in the range of hundreds of microseconds to few milliseconds for the common Er- and Yb-gain materials. This generally leads to a CEO frequency modulation bandwidth that is limited to some tens of kilohertz in frequency combs with a repetition rate in the 100-MHz range based on these gain materials [14], [15], and up to a few hundreds of kilohertz in GHz repetition rate DPSSL combs [12], [13]. Even if the overall bandwidth of the CEO stabilization loop can be extended up to several hundred kilohertz, or in some special cases to the MHz-range, with the use of properly designed loop filters (including a phase-lead filter) [16], the availability of intrinsically faster actuators is beneficial to many applications that require low residual phase noise of the CEO beat. Therefore, alternative methods have been developed for higher bandwidth control of f_{CEO} based on intra-cavity acousto-optic or electro-optic modulators [17]. They offer a high modulation bandwidth, but an additional element used in transmission needs to be inserted in the laser cavity. This can add significant nonlinearity and is challenging to place in high repetition rate lasers in the GHz range due to geometric constraints. A different approach was demonstrated with an electro-optic graphene modulator used as an electrically-controlled reflective mirror that achieved a modulation bandwidth higher than 1 MHz in a Tm:fiber laser [18]. However, such an approach is challenging to implement in bulk solid-state lasers due to the introduced insertion losses of a few percent and the limited mode area. Recently, an intra-cavity electro-optic modulator acting on the group velocity was reported in an Er:fiber laser mode-locked by a nonlinear amplifying loop mirror [19]. The modulator was designed for fast CEO modulation (up to 2 MHz was reported) with a high degree of decoupling from the repetition rate. Another method implemented in an Er:Yb:glass DPSSL was based on shining a high-power 1.5-μm laser signal onto the gain medium. This enlarged the CEO modulation bandwidth up to 70 kHz by by-passing the slow energy transfer from the ytterbium ions to the erbium ions [20].

In this article, we show that OOM of a semiconductor chip is a simple and efficient method for high bandwidth modulation and stabilization of the CEO frequency in different types of mode-locked solid-state and fiber frequency combs. In Section II, we will first review our initial demonstration of this method in DPSSLs where the semiconductor saturable absorber mirror (SESAM) used to mode-lock the laser was additionally pumped by a CW laser for OOM. The method, first demonstrated in a low repetition rate DPSSL at 1.5 μm [21] was recently extended to a 1-μm DPSSL with 1-GHz repetition rate [22]. Then, we will show in Section III that a similar approach can be applied also to fiber lasers. We added a semiconductor chip in a 1-μm Yb:fiber laser mode-locked by nonlinear polarization rotation for OOM and stabilized the CEO frequency using this actuator. In all these systems, we have used so far existing components that were not specifically designed for OOM functionality. In Section IV, we will discuss design guidelines of semiconductor chips optimized for OOM. Finally, Section V will conclude the article.

II. CEO STABILIZATION OF DPSSL COMBS VIA SESAM-OOM

In SESAM-mode-locked DPSSLs, OOM can be implemented using an additional (low-power) CW laser to pump the SESAM in order to change its reflectivity for the intra-cavity fs-pulses. In this way, the same element is used for mode-locking and OOM, which allows for fast intra-cavity power modulation and, hence, for fast CEO frequency control, without the need to insert an additional element in the cavity that may compromise the laser performance. In Section II-A, we first review our initial proof-of-principle demonstration realized in a 1.5-μm Er:Yb:glass oscillator (ERGO) where the induced modulation was believed to be mainly of thermal origin, and we show also some additional results about the effect of the OOM onto the repetition rate of the laser. Then, we report in Section II-B more recent results obtained in an Yb:CALGO DPSSL at 1 μm with a much higher repetition rate of 1 GHz, and present the different behavior observed at low and higher pumping average powers onto the SESAM where thermal effects are negligible and dominant, respectively.

A. 75-MHz ERGO Laser at 1.5 μm

The first SESAM-OOM demonstration [21] has been realized in an ERGO laser emitting ∼110 mW at 1558 nm in 170-fs pulses at a repetition rate of 75 MHz [15]. Self-starting mode-locked operation was obtained using a standard anti-resonant SESAM with 25 pairs of AlAs and GaAs quarter-wave layers and a single 15-nm thick $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ quantum well embedded in GaAs spacer layers (see Fig. 1). An additional beam from an 812-nm multimode fiber-coupled laser diode was focused onto the SESAM at an incidence angle of 5°. The spot size on the SESAM was roughly two times larger than the one

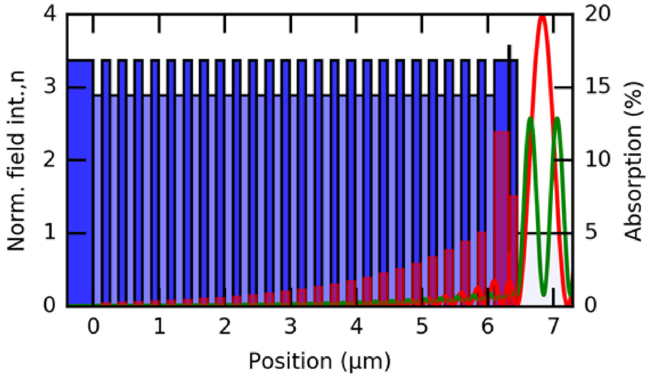
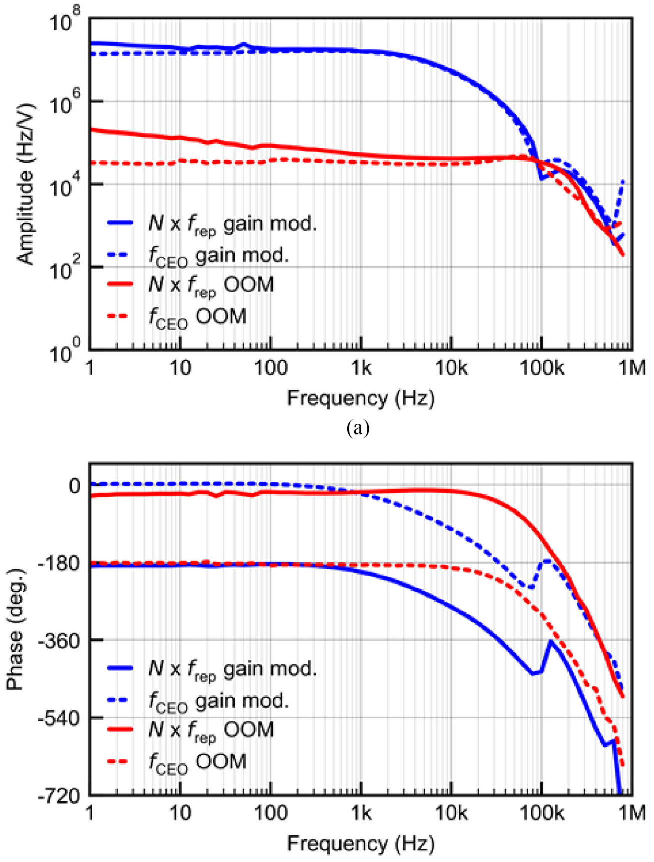


Fig. 1. Schematic structure of the used SESAM: refractive index profile (blue bars), standing-wave pattern of the 1.55-μm light at the designed incident angle of 0° (red) and for a wavelength of 812 nm at an incidence angle of 5° and s-polarized (green). The relative integrated absorption of the 812-nm pump light calculated for each layer is displayed in purple bars (right scale).

of the intra-cavity laser mode and overlapped with it. Since the bandgap of GaAs is around 870 nm, the 812-nm pump light with an optical power of less than 100 mW was strongly absorbed in the SESAM. From a standard transfer-matrix simulation of the SESAM, we estimated that less than 25% of this SESAM-OOM pump power was absorbed in the quantum well absorber and its embedding GaAs layers. Almost 40% of the power is expected to be absorbed in the GaAs layers of the distributed Bragg reflector (DBR). More than 35% was reflected on the topmost GaAs layer due to Fresnel reflection and the last 1.5% was transmitted due to the wavelength mismatch between the DBR design wavelength and the 812-nm pump light.

Changing the 812-nm incident power on the SESAM slightly modified its nonlinear reflectivity, which enabled fine control of the intra-cavity power and a corresponding tuning of the CEO frequency at a rate of around 3 kHz/mW (with respect to the incident power onto the SESAM). The modulation bandwidth of the OOM was measured by applying a sine waveform to the SESAM pump diode current, and by recording the corresponding transfer function of f_{CEO} (in amplitude and phase) using a frequency discriminator [23] and a lock-in detection. Results are displayed in Fig. 2 (red dashed lines) and are compared with the transfer function obtained for pump gain modulation (blue dashed lines). The SESAM-OOM bandwidth is enlarged by a factor $\sim$20 in amplitude (at 3 dB) and $\sim$10 at the 90° phase shift compared to the traditional gain modulation. A modulation bandwidth of $\sim$70 kHz was achieved for f_{CEO} (at 90° phase shift), enabling a very tight lock with low residual integrated phase noise to be obtained. This results from the relatively low frequency noise of the free-running CEO beat in this laser that requires only a few kilohertz of feedback bandwidth to achieve a tight CEO lock [15]. Hence, a residual integrated phase noise of 63 mrad [1 Hz–100 kHz] was obtained for the stabilization of f_{CEO} using feedback to the SESAM-OOM pump laser with a loop bandwidth of $\sim$40 kHz assessed from the position of the servo bump. This is an improvement of more than an order of magnitude compared to the value previously obtained for gain pump modulation in the same laser [24]. Part of the residual phase noise resulted from parasitic peaks at 50 Hz and harmonics thereof, which were of technical origin in the stabilization loop. Therefore, the integrated phase noise could in principle be reduced below 30 mrad if this technical noise is suppressed.



(a)

(b)

Fig. 2. Transfer function in amplitude (a) and phase (b) obtained for SESAM-OOM (red) and traditional gain pump modulation (blue) for the CEO frequency f_{CEO} (dashed lines) and for the repetition rate f_{rep} up-scaled by the mode number $N \approx 2.6 \cdot 10^6$ (solid lines).

In addition to its effect on f_{CEO}, the influence of the SESAM-OOM on the second comb parameter, i.e., the repetition rate f_{rep}, was also investigated. It is known that the actuators used to stabilize a frequency comb are usually not fully independent and have a cross-influence [25]. As the effect of the SESAM-OOM on f_{rep} was relatively tiny, the measurement was performed in the optical domain where it is enhanced by the mode number N, in the order of $2.6 \cdot 10^6$ here. For this purpose, one comb line was heterodyned with a CW laser and the beat note was mixed with the CEO beat in a double-balanced mixer in order to remove the contribution of f_{CEO} and obtain a CEO-free beat signal that contained only the effect of the SESAM-OOM on f_{rep}, scaled up by N. The frequency modulation of this CEO-free beat was measured with the same frequency discriminator and lock-in detection scheme as for f_{CEO} for a modulation of the SESAM pump power. The results are also displayed in Fig. 2 (solid lines). One notices that the transfer functions obtained for $N \cdot f_{\mathrm{rep}}$ and f_{CEO} are very similar, both in shape and amplitude, meaning that the effect of the OOM on a comb line has similar

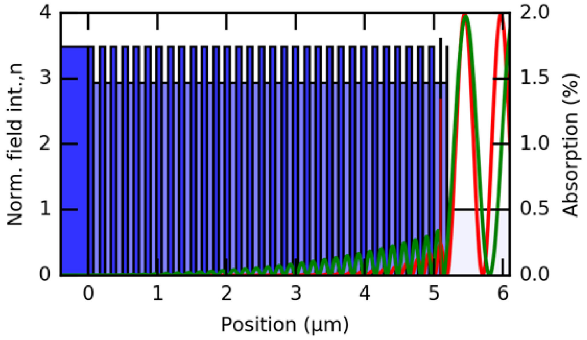


Fig. 3. SESAM structure along with the propagation of the electrical field of the 981-nm pump light at an incidence angle of 45° and s-polarized (green) and of the 1050-nm light at the designed incident angle of 0° (red).

contribution from f_{rep} and f_{CEO}. This is also the case for a modulation of the gain pump power. Therefore, the SESAM-OOM can also be used to lock one line of the comb to an optical reference, as it can be done via the pump power [26].

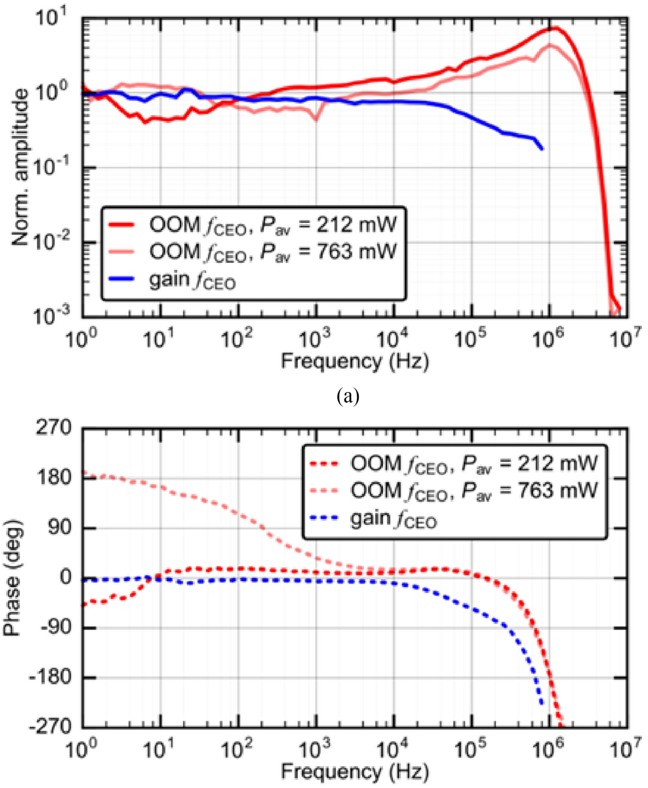
The initial SESAM-OOM demonstration reviewed here was limited in modulation bandwidth to around 50 kHz, likely by the fact that the induced effect was mainly thermal, since most of the optical power was absorbed in the DBR region and not in the quantum well absorber.

B. 1-GHz Yb:CALGO Laser at 1 µm

In 2014, the first CEO stabilization of an Yb:CALGO DPSSL with a gigahertz repetition rate was demonstrated using pump control [12]. Recently, we compared the performance of pump control with SESAM-OOM for CEO stabilization of such a laser [22]. In contrast to the first demonstration of OOM reported in the previous section, the self-referenced stabilization of f_{CEO} in this GHz laser required a much larger locking bandwidth as a result of the higher frequency noise of the free-running CEO beat. The SESAM-OOM method was thus particularly attractive in this case to enhance the stabilization bandwidth.

The laser was based on the design presented in [12] and emitted more than 2.1-W average output power in 96-fs pulses at a repetition rate of 1.05 GHz and a central wavelength of 1055 nm [13]. It was pumped with a commercial laser diode array wavelength-stabilized at 980 nm with a volume holographic grating. Self-starting mode-locking was obtained with an InGaAs SESAM with a modulation depth of 1.15%, non-saturable losses of 0.07%, and a saturation fluence of 10.69 μJ/cm^2. The structure of the SESAM is depicted in Fig. 3. It was operated at an intra-cavity laser fluence of 93.6 μJ/cm^2, close to the maximum of its nonlinear reflectivity curve.

The SESAM was additionally pumped by an s-polarized 981-nm laser beam at an incidence angle of $\sim$45° to implement the OOM. The same type of pump diode was used as for the laser crystal for convenience, but only a power of less than 200 mW was used for this purpose, in contrast to the 7.7 W used to pump the gain crystal. The OOM pump beam was aligned to overlap with the intra-cavity laser pulses onto the SESAM with a spot diameter of $\sim$300 μm. The CEO beat was detected using a standard f-to-$2f$ interferometer after supercontinuum spectrum generation in a photonic crystal fiber. Details on the laser design, CEO detection, pump modulation electronics and stabilization schemes are given in [13] and [22].



(a)

(b)

Fig. 4. Relative amplitude (a) and phase (b) of the transfer function (TF) of f_{CEO} for a modulation of the OOM pump at two different average powers P_{av} incident onto the SESAM: 212 mW (red) and 763 mW (light red). The TF of f_{CEO} for gain modulation (blue) is also shown for comparison.

Simulations of the electrical field propagation of the OOM pump light in the SESAM structure led to an estimated absorption of only 1.3% in the InGaAs quantum well absorber and 1.3% transmitted through the entire structure and eventually scattered at the unpolished back surface of the GaAs substrate, while the remaining 97.4% was calculated to be simply reflected by the Bragg mirror (Fig. 3). This major part of the pump light is not expected to play any role for the OOM. Therefore, no material other than the quantum well notably absorbs the OOM pump laser light since the GaAs SESAM material is transparent at the 981-nm pump wavelength, which is expected to minimize undesired temperature-induced effects compared to the first OOM experiment presented in the previous section, where such thermal effects were dominant and limited the achievable modulation bandwidth. The reflectivity change produced by the pump light was estimated from the induced frequency change of f_{CEO} to be typically two orders of magnitude smaller than the 1.15% SESAM modulation depth.

The normalized transfer functions of f_{CEO} displayed in Fig. 4 show that the modulation bandwidth (defined at the 90° phase shift) is enhanced to $\sim$630 kHz for the OOM, whereas it is limited to $\sim$280 kHz for gain modulation (resulting from the dynamics of the mode-locked laser cavity [13]). However, one should notice that the overall shape of the transfer function is different. It resembles a first-order low-pass filter in amplitude

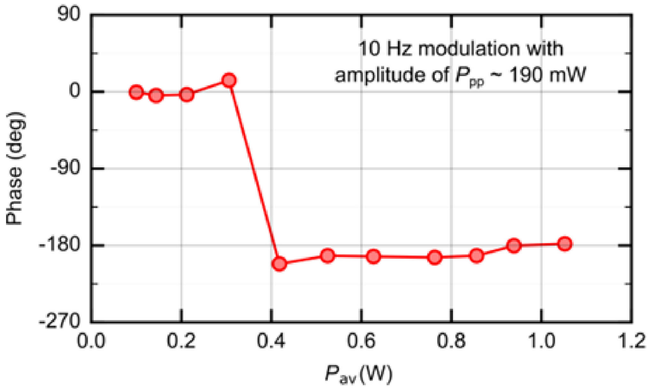


Fig. 5. Phase of the change of f_{CEO} induced by a slow modulation of the SESAM-OOM pump power at 10 Hz plotted as a function of the average optical power P_{av} incident onto the SESAM. A phase reversal occurs at $P_{\mathrm{av}} \approx$ 400 mW.

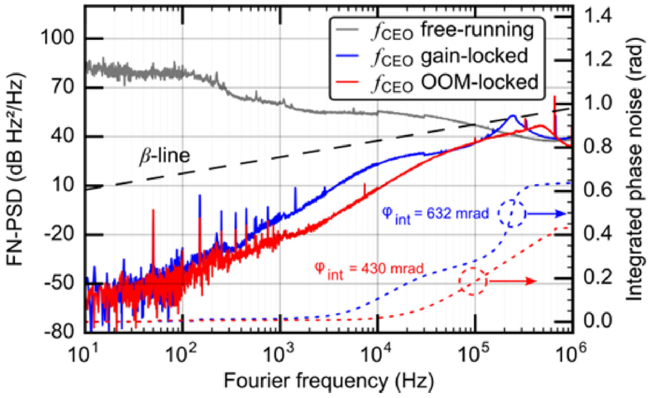


Fig. 6. Frequency noise power spectral density (FN-PSD) of the CEO beat in free-running mode (grey) and stabilized by gain modulation (blue) and by SESAM-OOM (red). The corresponding integrated phase noise is shown as a function of the upper cut-off frequency (right vertical axis).

for gain modulation, whereas it looks closer to a higher-order low-pass filter with a resonance frequency of around 1 MHz for the OOM. Associated with this behavior is a CEO response enhanced by almost one order of magnitude at the resonance frequency of ∼1 MHz compared to low frequencies, followed by a steep drop at higher frequencies. This gain behavior also needs to be taken into account in the defined CEO modulation bandwidth that cannot be assessed only by the aforementioned phase shift when comparing the feedback ability of the OOM and gain modulation. However, it will be shown later that the achieved CEO feedback bandwidth is enhanced by a factor ∼2 with the OOM, similar to the ratio of the previously mentioned CEO modulation bandwidth.

In absolute values, the change in f_{CEO} for a modulation of the SESAM pump power is ∼200 times smaller than the typical tuning coefficient of f_{CEO} with the laser pump power (∼1 kHz/mW vs ∼200 kHz/mW). The high bandwidth achieved with the OOM was obtained at a relatively low average pump power of 212 mW incident onto the SESAM (dark red curves in Fig. 4). At higher average SESAM pump powers (e.g., 763 mW as depicted by the light red curves in Fig. 4), a phase reversal of 180° was observed at low frequency in comparison to the low power case, while the phase of the transfer functions was equal in both cases at frequencies above ∼10 kHz. This is the consequence of a dominant slow thermal effect occurring at high average OOM pump power, which maybe be induced by spurious pump light absorption outside of the quantum well or by the local heating of the quantum well itself resulting in a thermally-induced wavelength shift. In contrast, the desired optically-induced change in the SESAM reflectivity prevails at lower average power. This phase reversal occurred at an average power of ∼400 mW incident onto the SESAM as evidenced in Fig. 5, which shows the phase evolution of f_{CEO} measured for a slow modulation of the SESAM pump power at 10 Hz as a function of the average pump power. This phase behavior and the resulting inadequate CEO transfer function prevented CEO locking at high pump power incident onto the SESAM. However, a tight CEO lock was successfully achieved at low incident power (typ. 210 mW) with a loop bandwidth of ∼500 kHz and a residual integrated phase noise of 430 mrad [10 Hz–1 MHz] (see Fig. 6). This constitutes an improvement by a factor 2 in terms of locking bandwidth, and by more than 30% for the integrated phase noise compared to stabilizing the CEO of the same laser via gain modulation (632 mrad). We should point out that a lower integrated phase noise value of 304 mrad [1 Hz–5 MHz] was obtained with pump power modulation in a similar laser where the CEO beat was detected after supercontinuum spectrum generation in a silicon nitride waveguide [27], resulting from the lower frequency noise of the free-running CEO beat. This was achieved with a similar feedback bandwidth as in our case with gain modulation. Therefore, a comparable improvement could be obtained by SESAM-OOM.

III. CEO STABILIZATION OF A FIBER COMB VIA OOM OF A SEMICONDUCTOR CHIP

Beside its application in DPSSLs that was previously described in this article and applied to a SESAM, OOM methods can also be implemented in other types of frequency combs, such as based on mode-locked fiber lasers. OOM can be applied via a SESAM in SESAM-mode-locked fiber lasers, or using an additional semiconductor element inserted into the laser cavity in case of fiber lasers mode-locked by other mechanisms. Here, we present the first OOM for CEO stabilization in a fiber laser, which was realized by integrating a vertical external-cavity semiconductor surface-emitting laser (VECSEL) chip into the cavity of an Yb femtosecond fiber laser. The used Yb:fiber laser was mode-locked by nonlinear polarization rotation (NPR). It contains a 55-cm long Yb-doped gain fiber (Coractive Yb401) and a wavelength-division multiplexer (WDM) for pump combining. The fibers are fixed with Kapton tape onto an aluminum plate to reduce the influence of thermal fluctuations and air drafts. A free-space section consists of two quarter-wave and two half-wave plates for polarization rotation, a polarizing beam-splitter for NPR rejection output, transmission gratings for dispersion management, and an optical isolator for unidirectional operation. A scheme of the setup is shown in Fig. 7. The laser was pumped by a 976-nm single-mode fiber-coupled laser diode

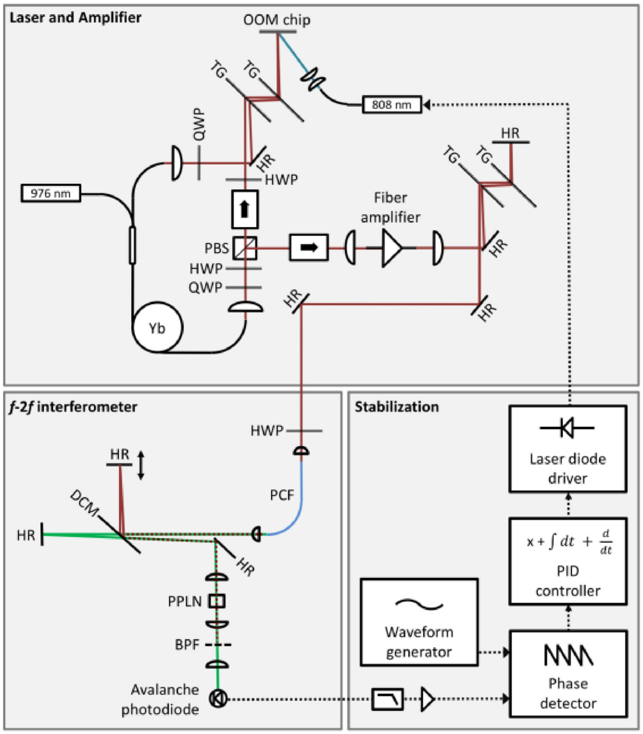


Fig. 7. Diagram of the complete setup including the Yb:fiber laser and amplifier (top), the *f*-to-2*f* interferometer for CEO detection (bottom left) and the laser stabilization electronics (bottom right). HWP: Half-wave plate, QWP: quarter-wave plate, PBS: Polarizing beamsplitter, TG: Transmission grating, HR: Highly reflective mirror, PCF: Photonic crystal fiber, DCM: Dichroic mirror, PPLN: Periodically-poled lithium niobate crystal, BPF: Band pass filter, PID: proportional-integral-derivative servo-controller.

with 500 mW of maximum output power. The total dispersion of the cavity was estimated to be around $+0.013 \pm 0.003\,\mathrm{ps}^2$. The laser operates at a repetition rate of 125 MHz. At the NPR rejection port used as output coupling, the laser delivered 160-fs pulses with 40 mW of average output power. The pulses were centered at a wavelength of 1030 nm with a full width at half-maximum (FWHM) optical bandwidth of 26 nm.

For OOM, we inserted a reflective semiconductor absorber into the fiber laser cavity. Compared to DPSSLs, gain and intra-cavity losses are significantly higher in a fiber laser. For instance, we estimate the total intra-cavity loss to be around 73% in our fiber laser. In order to modulate the intra-cavity power, we used an available commercial VECSEL gain chip as a folding mirror in this first proof-of-principle demonstration. Unfortunately, the detail of the structure is unknown as the manufacturer did not disclose it. However, we expect that it contains several quantum wells (typical designs for such chips are shown in [28]). This component was pumped at a low intensity of around 300 mW by an 808-nm fiber-coupled laser diode. The laser and pump spots were overlapped on the chip with a diameter of around 1 mm. In contrast, the operation of a typical VECSEL would require several watts of pump power at this spot size. Therefore, the absorber in the chip did not reach transparency and was simply used as a controllable semiconductor absorber with higher modulation depth and longer recovery dynamics than the SESAMs described in the previous sections. Therefore, the low intensity fluence modulation on the semiconductor chip acts as a loss modulation.

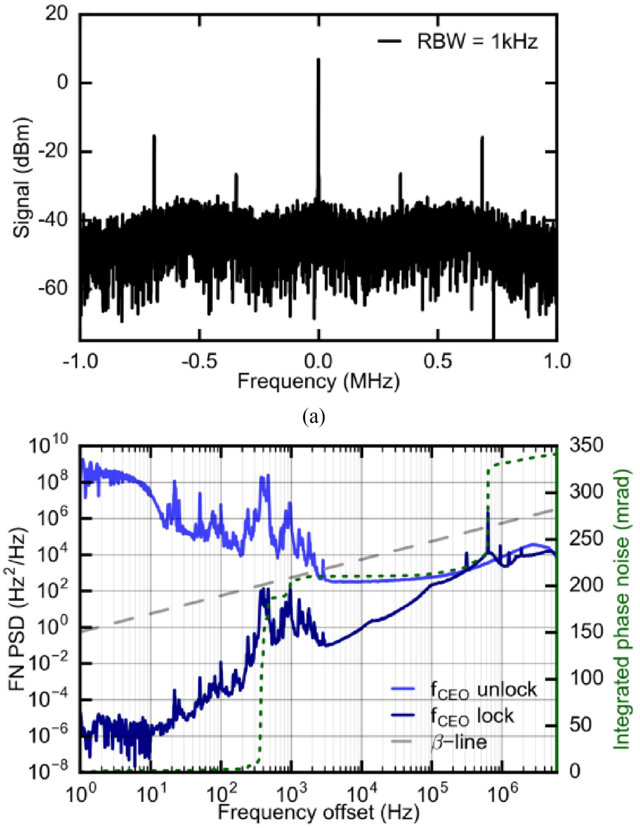
At the laser output, the emitted light passed through an optical isolator to prevent possible back reflections from disturbing the laser. Then, the signal was amplified in a polarization-maintaining (PM) Yb-doped fiber amplifier made of a 90-cm segment of Yb-doped fiber that could be pumped with up to 1 W at 976 nm. The amplified pulses were compressed into a grating compressor made of a pair of dielectric transmission gratings with 1250 grooves/mm separated by around 1 cm. The compressed output had up to 500-mW average power in sub-100-fs pulses. A standard common-path *f*-to-2*f* interferometer was used for CEO beat detection after coherent octave-spanning supercontinuum spectrum generation into a 50-cm-long photonic crystal fiber (NKT Photonics NL-3.2-945). The CEO beat was detected at 680 nm using an avalanche photodiode. The photodiode output signal at 20 MHz was amplified and filtered. It was then compared in a digital phase detector to a reference signal. The phase error signal was fed into a proportional-integral-derivative (PID) servo-controller whose output signal was modulating the 808-nm pump power of the VECSEL chip.

A tight lock of the CEO beat was achieved with the OOM of the semiconductor chip with a stabilization bandwidth of 600 kHz, assessed from the servo bump in the CEO frequency noise spectrum displayed in Fig. 8. The corresponding integrated phase noise of the locked CEO beat was 342 mrad (integrated from 1 Hz to 6 MHz). This first proof-of-principle demonstration proves the viability and benefit of the OOM method also in fiber lasers.

IV. DESIGN OF AN OPTIMIZED OOM CHIP

So far, all demonstrations of CEO stabilization by OOM reported in DPSSL and fiber combs have been realized using existing semiconductor chips that were not specifically designed for this purpose. For instance, SESAMs used for pulse formation in DPSSLs or a VECSEL chip in the Yb-fiber laser were exploited for OOM as described in the previous sections. Here we discuss challenges and give some design guidelines for semiconductor chips optimized for OOM functionality in DPSSLs for fast intra-cavity power modulation.

There are two major difficulties for directly modulating the saturable absorber in a standard SESAM. Firstly, its fast recovery makes it challenging to influence the saturation level of the absorber with CW light. Secondly, absorption of pump light may introduce unwanted thermal effects. The saturable absorbers in SESAMs are usually optimized for a fast recovery, which is advantageous for operation with short pulse durations. Optimized quantum-well and quantum-dot saturable absorbers typically decay at a short timescale well below 100 ps [29]. While such performance is beneficial for their use as a saturable absorber for mode-locking, it makes it difficult to control their saturation level with CW pump light. Indeed, only the fraction of the pump light emitted during the short decay time before the pulse hits the absorber is effectively changing the saturation level for the intra-cavity pulse, while the pump light absorbed during the other times only leads to thermally-induced changes.



(a)

(b)

Fig. 8. (a) RF spectrum of the CEO beat signal with 40-dB signal-to-noise ratio obtained at the output of the f-to-$2f$ interferometer (1-kHz resolution bandwidth). (b) Frequency noise power spectral density (FN PSD) of the CEO beat when free-running (light blue) and stabilized with the OOM (dark blue). Integrated phase noise as a function of the upper cut-off frequency (dashed green curve, right axis).

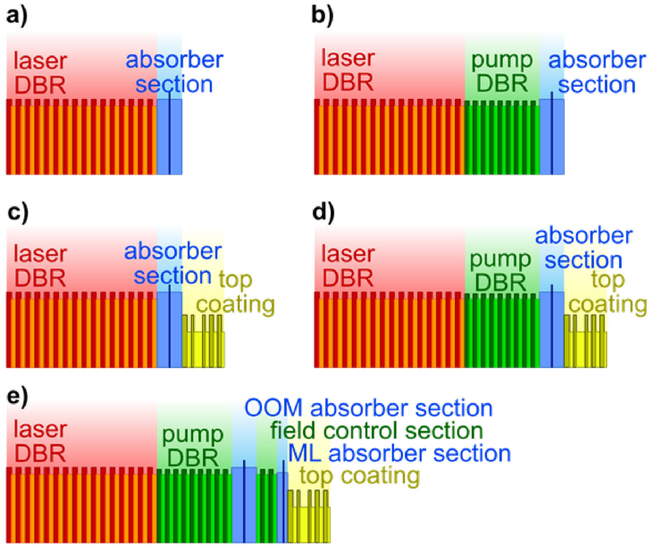


Fig. 9. Schematic design of different OOM structures. (a) Simplest approach similar to a SESAM, but with an absorber section with slow recovery of the carriers excited by the pump. (b) Design with a pump DBR added to minimize pump absorption besides the absorber section. (c) Design with additional top coating (e.g., a dielectric top coating) to control the field intensity of the laser and pump in the absorber section, as well as the group delay dispersion (GDD) for the laser light. (d) Design scheme combining the implementation of both sections added in (b) and (c). (e). Optimized OOM structure with a fast saturable absorber for mode-locking (ML absorber section) and a slow absorber for optical modulation (OOM absorber section).

For example, in the GHz laser presented in Section II-B, the cavity round-trip time is 1 ns. Assuming a recovery time of less than 10 ps, which is typical for this type of SESAMs, less than 1% of the pump light would lead to contribute to the saturation level experienced by the circulating pulse. The remaining 99% of light absorbed in the quantum well only contributes to thermal effects, which constitute another challenge for implementing fast OOM. Absorption in other parts of the structure (purple bars in Fig. 1) can lead to parasitic slow thermal modulations, which are slower and may in some cases even prevent CEO stabilization due to different phase responses for the slow thermal contribution and the fast saturable absorption (see Fig. 4).

In case of using existing SESAMs that are not designed for OOM, the choice of the pump wavelength and angle of incidence is critical for optimizing the performance of the OOM. If a short pump wavelength is chosen, like 812 nm for the laser presented in Section II-A using a SESAM based on an AlAs/GaAs DBR, a large part of the pump radiation is absorbed in the GaAs layers of the DBR (40% in this specific case). While stabilization was successful in this first proof-of-principle experiment, it is generally difficult to predict the exact effect of such thermal changes. For example, in the case of the 1-μm laser of Section II-B, we observed that if the same optical power modulation was used, but the overall pump power sent onto the SESAM was increased from <300 mW to >400 mW, CEO stabilization became impossible. This was most likely due to spurious pump light absorption outside of the quantum well or by the local heating of the quantum well itself resulting in a thermally-induced wavelength shift.

To optimize the design of semiconductor chips for OOM that prevent the aforementioned effects, we suggest placing the pump wavelength inside the reflection band of the DBR. The field strength inside the quantum well (QW) has to be taken into account in this case to quantify the OOM effect. For the laser presented in Section II-B, the chosen incidence angle of 45° with s-polarized pump light enabled an absorption in the well of 1.3%. In comparison, it would be only 0.4% for another angle of 36.4° and the unabsorbed pump light would be completely transmitted into the substrate.

In Fig. 9, we show some general design approaches that can be used for an OOM chip. We consider quantum wells as the best approach for OOM, since they are usually simpler to control than quantum dots and can provide sufficient functionality. The first scheme displayed in Fig. 9(a) shows a standard SESAM, which only consists of a DBR and a QW section. As described above, such a system is not optimal and special care is required in order to use it for OOM. In case of a stand-alone OOM chip that does not contribute to the pulse formation, a fast recombination is not required. Therefore, QWs typically grown for VECSEL structures are better suited to be applied as OOM for CEO frequency stabilization, since their longer recombination is in the ns timescale (resulting from the diffusion of the optically-excited carriers from the pump-absorbing layers into the well and their recombination) [30], [31]. Such a design is shown in Fig. 9(b). The quantum well is embedded in pump-absorbing layers, which is a better alternative than direct in-well pumping. This will significantly increase the efficiency of CW pumping and enable sufficient modulation for CEO control at substantially lower pump powers (e.g., less than 5 mW is expected to be sufficient in case of the 1-μm laser described above, compared to 200 mW previously used).

In order to minimize any parasitic absorption besides the absorber section, we suggest reflecting the pump light in a pump DBR consisting of high and low refractive index semiconductor materials that do not absorb the pump light [as depicted in Fig. 9(b), (d), (e)] or using such materials in the laser DBR. To enhance the effect, we propose to add a top coating over the absorber section [Fig. 9(c)–(e)]. It should be optimized to lead to a small field of the laser light in the absorber section, but a high absorption of the pump light. Moreover, dispersion management and multi-photon absorption have to be taken into account, which makes dielectric top coatings particular attractive for this task (similar to high power SESAM designs, see [32]). Hence, the influence onto the laser pulses is expected to be low, producing negligible disturbance of the laser operation. However, the resulting intra-cavity power modulation to control and stabilize the CEO frequency is low as well (as discussed in Section II-B). If the OOM chip has to act in parallel as a fast saturable absorber for mode-locking, one may also consider an approach similar to a mode-locked integrated external-cavity surface emitting laser (MIXSEL) structure [29], which contains a slow QW that can be optically-pumped and a fast QW for mode-locking. [Fig. 9(e)].

V. CONCLUSION

OOM of a semiconductor element has proven to be a viable and attractive solution for self-referenced CEO stabilization in various types of optical frequency combs from mode-locked solid-state and fiber lasers. In this article, we have shown its implementation in a 75-MHz DPSSL at 1.5 μm, in a GHz DPSSL at 1 μm and in a 125-MHz Yb:fiber laser at 1 μm. The use of different semiconductor elements pumped by an auxiliary laser source has been demonstrated, such as the same SESAM as employed for the pulse formation in SESAM-mode-locked DPSSLs or an additional VECSEL chip introduced in the cavity of a fiber laser.

The major benefit of the OOM is to modulate the losses in the ultrafast laser cavity and not the gain as in the traditional CEO stabilization via pump power modulation. This enables the bandwidth limitation arising from the cavity dynamics to be overcome, resulting in a strong enhancement of the stabilization bandwidth and in a significant improvement of the CEO noise performance. Whereas a standard semiconductor structure was used in the first proof-of-principle demonstrations of CEO stabilization by OOM presented in this article, dedicated structures can be designed and fabricated to optimize the effect on the CEO frequency, both in terms of speed and control range. These properties rely on an efficient absorption of the incident pump light in the quantum well absorber, avoiding parasitic absorption in other regions of the structure, which can lead to much slower thermal effects as observed in our first OOM demonstration in a low repetition rate DPSSL. We discussed some design challenges and presented guidelines towards the development of semiconductor chips optimized for OOM.

In addition to their high bandwidth capability, the extremely low losses of semiconductor OOM chips makes this technology compatible with a variety of mode-locked lasers, including high-power and high-energy ultrafast lasers such as thin disk lasers that operate in the kW intra-cavity power range.

REFERENCES

[1] T. Durhuus, B. Mikkelsen, C. Joergensen, S. L. Danielsen, and K. E. Stubkjaer, “All-optical wavelength conversion by semiconductor optical amplifiers,” *J. Lightw. Technol.*, vol. 14, no. 6, pp. 942–954, Jun. 1996.

[2] K. Obermann, S. Kindt, and D. Breuer, “Performance analysis of wavelength converters based on cross-gain modulation in semiconductor-optical amplifiers,” *J. Lightw. Technol.*, vol. 16, no. 1, pp. 78–85, Jan. 1998.

[3] G. Chen *et al.*, “High-speed all-optical modulation of a standard quantum cascade laser by front facet illumination,” *Appl. Phys. Lett.*, vol. 95, no. 10, Sep. 2009, Art. no. 101104.

[4] L. Tombez, S. Schilt, D. Hofstetter, and T. Südmeyer, “Active linewidth-narrowing of a mid-infrared quantum cascade laser without optical reference,” *Opt. Lett.*, vol. 38, no. 23, pp. 5079–5082, Dec. 2013.

[5] C. Peng *et al.*, “Purified frequency modulation of a quantum cascade laser with an all-optical approach,” *Opt. Lett.*, vol. 42, no. 21, pp. 4506–4509, Nov. 2017.

[6] V. G. Savitski, A. J. Kemp, S. Calvez, and D. Burns, “Optically pumped saturable Bragg reflectors: Nonlinear spectroscopy and application in ultrafast lasers,” *IEEE J. Quantum Electron.*, vol. 46, no. 11, pp. 1650–1655, Nov. 2010.

[7] H. R. Telle *et al.*, “Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation,” *Appl. Phys. B*, vol. 69, no. 4, pp. 327–332, 1999.

[8] D. J. Jones *et al.*, “Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis,” *Science*, vol. 288, no. 5466, pp. 635–639, Apr. 2000.

[9] A. Apolonski *et al.*, “Controlling the phase evolution of few-cycle light pulses,” *Phys. Rev. Lett.*, vol. 85, no. 4, pp. 740–743, Jul. 2000.

[10] S. A. Diddams, “The evolving optical frequency comb [Invited],” *J. Opt. Soc. Amer. B*, vol. 27, no. 11, pp. B51–B62, 2010.

[11] C. R. Locke, E. N. Ivanov, P. S. Light, F. Benabid, and A. N. Luiten, “Frequency stabilisation of a fibre-laser comb using a novel microstructured fibre,” *Opt. Express*, vol. 17, no. 7, pp. 5897–5904, 2009.

[12] A. Klenner, S. Schilt, T. Südmeyer, and U. Keller, “Gigahertz frequency comb from a diode-pumped solid-state laser,” *Opt. Express*, vol. 22, no. 25, pp. 31008–31019, Dec. 2014.

[13] S. Hakobyan *et al.*, “Full stabilization and characterization of an optical frequency comb from a diode-pumped solid-state laser with GHz repetition rate,” *Opt. Express*, vol. 25, no. 17, pp. 20437–20453, Aug. 2017.

[14] B. R. Washburn, W. C. Swann, and N. R. Newbury, “Response dynamics of the frequency comb output from a femtosecond fiber laser,” *Opt. Express*, vol. 13, no. 26, pp. 10622–10633, 2005.

[15] S. Schilt *et al.*, “Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-μm solid-state laser,” *Opt. Express*, vol. 19, no. 24, pp. 24171–24181, Nov. 2011.

[16] A. Cingöz *et al.*, “Broadband phase noise suppression in a Yb-fiber frequency comb,” *Opt. Lett.*, vol. 36, no. 5, pp. 743–745, 2011.

[17] C. Benko *et al.*, “Full phase stabilization of a Yb: Fiber femtosecond frequency comb via high-bandwidth transducers,” *Opt. Lett.*, vol. 37, no. 12, pp. 2196–2198, 2012.

[18] C.-C. Lee *et al.*, “Frequency comb stabilization with bandwidth beyond the limit of gain lifetime by an intracavity graphene electro-optic modulator,” *Opt. Lett.*, vol. 37, no. 15, pp. 3084–3086, 2012.

[19] W. Hänsel *et al.*, “Electro-optic modulator for rapid control of the carrier-envelope offset frequency,” in *Proc. Conf. Lasers Electro-Opt.*, 2017, Paper SF1C.5.

[20] L. Karlen, G. Buchs, E. Portuondo-Campa, and S. Lecomte, “Efficient carrier-envelope offset frequency stabilization through gain modulation via stimulated emission,” *Opt. Lett.*, vol. 41, no. 2, pp. 376–379, Jan. 2016.

[21] M. Hoffmann, S. Schilt, and T. Südmeyer, “CEO stabilization of a femtosecond laser using a SESAM as fast opto-optical modulator,” *Opt. Express*, vol. 21, no. 24, pp. 30054–30064, Dec. 2013.

[22] S. Hakobyan *et al.*, “Carrier-envelope offset stabilization of a GHz repetition rate femtosecond laser using opto-optical modulation of a SESAM,” *Opt. Lett.*, vol. 42, no. 22, pp. 4651–4654, Nov. 2017.

[23] S. Schilt *et al.*, “Frequency discriminators for the characterization of narrow-spectrum heterodyne beat signals: Application to the measurement of a sub-hertz carrier-envelope-offset beat in an optical frequency comb,” *Rev. Sci. Instrum.*, vol. 82, no. 12, 2011, Art. no. 123116.

[24] S. Schilt *et al.*, “Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-μm solid-state laser,” *Opt. Express*, vol. 19, no. 24, pp. 24171–24181, Nov. 2011.

[25] V. Dolgovskiy *et al.*, “Cross-influence between the two servo loops of a fully stabilized Er: fiber optical frequency comb,” *J. Opt. Soc. Amer. B*, vol. 29, no. 10, pp. 2944–2957, 2012.

[26] J. Millo *et al.*, “Ultra-low-noise microwave extraction from fiber-based optical frequency comb,” *Opt. Lett.*, vol. 34, no. 23, pp. 3707–3709, Dec. 2009.

[27] A. Klenner *et al.*, “Gigahertz frequency comb offset stabilization based on supercontinuum generation in silicon nitride waveguides,” *Opt. Express*, vol. 24, no. 10, pp. 11043–11053, May 2016.

[28] O. G. Okhotnikov, *Semiconductor Disk Lasers: Physics and Technology*. Hoboken, NJ, USA: Wiley, 2010.

[29] M. Mangold *et al.*, “Femtosecond pulses from a modelocked integrated external-cavity surface emitting laser (MIXSEL),” *Opt. Express*, vol. 21, no. 21, pp. 24904–24911, Oct. 2013.

[30] C. G. E. Alfieri *et al.*, “Optical efficiency and gain dynamics of mode locked semiconductor disk lasers,” *Opt. Express*, vol. 25, no. 6, pp. 6402–6420, Mar. 2017.

[31] J. Hader *et al.*, “Ultrafast non-equilibrium carrier dynamics in semiconductor laser mode-locking,” *Semicond. Sci. Technol.*, vol. 32, no. 1, 2017, Art. no. 013002.

[32] C. J. Saraceno *et al.*, “SESAMs for high-power oscillators: Design guidelines and damage thresholds,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 18, no. 1, pp. 29–41, Jan./Feb. 2012.

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