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Letter

178 fs, 1.2 nJ pulses from an all-polarization maintaining fiber figure 8 laser based on 3 × 3 coupler at 1 μm

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Abstract

We report on an Yb-doped all-polarization maintaining fiber mode-locked laser based on nonlinear-amplifying-loop mirror and 3 × 3 coupler. Thanks to this coupler inducing a non-reciprocal phase-bias, the mode-locked regime can be easily achieved at the high repetition rate of 52 MHz. The cavity delivers an average power of 62 mW corresponding to a pulse energy of 1.2 nJ. We have finally demonstrated an extra-cavity nonlinear spectral stage induced by the propagation along a standard nonlinear fiber. The pulse can be then compressed down to 178 fs via a grating compressor and the corresponding peak power is then around 6 kW.

Keywords: mode-locked lasers, figure 8, 3 × 3 coupler

(Some figures may appear in colour only in the online journal)

1. Introduction

Mode-locked (ML) fiber lasers are routinely used in many industrial and scientific fields like high precision micro-machining [1] and microscopy applications [2]. Due to the ever-growing demand to extend the lifetime of ML fiber lasers, there is still significant researches on this topic. Indeed, the predominant technology to achieve ML regime is based on a semiconductor saturable absorber mirror (SESAM) but it suffers from a small damage threshold [3] and so a short lifetime if the cavity is not correctly designed [4]. To avoid this drawback, different ML methods have been investigated over the last decade based on Kerr effect in polarization maintaining (PM) fiber: nonlinear polarization evolution (NPE) [5, 6] and Sagnac loop mirror [7, 8]. Most of these methods deliver pulses at a repetition rate below 15 MHz but the current industrial solutions operate at a repetition rate higher than 20 MHz. Therefore, all the amplifier architectures are designed for high repetition rate and a change of these parameters means to redesign the amplifier chain. The limitation in term of repetition rate of the SESAM free ML laser (like a nonlinear amplified loop mirror (NALM) ML laser) is driven by the requirement of a large amount of Kerr-induced nonlinear phase-shift to achieve a saturable absorption effect. This is obtained via the use of a long span of fiber leading so to a low repetition rate. To overcome this limitation, Hänsel *et al* have developed a design of NALM using a linear nonreciprocal phase bias [9]. Thank to this component, the transmission saturation of the NALM occurs for a lower nonlinear phase shift. The required fiber length is then lower than without this component. Nowadays, numerous laser cavity operating at high repetition rate have been reported at 1 μm wavelength [10, 11] but also at 1.5 μm [12, 13]. Until very recently, the use of a phase bias components has been based on free-space micro-optics using Faraday Rotators. It is expensive and has non-negligible insertion losses at 1030 nm. Furthermore, due to the un-perfect rotation induced by Faraday Rotators, these components can lead to pulses replica [14]. In 2019, Kim *et al* proposed to use a 3 × 3 coupler as NALM coupler to induce the nonreciprocal phase bias [15]. The reported laser is an all-PM figure 8 laser (i.e. with NALM operating in transmission) delivering pulses centered at 1560 nm and at 37 MHz repetition rate. This wavelength is not suitable for micro-machining application. The same laser architecture operating at 1 μm should be very attractive for numerous applications like micro-machining.

The implementation of this kind of figure 8 ml laser designed at 1 μm is not an easy task. Indeed, the ML dynamic is different because the sign of the group delay dispersion (GDD) of standard fiber is different at 1 μm compared to 1.56 μm [16]. At telecom wavelength, the GDD is negative (called anomalous dispersion) and it could compensate the chirp induced by self-phase modulation (SPM). This compensation leads to avoid pulse collapsing and to the soliton establishment. This dynamic helps to build up ML regime usually a solitonic one. At 1 μm, pulses acquire a positive chirp induced by the positive fiber GDD (called normal dispersion). Positively chirped pulses with high peak power experience a spectral broadening arising from SPM effect. Due to the large normal dispersion and the large spectral bandwidth, the pulse experiences a temporal broadening. These phenomena can be detrimental for the ML regime and its conservation along the time. The pulse stability from one roundtrip to another may be obtained via the use of grating compensating fiber GDD [17]. In all-normal dispersion (ANDI) cavity, dynamic stabilizing the ML regime called dissipative soliton (DS) have been largely studied [6–8, 18]. Contrary to the other ML dynamics, the dissipative soliton cavity uses the nonlinearities to stabilize the pulsed mechanism and the main pulse shaping mechanism is based on a chirped-pulse spectral filter [18]. The lasers based on this regime can deliver highly energetic pulses (few nanojoules) with a linear chirp making them easily compressible below 1 ps [6–8, 18]. These sources are a perfect candidate to seed chirped pulse amplification architecture because the pulses are already highly chirped.

In this letter, we report on, for the first time of our knowledge, an all-PM figure 8 mode-locked laser at 1 μm using a 3×3 coupler as phase-bias. The operation and phase shifts in 3×3 fused coupler are discussed in [19]. Thanks to this new coupler, the cavity stabilized by DS dynamic emits a stable pulse train at the high repetition rate of 52 MHz. The measured average power is 62 mW corresponding to 1.2 nJ pulse energy. To the best of our knowledge this is the highest pulse energy delivered by a ML laser based on NALM for such high repetition rate (higher than 15 MHz). The picosecond output pulse can be dechirped only down to 425 fs. To decrease the pulse duration, the output pulse spectrum is then nonlinearly broaden up to 18 nm along a nonlinear fiber. The pulse can be compressed then around 178 fs by means of a 4-f grating compressor and the corresponding peak power is about 6 kW. These different features highlight that our laser is a stand-alone source to seed microscope for nonlinear imaging or a good candidate to seed a double clad amplifier to reach high peak power for femtosecond micro-machining applications.

2. Experimental setup

The studied laser is depicted in figure 1. This is a figure 8 cavity fully built with standard PM fibers (PM980 fiber). The design consists of a main loop and a NALM linked by coupler.

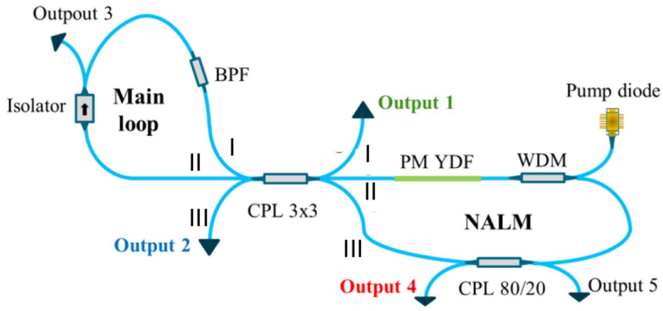

Figure 1. Schematic of the laser cavity (CPL: CouPLer; WDM: wavelength division multiplexer; YDF: Ytterbium doped fiber).

Here, the coupler is a 3×3 fused beam-splitter with an equal splitting ratio of 33%. The NALM consists of a 2×2 coupler extracting out the cavity 80% of the optical power and a short section of PM Ytterbium-doped fiber (YDF) (55 cm of coractive Yb-401-PM). This gain medium is pumped with a signal at 976 nm delivered by a laser diode and injected through a PM multiplexer. The YDF is spliced to the port II of the 3×3 coupler and the 80/20 coupler is connected to the port III. The high asymmetry in the NALM driven by the amplifying section and the highly asymmetric coupler helps to achieve the mode-locking. Indeed, with a 2×2 coupler with a ratio closed to 50%, the required nonlinear phase shift inside the NALM is too high and we cannot initiate the mode locking even when pumping with 950 mW, the maximum power available from the used pump diode. The main loop is made up of a high-power optical isolator and a bandpass filter. The isolator imposes an unidirectional optical path in the loop. This last component has an integrated polarizer aligned on the slow axis of PM fiber to ensure an unique linear polarization along the cavity. Its output is spliced to bandpass filter centered at 1030 nm with a full width at half maximum (FWHM) of 2.5 nm. This component is the key element in DS cavity. The filter acts like a pulse-shaper, it decreases the spectral bandwidth of the chirped pulse and so the duration of the pulses which are relaunched back into NALM. The output of the main loop is spliced to the port I of the 3×3 coupler and the input is linked to the port II. Thank to this ports arrangement, the 3×3 coupler induces a 60° phase difference to NALM transmission instead of 0° for a standard 2×2 coupler [15]. The overall configuration helps to achieve the mode-locking at high repetition rate, indeed figure 8 lasers based on NALM usually operate below 15 MHz [7, 8].

3. Results and discussion

All the laser outputs were fully characterized, however in this letter we only present results from the output 1, 2 and 4 because there are more relevant in term of output power.

The starting procedure of the ML regime is the same as other ML lasers based on Kerr effect [5].

The pump power must be increased up to 300 mW to achieve a multi-pulses ML regime and then it slowly decreases down to 216 mW to get the single pulse ML regime at a repetition rate of 52 MHz. This procedure should be considered as reliable because the single pulse ML regime is successfully obtained at every starting procedure without failing. When the ML regime is achieved, the pump power can be adjusted from 170 mW to 230 mW without losing it. Beyond the upper limit, temporal instability of the pulse train is observed, and the single pulse ML regime can switch to multi-pulses regime. Below the lower limit, the ML regime disappears, and the laser operates in CW regime. The filter bandwidth has a strong impact on the multi-pulses ML threshold and achievement reliability of the single pulse ML regime. Indeed, we tried a bandpass filter with a FWHM of 1.5 nm, the single pulse ML regime was not obtained at each time. This phenomenon has been already observed for ANDI lasers [20]. It could be explained by the strong pulse-shaping induced by the narrow filter. It leads to short pulse duration with high peak power generating too much nonlinear effect causing a wavebreaking

We first investigated the impact of pump power on the output average power from the port 1, 2 and 4, their evolution is represented in the figure 2(a). The average power from all the output monotonically increases with the pump power. The output 4 delivers the highest power of the cavity, at the maximum pump power we measure 62 mW corresponding to pulse energy of 1.2 nJ. This high value is logic because we extract about 80% of the power directly after the amplification section from the cavity. Moreover, the power efficiency is about 66%, this output seems behave as a preamplifier. Typically, lasers based on NALM for such high repetition rate deliver pulse with an energy about few tens pJ [10, 11]. It is not trivial to reach high energy with short cavity. Indeed, the small amount of accumulated GDD along the cavity is not enough to stretch the pulse. It results in a pulse with high peak power which may lead to wavebreaking. It should be also noted that this high output power is enough to directly seed standard double clad fiber amplifier with 10 μm diameter core and to saturate it. Then we do not require a preamplifier anymore. The average power from the output 1 and 2 respectively are 0.5 mW and 3.2 mW for the highest pump power. The corresponding pulse energies are respectively 9.6 pJ and 61 pJ. This is the typically average power delivered by ML regime based on SESAM [21]. So, our laser with this repetition rate and a low average power is already a good competitor to standard ML fiber laser without any required modification on the amplifier chains. These low levels of average power mean that a high input peak power is not required to reach the NALM transmission saturation and so the get the ML regime.

To understand more deeply the behavior of NALM, we study it as a fictive saturable absorber. Indeed, we calculate the transmission (related to the measured power on the outputs 3 dived by the tap ratio of the isolator and the power of the output 1) as a function of the input power (measured power on the output 1 multiplied by 2/3), the result is plotted in the figure 2(b). The transmission is quite similar to the standard NALM transmission [9], at the first order the transmission follows a sinus function. It first increases with the input power. This arises from the increase of input peak power inducing more nonlinear phase shift inside the loop. Then

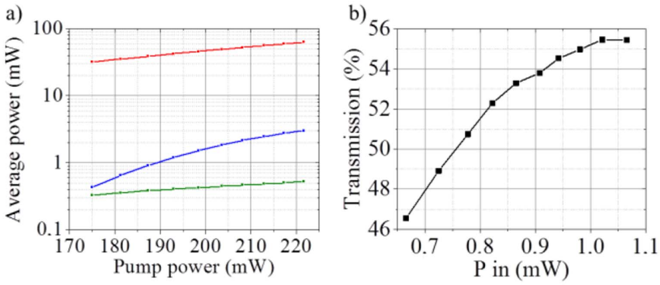

Figure 2. (a) Average power evolution as a function of total pump power at output 1 (green curve), output 2 (blue curve), and output 4 (red curve). (b) Nonlinear NALM transmission in percent as a function of the injected average power called pin.

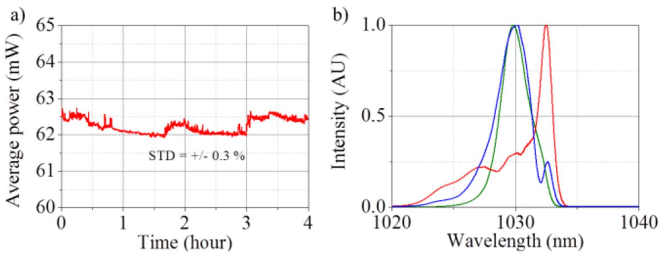

Figure 3. (a) Average power evolution at the output 4 tested over 4 h of continuous operation. (b) Normalized optical spectra at output 1 (green curve), output 2 (blue curve), and output 4 (red curve).

the transmission saturates because the nonlinear phase shift is around $\pi/2$. Finally, the transmission decreases. The NALM transmission decrease could be interpreted as an increase of the total cavity loss. Here losses increase faster than the cavity gain and then they are not equal anymore leading to destabilize the ML regime.

The average power of the output 4 was recorded for 4 h (see figure 3(a)) with a photodiode power sensor from Thorlabs having a resolution of 10 nW. We measured a RMS fluctuation of $\pm 0.3\%$, the usual stability for figure 8 laser at 1 μm is above $\pm 1\%$ [7]. This very high stability can be first attributed to the all-PM fiber architecture without any free-space optics. Furthermore, the stability is driven by the saturation of the NALM transmission. Indeed, when NALM is saturated, a slight variation of input power induced by any environmental effect has less impact on the transmission and so on the cavity losses. It results also in low sensitivity on the pump power variation. Therefore, we are less impacted by the pump noise.

The optical spectra from the three studied outputs were characterized at the highest pump power thanks to an optical spectrum analyzer from Yokogawa having a resolution of 20 pm. The spectral FWHM are 2.7 nm, 3.1 nm and 1.3 nm for the respective output 1, 2 and 4 (see figure 3(b)). The corresponding pulse durations of Fourier transform of the spectrum assuming a spectral phase equals to zero are 464 fs for the output 1, 183 fs for the output 2 and 206 fs for the output 4. The spectrum at the output 1 and 2 are smooth and centered at 1030 nm. The optical spectrum at the output 4 is getting thinner and its central wavelength experiences a red-shift. This spectral behavior is attributed to nonlinear effect driven by the

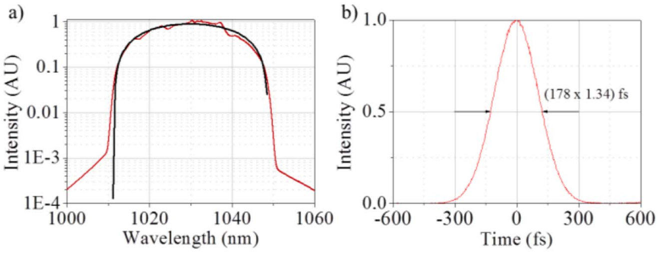

Figure 4. (a) Optical spectra at output of the nonlinear fiber in log -scale (dark red curve) with a parabolic pulse fit (black curve). (b) Autocorrelation traces of the de-chirped pulse at the output of the nonlinear fiber (red curve).

high peak power (around 700 W) at the output of the gain section.

We finally measured the pulse duration at the output 4 with a second order non-collinear autocorrelator, called 'pulseCheck', manufactured by APE. We estimate that the uncertainty on this measurement is equal to 5 fs. Note that we cannot measure the pulse duration from the other outputs because they deliver a too low average power and our autocorrelator is not enough sensitive. The pulse duration is 2.1 ps long assuming a Gaussian shape. As the cavity operates in ANDI regime, we may assume that the pulse is almost linearly chirped all along the cavity [18]. Indeed, this chirp can be compensated with a grating compressor (here a 4-f grating pair compressor) and the pulses can be then compressed down to 425 fs. It is twice the duration of the Fourier transformed limit. The uncompressed phase may be caused by the accumulation of nonlinear effect, the achromatic aberrations of our compressor and the third order dispersion (TOD) accumulated along the cavity. The calculated peak power is around 2.9 kW.

These long pulse duration and low peak power could be a limitation in some applications like nonlinear microscopy. Usually, duration below 200 fs with a peak power of 5 kW is preferred [2]. In order to reach these targeted values, the spectrum must be broaden while keeping the linear chirp. This can be obtained via parabolic evolution [21, 22]. With this in mind, we spliced the PM980 fiber of the output 4 to a 15 m long PM nonlinear fiber with a mode field diameter (MFD) of 3.6 μm (coractive SCF-UN-3/125-PM). Due to the MDF mismatch, the splice loss is about 0.6 dB with some splice process optimizations. Along the nonlinear fiber, the optical spectrum experiences nonlinear effects as SPM leading to a strong broadening, its FWMH is then 18.2 nm and it acquires an almost parabolic shape (see figure 4(a)). The corresponding pulse duration of Fourier transform of the spectrum assuming a spectral phase equals to zero is now 94 fs. At the output of the NL fiber, the pulse is 19 ps long but it can be dechirped down to 178 fs via a 4-f grating pair compressor (see figure 4(b)). The calculated time-bandwidth product is about 0.92. This is 1.9 times higher than the calculated time-bandwidth product with the transform-limited pulse.

The uncompensated phase should arise from the nonlinear phase of the seeded pulse, the nonlinear effect and the TOD accumulated along the NL fibers and the achromaticity of our compressor. The peak power of the compressed pulse is 6 kW.

To achieve a transform limited pulse duration even shorter, we have to increase the spectral bandwidth. Keeping this in mind, in our future work, we will first try to increase the pulse energy from the output 4. Indeed, we observed that the spectral width at the output of the nonlinear fiber increased with the input pulse energy. To do so, we will maximize the amount of nonlinear phase shift inside the cavity which increases with the output pulse energy [23]. Another working track will be to look to a nonlinear fiber with a smaller core diameter but with still a normal dispersion in order to avoid a detrimental solitonic compression and supercontinuum generation [24]. A smaller core diameter leads to increase the amount of self-phase modulation for a given pulse energy. Finally, we will also investigate the impact of the spectral bandwidth of the bandpass filter. Chong has demonstrated that for ANDI laser cavity the dechirped pulse duration is inversely proportional to the spectral bandwidth of the bandpass filter [23].

4. Conclusion

In summary, we demonstrate, to the best of our knowledge, the first all-PM Yb fiber laser mode-locked by a NALM using 3×3 coupler at 1 μm. With the assistant of this special coupler inducing a phase-bias, the cavity can operate in ML regime at the high repetition rate of 52 MHz. The laser operating in all-normal dispersion regime, delivers stable pulse train with an average power of 62 mW and pulse duration of 2.1 ps. Those pulses are linearly chirped and they are compressed down to 425 fs. Compared to other mode-locked lasers based on NALM operating at high repetition rate (above 15 MHz) [7, 8], our laser emits pulses with a higher energy around 1.2 nJ. To decrease the pulse duration to 200 fs, the optical spectrum was nonlinearly broaden up to 18 nm via the propagation along a step-index fiber with a small core. The resulted pulses can be dechirped to 178 fs via the use of a 4-f grating pair compressor. The corresponding peak power is then 6 kW. Thanks to the simplicity and the robustness of our all-PM architecture and its good output parameters, we believe that our laser a huge potential and it is a good replacement source to the SESAM cavity. Indeed, it could be directly used for nonlinear microscopy or to seed a double clad amplifier to reach high peak power required for micromachining application.

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