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Fundamentally Mode-locked 3 GHz Femtosecond Erbium Fiber Laser

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Abstract: Low jitter 500-fs pulse trains at a fundamental repetition rate of 3.2 GHz, from an Er-fiber laser with a saturable Bragg reflector. An increase in repetition rate of femtosecond fiber-lasers by one order of magnitude.

1. Introduction

Femtosecond sources with multi-gigahertz repetition rates at optical communications wavelengths are the critical building blocks for numerous applications such as femtosecond laser frequency comb generation for frequency metrology, optical arbitrary waveform generation, high speed optical sampling, and the calibration of astrophysical spectrographs [1,2]. Currently, only a few approaches [3,4] meet the stringent requirements in terms of pulse duration, repetition rate, operating wavelength, and noise performance simultaneously. However, these current approaches are bulky, expensive and of limited robustness, since they employ external Fabry-Perot filters locked to the mode comb for multiplying the repetition rate to the multi-gigahertz range, either inside or outside of the low fundamental-repetition-rate laser cavities. A more simple, compact, robust and cost efficient approach is desirable. Lasers with fundamental repetition rates in the multi-gigahertz range are ideal candidates for some of the intended applications.

With the constraints of achieving femtosecond pulse duration, and low timing jitter, passive mode-locking is the only path to reach multi-gigahertz fundamental repetition rate. Record high repetition rates of a few hundred MHz have been reported in previous attempts [3,5] using polarization additive pulse mode-locking (P-APM). Also passively mode-locked fiber lasers using saturable Bragg reflectors (SBRs) with up to 2 GHz repetition rate, with setups very similar to the one presented here, have been reported, however, those attempts failed to produce femtosecond pulses [6], which is of key importance for low jitter and for frequency metrology applications.

In this paper, we demonstrate, for the first time, a fundamentally mode-locked femtosecond erbium-doped fiber laser (EDFL) with a repetition rate of 3.2 GHz and a timing jitter of 48 fs [1kHz-10MHz]. This result exceeds previous attempts to increase the repetition rate of fiber lasers by about ten fold, and sets a clear pathway to achieving low timing jitter, mode-locked femtosecond sources at 1550 nm with up to ten GHz of repetition rate.

2. Design considerations

Since the cavity length of a multi-gigahertz repetition rate laser is only several centimetres, the P-APM mechanism is too weak; mode-locking by a SBR is however possible. SBR mode-locking only results in femtosecond pulses when soliton pulse shaping [7], governed by Eq. (1), can be employed. The average power and, therefore, pulse energy is limited by the available pump power and doping concentration of the gain fiber. In order to generate the shortest pulse duration τ with limited pulse energy W , the cavity dispersion D needs to be minimized and the cavity nonlinearity δ needs to be maximized. Note, that D needs to be kept negative for soliton formation.

$$W = \frac{4|D|}{\delta \cdot \tau} \quad (1)$$

Fortunately, unlike traditional fiber lasers, dispersion of the fiber section no longer dominates the total cavity dispersion for multi-gigahertz lasers. Other components such as the SBR play important roles for dispersion compensation. It is also critical to keep the finesse of the laser cavity high to increase pulse energy.

3. Experimental Setup

The experimental setup is shown in Fig. 1 (a). Guided by simulation based on the above considerations, we choose a 3 cm-long highly doped erbium-ytterbium fiber (NP Photonics) with a group-velocity dispersion (GVD) of $-60 \text{ fs}^2/\text{mm}$ and a nonlinear coefficient of $\sim 3 \text{ W}^{-1}\text{km}^{-1}$ as the gain medium. One end of the gain fiber is butt-coupled to an SBR, and the other to a 2% dielectric output coupler. We carefully choose the SBR so that the dispersion of the SBR is slightly positive with 1000 fs^2 to compensate about half of the negative dispersion from the gain fiber. The SBR also has a 6% modulation depth, a 2 ps recovery time, and a saturation fluence of $25 \text{ }\mu\text{J}/\text{cm}^2$. Pump light is provided by two polarization combined 500 mW 980-nm-laser diodes, free-space coupled

via an aspherical lens into the gain fiber through the output coupler. The output signal is separated from the pump light by a dichroic mirror.

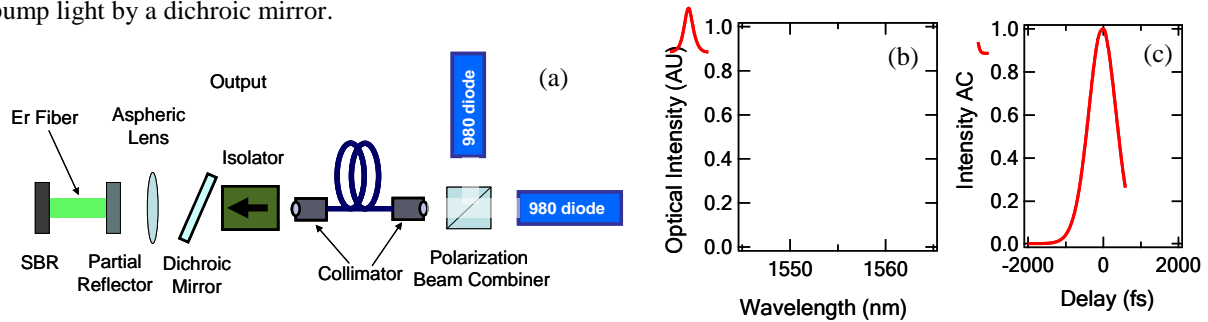


Fig. 1. (a) Experimental setup. (b) Optical spectrum of the pulse train. (c) Intensity autocorrelation measurement

The setup is simple, compact, and self-starting. This laser can be made reliable in a turn-key configuration. When the laser is pumped with ~ 700 mW of 980 nm pump power the mode-locked optical spectrum is 5.3 nm wide shown in Fig. 1(b). Fig. 1 (c) shows the intensity autocorrelation of the pulse train after amplification by an erbium-doped fiber amplifier resulting in a pulse duration of 600 fs, which was limited by dispersion compensation of the amplifier. Further compression to its transform-limited pulse duration of 500 fs is in progress. The average output power from the laser cavity is 2 mW and was used to seed a subsequent erbium doped fiber amplifier for applications demanding higher average power. The intracavity average power is calculated to be 100 mW yielding a pulse energy of 33 pJ. These numbers agree relatively well with soliton theory and our simulations.

Figure 2(a) shows the measured RF signal using a 10 GHz photodetector. Figure 2(b) shows one of the RF comb lines with a 3 kHz resolution bandwidth indicating clean mode-locked operation with a noise suppression better than 55 dB. Since the timing jitter is the critical characteristic for many applications, measurements of the timing jitter were carried out using an HP5052a signal source analyzer. Figure 2 (c) shows the single sideband phase noise measurement and the timing jitter progressively integrated from 10 MHz down to 1 kHz. The timing jitter integrated from 1 kHz to 100 MHz is 48 fs.

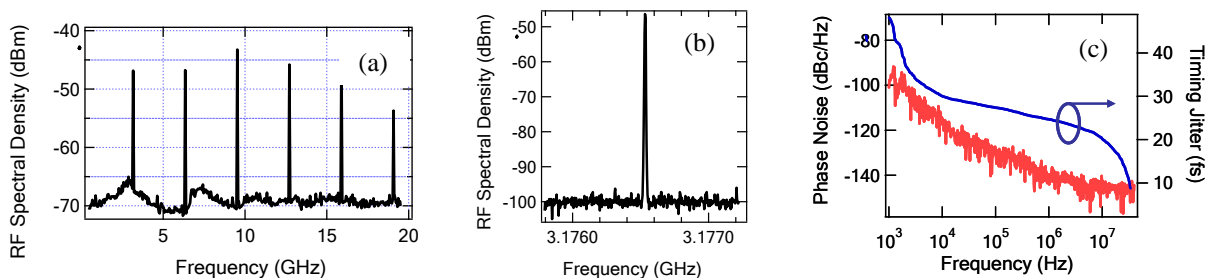


Fig. 2. (a) RF spectrum, span=20 GHz, (b) RF spectrum, span =2 MHz, RBW=3kHz, (c) Phase noise measurement, and integrated timing jitter starting from 10 MHz down to 1 kHz.

4. Conclusions

We have demonstrated the first compact, multi-gigahertz, fundamentally mode-locked EDFL producing femtosecond-duration pulses. The output pulse train exhibits a low timing jitter of 48 fs [1kHz-10MHz] as necessary for a range of applications from frequency metrology, arbitrary optical waveform generation, high speed sampling and calibration of astrophysical spectrographs. The laser design sets a clear pathway to achieve even shorter pulses and higher fundamental repetition rates beyond 10 GHz.

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