500 MHz spaced Yb:fiber laser frequency comb without amplifiers

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An optical frequency comb based on Yb:ring fiber laser was demonstrated. This is the first time, to our knowledge, f_{ceo} has been generated directly from the oscillator without further amplifications above 500 MHz repetition rate. The signal-to-noise ratio of the offset frequency was above 40 dB at 300 kHz resolution bandwidth, which supports easy stabilization. The offset frequency was stabilized for more than 6 h in an open air environment without temperature control. The stabilized repetition rate has an in-loop tracking stability of $4.46 \times 10^{-13}/\tau^{1/2}$.

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Yb:fiber lasers have attracted a lot of attention due to their higher efficiency, higher power, and lower cost [1–3] than solid-state lasers to build frequency combs. Particularly, high repetition rate fiber lasers are desirable to achieve sufficiently large comb line spacing for high-precision calibration of astronomical spectrographs [4,5]. The nonlinear polarization evolution (NPE) mode-locked fiber ring lasers with large modulation depth and essentially instantaneous response support a broad spectrum for sub-50-fs pulse generations [6,7]. These lasers have become popular seed pulse sources of laser frequency combs. However, limited by the ring cavity length, high fundamental repetition rate fiber lasers are still difficult to build. Recently, a demonstration was conducted with a high- repetition rate Yb:fiber laser operating at >500 MHz with free-space coupled high pump power and fiber-pigtailed wavelength division multiplexing components [8–12]. On the other hand, all-normal dispersion (ANDi) fiber laser [13] without the intracavity grating pair can contribute to high repetition rate as well [10]. However, experiments indicated that the large net normal dispersion of the fiber laser increases the noise level and the linewidth of carrier envelop offset frequency (f_{ceo}) [14,15]. Therefore, a fiber laser with intracavity dispersion compensation is preferred.

Along with the high repletion rate operation, the low pulse energy for a given pump's power is problematic, making the subsequent spectrum broadening difficult. Because of the limited single mode fiber coupled pump power, it is also difficult to increase the pulse energy very much. In this case, one may choose either to boost the pulse energy by a fiber amplifier, or to shrink the pulse width so that the pulse peak power remains high. So far, the successful frequency expansion and the detection of f_{ceo} has occurred in the fundamental frequency spacing as high as 490 and 386 MHz Yb:fiber lasers, respectively, both with amplifiers [11,16]. However, the pulse width is difficult to compress after the fiber amplification due to the mismatched third-order dispersion of the fiber and the grating pair. The compressed pulse in those high repetition rate pulses after the amplification was ~100 fs, with obvious side lobes [11,16]. The amplified spontaneous emission (ASE) can raise noise level and reduce f_{ceo} contrast ratio. The amplifiers also make the system complicated and high cost.

In this study, we demonstrate a 500 MHz ytterbium fiber laser comb without amplifiers. An octave-spanning spectrum from 600 to 1300 nm was generated when the coupled pulse energy was above 0.2 nJ. 40 dB signal-to-noise ratio (SNR) f_{ceo} signal was detected which supports long-term stabilization.

The schematic of the 500 MHz Yb fiber laser comb is shown in Fig. 1. The structure of the 500 MHz Yb:fiber laser was the same as Ref [17]. The output power was 450 mW at 1.07 W pump power showing a 40% optical-to-optical efficiency. The output pulse was compressed by a transmission grating pair with the separation of 2 mm. The compressed pulse was 46 fs and was directly coupled to a 25 cm long tapered photonic crystal fiber [18] with 5 kW peak power (the octave-spanning spectrum was shown in Fig. 2).

The octave-spanning spectrum was split into two beams by a dichroic mirror. The group delay can be compensated for by adjusting the optical distance of

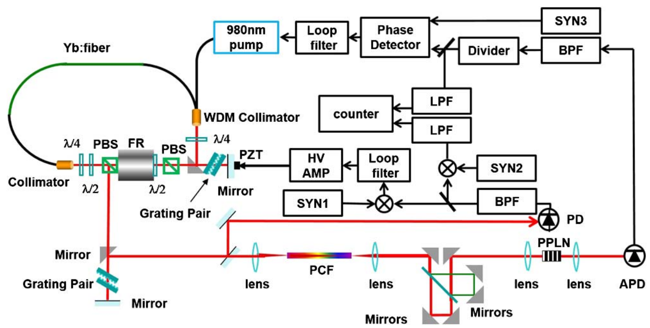

Fig. 1. Schematic of 500 MHz frequency comb based on Yb ring fiber laser (PBS, polarization beam splitter; FR, Faraday rotator; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; YDF, Yb-doped fiber; PCF, photonic crystal fiber; BPF, band pass filter; PD, photonic detector; APD, avalanche photonic detector; SYN, synthesizer; LPF, low pass filter).

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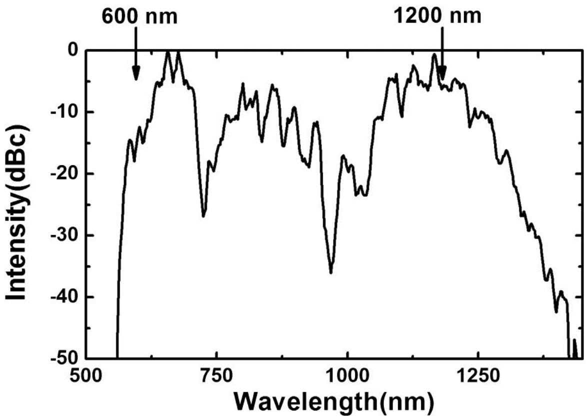

Fig. 2. Octave-spanning spectrum generation.

the short wavelength parts and the long wavelength ones. A $5 \times 7 \times 0.5$ mm fan-out PPLN was used to double the frequency of 1200 nm comb lines. The combined beam was focused on an Si avalanche photonic detector with a 10 nm band pass filter for f_{ceo} detection.

The f_{ceo} beat signals were measured to be 40 dB [with the resolution bandwidth (RBW) = 300 kHz] as shown in Fig. 3, which supports long-term electronic locking. The line width of the f_{ceo} signal was minimized by adjusting the net cavity dispersion to 220 kHz with Lorentzian fits (shown as the inset in Fig. 3), when the fiber laser operated at zero net cavity dispersion.

The schematic for the electronic locking system of repetition rate and offset frequency signals can be found in the right upper part of Fig. 1. To stabilize the repetition rate, the phase of the second-order harmonic was compared with the 1 GHz signal of a synthesizer (SYN1). The error signals were received by a loop filter, and then were fed back to the piezoelectric transducer (PZT) mounted with a retro-reflector in the laser cavity to adjust the cavity length. To measure the repetition rate stability, the second part of the signal detected by the photodetector (PD) was decreased to 1 kHz with a synthesizer (SYN2). The 1 kHz signal was counted with a unique counter at 1 s gates time. All the synthesizers and counter were referenced to a 10 MHz Rb clock, the stability of the Rb clock was greater than 1×10^{-12}/s.

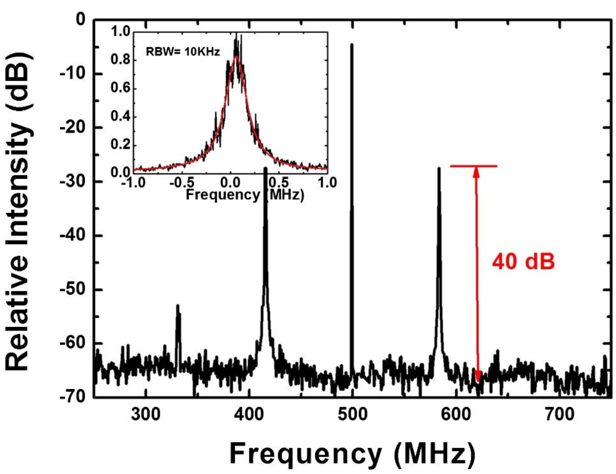

Fig. 3. 40 dB SNR f_{ceo} beat signal, the inset: 220 kHz linewidth f_{ceo} signal with Lorentzian fits at 10 kHz resolution bandwidth.

The measured frequency fluctuation of the 1 kHz signal is shown in Fig. 4(a). The standard deviation of the frequency offset was 0.5 mHz, corresponding to a relative instability of 4.46×10^{-13}. The calculated Allan deviation, shown in Fig. 4(b), indicates a tracking stability of $4.46 \times 10^{-13}/\tau^{1/2}$ for the integration time of less than 1000 s. All data was taken with an Rb clock as a reference source, which gives the Allan deviation of about 1×10^{-12}/s.

The offset frequency f_{ceo} was set to 40 MHz. The 40 MHz signal was filtered by a band pass filter, then divided to 1.25 MHz. The frequency of the reference signal from SYN3 was also adjusted to be 1.25 MHz. The phase of these two signals was detected by a digital phase detector. The phase signal was fed back to stabilize the offset signal by adjusting the pumping current of the ytterbium fiber laser. The stability of the offset signals was calculated from the 1.25 MHz signals wand that was separated into two parts. One was injected into the counter. The fluctuation of the signal with 1000 s integration time was 0.7 mHz, as shown in Fig. 5. The instability of the optical frequency combs contributed by the offset frequency was 7.4×10^{-17}/s. Therefore the frequency combs are primarily responsible for the instability of the repetition rate. Limited by our stabilization technique, no linewidth narrowing of the offset signal was obviously observed after the stabilization.

The phase noise power spectral density (PSD) of the second harmonic repetition rate signals was measured and is shown in Fig. 6. The blue line identified the phase noise PSD of the Rb Clock, which had a low frequency noise of −43 dBc at 1 Hz. The phase noise of the f_{rep}

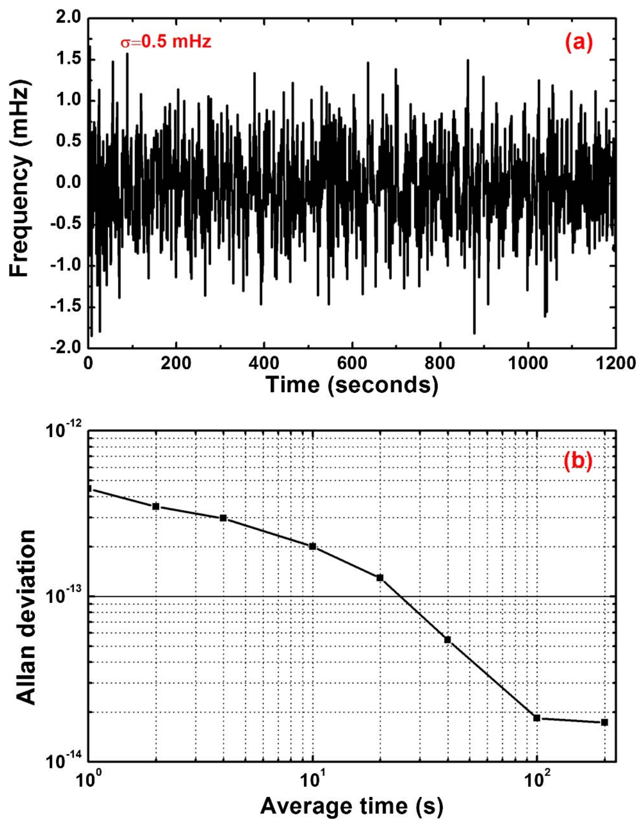

Fig. 4. (a) Residual fluctuations of the second harmonic of the repetition rate and (b) the Allan deviation calculated by data shown in (a).

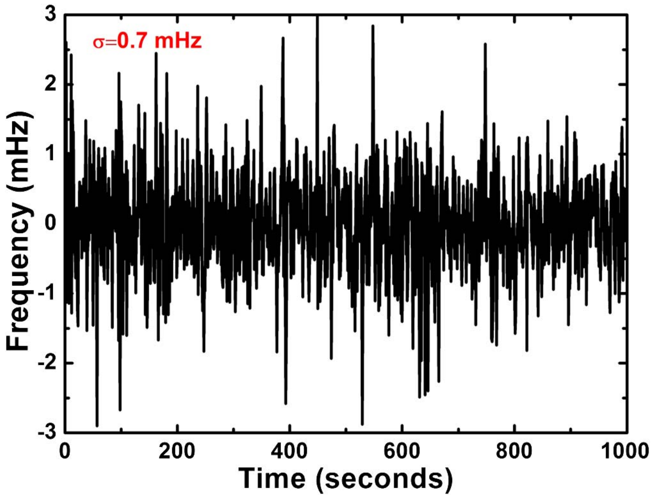

Fig. 5. Residual fluctuations of the offset frequency.

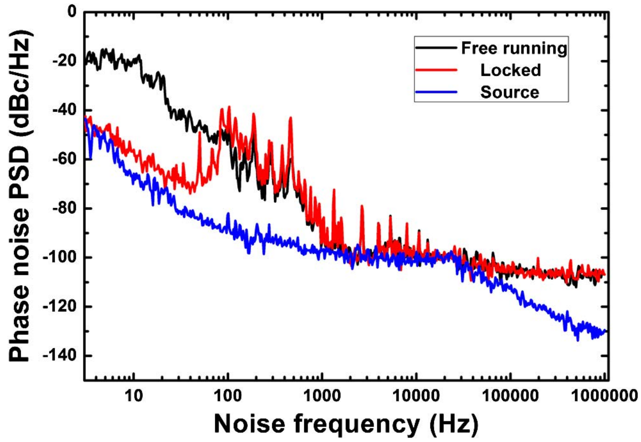

Fig. 6. Phase noise PSD of the second-order harmonic repetition rate (free running, after stabilization) and the Rb clock.

signals before stabilization was −20 dBc at 1 Hz, as shown by the black line in Fig. 6 The red line shows their PSD after the stabilization. We can see that the phase noise below 80 Hz was mostly compensated, limited by the speed of our PZT. The high-frequency noise will be compensated for in the future by using an EOM in the laser cavity.

There two key points that lead to the direct detection of f_{ceo} beat signal: direct short pulse output from the laser and the high nonlinear fiber. The direct short pulse (<50 fs) ensures the coherence crossing octave-spanning spectrum, and the tapered photonic crystal fiber expands the spectrum at sub-100-pJ pulse energy so that the pulse does not need to be amplified before it enters the tapered photonic crystal fiber. Removing the amplifier stage avoids a lot of ASE noise in the fiber amplifier so that the direct detection of the f_{ceo} beat signal can be possible.

In summary, we demonstrated an optical frequency comb based on 500 MHz ytterbium ring cavity fiber laser. This is the first time to our knowledge f_{ceo} was generated directly from the oscillator without further amplifications above the 500 MHz repetition rate. The SNR of the offset frequency was above 40 dB at 300 kHz RBW, which supports easy stabilization. The offset frequency was stabilized more than 6 h in an open air environment without temperature control. The stabilized repetition rate has an in-loop tracking stability of $4.46 \times 10^{-13}/\tau^{1/2}$. Such stability can support the frequency comb used in any frequency source. The characterization of the EOM stabilized comb will be reported elsewhere in the future.

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