Development and characterization of all-normal dispersion fiber laser for frequency comb generation

Çağrı Şenel[1], F. Ömer Ilday[1], Oğuzhan Kara[2], Ramiz Hamid[3], Cihangir Erdoğan[3]

[1]Department of Physics, Bilkent University, TR-06800, Ankara, Turkey
[2]Department of Physics Engineering, Hacettepe University, TR-06532, Ankara, Turkey
[3]TÜBİTAK, Ulusal Metroloji Enstitüsü (UME), PO 54, TR-41470, Gebze-Kocaeli, Turkey

Abstract: Development of an all-normal-dispersion Yb-doped fiber laser-based frequency comb is reported. Repetition-frequency stabilization to the cesium standard, amplitude and phase noise measurements indicate low-noise performance.

OCIS codes: (320.0320) Ultrafast optics; (060.3510) Lasers, fiber; (120.3940) Metrology; (140.3425) Laser stabilization; (140.3538) Lasers pulsed; (320.7090) Ultrafast Lasers; (320.6629) Supercontinuum generation

Mode-locked fiber lasers have emerged as very attractive sources for frequency metrology. Even though the best performance is usually obtained with Ti:sapphire-based combs, the superior robustness of fiber lasers and the ease that this brings for experiments have led to their wide usage in the metrology community [1]. Most of these lasers are Er-doped fiber-based, operating at 1550 nm. Meanwhile, Yb-doped fiber lasers centered at 1 μm offer higher powers and the proximity of their central wavelength to the most commonly used optical reference lines, such as I_2, Rb, Cs are among their attractive features. There are few reports on frequency combs in this wavelength range [2]. Recently developed, Yb-doped all-normal dispersion (ANDi) fiber lasers have found themselves a wide range of applications due to their simplicity, compactness and much higher pulse energies [3]. There is very strong motivation to evaluate the suitability of this new mode-locking regime for the frequency comb generation. The first work to address this issue, has reported relatively poor noise performance for ANDi-type lasers, suggesting that they may not be well-suited for this application [4]. Given the potentially very substantial advantages that ANDi lasers can offer for comb generation, this is an important claim that needs to be verified and the reasons for any poor performance should be well understood.

Here, we report on the development of a frequency comb based on an Yb-doped ANDi-type fiber laser and the characterization of its performance for metrology applications. We place particular emphasis on its long-term stability and transportability. Part of the experimental setup is shown in Fig. 1. As a first step, the repetition rate of this oscillator has been locked to a frequency synthesizer, disciplined by a Cs-atomic clock. The cavity length is controlled via a slow motorized translation stage and a fast piezo-based fiber stretcher placed within the laser cavity. The laser repetition rate is roughly set to the desired value by the motorized stage and locked to the electronic reference by fiber stretcher. The repetition rate of the laser is 108.33 MHz (12th sub-harmonic of 1.3 GHz). The oscillator produces strongly chirped pulses with 0.8 nJ energy, which can be dechirped to 127 fs. Spectrum of the laser is shown below (inset of Fig. 1(b)). The short and long-term stability of the laser is characterized by relative intensity noise (RIN), single-side band RF phase noise and Allan variance measurements. RIN of the laser is measured as 0.072% within a bandwidth from 1 Hz to 250 kHz (Fig. 1(b)). Phase noise of the laser is measured at 1.3 GHz (corresponding to 12th harmonic of the repetition rate) using a 12 GHz photodetector and a signal source analyzer (SSA). The measurement is limited by the excess noise from the photodetection process and the SSA and should be evaluated as an upper limit to the actual phase noise. RMS timing jitter is measured to be 41 fs from 1 kHz to 30 MHz. The RF spectrum of the laser shows 100-dB suppression of the sidebands, which we believe to be caused by the laser power supply (Fig. 2(a)).

Repetition-rate locking of the ANDi laser to the Cs clock is accomplished with a phase-locked loop (PLL) using a PID controller (Fig. 1(a)). The error signal for the PLL, which acts on the piezo stretcher upon amplification, is generated by mixing the reference signal with the corresponding harmonic of the photodiode output of the laser (using the harmonic at 1.3 GHz). The Cs atomic clock used in this study, located at UME, is a reference source for the UTC(UME) time scaling generation. Long-term frequency stability of the atomic clock is around $2\text{x}10^{-14}$. The 10-MHz reference signal from the Cs atomic clock at UME is up-converted to 1.3 GHz through an externally Cs-standard referenced DRO. Upon locking the laser to the Cs-generated reference signal, the long-term stability performance fiber laser is characterized using Allan deviation [5]. The 108.33 MHz electrical signal coming from the laser through an out-of-loop photodiode-lowpass filter combination is measured with a time interval and frequency counter, which is externally triggered from the Cs standard. Instead of direct frequency count, time interval measurement method is preferred for improved fidelity. To this end, 1 pps signal from the same Cs-atomic clock is supplied to the counter to implement the phase difference count method. In order to determine effects of the atomic clock and the frequency counter on the stability measurements of the laser in the final setup, the frequency stability of two similar Cs atomic clocks were measured using a short cable in the same room. During this measurement, frequency counter was operated in time interval counter mode and externally triggered with the 10 MHz reference output signal of the second similar atomic clock. 1 pps outputs of both the reference Cs atomic clock used in the laser stabilization experiment and of the other Cs atomic clock were fed to the counter to investigate their time difference through long-term Allan variance statistics. The results are given in Fig. 2(b). As expected, white noise is dominant and long-term stability is around 2x10^{-14}. This measurement method also reflects the stability of 10 MHz RF signal output of the clock.

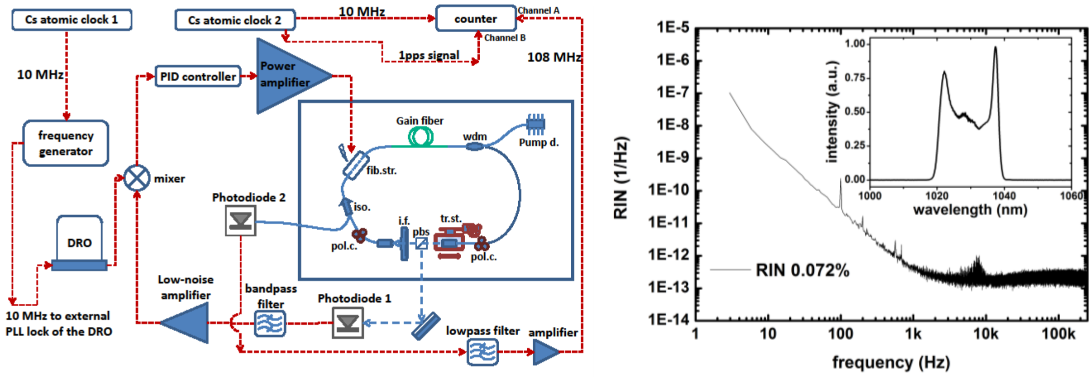

Fig. 1. (a) Overview of the experimental setup including schematic of the ANDi fiber laser and the PLL system. (b) Measured relative intensity noise (RIN) of the Yb-doped fiber laser, inset: optical spectrum of the fiber laser.

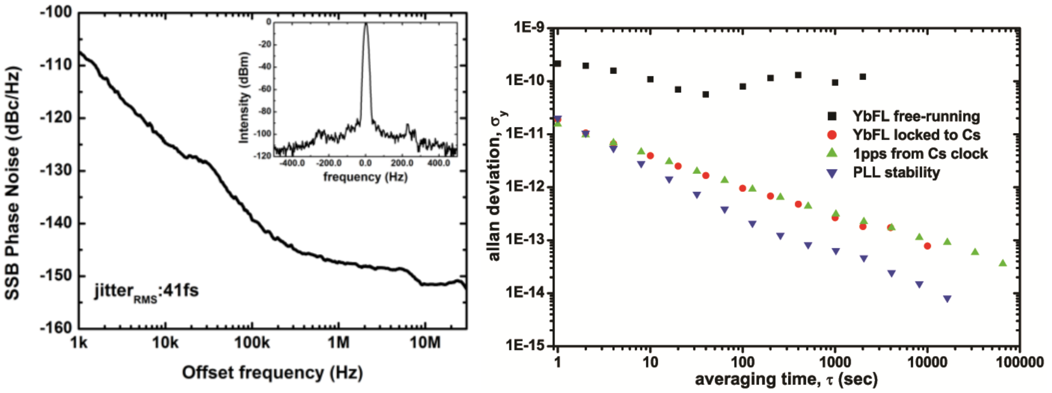

Fig. 2. (a) Single side band phase noise of the laser, inset: RF spectrum of the repetition frequency of the laser. (b) Allan deviation measurements of free-running YbFL, 1 pps signal from Cs atomic clock, Cs-locked YbFL and the PLL.

The long-term stability of the laser in both free-running and Cs-locked mode is given in Fig. 2 (b). For the free-running operation, repetition rate stability is dominated by drift noise. Stability at 1 second averaging time is about 2x10^{-10}, and oscillates between 6x10^{-11} and 2x10^{-10} due to thermal drifts. When the repetition rate of the laser is locked to the Cs atomic clock, it inherits the stability of the Cs clock and it reaches a stability of 4x10^{-14} after 65536 seconds averaging time. It can be said that stability of 2x10^{-14} can be reached after 100000 seconds averaging time, which is the long term stability of Cs clock. These measurements confirm that flicker and drift noise does not affect its stability in the long term.

In order to generate an octave-spanning frequency comb, we built a cladding-pumped Yb-doped fiber amplifier and a grating compressor to reach the necessary power for the supercontinuum generation, similar to the setup described in [5]. The amplified pulses are compressed to sub-300 fs at an average power of 2 W. The beam is coupled into 60-cm-long nonlinear photonic crystal fiber (PCF) using a 10x high-power-compatible objective and a fiber alignment stage. The PCF has zero dispersion at 1050 nm and a parabolic, normal dispersion profile around this wavelength. Resulting spectrum at the end of the PCF covers more than an octave (Fig. 3(a)). An f-2f interferometer (using second-harmonic of the components at 1400 nm in a BBO crystal and light at 700 nm) for the measurement and stabilization of f_{ceo} is currently under construction. However, the beat note measurement has not been obtained in time for this submission.

We further aim to utilize the comb system in comparisons with single-frequency lasers locked to optical references in the visible and NIR range. For these experiments, it is necessary to have a beat signal with SNR greater than 30 dB to be able to realiably measure the beat frequency using a frequency counter. In order to determine the power requirements for the octave-spanning frequency comb that we are developing, we performed a beat experiment with Nd:YAG laser at UME. A secondary goal is to provide an independent measurement of the optical phase noise of the fiber comb. A second fiber amplifier has been constructed, which allows to broaden the spectrum of the ANDi laser to cover the 1064 nm range through nonlinear spectral broadening. The amplified pulses are passed through a narrow bandpass filter at 1064 nm. The beam from the Nd:YAG laser and the ANDi laser are overlapped on a beamsplitter and the resulting heterodyne beat signal is detected by a photodetector and measured with an RF spectrum analyzer (Fig. 3(b)). Resulting beat signal has a 3-dB bandwidth smaller than 30 kHz. During this measurement, the fiber laser was not repetition-rate locked and the width of this beat signal is consistent with the measured RF phase noise of the fiber laser.

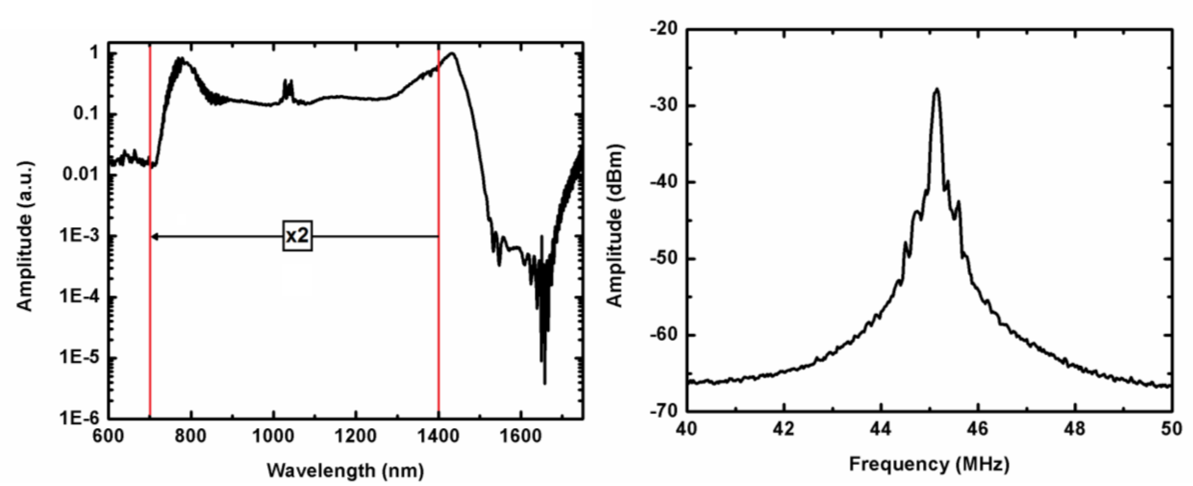

Fig. 3. (a) Spectrum recorded after supercontinuum generation. The wavelength range is limited by that of the optical spectrum analyzer. (b) RF spectrum of the heterodyne beat signal between the single-frequency Nd:YAG laser and the ANDi fiber laser.

In conclusion, an Yb-doped fiber laser operating in the all-normal dispersion regime has been constructed and repetition rate locked to a Cs atomic clock. Allan deviation measurements indicate that the laser successfully inherits the stability of the Cs reference. The short-term stability of the laser is characterized via RIN and phase noise measurements, both of which indicate performance meeting or exceeding the performance with other types of fiber lasers. The laser has been beat with a narrow-linewidth, single-frequency Nd:YAG, during which the laser was free running. Finally, an octave-spanning supercontinuum has been stably generated. Efforts are under way to characterize and stabilize the carrier-envelope offset phase. The long-term stability of the laser is excellent and surpasses the other fiber lasers we have so far tested: During the Allan deviation measurements lasting about one week, the laser has maintained mode-locked operation, as well as repetition rate lock to the Cs reference without interruption, even though it was placed on an ordinary table, without any vibration isolation.

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