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Compact passively mode-locked fiber laser at 1.55 μm with low timing jitter of 8 fs

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ABSTRACT

Mode-locked fiber lasers with low timing jitter and high repetition rate is desired for various applications including photonics analog-to-digital conversion, microwave synthesis and high-precision clock distribution. We demonstrate a compact all fiber laser mode locked by semiconductor saturable absorber mirror with linear cavity. The laser is operating near 1.55 μm . It has a repetition rate of 250 MHz and the root-mean-square timing jitter is 8 fs integrated from 100 Hz to 1 MHz measured at the third harmonic frequency of 750 MHz.

Keywords: fiber laser, mode-locked laser, timing jitter, noise

1. INTRODUCTION

Mode-locked fiber lasers with low noise, especially timing phase noise or timing jitter, have attracted significant interest for their important applications including photonics analog-to-digital conversion (ADC) [1], microwave synthesis [2] and high-precision clock distribution [3], etc. Many different noise mechanisms have been investigated theoretically [4-5] and experimentally [6-12]. Meanwhile, high repetition rate is always desired for mode-locked lasers in these applications [13-15]. For example, mode-locked lasers with higher repetition rate can generate faster clock in photonics ADC and achieve higher sampling rate, or can allow higher operation speed in clock distribution application. Currently most reported mode-locked lasers with both low noise and high repetition rate are based on free space design. Very high specifications of these designs have been shown. However, free space design based on mechanic translation stages is more vulnerable to the mechanical vibration or other environment disturbance than an all fiber design. Therefore, we are more interested to see if we can obtain an all-fiber mode-locked laser also with low noise and high repetition rate. In this paper, we demonstrate a compact all fiber laser mode locked by semiconductor saturable absorber mirror (SESAM) with linear cavity. The laser has a repetition rate of 250 MHz and the root-mean-square timing jitter is 8 fs integrated from 100 Hz to 1 MHz measured at the third harmonic frequency of 750 MHz.

2. DESIGN OF MODE-LOCKED LASERS

2.1 Cavity design

Typically, there are two cavity designs – ring cavity and linear cavity. The first consideration is which cavity design is better for such an all-fiber mode-locked laser with high repetition rate. Fig.1 shows the structure of ring cavity and linear cavity. The ring cavity is either mode locked by fiber nonlinearity (Kerr nonlinear effect) or by material saturable absorbers such as SESAM, carbon nanotubes or graphene. The cavity contains fiber wavelength division multiplexer (WDM) to couple the pump light such as 980 nm light into the cavity, fiber isolator to guarantee the unidirectional operation, fiber output coupler to extract the power from the cavity, Erbium doped fiber (EDF) to provide the gain and polarization controller to control the polarization states. An additional fiber polarizer is needed for the mode locking based on fiber nonlinearity such as nonlinear polarization rotation (NPR), or an additional fiber circulator is needed for the mode locking based on reflection saturable absorber such as SESAM. All these fiber components have a certain length of fiber pigtails. And these fiber pigtails cannot be cut to very short length limited by the requirement of fiber splicing. Currently the highest repetition rate achieved by mode-locked fiber laser with ring cavity is ~200 MHz [16]. In comparison, a linear cavity allows much simpler design. The 980/1550 WDM can be moved outside the cavity. A

coating layer on the fiber end between the WDM and laser cavity is functioned as a transparent layer for 980 nm pump light and a partial reflection mirror (or 10% output coupler) for 1.55 μm light inside the cavity. The SESAM at the other end of the cavity is both functioned as a saturable absorber and a total reflection end mirror. Therefore, the cavity length is only limited by the length of EDF and standard single mode fiber (SMF) inside the cavity.

Figure 1. Comparison of two kinds of laser cavity (a) ring cavity and (b) linear cavity. It can be seen that ring cavity has many components inside the cavity. So its total cavity length is limited by the fiber pigtailed of all these components. In comparison, the length of linear cavity is only limited by the EDF inside the cavity. Erbium doped fiber; WDM: wavelength division multiplexer; SA: saturable absorber

The second consideration is the choice of cavity net dispersion. As we all know, different cavity dispersion leads to different operation. For example, a laser cavity with net negative dispersion usually results in soliton operation. A laser cavity with nearly zero net dispersion is related to stretched pulse operation. A cavity with net positive dispersion usually generates dissipative solitons. A few results have shown that laser cavities with nearly zero or negative dispersion can have better phase noise and lower timing jitter [12]. Therefore, such cavities are chosen for our laser cavity design.

2.2 Experiment and results

The exact design of a linear cavity for our experiment is shown in Fig.2. A 980/1550 WDM allows the 980 nm pump light to enter the laser cavity. A 976 nm diode with maximum 700 mW power is used as the pump. Dielectric coating on the fiber end forms the partial reflection mirror for the laser cavity. This partial reflection mirror reflects 90% of the 1550 nm light back into the cavity and allows 10% of the power to output. Meanwhile it is transparent to the pump wavelength at 980 nm to avoid additional loss of the pump. At the other end of the cavity, a SESAM is both functioned as saturable absorber and total reflection end mirror. The SESAM has a modulation depth of $\sim 6\%$ and non-saturable absorption of $\sim 3\%$. The SESAM chip is butt coupled on a FC/PC fiber end with epoxy glue. The coupling is ~ 0.5 dB. The back side of the SESAM is connected with a copper heat sink via thermal conductive grease to dissipate the heat generated during the laser operation. The cavity consists of ~ 10 cm highly doped EDF and ~ 30 cm standard SMF. The EDF has similar dispersion to the SMF. This leads to a total net dispersion of $8.8 \times 10^{-3} \text{ ps}^2$. Further reducing the cavity dispersion can be realized by using EDF of positive dispersion. But meanwhile, this will lead to a much higher mode-locking threshold. For our laser, the laser is self mode locked when the injected pump power is above 110 mW. In an optimum condition of 150 mW pump, the laser has a repetition rate of 250 MHz (fundamental mode locking), a 3-dB bandwidth of 11 nm, a center wavelength of 1560 nm and an output power of ~ 6 dBm. Fig.3 shows the optical spectrum and autocorrelation trace of the laser. The pulse width is ~ 1 ps. We shall notice that due to the SMF outside the laser output, the pulse width has been increased.

Figure 2. Experiment setup of the mode-locked fiber laser with linear cavity. WDM: wavelength division multiplexer; EDF: Erbium doped fiber; SESAM: semiconductor saturable absorber mirror

Figure 3. (a) Output optical spectrum and (b) autocorrelation trace of the optical pulse

2.3 Long-term frequency stability

It is known that fiber length and refractive index can be affected by various perturbations such as temperature, air flow, etc. Some analysis has been done and shows that the temperature fluctuation is the main source affecting the long term frequency stability of the mode-locked laser. The relation can be given by the following equation.

$$\frac{\Delta(nL)}{nL} \approx 10^{-5} / ^\circ C \quad (1)$$

where n is the effective refractive index and L is the physical length of fiber. So if the temperature is increased by 1 degree, the optical length of the fiber will be increased by 10^{-5} compared to the original optical length. Since the repetition frequency of a linear-cavity mode-locked laser is given by

$$f_R = \frac{c}{2nL} \quad (2)$$

where f_R is the repetition frequency and c is the speed of light in vacuum. It can be obtained that

$$\frac{\Delta f_R}{f_R} = \frac{\Delta(nL)}{nL} \approx 10^{-5} / ^\circ C \quad (3)$$

where Δf_R is the absolute drift of the repetition frequency. Fig.4 (a) shows the frequency drift in a measurement time of 10 minutes in a lab environment. The fourth harmonic frequency near 1 GHz is measured. The RF spectrum is set at “max hold” mode which means only the maximum values during the measurement time are displayed and recorded. So the width of the flat top of this figure tells the maximum drift of the frequency. It can be seen that this drift is ~2.5 kHz, corresponding to a relative frequency drift of $\Delta f/f=2.5e-6$. Then we seal the whole laser in a foam box to isolate the temperature drift and do the same measurement for 10 minutes. The result is shown in Fig.4 (b). It can be seen that the drift of the frequency has been significantly reduced to ~250 Hz, meaning that the frequency drift has been reduced to $\Delta f/f=2.5e-7$. One can also find some small frequency peaks in the figure. They are obtained when we knock the table during the measurement. These means vibration can also lead to some fluctuation of the frequency. The small amplitudes of these peaks indicate that these frequency fluctuations are very fast because they disappear before the RF spectrum can fully measure their power. This result also indicates that vibration induced frequency fluctuation cannot be well isolated by the foam box itself. Other protection such as sponge is needed.

Figure 4. Long term frequency stability measured in 10 minutes when the laser cavity is (a) put directly in a lab environment and (b) sealed in a foam box. The RF spectrum analyzer is set at “max hold” mode to only display the maximum value at each frequency. The small peaks in (b) is obtained by knocking the table during the measurement.

2.4 Phase noise and timing jitter

Different from the long term stability, phase noise and timing jitter describe the short term stability of the mode-locked laser. The measurement is done by using a photodetector to convert the optical signal to electrical signal and then feeding the signal to a signal source analyzer (SSA, R&S FSUP26). The SSA has a noise floor around -150 dBc/Hz at 1 MHz offset frequency. Fig.5 shows the measurement result of the phase noise at the third harmonic frequency of 750 MHz. The phase noise spectrum is -115 dBc/Hz at 100 Hz and -145 dBc/Hz at 1 kHz offset frequency. The integrated timing jitter from 100 Hz to 1 MHz is ~8 fs.

Figure 5. Phase noise spectrum of the mode-locked laser measured at third harmonic frequency of 750 MHz. The integrated timing jitter from 100 Hz to 1 MHz is ~ 8 fs.

3. CONCLUSION

In conclusion, we demonstrate a fiber laser with linear cavity and passively mode locked by SESAM at 1560 nm. The laser has a repetition rate of 250 MHz, a 3-dB bandwidth of 11 nm and an output power of ~ 6 dBm. The rms timing jitter of the laser is ~ 8 fs integrated from 100 Hz to 1 MHz measured at the third harmonic of 750 MHz.

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