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Carrier envelope offset frequency detection and stabilization of a diode-pumped mode-locked Ti:sapphire laser

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We demonstrate the first diode-pumped Ti:sapphire laser frequency comb. It is pumped by two green laser diodes with a total pump power of 3 W. The Ti:sapphire laser generates 250 mW of average output power in 61-fs pulses at a repetition rate of 216 MHz. We generated an octave-spanning supercontinuum spectrum in a photonic-crystal fiber and detected the carrier envelope offset (CEO) frequency in a standard f-to-$2f$ interferometer setup. We stabilized the CEO-frequency through direct current modulation of one of the green pump diodes with a feedback bandwidth of 55 kHz limited by the pump diode driver used in this experiment. We achieved a reduction of the CEO phase noise power spectral density by 140 dB at 1 Hz offset frequency. An advantage of diode pumping is the ability for high-bandwidth modulation of the pump power via direct current modulation. After this experiment, we studied the modulation capabilities and noise properties of green pump laser diodes with improved driver electronics. The current-to-output-power modulation transfer function shows a bandwidth larger than 1 MHz, which should be sufficient to fully exploit the modulation bandwidth of the Ti:sapphire gain for CEO stabilization in future experiments.

OCIS codes: (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3590) Lasers, titanium; (120.3940) Metrology.

The stabilization of the carrier envelope offset (CEO) frequency and the realization of optical frequency combs was a major breakthrough in optical science and photonics. Optical frequency combs can serve as extremely accurate rulers in the frequency domain and provide a phase-stable link between microwave and optical frequencies [1–3]. They have been enabling an impressive progress in a wide scientific range, for instance precision metrology [4] and spectroscopy [5], calibration of astronomical spectrometers [6,7], waveform synthesis [3], stable microwave generation [8], and optical clocks [9]. The first stable frequency combs were generated from ultrafast Ti:sapphire lasers [2,3]. The emission bandwidth of Ti:sapphire extends from 650 up to 1200 nm, which makes it one of the best suited materials for ultrashort pulse generation [10]. It requires pumping in the blue-green region of the spectrum, which until recently required complex and expensive laser systems. Initially, Ti:sapphire crystals were pumped by Ar:Ion lasers, which are very unpractical because of their limited lifetime and low wall-plug efficiency, which is typically in the range of 0.1%. Today, they have been mostly replaced by frequency-doubled solid-state lasers, which reach tens of watts of output power with single-mode transverse beam quality. However, their cost, complexity, and size is a major disadvantage for Ti:sapphire lasers compared to ultrafast laser systems that can be directly diode-pumped like Yb- and Er-doped fiber and solid-state lasers [11], which are currently the dominant techniques for frequency combs [12].

The recent development of blue and green laser diodes [13] finally enabled simpler and cheaper pumping options for Ti:sapphire lasers. Recently, we have reported on a green diode-pumped mode-locked Ti:sapphire laser reaching output powers of 650 mW in continuous wave and 450 mW in mode-locked operation [14], which is sufficient for many application areas. However, the spectral purity and spatial beam quality of the blue and green laser diodes are significantly worse than frequency-doubled solid-state lasers, which typically operate in the fundamental transverse-mode. The noise properties of green pump diodes have not been studied in detail and so far, it was not clear if diode-pumping of Ti:sapphire lasers was a viable alternative to traditional pumping schemes for frequency metrology applications. In this Letter, we report on, to the best of our knowledge, the first detection and stabilization of the CEO frequency of a diode-pumped mode-locked Ti:sapphire laser. The stabilization was realized by direct modulation of the pump diode current, rather than using an external acousto-optic modulator, which is often required in Ti:sapphire lasers pumped by frequency doubled solid-state lasers [15]. We also show that the currently available green laser diodes have noise properties that are compatible with frequency comb generation and can be directly modulated in the MHz range.

The laser gain is a 4-mm long Brewster-cut Ti:sapphire crystal with 0.25% weight doping, 4.1 cm^{-1} ($\pm$20%) of small signal pump absorption at 532 nm and a figure of merit (FOM) of

150 for the ratio of the absorption cross section at 820 and 514 nm. The cavity follows an X-shape configuration with the gain crystal pumped from each side by a green laser diode (model NDG7475 from Nichia Inc.). The pump diodes are packaged in 8-mm TO cans and can each deliver up to 1.5 W of output power, running at 12% wall-plug efficiency. We mounted them into copper heat sinks, which are water-cooled at 15°C. The two pump beams have M^2 values of 2.7 × 5.5 and 2.2 × 5.4 in the fast and slow axes, respectively. The diodes emit at a central wavelength of 520 nm with a bandwidth of ~2.5 nm. The pump configuration consists of a 4-mm focal length collimating lens, followed by an expanding telescope in the slow axis and a focusing lens with 75-mm focal length. More details on the pump configuration can be found in Ref. [14]. A scheme of the laser cavity is shown in Fig. 1. Compared to the realization presented in Ref. [14], the resonator is extended in the cavity arm containing the SESAM to obtain a lower repetition rate. This arm also includes a Brewster plate to generate additional self-phase modulation. The beam is then focused onto a semiconductor saturable absorber mirror (SESAM) with a modulation depth of approximately 1% at 810 nm that acts as an end mirror. In the other arm of the cavity, the laser beam bounces twice on two Gires–Tournois-interferometer (GTI) mirrors with a dispersion value of −150 and −120 fs^2, respectively. This cavity arm ends with an output coupler of 3%. The pulses are then compressed by another set of dispersive mirrors giving a total dispersion of −270 fs^2 to compensate for the material dispersion of the output coupler and of a subsequent lens that collimates the slightly diverging beam. A small fraction of the output power is reflected by a beam sampler for diagnostics.

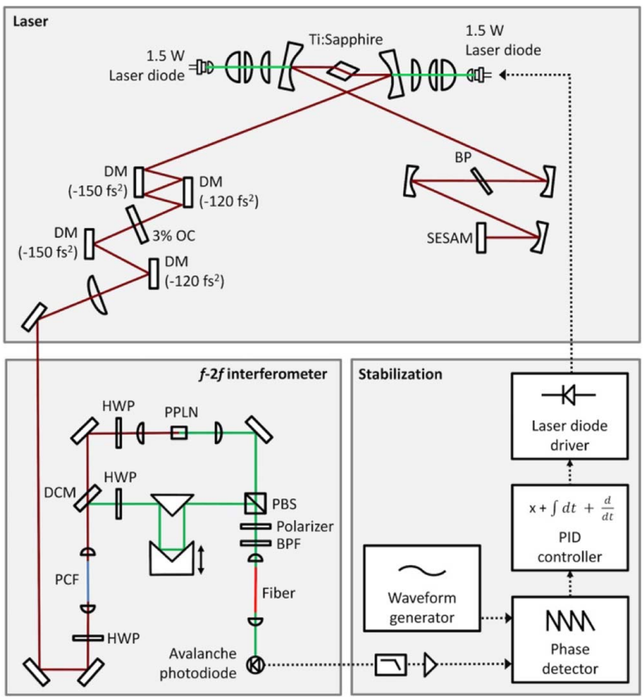

Fig. 1. Diagram of the complete setup (OC, output coupler; DM, dispersive mirror; BP, Brewster plate; HWP, half wave plate; PCF, photonic crystal fiber; PPLN, periodically-poled lithium niobate crystal; PBS, polarizing beam splitter; BPF, band pass filter; DCM, dichroic mirror).

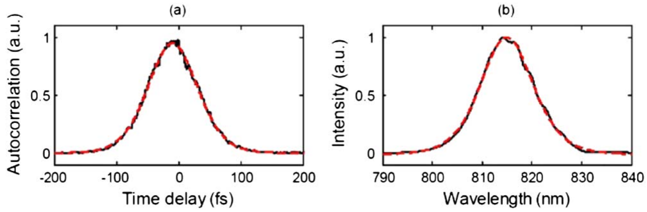

Fig. 2. (a) Autocorrelation trace of the pulse train (solid, black) with a fit by a sech^2-pulse (dashed, red). (b) Optical spectrum measured at a resolution bandwidth (RBW) of 0.5 nm (solid, black) with a sech^2 fit (dashed, red).

The laser is SESAM-mode-locked with self-starting operation. SESAM mode-locking operation of the laser was preferred to Kerr-lens mode-locking that we also implemented previously with this laser [14] for its better long-term stability that is required for frequency comb applications. The laser emits 250 mW of average output power with 61-fs pulse duration [Fig. 2(a)] at a repetition rate of 216 MHz. The optical spectrum is centered at 815 nm with a full width at half maximum of 12 nm as shown in Fig. 2(b).

The collimated beam was sent through a half wave plate to optimize its polarization and was coupled into a polarization maintaining (PM) photonic crystal fiber (PCF) using an anti-reflection-coated aspheric lens with 4.5-mm focal length. The PCF (model NKT NL-PM-750) is 8 cm long, has 1.8-μm core diameter and a zero-dispersion wavelength of 750 nm. To prevent possible back reflections from perturbing the laser, the fiber ends were angle-cleaved at ~20°. The light exiting the PCF was collimated using another anti-reflection coated aspheric lens with a focal length of 8 mm. An octave-spanning supercontinuum spectrum was generated with significant peaks approximately 532 and 1064 nm as shown in Fig. 3(a). The supercontinuum spectrum with 70 mW of average power was launched into a standard f-to-$2f$ interferometer. A dichroic mirror at the input of the interferometer split the

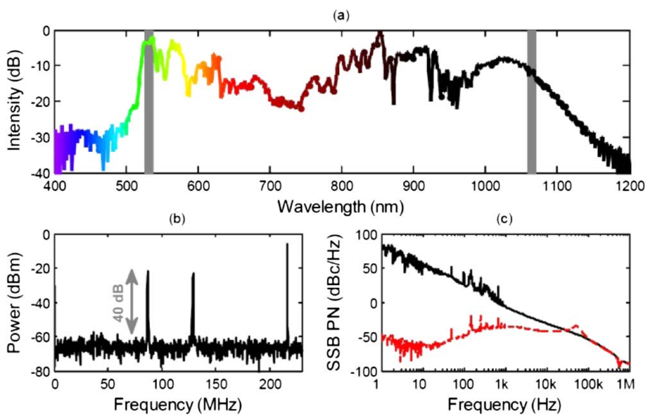

Fig. 3. (a) Octave-spanning supercontinuum spectrum obtained by launching the laser pulses into an 8-cm long PCF (RBW = 1 nm). (b) RF spectrum of the CEO beat signal with 40-dB SNR obtained at the output of an f-to-$2f$ interferometer (RBW = 100 kHz). (c) Single sideband (SSB) phase noise (PN) power spectral density of the CEO beat when free-running (solid, black) and stabilized (dashed, red).

532-nm component into one arm and the 1064-nm component into the other arm, where it was frequency-doubled in a 10-mm long MgO-doped periodically-poled lithium niobate (PPLN) crystal with a poling period of 6.90 μm (from Covesion Inc.). The two beams were then recombined in a polarizing beam combiner and passed through a polarizer to align their polarization. A 10-nm-wide spectral band centered at 532 nm was filtered, then the two beams were coupled into a single-mode fiber to enhance their spatial overlap. A beat signal was finally detected in an amplified avalanche photodetector (model APD430A from Thorlabs). The beat signal was measured at approximately 87 MHz with a signal-to-noise ratio (SNR) of 40 dB at a resolution bandwidth (RBW) of 100 kHz [Fig. 3(b)]. The output signal of the detector was low-pass filtered to extract the lowest frequency CEO beat signal, which was then amplified to a power of approximately 0 dBm. The amplified CEO beat signal was compared in a digital phase detector (model DXD200 from Menlo Systems) to a reference signal delivered by a waveform generator. The resulting phase error signal was fed into an analog proportional-integral-derivative (PID) controller (model D2-125 from Vescent Photonics) and the amplified correction signal directly controlled the pump laser driver (model 525 from Newport). The phase noise spectra of the free-running and stabilized CEO beat, measured with a phase noise analyzer (FSWP from Rohde–Schwarz), are shown in Fig. 3(c). The phase noise is reduced by up to 140 dB at 1 Hz offset frequency when the CEO frequency is locked. The servo bump observed at approximately 55 kHz corresponds to the stabilization bandwidth, which was limited by the phase shift of the pump diode driver used in this experiment.

In a separate, later performed experiment, we investigated the modulation capabilities of the 1.5-W green laser diodes. For this purpose, we developed an in-house modulation box capable of delivering an AC current with an amplitude of up to 1 A and a modulation bandwidth of at least 1 MHz. A constant current source was used in parallel with this modulator. We measured the diode-current-to-output-power modulation transfer function in amplitude and phase using a lock-in amplifier (model HF2LI from Zurich Instruments). The measured curves show a −3 d Bcutoff frequency of 4 MHz and a phase shift of −90° at 2 MHz as displayed in Fig. 4. Both the amplitude and phase responses are very flat up to at least 1 MHz. These modulation properties are sufficient to exploit the full modulation bandwidth of the Ti:sapphire gain for fast CEO control, which is typically in the range of 500 kHz to 1 MHz [16]. The implementation of such a high

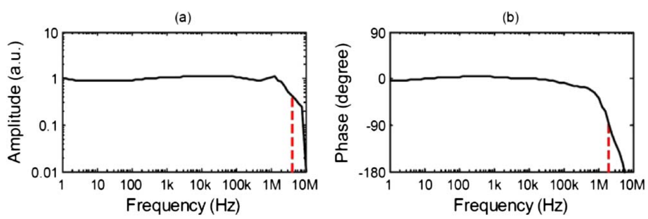

Fig. 4. Normalized current-to-output-power modulation transfer function of the green pump diode in amplitude (a) and phase (b). The respective bandwidths are 4 MHz (at −3 dB) and 2 MHz (at −90° phase shift).

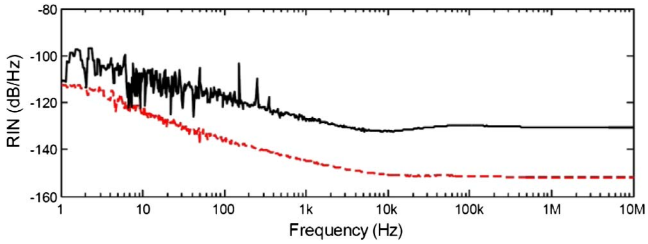

Fig. 5. Relative intensity noise of the Nichia green laser diode (solid, black) operated at 1.5 W of output power plotted along with the measurement noise floor (dashed, red).

CEO modulation bandwidth in our laser will enable a significant improvement of the CEO lock.

Moreover, we measured the relative intensity noise (RIN) of the green laser diode operated at 1.5 W of output power (Fig. 5). An RMS RIN of 0.04% was obtained from this spectrum, integrated from 1 Hz to 1 MHz. This noise level is comparable to the value of approximately 0.02% integrated from 2 Hz to 625 kHz reported for commercially-available standard Ti:sapphire pump lasers [15].

In summary, we have demonstrated the first proof-of-principle detection and stabilization of the CEO frequency of a diode-pumped Ti:sapphire laser. We achieved coherent octave-spanning supercontinuum spectrum generation. We measured a CEO beat signal with an SNR of 40 dB in 100-kHz RBW, which is sufficient for phase locking. We stabilized the CEO frequency by direct pump current modulation with a feedback bandwidth of ∼55 kHz, reaching a noise reduction of 140 dB at 1 Hz offset frequency. This stabilization scheme circumvents the need for an additional external optical modulator. We showed low noise operation of the pump diodes with an RMS RIN of 0.04%. We investigated the modulation capabilities of these green diodes, demonstrating a bandwidth of >1 MHz. This is sufficient for high bandwidth CEO stabilization that is not limited by the pump power modulation. Our results show that expensive and complex green pump sources are not necessary for the realization of Ti:sapphire optical frequency combs. Instead, diode laser pumping is a suitable solution for simple, robust, energy efficient and cost-effective Ti:sapphire frequency combs.

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