Mode-locked femtosecond all-normal all-PM Yb-doped fiber laser using a nonlinear amplifying loop mirror

Claude Aguergaray, Neil G. R. Broderick, Miro Erkintalo, Jocelyn S. Y. Chen, and Vladimir Kruglov

1Department of Physics, University of Auckland, Auckland, New Zealand
2Southern Photonics Ltd. 49 Symonds Street, Auckland, New Zealand

Abstract: We report on a new design for a passively mode locked fibre laser employing all normal dispersion polarisation maintaining fibres operating at 1 µm. The laser produces linearly polarized, linearly chirped pulses that can be recompressed down to 344 fs. Compared to previous laser designs the cavity is mode-locked using a nonlinear amplifying fibre loop mirror that provides an additional degree of freedom allowing easy control over the pulse parameters. This is a robust laser design with excellent reliability and lifetime.

© 2012 Optical Society of America

OCIS codes: (140.3510) Lasers, fiber; (140.7090) Ultrafast lasers; (060.5530) Pulse propagation and solitons.

References and links
1. B. Ortac¸, M. Pl¨otner, J. Limpert, and A. T¨unnermann, “Self-starting passively mode-locked chirped-pulse fiber laser,” Opt. Express 15, 16794–16799 (2007).
2. S. Lefranc¸ois, K. Kieu, Y. Deng, J. D. Kafka, and F. W. Wise, “Scaling of dissipative soliton fiber lasers to megawatt peak powers by use of large-area photonic crystal fiber,” Opt. Lett. 35, 1569–1571 (2010).
3. W. H. Renninger, A. Chong, and F. W. Wise, “Self-similar pulse evolution in an all-normal-dispersion laser,” Phys. Rev. A 82, 021805 (2010).
4. J. R. Buckley, F. W. Wise, F. O. Ilday, and T. Sosnowski, “Femtosecond fiber lasers with pulse energies above 10 nJ,” Opt. Lett. 30, 1888–1890 (2005).
5. F. O. Ilday, J. R. Buckley, H. Lim, F. W. Wise, and W. G. Clark, “Generation of 50-fs, 5-nJ pulses at 1.03 µm from a wave-breaking-free fiber laser,” Opt. Lett. 28, 1365–1367 (2003).
6. H. A. Haus, “Mode-locking of lasers,” IEEE J. Sel. Top. Quantum Electron. 6, 1173–1185 (2000).
7. I. N. Duling III, “All-fiber laser mode locked with a nonlinear mirror,” Opt. Lett. 16, 539–541 (1991).
8. H. A. Haus, K. Tamura, L. E. Nelson, and E. P. Ippen, “Stretched-pulse additive pulse mode-locking in fiber ring lasers: theory and experiment,” IEEE J. Quantum Electron. 31, 591–598 (1995).
9. B. Ortac¸, J. Limpert, and A. T¨unnermann, “High-energy femtosecond Yb-doped fiber laser operating in the anomalous dispersion regime,” Opt. Lett. 32, 2149–2151 (2007).
10. B. Ortac¸, A. Hidleur, T. Chartier, M. Brunel, C. Ozkul, and F. Sanchez, “90-fs stretched-pulse ytterbium-doped double-clad fiber laser,” Opt. Lett. 28, 1305–1307 (2003).
11. C. K. Nielsen, B. Ortac¸, T. Schreiber, J. Limpert, R. Holmuth, W. Richter, and A. T¨unnermann, “Self starting self-similar all-polarization maintaining Yb-doped fiber laser,” Opt. Express 13, 9346–9351 (2005).
12. F. O. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, “Self-similar evolution of parabolic pulses in a laser,” Phys.Rev. Lett. 92, 213902 (2004).
13. I. Hartl, G. Imeshev, G. C. Cho, and M. E. Fermann, “Ultra-compact dispersion compensated femtosecond fiber oscillators and amplifiers,” in Conference on Laser and Electro-Optics, Cleo 2005 (Optical Society of America, 2005), paper CThG1.
14. A. Ruehl, O. Prochnow, M. Engelbrecht, D. Wandt, and D. Kracht, “Similariton fiber laser with photonic bandgap fiber for dispersion control,” Opt. Lett. 32, 1084–1086 (2007).
15. S. Ramachandran, S. Ghalmi, J. W. Nicholson, M. F. Yan, P. Wisk, E. Monberg, and F. V. Dimarcello, “Anomalous dispersion in a solid, silica-based fiber,” Opt. Lett. 31, 2532–2534 (2006).
16. R. Herda, and O. G. Okhotnikov, “Dispersion compensation-free fiber laser mode-locked and stabilized by high-contrast saturable absorber mirror,” IEEE J. Quantum Electron. 40, 893–899 (2004).
17. A. Chong, J. Buckley, W. Renninger, and F. Wise, “All-normal dispersion femtosecond fiber laser,” Opt. Express 14, 10095–10100 (2006).
18. B. Ortac, O. Schmidt, T. Schreiber, J. Limpert, A. Tunnermann, and A. Hideur, “High-energy femtosecond Yb-doped dispersion compensation free fiber laser,” Opt. Express 15, 10725–10732 (2007).
19. A. C. Peacock, V. I. Kruglov, B. C. Thomsen, J. D. Harvey, M. E. Fermann, G. Sucha, D. Harter, and J. M. Dudley, “Generation and interaction of parabolic pulses in high gain fiber amplifiers and oscillators,” OFC 2001, Anaheim, paper WP4, March 2001.
20. A. Ruehl, O. Prochnow, D. Wandt, D. Kracht, B. Burgoyne, N. Godbout, and S. Lacroix, “Dynamics of parabolic pulses in an ultrafast fiber laser,” Opt. Lett. 31, 2734–2736 (2006).
21. C. Aguergaray, D. Méchin, V. Kruglov, and J. D. Harvey, "Experimental realization of a Mode-locked parabolic Raman fiber oscillator," Opt. Express 18, 8680–8687 (2010).
22. C. F. Amrani, M. Salhi, P. Grelu, H. Leblond, and F. Sanchez, “Universal soliton pattern formations in passively mode-locked fiber lasers,” Opt. Lett. 36, 1545–1547 (2011).
23. J. W. Nicholson, S. Ramachandran, and S. Ghalmi, “A passively-modelocked, Yb-doped, figure-eight, fiber laser utilizing anomalous-dispersion higher-order-mode fiber,” Opt. Express 15, 6623–6628 (2007).
24. C. Barnard, P. Myśliński, J. Chróstowski, and M. Kavehrad, “Analytical model for rare-earth-doped fiber amplifiers and lasers,” IEEE J. Quant. Electron. 30, 1817–1830 (1994).
25. O. Prochnow, A. Ruehl, M. Schultz, D. Wandt, and D. Kracht, “All-fiber similariton laser at 1 µm without dispersion compensation,” Opt. Express 15, 6889–6893 (2007).
26. C. W. H. Renninger, A. Chong, and F. W. Wise, “Giant-chirp oscillators for short-pulse fiber amplifiers,” Opt. Lett. 33, 3025–3027 (2008).

1. Introduction

In recent years there has been significant progress in the development of mode-locked fibre lasers operating at 1 µm [1–5]. These lasers are now well developed reliable devices which are used in many different fields such as optical imaging or metrology. Much effort has been dedicated to increase the peak power of the pulses delivered by fiber based oscillators since their stability, their compactness, and their lack of misalignment make them a good alternative to bulk solid-state lasers. The increase in the energy delivered by such lasers is due to both the improvement in the design and the fabrication of large mode area fibers and the realisation that even with net normal dispersion at 1 µm, self-similar pulses can exist in the cavity. Such pulsed-laser systems behave very differently compared to more usual soliton fibre lasers since there is a large degree of pulse evolution during a single round trip. Mode-locked fiber lasers pulse formation is based on a complex interaction between the gain, the dispersion and nonlinear effects [6]. In a soliton laser the anomalous dispersion and the self-phase modulation (SPM) interplay to maintain the shape and the duration of the fundamental soliton (sech² shaped pulses) [7]. However such lasers are limited in energy because of the wave breaking effect to some tens of pic joules [8]. To overcome this limitation several pulse dynamics have been proposed. A successful cavity architecture called dispersion managed cavities is made of two main sections with normal and anomalous dispersion. Depending on the net cavity dispersion numerous pulse evolution can take place leading to very different output pulse characteristics. For an anomalous net cavity dispersion the pulse experiences small temporal breathing throughout one round trip. Such dispersion-managed soliton regime has been implemented successfully to produce high energy pulses using low-nonlinearity large-mode-area fibers [9]. If the net cavity dispersion is close to zero, the resulting pulse experiences much larger temporal breathing leading to a reduction of the peak power thus diminishing the amount of nonlinear phase accumulated by the pulse. As a consequence much higher pulse energies have been reported using this stretched pulse regime [10]. Similarly, for positive net cavity dispersion (wave breaking-
free regime), higher pulse energies can be obtained together with positively chirped pulses [11]. Several types of elements have been used to provide anomalous dispersion at 1 µm such as grating pairs [12], chirped fiber Bragg gratings [13], photonic crystal fibers [14] or higher-order mode fibers [15].

A final architecture for the design of a mode-locked ytterbium fiber laser implements exclusively normal dispersion components. Such all-normal dispersion (ANDi) lasers typically produce picosecond pulses with a very strong positive chirp. The generation of picosecond [16] and femtosecond [17] pulses after recompression outside the cavity or very high energy output pulses as high as 200 nJ using low-nonlinearity large-mode area fiber [18] have been reported. The stable mode-locking operation is possible due to filtering effects in the cavity which ensure that the cavity boundary conditions are respected. This filtering action can be achieved by using a bandpass filter or a saturable absorber but can also arise intrinsically from the finite gain bandwidth of the active fibre.

A subcategory of the wave breaking-free regime is the similariton laser [12, 19]. In this case, the output pulses have a parabolic temporal and spectral shape and a linear positive chirp. Such a laser uses self-similar propagation in the gain medium to broaden temporally and spectrally the pulse without changing its parabolic shape. In the present category the filtering effects are more stringent because of the high chirp of the pulses [20].

While a variety of lasers based on similariton propagation have been demonstrated the main differences lie in the mechanism for mode-locking with the main ones being either the use of a saturable absorber [1, 11, 18] or nonlinear polarisation evolution (NPE) [2, 3, 10]. However both methods suffer from drawbacks which limit their suitability for industrial applications. NPE while easy to demonstrate in the laboratory requires adjustable control of the polarisation and saturable absorbers suffer from long-term reliability problems and are limited in their power-handling capabilities. In contrast, we previously demonstrated a parabolic pulse fiber laser [21] based on a nonlinear optical loop mirror (NOLM) which did not suffer from these drawbacks. However, precise control of the loss and coupling ratio of the NOLM was required while the long cavity length made the laser unsuitable for many applications.

In this paper we demonstrate a short cavity ring laser with a second amplifying stage in the NOLM turning it into a nonlinear amplifying loop mirror (NALM) allowing better control and easier mode-locking operation [22]. The laser delivers 7.6 ps pulses with an energy of 0.3 nJ that can be recompressed down to 344 fs with a pair of gratings outside the cavity.

2. Laser architecture

The experimental configuration of the all-PM-Yb-fibre laser reported in this work is schematically illustrated in Fig. 1(a) while Fig. 1(b) shows simulation results highlighting the evolution of the pulse inside the cavity over a single roundtrip. The laser can be thought of as consisting of two separate modules, where the first is a standard ANDi ring cavity consisting of a length of doped fibre, an isolator, an output coupler and a narrow-band bandpass filter. On its own, this module produces a narrow band continuous wave output with a spectral bandwidth of less than 0.1 nm. The second module is a mode-locking element which can be anything such as a saturable absorber, NPE or in our case a NALM. Note that all components and fibers are polarisation maintaining. We have estimated a total cavity dispersion of about 0.53 ps². In the main loop we use as gain medium a low ytterbium-doped (80.0 dB/m core absorption at 975 nm) single clad fiber with a mode-field diameter of 6.5 µm. The Yb-doped fiber is pumped with a single mode diode emitting at 976 nm injected through a PM-WDM 980/1030 and 20% of the power is coupled out of the laser via an 80/20 PM coupler. Finally a bandpass pigtailed PM filter with a transmission bandwidth of 1.7 nm ensures that the cavity’s boundary conditions are respected by decreasing the chirp and bandwidth of the pulse reinjected into the amplifier.
The modelocking of the laser is achieved by means of a NALM placed before the output coupler. The NALM consists of a length of PM 980 single mode fibre and a short length of highly doped Yb\textsuperscript{3+} fibre pumped by a second 976 nm fibre coupled diode. Only the central part of the pulses which are more intense and thus accumulate a higher nonlinear phase than the wings interfere constructively and exit the coupler towards the output coupler and the bandpass filter. This temporal selection enables the mode-locking operation. We have tested a variety of coupling ratios and found that a 60 : 40 splitter worked best (although 50 : 50 and 55 : 45 splitters worked as well). When we included the mode-locking element the laser produces stable and spectrally broad pulses. It should be noted that previously J. W. Nicholson et al. have reported a mode-locked figure eight laser using all normal dispersion fibres. However, their cavity design is significantly different from ours since it does not include a second length of amplifying fibre or a narrow band filter and so cannot be said to support similariton propagation [23].

![Fig. 1. (a) Schematic of the laser; (b) Evolution of the pulse throughout the cavity (OC: Output Coupler).](image)

The NALM as mode-locking device allows better control over a NOLM (cf. [23]) in which only the loss and the coupling ratio can be adjusted. Indeed, the possibility of varying the amplification in the gain segment of the NALM allows for a simple route to vary and fine tune the characteristics of the mode-locked device. This extra degree of freedom gives to this design a big advantage to obtain mode-locked pulses. Furthermore the laser does not suffer from any drawback due to a limited life time. Since all the components forming the NALM as well as the cavity, are pigtailed, simple and robust the laser performance does not evolve or degrade over time. The laser is intrinsically environmentally stable. Once the single pulse mode-locking operation is obtained no further adjustment is required to maintain the mode-locking regime over short or long period of time.

In addition to experiments we have conducted extensive simulations so as to numerically study the operation of the laser. Our simulations are based on an accurate model of the experimental all-fibre cavity where each segment is modelled using the generalized nonlinear Schrödinger equation.

\[
\frac{\partial A}{\partial z} - \sum_{k=2}^{\infty} \frac{i^{k-1}}{k!} \beta_k \frac{\partial^k A}{\partial T^k} = \frac{g(z, \omega)}{2} A + i\gamma \left( 1 + \frac{i}{\omega_0} \frac{\partial}{\partial T} \right) \left( A \int_{-\infty}^{+\infty} R(T') |A(z, T - T')|^2 dT' \right) \tag{1}
\]

Here \(A(z, T)\) represents the electric field envelope centered at \(\omega_0\), and the \(\beta_k\)'s and \(\gamma\) are the usual dispersion and nonlinear coefficients. The nonlinear response function \(R(T) = (1 - f_R) \delta(T) + f_R h_R(T)\) includes both instantaneous electronic and delayed Raman contributions with \(f_R = 0.18\) the fractional Raman contribution and \(h_R(T)\) obtained from experimentally measured fused silica Raman cross section. The time derivative on the right-hand side is associated with the dispersion of the nonlinearity and gives rise to effects such as self-steepening.
and optical shock formation. The gain $g(z, \omega)$ is nonzero only along the active fibres where it is modelled using an analytical three-level model [24], and is assumed to be associated with an implicit parabolic frequency dependence with a 30 nm bandwidth. The NALM is modelled by separately simulating both counter-propagating pathways, taking into account the appropriate coupler-induced phase shifts and splitting ratios. Effects of the output coupler and the spectral filter are modelled as lumped elements while propagation through all other elements are simulated using the Eq. (1). The simulations are seeded with random noise and stable operation regime is obtained after a large number of roundtrips. At this point we wish to note that, in order to ease visualization, Fig. 1(b) simplifies the NALM portion by only displaying the clockwise propagating field up-scaled by the coupling ratio. All the simulations themselves of course accurately consider fields propagating in both directions as well as the appropriate coupling ratios and phase shifts as mentioned.

3. Experimental results

The laser was pumped with two fibre coupled 980 nm diodes each with a maximum output power of 600 mW. However, it was found that stable single pulse operation occurred with substantially smaller pump powers with $\sim 50$ mW being coupled into the main amplifier and $\sim 40$ mW for the NALM. Such power levels are considerably lower than other ANDi laser [1, 25].

In order to initiate mode-locking the coupled pump power was increased above these levels (respectively $\sim 75$ mW and $\sim 60$ mW) until the cavity spontaneously mode-locked with several pulses in the cavity. Reducing the pump diode powers to the above level then resulted in a $\sim 10$ MHz pulse train (see Fig. 2(a)). While the total cavity dispersion does play an important role in the pulse formation process we have found that repetition rates of between 6 and $\sim 10$ MHz can be achieved by adding additional fiber lengths without significantly changing the laser’s output characteristics.

The stable mode-locking regime of the laser is characterised by a very low noise level which is about 30 dB lower than the pulse as can be seen in Fig. 2(a) and 2(b). This is due to the positioning of the output coupler after the NALM. Indeed the spectral output immediately after the Yb amplifier shows a significantly higher level of noise which is then rejected by the NALM. The single pulse operation has been verified using a long range scan frequency-resolved optical gating (FROG) (150 ps scanning range) and a fast photodiode featuring a rise time of 12 ps in conjunction with a 15 GHz oscilloscope.

The output power of the laser in the fundamental mode-locking regime is 3 mW correspond-
ing to a pulse energy of 0.3 nJ. A typical spectrum of the pulses is shown on logarithmic scale and a linear scale in Fig. 2(b). The spectrum has steep edges which is a characteristic feature of pulses formed in a fiber laser operating in the highly positive dispersion regime. Furthermore, as we increase the pump power of the amplifier in the main loop, a slight increase of the bandwidth without change of the spectral shape could be observed before the multiple pulsing regime starts. This behaviour is representative of self-similar propagation in the gain section. The pulse spectrum is centered at 1027 nm with a bandwidth as large as 5 nm (3dB). The spectrum in the mode-locked regime is significantly larger than the 1.7 nm bandwidth of the bandpass filter (centered at 1027 nm) showing that considerable pulse evolution and nonlinear spectral broadening is occurring inside the laser each round trip. These dynamics are confirmed by our simulations (see Fig. 1(b)).

![Image]

Fig. 3. Recovered pulse intensity from a FROG trace done: (a) at the output of the laser, (b) after recompression with gratings (dotted line is the theoretical best recompression: 320 fs)

A FROG measurement of the laser output pulse was made and the recovered trace is shown in Fig. 3(a) together with our simulation results. Excellent agreement can be found between the predicted pulse shape and the experimental data. It can be seen that the temporal duration is 7.6 ps and has an approximately rectangular shaped temporal profile. More importantly the pulse has a linear chirp across it and could be recompressed outside the cavity with a grating based compressor. The gratings feature 1200 lines/mm introducing a $\beta_2 = -5.7345 \text{ ps}^2/\text{m}$ and a $\beta_3 = 0.02103 \text{ ps}^3/\text{m}$. Such pulse features are typical of similariton pulse regime in the laser cavity. The compressed pulse, shown in Fig. 3(b), is 344 fs long indicating a compression factor of 22. Despite the non-compensation of third order dispersion terms between the laser and the compressor, the shape of the compressed pulse is very good. Some small pre and post-pulses characteristic from remaining TOD and SPM induced phase can be observed but they remain small since 90% of the energy is contained into the main pulse.

4. Conclusion

In conclusion we have demonstrated a passively mode-locked all-fibre laser based on a robust design using a NALM as the mode-locking element. The output pulses are linearly chirped and can be compressed down to 344fs. The second amplifier stage located in the NALM provides an important control parameter allowing stable mode-locking for a variety of output couplers, fibre lengths, filter bandwidths and repetition rates. The laser operates at a repetition rate of 10 MHz which is lower than comparable ANDi laser with the exception of [26]. The laser is a true all-fiber system and therefore environmentally stable. It does not suffer from life-time issue since all the components are passive and do not degrade over time. The laser has now cumulated almost 3000 hours of continuous operation without any discontinuity or fluctuation of the mode-locking operation proving the robustness of the design. We have also simulated the
pulse evolution in the fibre laser with good accuracy and we believe that substantial reductions to the pulse duration are achievable. Further increase of the pulse energy and compression below 100 fs will be the focus of future work. Such a laser architecture will have important applications for chirped pulse amplification systems.

Acknowledgments

The authors gratefully acknowledge Dr. N.S. Kim from EOTechnics for his support including the loan of a fusion splicer, and Southern Photonics Ltd for providing the Pulse Analyser.