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Carrier-Envelope Offset Frequency Stabilization of a Fiber Laser by Cross Gain Modulation

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Abstract: We present the first carrier-envelope offset (CEO) frequency stabilization of a fiber laser by cross gain modulation. The Yb-doped fiber laser is mode-locked by nonlinear polarization evolution and emits 32-nm wide dissipative solitons at a repetition rate of 125 MHz with 150 mW of average output power. A continuous wave laser signal at a wavelength of 1025 nm is used as an intracavity power modulator. A low power of only 200 μW of modulator signal is coupled into the fiber laser and amplified in the gain segment. This signal cross modulates the laser gain, achieving 40 times larger modulation bandwidth of the intracavity laser power than with standard pump-current control. A tight CEO lock is demonstrated with 361 mrad of residual integrated phase noise (from 1 Hz to 1 MHz). The method allows easy implementation in many existing fiber laser frequency combs based on various saturable absorbers and fiber configurations.

Index Terms: Mode-locked lasers, fiber lasers, optical frequency comb, stabilization, metrology.

1. Introduction

Optical frequency combs from mode-locked lasers [1]–[3] have proven to be a powerful tool in many application areas such as molecular spectroscopy [4], [5], optical frequency metrology [6], [7] and atomic clocks [8], [9]. Fiber lasers have been the preferred frequency comb sources in the last decade owing to their compactness, versatility and high reliability. The most challenging aspect for fiber laser frequency combs concerns the phase-stabilization of the carrier-envelope-offset (CEO) frequency f_{CEO}. This is traditionally achieved by using a phase-locked loop with feedback applied to the pump power of the femtosecond laser, after detection of the CEO beat using non-linear f-to-$2f$ interferometry [1]. The pump control method is reliable and convenient to implement in diode-pumped femtosecond lasers, for which the injection current of the pump diode can be directly modulated. However, the stabilization bandwidth is typically limited by the cavity dynamics and the upper-state lifetime of the gain material, which is usually in the range of few hundreds of μs to few ms for the most common ion dopants used in fiber lasers, such as erbium and ytterbium. In order to overcome this limitation, alternative stabilization methods have been proposed. Intra-cavity electro-optic modulators (EOM) have been first introduced in Er:fiber combs for fast frequency stabilization of the repetition rate f_{rep} to a radio-frequency reference [10] and later on as a high bandwidth actuator to phase-lock one comb line to an optical reference [11], [12]. A similar approach was also applied later in an Yb:fiber laser at 1 μm [13]. Furthermore, intra-cavity EOMs can also be used for fast CEO frequency control and stabilization as they generally have a direct influence on f_{CEO} [12]. Recently, ultra-low noise performance of an Er:fiber frequency comb was demonstrated using two orthogonal intra-cavity EOMs for simultaneous fast stabilization of both f_{rep} and f_{CEO} [14]. However, this increases the complexity and cost of the system. Lee *et al*. have demonstrated intra-cavity loss modulation by using a graphene EOM, achieving low-noise CEO stabilization in a Tm-fiber laser [15]. Though, disadvantages stem from the lack of flatness in the achieved modulation response, and from the usual need of a complementary slow stabilization channel via pump modulation for long-term stability. Other methods to enlarge the modulation bandwidth resulting from the same limitations in diode-pumped solid-state lasers have also been reported. Karlen *et al*. demonstrated CEO stabilization in an Er:Yb:glass solid-state laser by shining a high power 1.5-μm laser signal to the gain medium of the mode-locked laser in order to bypass the slow energy transfer from the ytterbium ions to the erbium ions [16]. Nevertheless, additional pump modulation was still required to achieve a stable CEO lock. We also demonstrated opto-optical modulation of a semiconductor saturable absorber mirror (SESAM) for CEO stabilization in a low repetition rate Er:Yb:glass laser [17], and more recently in a GHz repetition rate frequency comb [18]. This technique can also be applied to fiber lasers, incorporating a semiconductor absorber chip [19]. Finally, the feedforward method using an extra-cavity acousto-optic frequency-shifter (AOFS) that was first demonstrated in a Ti:Sapphire laser [20], does not require any locking electronics and can correct CEO fluctuations in a bandwidth that is only limited by the acoustic delay in the AOFS, typically in the megahertz range.

In this article, we demonstrate for the first-time cross gain modulation (XGM) as a novel standalone method for stabilizing the CEO frequency of a fiber laser. XGM was initially 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 [21], [22]. A continuous wave (CW) laser signal at a desired wavelength was injected into an SOA along with the optical data signal. The saturated SOA allocated the gain between the two signals and transferred the data stream to the CW signal with bit inversion. The original data signal was then filtered out.

As a proof-of-principle demonstration, we apply XGM for CEO control in a standard Yb:fiber mode-locked laser. We use XGM in the fiber laser gain segment to amplify a modulated CW signal, which transfers the modulation to the intra-cavity laser signal without bandwidth limitation by the gain lifetime. The saturated gain of fiber lasers enables efficient modulation transfer, requiring minimal modulator power levels ($<$1 mW). Therefore, the method can be easily implemented using an inexpensive low-power laser. We achieved 400 kHz of modulation bandwidth of the intra-cavity laser power, limited by the underlying laser dynamics. This is forty times larger than the standard method of pump modulation, which is limited to 10 kHz in our laser (mainly by the upper-state lifetime of the gain). We tightly locked the CEO frequency and achieved 361 mrad of residual integrated phase noise (integrated from 1 Hz to 1 MHz) in this first proof-of-principle demonstration. Applying XGM to intrinsically low-noise fiber lasers, such as SESAM or nonlinear amplifying loop mirror (NALM) mode-locked lasers with polarization-maintaining (PM) fiber [23]–[25], is expected to produce state-of-the-art fiber laser frequency combs.

2. Experiment and Results

The fiber laser is based on an Yb-doped fiber and is mode-locked by nonlinear polarization evolution (NPE). The fiber segment contains a 55-cm long Yb-doped gain fiber (Coractive YB401), a wavelength-division multiplexer (WDM) for pump combining and single mode fiber collimators. The free-space portion of the laser consists of wave plates for polarization rotation, a polarizing beam splitter for NPE rejection output, transmission gratings for dispersion compensation, and an optical

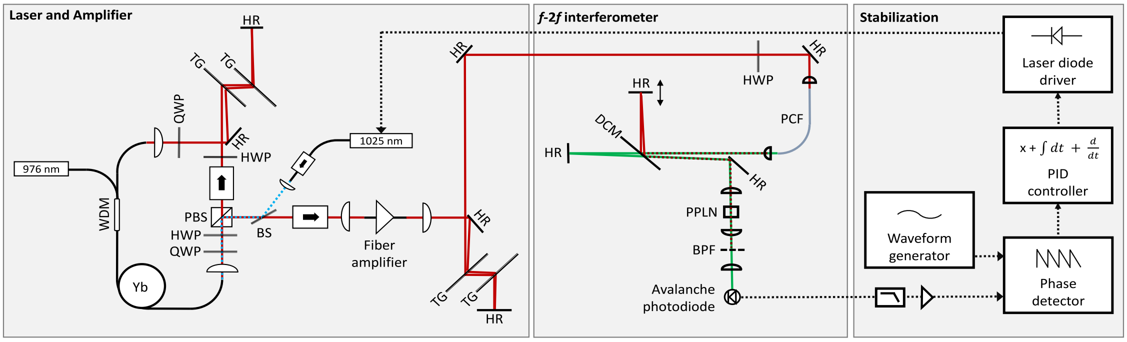

Fig. 1. Diagram of the complete setup (WDM: wavelength division multiplexer, QWP: quarter wave plate, HWP: half wave plate, HR: highly reflective mirror, TG: transmission gratings, PBS: polarizing beam splitter, BS: beam sampler, PCF: photonic crystal fiber, DCM: dichroic mirror, PPLN: periodically poled lithium niobate crystal, BPF: bandpass filter, PID: proportional-integral-derivative servo controller).

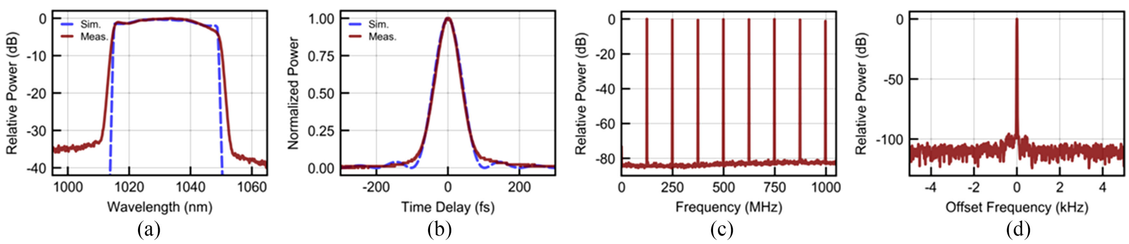

Fig. 2. (a) Simulated (blue, dashed) and measured (red, solid) optical spectrum of the fiber laser with a FWHM bandwidth of 32 nm. (b) Measured (red, solid) and simulated (blue, dashed) temporal pulse profile of the beam before entering the PCF. (c) RF spectrum of the laser output measured up to 1 GHz (resolution bandwidth (RBW): 1 kHz). (d) RF spectrum of the repetition rate frequency, offset by $f_{\text{rep}} = 125$ MHz (RBW = 10 Hz).

isolator for unidirectional operation. A diagram of the setup is shown in Fig. 1. The total dispersion of the cavity is estimated to be $+0.013 \pm 0.002\,\text{ps}^2$. The gain fiber is pumped by 550 mW of power at 976 nm. The fiber laser emits 150 mW of average output power from the NPE rejection port, at a pulse repetition rate of 125 MHz with a full width at half maximum (FWHM) spectral bandwidth of 32 nm at a center wavelength of 1030 nm [Fig. 2(a), (c), and (d)]. The laser operates in the dissipative soliton regime, as evidenced by the steep edges of its optical spectrum. Numerical simulations based on a modified version of the nonlinear Schrödinger equation [26] were conducted to validate the laser operation [Fig. 2(a)].

A beam sampler (i.e., an optical substrate with an uncoated surface that causes a small Fresnel reflection), is placed at the laser output to inject the modulator signal into the fiber laser cavity. We used a 1025-nm fiber-coupled laser diode emitting around 2 mW in CW operation as an auxiliary signal for the modulation. This signal was passed through a fiber-coupled isolator with a specified isolation rate of >33 dB and was then partially reflected by the beam sampler. A resulting power of around 200 μW was finally coupled into the fiber laser cavity. The discrimination of the modulator signal from the laser pulses can easily be implemented in many ways, e.g., by counter-propagation in a configuration made of standard single mode fibers, by polarization combining/splitting in a configuration with PM fibers, or by spectral filtering. In our case, the counter-propagating modulator signal got amplified in the gain fiber and was finally dumped by the isolator. As the isolation rate is much larger than the estimated amplification in the fiber segment (<13 dB), the auxiliary 1025-nm light has no effect on the mode-locking operation of the laser. We measured the transfer function of the intra-cavity laser power (obtained from the light reflected by a diffraction grating used for dispersion compensation) for a modulation of the auxiliary laser current. We compared it with the

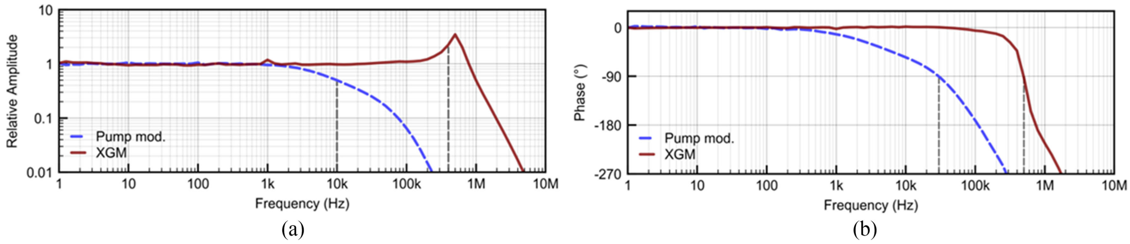

Fig. 3. Modulation transfer function of the laser intra-cavity power for pump current modulation (blue, dashed) and XGM (red, solid) in (a) relative amplitude and (b) phase. The cutoff frequencies are 10 kHz and 400 kHz, respectively, limited by either the ±3 dB amplitude change or the 90° phase shift. The phase for XGM has been offset by 180° for easier comparison with the case of pump modulation.

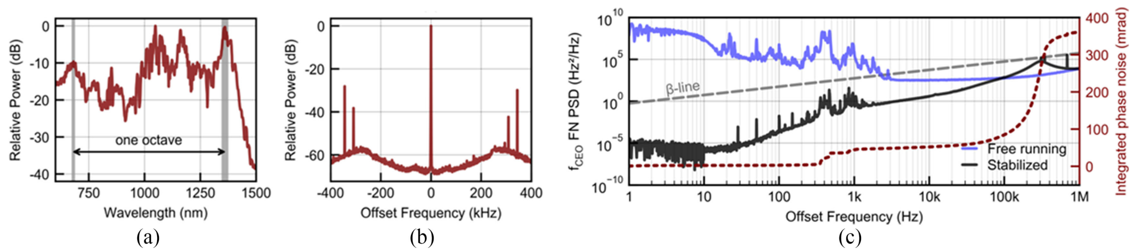

Fig. 4. (a) Octave-spanning supercontinuum spectrum obtained at the output of a 50-cm long PCF. (b) RF spectrum of the stabilized CEO beat signal with 57-dB signal-to-noise ratio relative to the servo bump obtained at the output of the f-to-$2f$ interferometer (RBW = 100 Hz). (c) Single sideband frequency noise (FN) power spectral density (PSD) of the free running (blue, solid) and stabilized (black, solid) CEO beat along with the integrated root mean square phase noise (red dashed line, vertical axis) and the β-separation line [28] (gray, dashed). The narrow noise peaks at ∼350 kHz and ∼700 kHz in the noise spectrum of the locked CEO beat are induced by the servo controller.

result obtained by directly modulating the current of the pump laser. The amplitude and phase of the measured transfer functions are shown in Fig. 3. We achieved a modulation bandwidth of ∼10 kHz for pump modulation and ∼400 kHz for XGM, respectively, limited by either the ±3 dB change in amplitude or a −90° phase shift. The XGM transfer function exhibits a flat response to the modulation of the auxiliary laser up to more than 100 kHz, requiring no lead-lag compensation for its use as a fast actuator for CEO stabilization. A very similar modulation bandwidth is expected for the CEO frequency as previously shown in various solid-state mode-locked lasers [27]. The resonance occurring at ∼500 kHz corresponds to the relaxation oscillation frequency of the laser. The power of the injected auxiliary signal can be controlled as a simple mean to adjust the modulation depth. This is a useful feature for fiber lasers, which usually exhibit higher noise levels than solid state lasers, requiring higher modulation depth and bandwidth for their stabilization.

An optical isolator was placed after the beam sampler at the laser output to prevent possible reflections from being fed back into the laser cavity and causing disturbances. The isolated signal was then coupled into a PM fiber amplifier consisting of an 80-cm Yb-doped fiber segment pumped by a 976-nm fiber-coupled diode with a power of up to 1 W, leading to an output power of up to 600 mW. The amplified signal was recompressed to a duration of 84 fs by a grating compressor, in good agreement with the simulated transform-limited temporal pulse profile [Fig. 2(b)].

For CEO detection, we used the standard f-to-$2f$ nonlinear interferometry method [1]. The compressed pulses were coupled into a 50-cm long collapse-cleaved photonic crystal fiber (PCF, NKT Photonics NL-3.2-945) to generate a coherent octave-spanning supercontinuum spectrum [Fig. 4(a)]. Afterwards, the beam was sent into a quasi-common-path f-to-$2f$ interferometer. The output beam of the PCF was first separated by a dichroic mirror into spectral regions below and above 950 nm. Light in both beams was reflected by distinct mirrors and recombined by the dichroic mirror. One of the mirrors was mounted on a translation stage providing an adjustable delay line in order to ensure the temporal overlap of the two pulses at the output of the interferometer. The recombined beam was focused into an MgO:PPLN crystal for second harmonic generation (SHG) from the 1360-nm spectral component of the supercontinuum. The beam at the output of the crystal was collimated and bandpass filtered in the spectral range of 680 nm containing the original and the frequency-doubled components of the supercontinuum. The filtered beam was then focused onto an avalanche photodiode.

The output signal of the photodiode was bandpass filtered and amplified to isolate the CEO beat at ∼20 MHz. The beat signal was then compared to a reference signal in a digital phase detector. The phase error signal was fed into a proportional-integral-derivative (PID) servo controller, whose output signal was driving the modulator laser through its current driver. We achieved a tight CEO lock as shown in Fig. 4(b). The stabilized CEO frequency noise power spectral density (PSD) is shown in Fig. 4(c), along with the typical free-running CEO frequency noise PSD. Using XGM, we achieved a feedback bandwidth of ∼300 kHz, assessed from the servo bump in the phase noise spectrum. Integrating the phase noise PSD from 1 Hz to 1 MHz results in a residual integrated phase noise of 361 mrad, largely due to the contribution of the servo bump. The tight lock of the CEO beat stands stable, as long as vibrational impacts to the laser are prevented.

3. Conclusion

In conclusion, we have presented the first fiber laser frequency comb stabilized by XGM. The gain fiber was simultaneously used for amplification of the laser pulses and fast intra-cavity power modulation via an auxiliary CW laser. The Yb-doped fiber laser emits pulses at 1030 nm with a spectral bandwidth of 32 nm at a repetition rate of 125 MHz. The laser signal was amplified, compressed and self-referenced using an f-to-$2f$ interferometer to detect the CEO beat. The modulator signal was coupled into the fiber laser using a beam sampler and was counter-propagating to the laser pulses inside the gain medium. Less than 200 μW of CW modulator signal power were sufficient for CEO stabilization. Using the standard stabilization method based on pump power modulation, the intra-cavity laser power control bandwidths are limited to about 10 kHz. In contrast, we achieved a modulation bandwidth of 400 kHz using XGM, which demonstrates the high potential of this method for fast frequency control and self-referencing of fiber lasers. A tight lock of the CEO frequency was achieved with a residual integrated phase noise of 361 mrad (1 Hz–1 MHz). Due to the nature of the stabilization method, it can be directly implemented into existing fiber laser frequency comb systems employing various saturable absorbers (such as NPE, SESAM, NALM, graphene or carbon nanotubes) and fiber configurations (such as PM and non-PM). Our results show that XGM is a straightforward, standalone, easy-to-implement and efficient solution for stabilizing fiber laser frequency combs.

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