⁸⁷Rb-stabilized 375-MHz Yb:fiber femtosecond frequency comb

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Abstract: We report a fully stabilized 1030-nm Yb-fiber frequency comb operating at a pulse repetition frequency of 375 MHz. The comb spacing was referenced to a Rb-stabilized microwave synthesizer and the comb offset was stabilized by generating a super-continuum containing a coherent component at 780.2 nm which was heterodyned with a ⁸⁷Rb-stabilized external cavity diode laser to produce a radio-frequency beat used to actuate the carrier-envelope offset frequency of the Yb-fiber laser. The two-sample frequency deviation of the locked comb was 235 kHz for an averaging time of 50 seconds, and the comb remained locked for over 60 minutes with a root mean squared deviation of 236 kHz.

References and links

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1. Introduction

Femtosecond frequency combs have enabled fundamental metrology to be performed with exquisite precision, limited only by the quality of the frequency reference used to stabilize the comb, with precisions of 10^{-17}–10^{-18} being reported [1]. Many practical applications of frequency-combs only require orders of magnitude lower accuracy than this, and are in any case normally reliant on GPS-based references, which provide instabilities around 10^{-11} for convenient averaging times [2]. The extension of frequency-comb technology to a broader user base in engineering, chemistry and physics for applications like distance measurement, high-resolution spectroscopy and optical source calibration requires a new paradigm in which expensive, complex, facility-based but highly accurate systems are augmented by small, robust and portable combs with modest accuracy but exceptional long-term reliability and low environmental sensitivity. Yb-based fiber lasers are promising candidates as the basis of such combs [3], because they offer efficient, broadband operation from a directly diode-pumped system. Previously reported femtosecond Yb-fiber combs [3, 4] relied on amplifying the Yb-fiber oscillator to >1 W to provide pulses of sufficient peak power to obtain the octave-spanning super-continuum needed for f-to-2f carrier-envelope offset stabilization [5, 6], a problem which becomes increasingly acute at higher repetition frequencies [4]. While modelocked Yb:fiber lasers are available at repetition frequencies approaching 1 GHz [7], achieving pulses with the sufficiently short durations and high peak powers needed to generate a coherent octave-spanning spectrum becomes very difficult; conversely, the power per comb mode increases with higher repetition rates, implying that an approach based on a linear stabilization technique should be favorable. Heterodyne beats between stabilized CW lasers and adjacent comb teeth have previously been used to lock the offset frequency of Ti:sapphire combs using a 1064-nm iodine-referenced Nd:YAG laser [8], a 822-nm cesium-referenced external cavity diode laser (ECDL) [9], a 3.39-µm methane-referenced HeNe laser [10] and a 698-nm cavity-stabilized ECDL [11]. Similar techniques were used to stabilize Er:fiber combs to a 780-nm Rb-referenced ECDL [12] and to two Rb resonances based on electromagnetically induced transparency absorption and two-photon absorption [13].

In this paper we describe an approach based on an unamplified high-average-power 375-MHz Yb:fiber femtosecond oscillator operating in the net normal dispersion regime [14]. As an alternative to f-to-2f self-referencing we employ an absolute optical frequency reference based on a crossover resonance in ^{87}Rb which is used to stabilize a 780.2-nm ECDL.

2. Experimental configuration

The Yb-fiber laser (Fig. 1.), similar in design to that described in [14], produced chirped 750-fs pulses directly from the cavity which were dechirped after multiple reflections on a pair of Gires-Tournois interferometer (GTI) mirrors to 110-fs durations. Control of the repetition frequency, f_{REP}, proceeded by sampling the pulses after the GTI mirrors using a glass wedge and a fast photodetector. After passing through a 500-MHz low-pass filter the signal was mixed with a 375-MHz reference from a microwave synthesizer to give an error signal which was amplified and applied to a piezo-electric actuator (PZT) to tune the length of the laser

cavity. With the synthesizer locked to a Rb-stabilized 10-MHz quartz oscillator the two-sample frequency deviation of f_{REP} was measured to be 5.8 mHz with a 50-s averaging time.
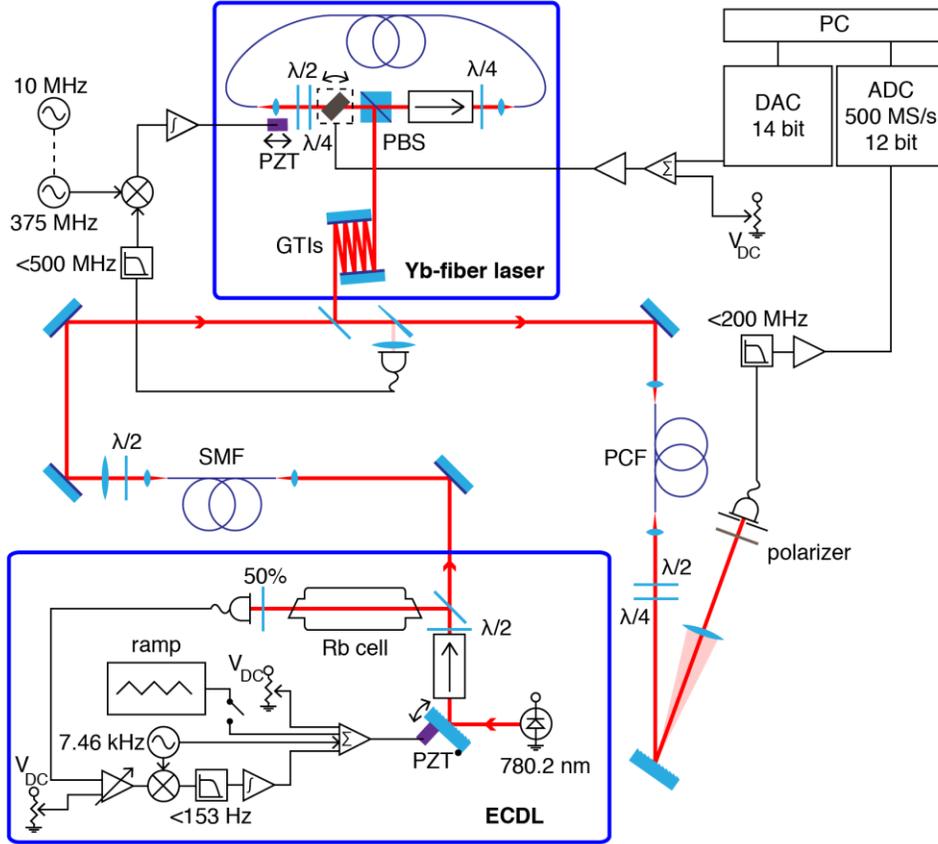
Fig. 1. Configurations of the Yb:fiber laser and Rb-referenced ECDL (upper and lower blue boxes) and the comb stabilization scheme. PBS, polarizing beamsplitter; PC, personal computer; DAC, digital to analog converter; ADC, analog to digital convertor. For clarity, the pumping scheme for the Yb:fiber is not shown, however was the same as in [14].

The optical frequency reference used to stabilize the Yb:fiber comb offset was an ECDL dither locked at 7.46 kHz to the ^{87}Rb F = 2 → F′ = 2, 3 cross-over peak near 780.2 nm, which has an absolute frequency of 384,227,981.9 MHz [15]. Light from the Rb-stabilized ECDL was coupled into a single-mode fiber (SMF) to obtain a Gaussian mode and was then combined with the output from the Yb:fiber laser using a dichroic beamsplitter (HR 1030 nm, HT 780 nm). The resulting beam was introduced into a 1.5-m photonic crystal fiber (NKT SC-3.7-975) in which soliton and accompanying dispersive-wave generation seeded by the modelocked pulses produced a coherent 10-nm wide component around 780 nm. The spectra of the Yb:fiber laser pulses before and after the PCF appear in Fig. 2(a) and Fig. 2(b) respectively. Propagation through the PCF left the ECDL spectrum unchanged, and this is shown individually in Fig. 2(c) and together with the super-continuum in Fig. 2(d). The common 780-nm component leaving the PCF was formatted to the appropriate polarization state using quarter- and half-wave plates before entering a monochromator comprising an 1800 lines mm^{-1} diffraction grating and a plano-convex lens with a focal length of 500 mm. An avalanche photodiode (APD) situated at the focal plane of the monochromator was used to detect the heterodyne beat signal between the ECDL light and the adjacent comb modes in the

super-continuum light, indicating the offset between these comb modes and the ECDL frequency.
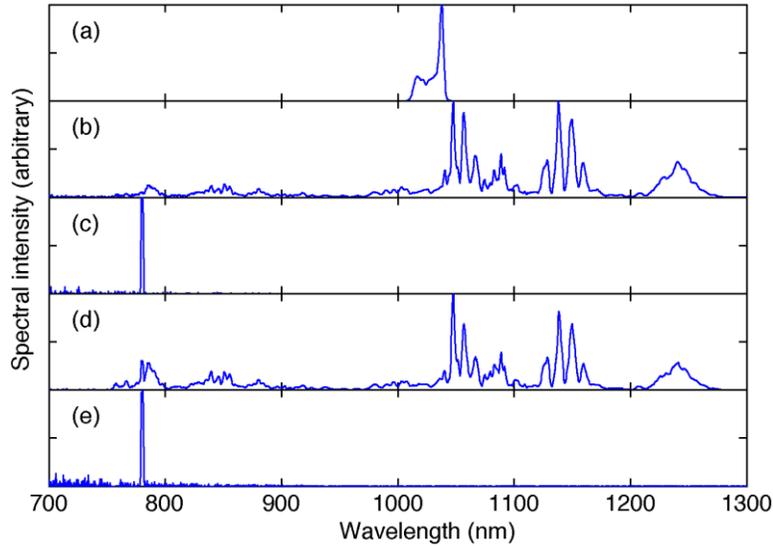
Fig. 2. (a) Yb-fiber laser spectrum; (b) super-continuum produced by the Yb:fiber laser; (c) spectrum of the Rb-locked ECDL; (d) spectrum of the ECDL and super-continuum light measured after the PCF; (e) combined ECDL and super-continuum spectra measured before the APD in the focal plane of the monochromator. All spectral intensity scales are linear.

The grating was illuminated with a beam of diameter approximately 3 mm, corresponding to a theoretical resolution of 0.14 nm, limited experimentally to 0.18 nm by the 230-µm diameter of the APD. When adjusted to obtain the highest signal-to-noise ratio (SNR), the relative powers of the ECDL and comb light immediately before the APD were 20 µW each (measured using a 200-µm diameter pinhole). These parameters imply a power per comb mode of around 100 nW and a maximum possible SNR of 23 dB, which was only slightly higher than the best SNR of 20 dB observed experimentally with a 20-MHz span and sufficient resolution bandwidth. Fig. 3 presents the radio-frequency (RF) spectrum of the APD signal on a span which shows the heterodyne beats between the ECDL and two adjacent comb modes, along with f_{REP} at 375 MHz.
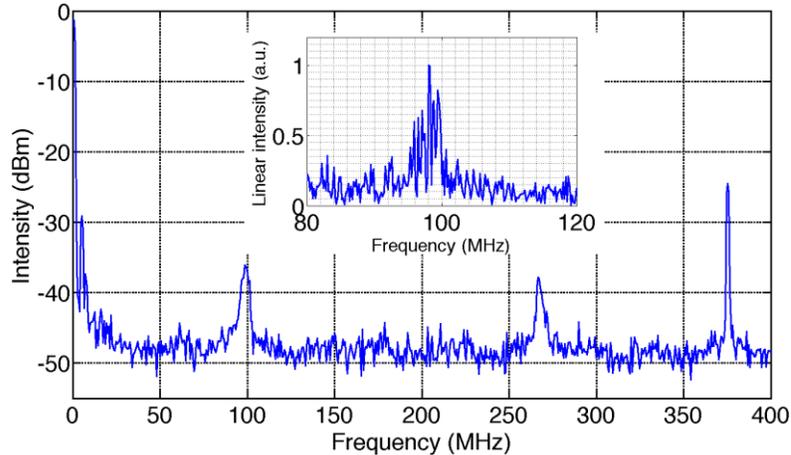
Fig. 3. RF spectrum of the heterodyne signal recorded with the repetition frequency of the Yb:fiber laser locked but without comb-offset stabilization. The signal at 375 MHz is f_{REP} and those at 99 MHz and 276 MHz are the beats between the ECDL and the adjacent Yb:fiber

Locking of the frequency comb offset was achieved by isolating the lower-frequency beat by using a 200-MHz low-pass filter, amplifying this signal then acquiring its center frequency using a 12-bit analogue-to-digital converter sampling 2048 points at 500 MS/s (a frequency resolution of 244 kHz). A software algorithm compared this value with a predefined set-point and provided an error signal through a 14-bit digital-to-analogue converter. After applying a DC offset using a summing amplifier and then subsequent amplification, this signal was used to actuate the angle of the intracavity dielectric filter within the Yb:fiber laser via a galvanometer motor. Tuning the filter angle caused the carrier-envelope offset frequency of the laser (f_{CEO}) to change at a rate of 150 MHz mrad^{-1}, providing a means of tuning f_{CEO} through several multiples of f_{REP} while maintaining modelocking, and providing a much greater tuning than pump-power modulation.

3. Results and discussion

The stability of the frequency comb offset was evaluated by counting the heterodyne beat frequency for averaging times of 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 50 seconds over a large number of samples. The calculated root-mean-squared (RMS) deviation and two-sample frequency deviation at each gate time are presented in Fig. 4, with all data acquired with f_{REP} locked but with comparative data obtained for comb-offset stabilization turned on (filled symbols) and turned off (open symbols).
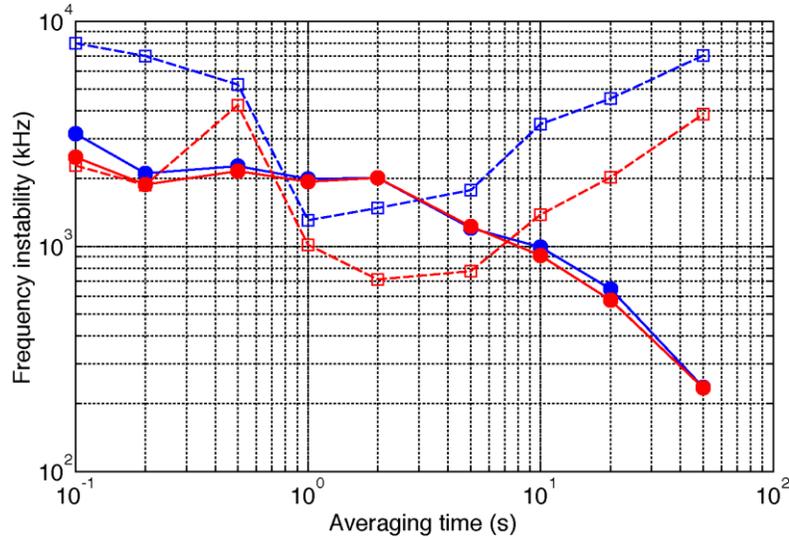
Fig. 4. The RMS deviation (blue) and two-sample frequency deviation (red) of the comb-offset beat signal for comb-offset stabilization turned on (filled symbols) and turned off (open symbols). All data were recorded while the repetition frequency of the Yb:fiber was stabilized.

The data show the expected behavior, with the locked comb-offset frequency exhibiting far better stability at longer averaging times, however below a few seconds they show poorer stability than the unlocked signal. This noise is written onto the laser by ~100-µrad-level mains-frequency excursions of the galvanometer motor used to control the offset signal, which introduce a periodic modulation of the beat signal which is most noticeable at low averaging times, over which the passive stability of the unlocked comb is better. This noise source can be eliminated by actuating the tunable filter in a different way, such as directly mounting it onto a PZT actuator.

The long-term stability of the locked comb is illustrated in Fig. 5, which presents the fluctuations in the beat frequency relative to the mean for f_{REP} locked but with comb-offset

stabilization turned on (green symbols) and turned off (blue symbols). The periodic changes in the unlocked comb offset are caused by the air-conditioning cycle in the lab. These data show that, when locked, the system holds the comb offset constant about a chosen set-point for at least 60 minutes with a RMS deviation of 236 kHz and a two-sample frequency deviation of 235 kHz, eliminating long-term environmental drifts over a considerable period of time. The fractional frequency instability at a 50-second averaging time was 6.1×10^{-10}, around an order of magnitude greater than that of the Rb-stabilized Er:fiber system presented in [12], which used a fiber amplifier to obtain a considerably stronger beat signal than in our work. Improvements including a hardware-accelerated feedback algorithm and a PZT-based actuator for the CEO frequency are expected to deliver significantly lower instabilities.
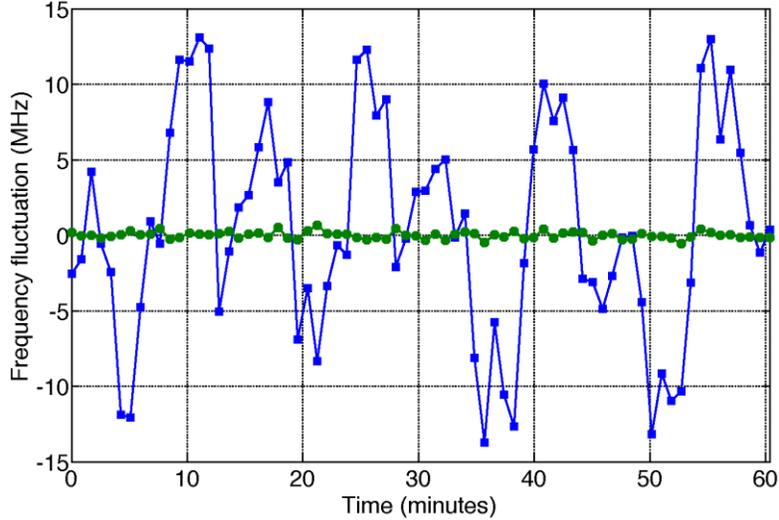
Fig. 5. Comparison of the fluctuations in the beat frequency relative to the mean with comb-offset stabilization turned on (green symbols) and turned off (blue symbols) for averaging times of 50 s over a period of 60 minutes. All data were recorded while the repetition frequency of the Yb:fiber was stabilized.

4. Conclusions

In summary, we have presented a new method for stabilizing the offset frequency of a 1030-nm Yb-fiber laser frequency comb based on a 780.2-nm optical frequency standard. The locked comb exhibited a two-sample frequency deviation of 235 kHz for an averaging time of 50 seconds, remaining locked for over 60 minutes with an RMS deviation of 236 kHz, comparable to the expected linewidth of the Rb-ECDL reference. The combination of the wide capture range of the software-based feedback loop with the considerable tunability in f_{CEO} available by actuating the intracavity filter allows the system to remain locked for long periods. Current performance of the system is limited by the ~100-Hz bandwidth of the software control loop, which will be significantly increased by adopting a hardware-based approach (e.g. a field programmable gate array). Replacing the galvanometer motor with a PZT actuator along with other environmental isolation measures are also expected to substantially improve the short-term stability of the comb.

Acknowledgment