Nanosecond Pulse Generation near 1.55 Micron in the All-Fiber Figure-Eight Mode-Lock Laser with Passive Nonlinear Loop Mirror

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Abstract: Figure-eight mode-lock all-fiber laser based on a passive nonlinear loop mirror emitting nanosecond pulses at wavelength near 1.55 μm has been realized for the first time. Influence of the total laser dispersion on output characteristics of the laser has been studied. It is revealed that the main problem of utilization fibers with anomalous dispersion inside the passive nonlinear loop mirror is generation of low-energy optical solitons accompanied with nanosecond pulse break up. Solutions of this problem are discussed and stable laser schemes (i.e. all-polarization maintaining) are realized.

1 INTRODUCTION

Laser sources delivering nanosecond pulses are widely used in the industry of micromachining, LIDARs, systems of frequency conversion, and supercontinuum generation. However simple and stable scheme of sub-ns and few ns pulses generation is still a challenge. Direct formation of such pulses by electrical modulation of low-power laser diodes is possible (Myrén and Margulis, 2005; Villegas et al., 2011) but it requires complicated electronics control and a multi-stage amplification with suppression of amplified spontaneous emission. Also it is possible to use alternative schemes based on mode–locking (Kelleher et al., 2009) or passive Q-switching (Fotiadi et al., 2007; Kurkov et al., 2009; Kurkov et al., 2010; Dvoyrin et al., 2007; Dvoyrin, 2012; Jin et al., 2013). However all these schemes suffer from long-term or short-term instabilities (jitter, damage of elements due to abnormal Q-switch pulse generation, absence of polarization control and etc).

Recently a new all-fiber master-oscillator laser scheme based on mode locking in a passive nonlinear loop mirror (PNLM) has been proposed (Likhachev et al., 2014). The main advantages of the proposed laser design are the absence of adjustment elements (monolithic all-polarization-maintaining fiber laser scheme was realized), reliability (stable long-time operation for more than 1000 hours was demonstrated) and simplicity (just small sets of standard components was used). Moreover small modulation depth of PNLM provided a low lasing threshold (twice lower compared to the figure-eight scheme based on nonlinear amplifying loop mirror) and "safe" start (the scheme start to operate from CW regime instead of Q-switch regime for “classic” figure-eight schemes). Stable pulse generation with a rectangular temporal profile and spectral bandwidth of less than 0.02 nm (less then spectrum analyzer resolution) was demonstrated (Likhachev et al., 2014).

It should be noted that nanosecond pulses in the proposed scheme has been demonstrated only for 1 μm spectral range. At the same time numerous applications (first of all – different types of LIDAR) requires an eye-safe operation and therefore wavelengths region near 1.55 microns is of great interest. It is important to emphasize that the fundamental difference between two spectral regions (1 μm and 1.55 μm) is that optical fibers have opposite dispersion sign (normal dispersion at 1 μm and anomalous dispersion at 1.55 μm) that can dramatically change the mechanism of pulses formation, and even prevent correct operation of the proposed scheme.

The purpose of the present work was realization of stable nanosecond master-oscillator for the 1.55 μm spectral region as well as analysis of the dispersion impact on the properties of the figure-eight mode-locked lasers based on PNLM.

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2 EXPERIMENTAL SETUP

The scheme of the all-fiber figure-eight laser is depicted in Figure 1. Commercially available 210 mW semiconductor diode at 1460 nm pigtailed with singlemode optical fiber was used to pump Er-doped fiber. The Er-doped fiber had absorption of about 2 dB/m at wavelength of 1460 nm and 11 m of the fiber was used in the scheme. The fiber dispersion was about -30ps/(nm km). An isolator was placed between Er-doped fiber and PNLM to ensure the unidirectional operation. The PNLM was built by X-type 30:70 fiber coupler and a passive single-mode fiber. A 4.5% fiber coupler was used for signal output. It is worth to note, that unabsorbed 1460 nm pump could pass through the isolator and coupler, so it was suppressed by a fiber 1460/1550 nm filter WDM placed after 4.5% coupler port. The Yokogawa AQ6370B optical spectrum analyzer (OSA) and a 500 MHz Tektronix TDS 3054C oscilloscope were used to monitor the output spectrum and the pulse train, correspondingly.

2.1 All-anomalous Dispersion Scheme

The laser scheme based on polarization-insensitive components was tested at first. To adjust the polarization state of the system a fiber polarization controller was added to the scheme. Standard single mode fiber (Corning SMF28) with length of about 160 m was used to form the PNLM. The fiber dispersion was about 20 ps/(nm km). Passive elements used inside the laser were also pigtailed by SMF28 fiber. As a result the net cavity dispersion was anomalous (β_2~-4 ps^2/km).

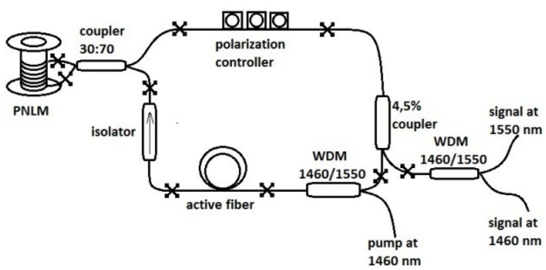

Figure 1: Laser scheme.

Three main regimes of pulse generation were observed at the output of this laser scheme (Figure 2 and Figure 3). The most reproducible one was a set of irregular low intensity pulses with a typical soliton spectrum (Figure 2a and Figure 3a). It worth noting that the regime was not observed early in the laser scheme operated near 1µm. The reason is that in the

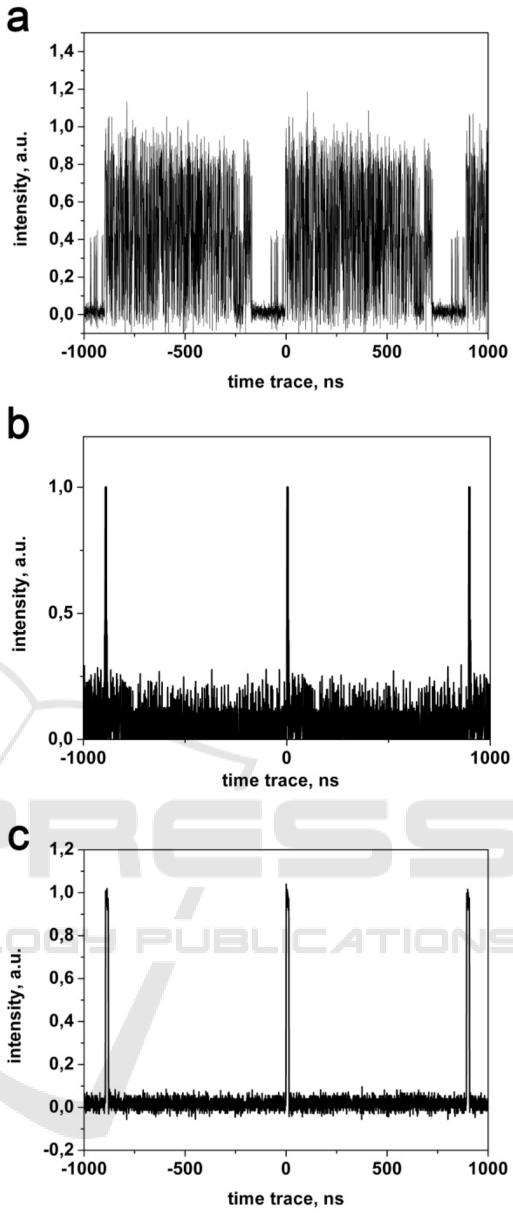

Figure 2: Regimes of pulse generation in all-anomalous dispersion non-PM scheme. a – solitons regime; b – regime of cooperative solitons and nanosecond pulse propagation; c – regime of nanosecond pulse propagation.

1 µm spectral range standard fibers have normal dispersion and formation of solitons propagating over hundred of meters is not possible. It is completely different from the case of pulse formation in the 1.55 µm spectral range, where standard fibers have anomalous dispersion and could propagate solitons over a long fiber distances. The second regime of pulse generation (also easily reproducible) is connected with existence in the cavity nanosecond pulses and numerous low-intensity solitons,

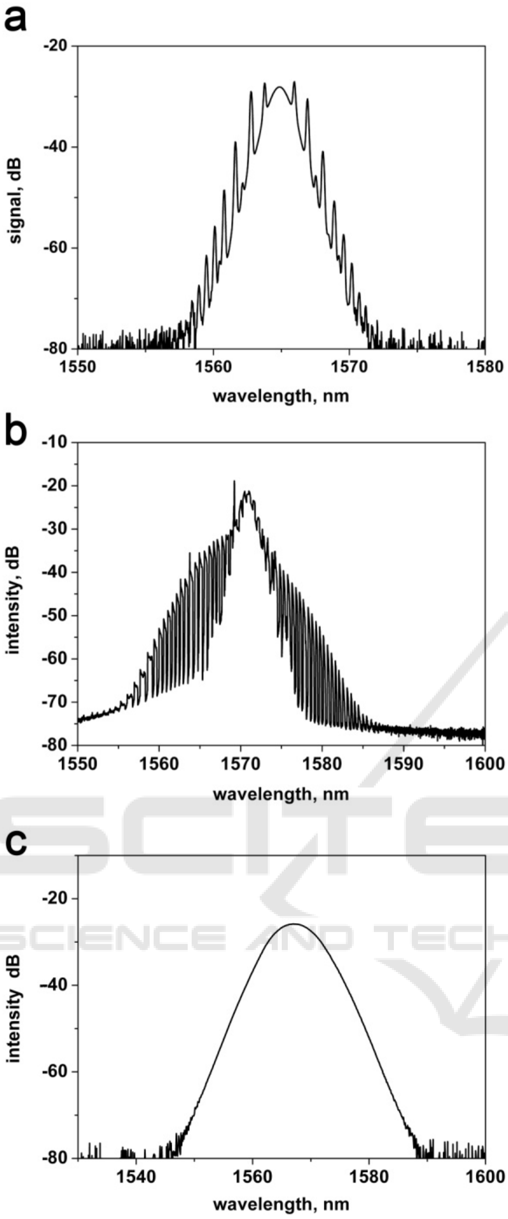

Figure 3: Spectrum of the pulses in all-anomalous dispersion non-PM scheme. a – solitons regime; b – regime of cooperative solitons and nanosecond pulse propagation; c – regime of nanosecond pulse propagation.

simultaneously (Figure 2b and Figure 3b). The shape of the nanosecond pulses varies quickly in this case. Only by careful adjusting of the polarization controller a stable self-started (at pump power more than 60 mW) rectangle pulses was generated (Figure 2c and Figure 3c). It is significant that mode-locked pulses were generated even when pump power was decreased down to 20 mW that is known as pump hysteresis effect (Nakazawa et al., 1991). Dependences of the pulse duration on pump power and estimated average power inside the cavity, correspondingly, was linear (Figure 4 and Figure 5) and pulses peak power did not change with the pump power. The same behavior was also observed for the pulse generation in the scheme with PNLM in 1 μm spectral range and all-normal dispersion (Likhachev et al., 2014) and corresponded to the peak-power-locking inside PNLM (the PNLM has maximum transition at fixed signal peak power). It is interesting to note an important difference compared to the 1 μm laser scheme in this case - the spectral bandwidth was about of 8 nm (Figure 3c) as compared to less than 0.02 nm bandwidth (limited by spectrum analyzer resolution) in the case of 1 μm laser.

Measured pulse repetition rate was 1.12 MHz. Part of the power propagating between the pulses was measured using integrating photodetector scheme (Kotov et al., 2015) and it was found that 99% of the signal located inside the pulse and less than 1% (inaccuracy and systematic error of measurements) of output power was concentrated between them. Thus no low-energy solitons was generated in this case and clear nanosecond pulses were generated.

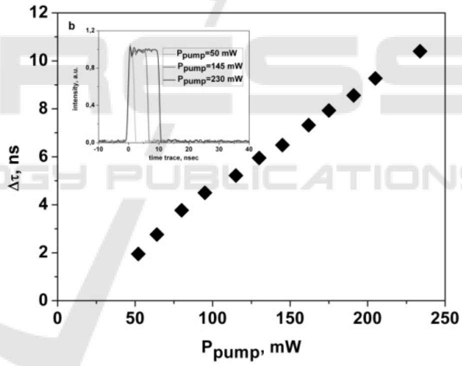

Figure 4: Dependence of pulse duration from pump power; time traces of the output pulses vs pump power on the inset.

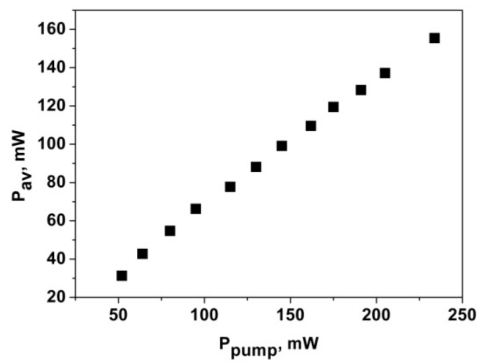

Figure 5: Dependence of pulse duration and average power from pump power after WDM.

2.2 PM-Scheme for Pulse Generation

As could be seen from previous paragraph, regime of generation was strongly changed by adjustment of polarization controller in the case of non-polarization-maintaining laser scheme. As a result this scheme will suffer from a long-term instability due to small variation of external stress and temperature changes. PM-scheme is required for practical applications.

PM laser scheme was realized by replacement of standard components based on SMF 28 fiber on a similar one with ability to maintain polarization (PM1550 PANDA type optical fiber was used as pigtail). The PNLM was made by 20:80 X-type PM fiber coupler and standard PM 9/125 µm fiber. The isolator was designed to pass only slow polarization state (the fast axis was blocked) to achieve single-polarization operation.

At first a 160 m of passive PM 9/125 µm fiber was used inside the PNLM. In this case strong solitons oscillations together with nanosecond pulses were observed. Typical spectrum and time trace are shown in Figure 6 and Figure 7.

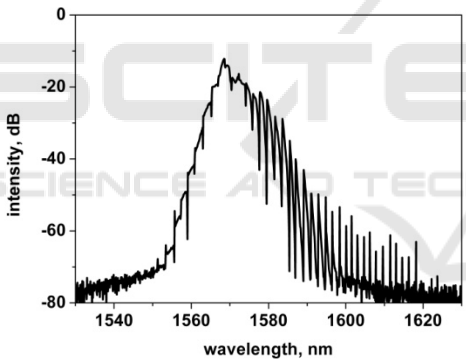

Figure 6: Measured spectrum of the soliton and nanosecond pulse generation.

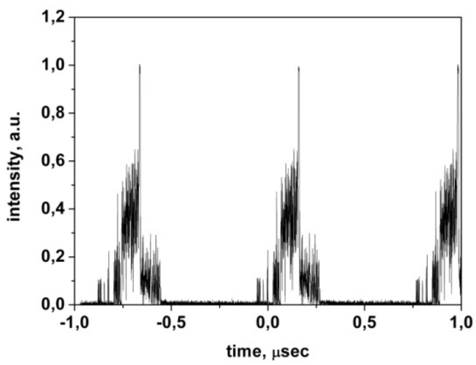

Figure 7: Measured time trace of the generation regime.

It is interesting to note that estimated peak power of second order solution was about 30 W that is close to the peak power of maximum transmission of the PNLM. Suppression of solitons generation could be enhanced by increasing of the maximum-transition-peak-power of PNLM (it will increase power loss of solitons propagating through PNLM). To check this idea we have reduced PNLM length down to 80m, and thus have increased power of maximum transmission through PNLM up to 70 W. A stable nanosecond pulse generation was observed in this case (see Figure 8). Long-term stability was tested for operation at more than 100 hours and we did not observe any variations of output power and pulse form.

It worth noting that decreasing of nonlinearity inside the cavity resulted in growth of the threshold of pulse generation up to 140 mW. Repetition rate was 2.216 MHz. Similar to the case of non-PM laser scheme the spectral bandwidth was very wide - about 12 nm on the level of 3 dB (see Figure 9).

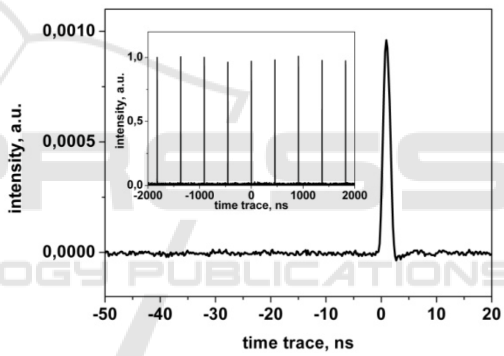

Figure 8: Time trace of the pulses in the PM scheme.

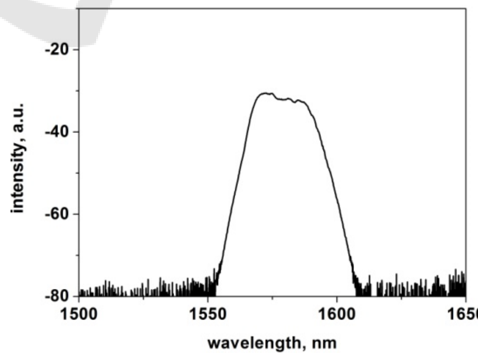

Figure 9: Measured spectrum of the pulses oscillating in the PM scheme.

2.3 All-normal Dispersion Scheme of Nanosecond Pulse Generation at 1.55 Nm

In order to determine the impact of the dispersion on the output characteristics of the laser system a special home-made single-mode fiber with negative dispersion at operating wavelength (D=-18 ns/(nm km)) was used to form the PNLM. The fiber had mode filed diameter of about 4.3 µm and cladding diameter of 125 µm. Splicing loss with SMF28 fiber after optimization splicing regimes was less than 0.5 dB. The length of the fiber inside PNLM was about 100 m. Except of the change of fiber inside PNLM the laser scheme was identical to polarization-insensitive scheme used in paragraph of 2.1.

Stable regime generation was achieved by the appropriate adjustment of polarization controller. No low-energy solitons generation was observed at all positions of polarization controller that is due to impossibility of soliton propagation over a long length of fiber with normal dispersion. Self-starting mode-lock regime was observed after pump power turning on. Output laser characteristics were similar to those of 1 µm laser (Likhachev et al., 2014) (Figure 10 and Figure 11). The main feature is that contrary to anomalous dispersion regime the output spectrum with a narrow peak (width is less than 0.02 nm) was obtained at the pulse duration of 1 ns. As in the case of (Likhachev et al., 2014) pulse duration increased with pump power growth from 1 ns to 8 ns, pulse amplitude did not change. It should be noted that increasing of the pump power led to increasing of the intense peaks number in the spectrum. Apparently it was due to the incorrect configuration of the polarization controller (the polarization state is not fully reproduced in the round-trip cavity): small instability was able to induce additional generation at neighbour wavelengths. It is important to say that according to data of temporal trace pulses propagated with the same velocity and composed the only one pulse. Similar behaviour was observed for non-PM laser scheme operating at 1 µm (Likhachev et al., 2014). Suppression of the additional spectral components generation could be achieved using polarization-maintaining laser scheme.

Additional results will be presented at the conference.

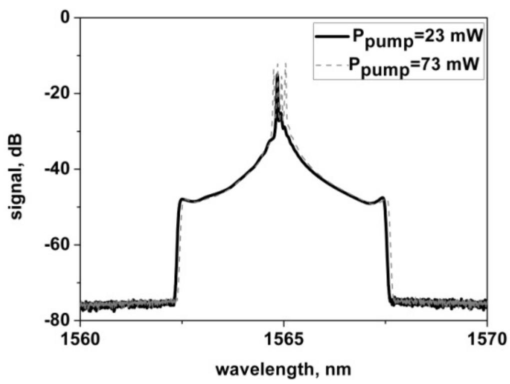

Figure 10: Measured spectrum of the pulses oscillating in all-normal dispersion scheme.

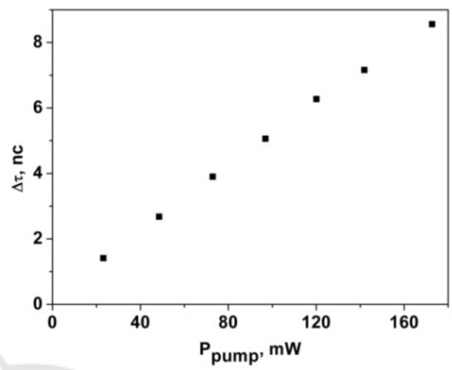

Figure 11: Dependence of pulse duration on pump power.

3 CONCLUSIONS

In summary, investigation of nanosecond pulse generation regimes in the figure-8 laser scheme with PNLM was carried out for the 1.55 µm spectral range. It was shown that stable self-starting nanosecond rectangular pulses can be obtained in the scheme both with net-normal and net-anomalous dispersion. However output laser spectrum is strongly depends on the cavity dispersion: narrow-width spectrum can be realized in the scheme with all-normal dispersion only. It is experimentally demonstrated that the major problem of nanosecond pulse generation in all-anomalous dispersion scheme is appearance of low-energy solitons. Such a regime can be efficiently suppressed by appropriate polarization controller adjustment in non-PM laser scheme or by decreasing of PNLM length in the case of PM scheme. All-PM scheme was created to exclude the degree of freedom coursed by the possibility of adjusting the polarization controller. A stable in the time nanosecond pulses (similar to the case of pulse generation in non-PM scheme) were observed in this case.

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