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Robust 700 MHz mode-locked Yb:fiber laser with a biased nonlinear amplifying loop mirror

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Abstract: We demonstrate a self-starting 700 MHz repetition rate Yb:fiber laser incorporated with a phase biased nonlinear amplifying loop mirror as an artificial saturable absorber. The laser delivers a maximum power of 150 mW and a pulse width of 215 fs at a pump power of 710 mW. The integration of relative intensity noise (RIN) between 10 Hz and 10 MHz results in a minimum integrated RIN of 0.015%. The phase noise of the fundamental repetition rate was also characterized at different net-cavity dispersion. Although the laser is made of nonpolarization maintaining fiber, the mode locking sustains over two weeks in open air, showing its environmental stability.

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1. Introduction

High repetition rate femtosecond lasers have a larger mode spacing which permits the manipulation of each individual mode at high power. This characteristics make the high repetition rate fiber lasers and combs to have broad applications such as astronomical spectrum calibration, pulse stacking, high efficient micro-machining, optical metrology and high-resolution spectroscopy [1-4]. Mode locked GHz femtosecond lasers have been realized in solid-state [5], semiconductor [6] and fiber lasers [7]. Due to the short direct output pulses, compactness, low-cost, stability and maintenance-free, fiber-based lasers are more favorable.

However, nonlinear polarization evolution (NPE) based GHz fiber laser is somewhat sensitive to the environment variations such as temperature, pressure and vibrations [8]. Once the mode locking stops, the realignment and restarting may not recover the previous pulse status, which limits their suitability for industrial applications. On the other hand, linear cavity fiber laser by all polarization maintaining (PM) can achieve the gigahertz level fundamental repetition rate, because of the external fiber-tailed wavelength division multiplexer (WDM) [9,10]. However they must use saturable absorber to start mode locking which limits the pulse width and the output power. Therefore, more robust mode locking technologies are desirable for high repetition rate femtosecond fiber lasers.

The fiber laser based on the nonlinear amplifying loop mirror (NALM) [11] is a promising candidate for robust fiber lasers with intrinsic low noise [12-15], and it was found that the phase bias can help the mode locking self-starting [16-18]. Hansel et al. reported a NALM mode locked all-PM-fiber based 250MHz repetition rate Er:fiber laser. The average power is 3 mW [19]. However, it is difficult to make the cavity further shorter so that the laser can work at high repetition rates, because of the physical size of the available optical components such as the WDM and the availability of the highly doped PM fiber

In this paper, we demonstrate a 700 MHz mode locked fiber laser with the phase biased NALM with our integrated WDM-collimator and non PM gain fiber. To the best of our knowledge, this is the highest repetition rate in a NALM mode-locked Yb:fiber laser.

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Although the fiber is non PM, the mode locking is self-starting and robust. The laser has two output ports delivered output power of 150 mW and 52 mW respectively at a pump power of 710 mW. The pulse width of the direct output is 215 fs. The relative intensity noise and phase noise were also characterized.

2. Experiment configuration

The first key component is the short gain fiber for building up a short cavity. Because the highly doped PM fiber is not commercially available, we have to use the non-PM fiber (single-mode Yb:fiber CorActive Yb550). The total fiber length we can adopt into the cavity is 90mm and no non-gain fiber was used in the cavity.

The next key component is the WDM-collimator as we have used in the NPE mode locked fiber laser [8]. For achieving enough gain, both ends of the fiber are capped with WDM-collimators for pump. A set of polarization-combined 976 nm laser diodes with 1.06W max average power was spiced to WDM-collimator1.

The schematic of the experimental setup is shown in Fig. 1. To make a loop mirror, the fiber has to be revolved and the radius of curvature in for this fiber length is 22 mm. Such a small curvature radius introduces a loss of 0.39 dB, but it makes the fiber more like the polarization maintaining fiber. To confirm this, we measured the degree of polarization by incidence of a linearly polarized beam into such a fiber and measured the transmission light intensity through a PBS. The result shows that the degree of polarization maintains nearly 99% in such a 90 mm long single mode fiber. Slightly shaking the fiber results in < 3% of polarization degradation. Therefore we believe that such a bent SM fiber can act as the PM fiber.

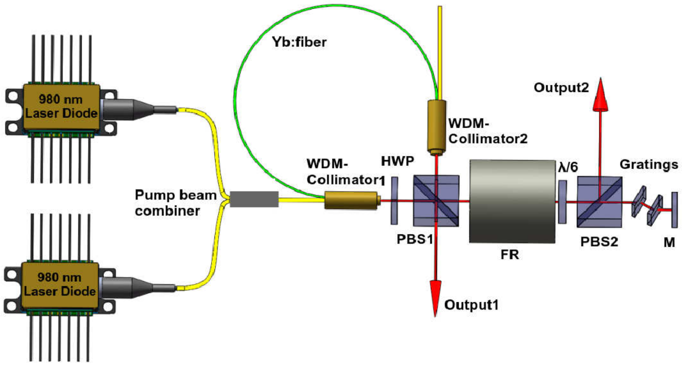

Fig. 1. Schematic of the laser; PBS, polarization beam splitter;FR, Faraday rotator; HWP, half-wave plate; M, mirror; WDM-collimator, combined collimator andwavelength division multiplexer.

A half-waveplate was mounted in between the WDM-collimator1 and polarization beam splitter (PBS1) is used to adjusted the polarization of counter-propagated pulses. The combination of a 1/6 waveplate and the Faraday rotator serves the non-reciprocal phase bias of 2π/3 in round-trip. A transmission grating pair with the groove density of 1000 lines/mm offers the intra-cavity dispersion compensation. The laser have two ports for output: PBS1 and PBS2 as shown in Fig. 1.

The two counter propagating and crossly polarized beams from the loop combine into one in PBS1, and acquired a non-reciprocal phase shift between the two polarizations by passing the Faraday rotator and the 1/6 waveplate. Then the two orthogonal polarizations of the combined beam are projected on both *p* and *s* directions of the PBS2. The coherent interference between the two combined beams allows the pulses with a larger nonlinear phase difference to transmit the PBS2 and otherwise to be rejected from the PBS2. This process forms the pulse discrimination mechanism, or an artificial "saturable absorber".

3. Experiment results and discussions

The laser started to mode lock at the pump power of 1.06W from WDM-collimator1. Slightly rotating the waveplate is necessary for the initial alignment and is never needed again. It is also necessary to eliminate the CW component in the spectrum by reducing the pump power to 710 mW after the mode locking starts. The pulse repetition rate was 700.1 MHz (Fig. 2(a)).The amount of the output power from the PBS1 and PBS2 can be adjusted by rotating the corresponding half-waveplate.

When the mode locking is stabilized at the pump power of 710 mW, the average output power was 150 mW and 52 mW from the PBS1 and PBS2 respectively. As in all mode locked lasers, the pulse spectrum is dependent on the intra-cavity dispersion. The measured spectra are shown in Fig. 2(b). The broadest pulse spectrum was observed at the grating separation of 3.1 mm corresponding to the net group velocity dispersion of ~–0.016ps^2. The spectral width of pulses was 7.8 nm from PBS1 (red curve) and 5.0 nm (black curve) from PBS2. Both fringe resolved and intensity autocorrelations were measured for both the outputs without extra-cavity dispersion compensation. The pulse width was 215 fs (Fig. 2(c)) and 325 fs (Fig. 2(d)) for the pulses from PBS1 and PBS2 respectively, with the Gaussian profile assumed. The corresponding pulse width is about 1.1 times of transform limited and near transform limited respectively. This told that the intra-cavity dispersion is almost fully compensated.

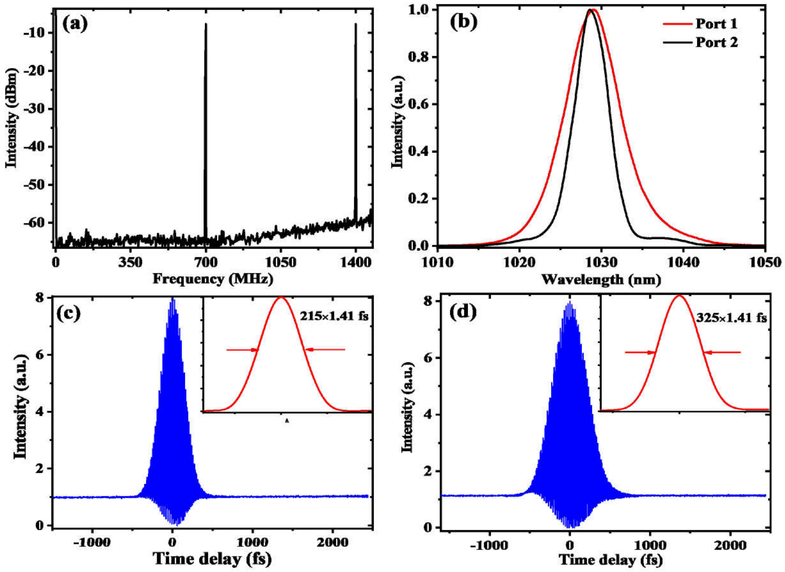

Fig. 2. (a) Radio frequency spectrum of the laser; (b) Measured spectra of the pulses output from PBS1 (red curve) and PBS2 (black curve); (c) Fringe-resolved and intensity autocorrelation (inset) trace of the direct output pulses from PBS1; (d) Fringe-resolved and intensity autocorrelation (inset) trace of the direct output pulses from PBS2.

Because the laser can be pumped through both WDM-collimators, the way of pumping on the mode locking starting should be examined. When the laser was simultaneously pumped from both WDM-collimators, the mode locking was extremely difficult to start. However, when the laser was pumped through the collimator1, the mode locking was self-starting readily. It can be understood from the fact that for such a short fiber cavity, the pulse running clockwisely experienced a higher gain than does the counter-propagated pulse, so that the nonlinear phase shift became pronounced. This is a further evidence of the mode locking mechanism of nonlinear loop mirror.

The mode locking is extremely robust although the fiber is not polarization maintaining. Gently shaking the fiber does not stop the mode locking but just slightly varies the output power (<3%). It is understandable that the mode locking is the result of interference rather than the polarization rotation, and the slight twist of short fiber does not change the polarization as much as half π.

We monitored the average power in open air at room temperature to check the power stability. The power fluctuation was approximately 0.48% root mean square (RMS) when the laser was continuously running over two weeks without observing of the break of the mode locking (which would result in a dramatic decrease in the output power), as shown in Fig. 3(a).

With a carboard box to isolate the air-current, the power fluctuations became much smaller, as shown in Fig. 3(b).The stability of the fiber laser is benefited from the short fiber, which is less prone to be affected by environment perturbations. The power fluctuations should be further reduced by power regulation feedback loop and with a better isolation.

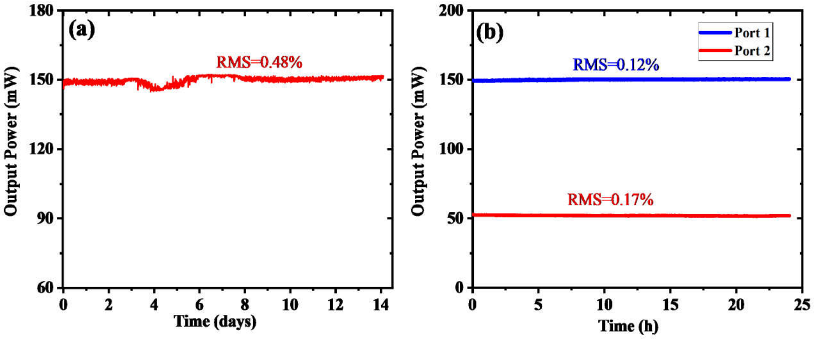

Fig. 3. Power stability of output laser: (a) averagepower of the output1of the laser over 14 days in the open air; (b)average power of the output1 (blue curve) and output2 (red curve) of the laser over 24 hours covered by a box.

It is also important to know the noise characteristics of such a laser. Both the relative intensity noise (RIN) and phase noise traces of two output ports of the laser at free running were measured. The RIN of the two output ports is shown in Fig. 4. The relative intensity fluctuation, indicated by the square root of the integral of the power spectral density (PSD) from 10 MHz to 10 Hz, is approximately 0.015% at PBS1 and 0.016% at PBS2, which is lower than the one of the laser in linear cavity based on SESAM mode locking [10]. We measured relative intensity noise of the 750 MHz fiber laser [20] based on NPE mode locking with the same detector. The RIN trace was also plotted in Fig. 4 (purple curve), the integration of RIN between 10 Hz and 10 MHz results in an integrated RIN of 0.016%, which is similar to ones of the 700 MHz NALM fiber laser.

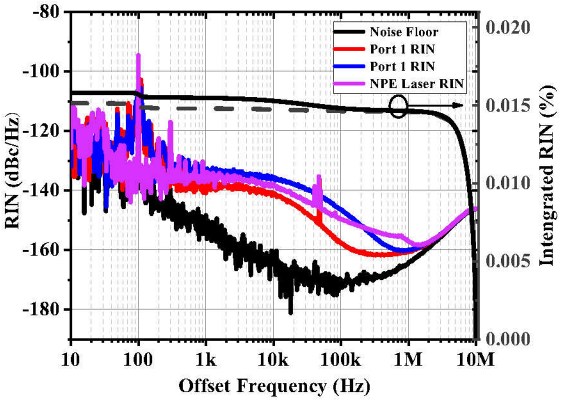

Fig. 4. Relative intensity noise (RIN) traces of noise floor (black curve), port 1 (red curve),port 2 (blue curve) and 750 MHz NPE laser (purple curve); Axis on the right: integrated relative intensity fluctuation of port 1 (dashed curve) and port 2 (solid curve).

The phase noise spectra of the two output ports with −0.016 ps^2 net cavity dispersion are shown in Fig. 5(a). The superimposed is the one of the 750 MHz fiber laser [20] based on NPE mode locking, the 750 MHz fiber laser worked at the similar net cavity dispersion and was pumped by two laser diodes, which is used to pump 700 MHz NALM laser. The output power of the NPE laser is 320 mW at a pump power of 2.1 W. The values of phase noises from the two ports are nearly the same. They gradually decrease from −30 dBc/Hz to −151 dBc/Hz for the offset frequency from 10 Hz to 10 MHz. In contrast, in the frequency range from 1 kHz to 10 MHz, the phase noise of this fiber laser is one order of magnitude lower than that of the NPE mode locked fiber laser. The higher noise of NPE mode locked fiber laser may be considered from the one additional pump laser diode.

In addition, in the frequency range from 100 kHz to 10 MHz, the phase noise from both ports is −150 dBc/Hz, which is lower than the fiber laser reported in [10].The integrated timing jitter is 21 fs for both outputs, which is also lower than 90 fs of the 750 MHz NPE fiber laser .

However, the phase noise is higher than that of the NPE mode locked fiber laser in the frequency from 10 Hz to 1 kHz. This might be due to the poor shelter in our case.

The phase noise spectrum dependence on the cavity dispersion from −0.012 ps^2 to −0.04 ps^2 is shown in Fig. 5(b). The phase noise is almost unchanged as the cavity dispersion decreases at the frequency below ~1 kHz. From 1 kHz to 1 MHz, the phase noise intensity decreases significantly as the net cavity dispersion approaches −0.012 ps^2 from −0.040 ps^2. Above the frequency offset, they all become the same and flat, reaching the floor of the measurement. It is expected that zero cavity dispersion should give the lowest phase noise. However, when the net cavity dispersion closes zero, the mode locking stops and was extremely difficult to start again.

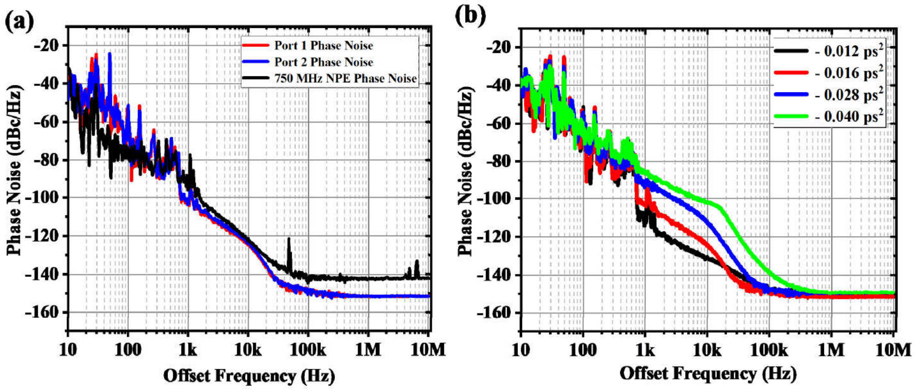

Fig. 5. Phase noise characteristics of the high repetition rate NALM Yb:laser: (a) The measurements of the phase noise of port 1 (red curve) and port 2 (blue curve) and NPE fiber laser (black curve); (b) The phase noise at various net cavity dispersion.

4. Conclusions

We have demonstrated a compact phase-biased 700MHz NALM mode locked Yb:fiber laser. The mode locking is self-starting and is maintained stable over, but not limited to, two weeks. The relative intensity fluctuation, indicated by the square root of the integral of the power spectral density (PSD) from 10 MHz to 10 Hz, is approximately 0.015% at PBS1 and 0.016% at PBS2. In the frequency range from 100 kHz to 10 MHz, the phase noise spectral density is about −150 dBc/Hz, which is one order of magnitude lower than that of the NPE mode locked fiber laser in the similar repetition rate. The integrated timing jitter is 21 fs.

The repetition rate and stability can be further increased by improving the architecture to shrink the free-space of the cavity and a better isolation. This kind of fiber laser has potential in robust optical frequency comb generation and other applications.

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