

Doubly active Q switching and mode locking of an all-fiber laser

Christian Cuadrado-Laborde,^{1,2,*} Antonio Díez,¹ Jose L. Cruz,¹ and Miguel V. Andrés¹

¹*Departamento de Física Aplicada y Electromagnetismo, Institut Universitari de Ciència dels Materials, Universidad de Valencia, C/ Dr. Moliner 50, Burjassot 46100, Valencia, Spain*

²*Centro de Investigaciones Ópticas (CONICET-CIC), P.O. Box 3, Gonnet 1897, Buenos Aires, Argentina*

*Corresponding author: *Christian.Cuadrado@uv.es*

Received June 9, 2009; revised July 27, 2009; accepted July 31, 2009;
posted August 17, 2009 (Doc. ID 112412); published September 4, 2009

Simultaneous and independent active Q switching and active mode locking of an erbium-doped fiber laser is demonstrated using all-fiber modulation techniques. A magnetostrictive rod attached to the output fiber Bragg grating modulates the Q factor of the Fabry–Perot cavity, whereas active mode locking is achieved by amplitude modulation with a Bragg-grating-based acousto-optic device. Fully modulated Q -switched mode-locked trains of optical pulses were obtained for a wide range of pump powers and repetition rates. For a Q -switched repetition rate of 500 Hz and a pump power of 100 mW, the laser generates trains of 12–14 mode-locked pulses of about 1 ns each, within an envelope of 550 ns, an overall energy of 0.65 μ J, and a peak power higher than 250 W for the central pulses of the train. © 2009 Optical Society of America

OCIS codes: 140.4050, 140.3540, 140.3510, 140.3500.

Mode-locking lasers are widely used in generating ultrashort optical pulses at high frequencies, with uses encompassing optical communications, supercontinuum generation, and nonlinear optics, to mention just a few applications [1]. The generally high pulse repetition rate precludes reaching high pulse energies in these lasers. However, energy enhancement has been reached at ultralow repetition rates, but with consequently ultralong cavity lengths [2]. On the other side, optical pulses generated by Q -switched lasers have lower repetition rates but higher energies. However, their pulses are considerably wider than in mode-locked lasers. Therefore, by combining both operations in a single laser, i.e., a Q -switched mode-locked laser (QML), superior performance is achieved with higher peak powers compared with ordinary mode-locked lasers, but almost the same pulse width as in a mode-locked laser is retained [3–5]. Thus, the peak power of the central pulses of the mode-locked train, underneath the Q -switched envelope, can be greatly enhanced. The increased peak power provided by the Q -switching technique can be advantageous in applications such as wavelength conversion or supercontinuum generation.

All-fiber lasers have the potential of the highest power efficiency, since the cavity losses can be negligible. In addition, they are compact and robust, require virtually no maintenance, produce a good quality beam, and are readily compatible with optical fiber systems. Very few active mode-locked all-fiber lasers have been developed [6–10]. Among them we recently presented an amplitude-modulated (AM) mode-locked all-fiber laser based on an acousto-optic superlattice modulator [10]. Here we expand its applicability by demonstrating simultaneous active Q switching and AM mode-locking operation. To this end, we have been able to combine in the same fiber laser the active mode-locking technique with an active Q -switching technique based on fiber Bragg grating fast modulation using a magnetostrictive device

[11]. This fiber grating modulation technique has a performance superior to the piezoelectric-based approach [12], as we will comment on later. No passive or self-oscillating mechanism is used in our setup, neither for Q switching nor for mode locking. This feature provides direct control of the repetition rate and a fully modulated train of mode-locked pulses. To the best of our knowledge, this is the first doubly active Q -switched mode-locked all-fiber laser presented.

The setup of our QML all-fiber laser is schematically illustrated in Fig. 1. It is composed of a Fabry–Perot cavity in which the gain is provided by 1.5 m of erbium-doped fiber containing 300 parts in 10^6 (ppm) Er^{3+} , with a cutoff wavelength of 939 nm and an NA of 0.24. The active fiber was pumped through a wavelength division multiplexing coupler by a pigtailed laser diode emitting at 976 nm, providing a maximum pump power of 160 mW. The acousto-optically modulated fiber Bragg grating (AOM-FBG) and a short delay line followed by a second fiber Bragg grating, FBG₂, were fusion spliced at each end of the active fiber. The AOM-FBG in turn is composed of an rf source, a piezoelectric disk, and a silica horn and a fiber Bragg grating (FBG₁). The tip of the silica horn was reduced to the same diameter of FBG₁, 125 μm , and subsequently fusion spliced to the grating. A 15-mm-long (1 mm² cross-section) magnetostrictive rod of Terfenol-D was bonded to the fiber at the site of FBG₂; see Fig. 1. The rod and the fiber were placed

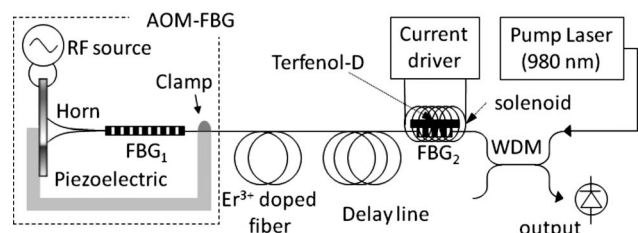


Fig. 1. Doubly active Q -switched mode-locked all-fiber laser setup.

inside a small coil driven by an electronic circuit designed to drive square current pulses with amplitudes up to 260 mA of any required duty cycle. Both uniform gratings were written in photosensitive fiber using a doubled argon laser and a uniform period mask. The FBG₁ was 120 mm long and with a Bragg wavelength of 1531.15 nm, whereas FBG₂ was 10 mm long with a Bragg wavelength of 1530.2 nm.

When a longitudinal acoustic wave in the MHz range is established along the FBG₁, new reflection bands appear symmetrically at both sides of the original Bragg wavelength. The position and strength of these sidebands can be controlled by varying the frequency (ν_{PZT}) and voltage applied to the piezoelectric, respectively [13,14]. In the case of standing acoustic waves, the amplitude of the sidebands is modulated at twice the frequency of the electrical signal used to drive the piezoelectric [10], i.e., $\nu_{M-L} = 2 \times \nu_{PZT}$, where ν_{M-L} is the AM frequency.

Figure 2 illustrates not only the spectral position of both FBGs but also the principle of operation of the QML laser. When the magnetic pulses generated in the solenoid stretch FBG₂, its central wavelength is brought to match the short-wavelength sideband of FBG₁ for short periods of time, which results in an increased Q value. In this way, by modulating the coil current with a frequency ν_{Q-S} , the Q factor is actively modulated at the same frequency. Since the frequency response of the magnetostrictive transducer is basically flat within a wide range of frequencies, the magnetostriction permits continuous tuning of both the Q -switching repetition rate and the duty cycle of the modulation pulses. The modulator that was used in our experiments had a time response of $\sim 1 \mu s$, shorter than the buildup time of the Q -switched pulses. The dependence of the wavelength shift with the coil current was measured by illuminating FBG₂ with a tunable laser source and detecting the reflected light. A quasi-linear behavior was observed as a result of using moderate magnetic fields.

Now we discuss the QML laser operation. The delay line length (see Fig. 1) was selected to match the

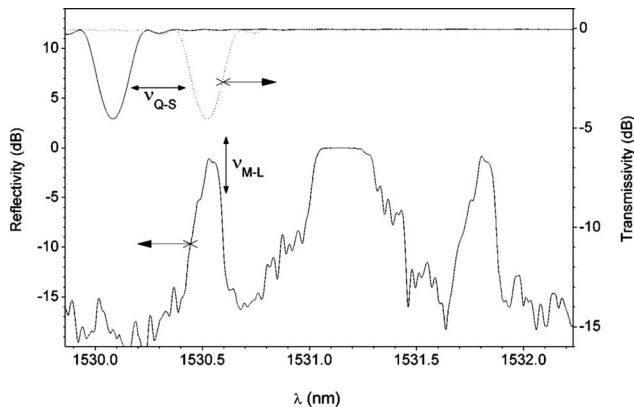


Fig. 2. Reflection spectrum of the AOM-FBG when an RF signal of 4.55 MHz and 16 V (peak-to-peak) is applied to the piezoelectric (left ordinate). Transmissivity of FBG₂ (solid curve) for zero coil current; the dotted curve shows the new spectral position of FBG₂ for a dc coil current of 100 mA (right ordinate).

round-trip time with the reciprocal of the optical modulation frequency, i.e., $2L = c(n\nu_{M-L})^{-1}$, where c is the speed of light in vacuum, n the modal index (~ 1.447), and L is the cavity length. Since the selected piezoelectric operation point was $\nu_{PZT} = 4.55$ MHz (i.e., $\nu_{M-L} = 9.1$ MHz) this results in a cavity length of 11.4 m. The laser emission wavelength is 1530.55 nm, since the overlapping between the short-wavelength sideband of FBG₁ and the shifted position of FBG₂ takes place at this wavelength; see Fig. 2. Figure 3(a) exemplifies the QML laser behavior showing the train of optical pulses generated for a pump power of 70 mW (1 GHz–1 GS/s real-time oscilloscope). The optical QML pulses are 2 ms apart, since the repetition rate of the train of voltage pulses applied to the current driver was of $\nu_{Q-S} = 500$ Hz. The laser arrangement did not include any polarization filter, and different adjustments of a polarization controller located within the laser cavity did not produce significant changes on the laser output. Figure 3(b) shows a single Q -switched envelope with an FWHM of 550 ns; it has between 12 and 14 fully modulated mode-locked pulses, with the expected temporal separation given by $1/\nu_{M-L} \approx 110$ ns. As observed, the QML pulses of this laser have excellent interpulse

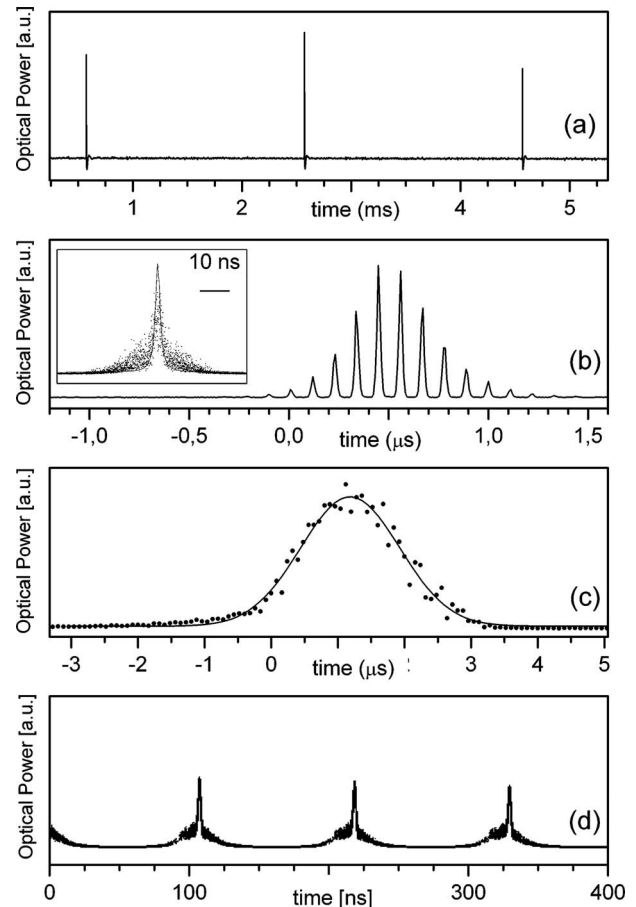


Fig. 3. (a) Q -switched mode-locked train of pulses. (b) Single Q -switched pulse enveloping a train of 12–14 mode-locked pulses; the inset shows a single mode-locked pulse. (c) Single Q -switched pulse with no mode locking. (d) CW mode locking operation of the laser with no Q switching. In all cases, the pump power was 70 mW.

characteristics. However, the individual short pulses are broadened owing to the limited bandwidth and sampling rate of the oscilloscope. To measure the FWHM of the individual short pulses, a 50 GHz sampling oscilloscope was used. In this case, the large difference between the independent frequencies ν_{Q-S} and ν_{M-L} make it difficult to trigger properly the oscilloscope. Even so, relatively good traces were recorded as the one depicted in the inset of Fig. 3(b). This trace includes samples from different pulses, which are likely to have different amplitudes and some timing jitter, but it permits us to establish that the pulses are about 1 ns width. Generally, the presence of Q switching is not likely responsible of temporally broadening each mode-locked pulse [15]. Therefore, we can assume that the pulses are in the subnanosecond range as reported in [10]. It is worthwhile to mention that in this setup the tuning sensitivity between the rf signal applied to the piezoelectric and the cavity round trip is not too critical. Only when the detuning is considerable, e.g., by a few kHz, the pulse clearly deteriorates. Figure 3(c) shows the Q -switched pulse obtained by avoiding the mode-locking pulse formation, just by detuning ν_{PZT} by 10 kHz, in this way only the Q -switching operation is allowed within the cavity. As expected, the Q -switched pulse reproduces the waveform of the envelope of the QML pulses shown in Fig. 3(b), but with a much lower peak power (by a factor of $\sim 4 \times 10^{-3}$) and an increased temporal width. The transition from the fully modulated QML pulses to the pure Q -switching operation, i.e. from Fig. 3(b) to 3(c) was progressive as we detuned ν_{PZT} . Finally, Fig. 3(d) shows the behavior of this laser when we turn off the active Q -switching, i.e., CW mode-locking operation of the laser. To this end, a dc current was driven to the coil of the magnetostrictive device in order to achieve stationary overlap with the short-wavelength sideband of the AOM-FBG. The trace of Fig. 3(d) was recorded with the 1 GHz oscilloscope. In this case, the thermal effects produced by the dc current made difficult an optimum and stable adjustment of FBG₂. The comparison of Figs. 3(b) and 3(d) illustrates the

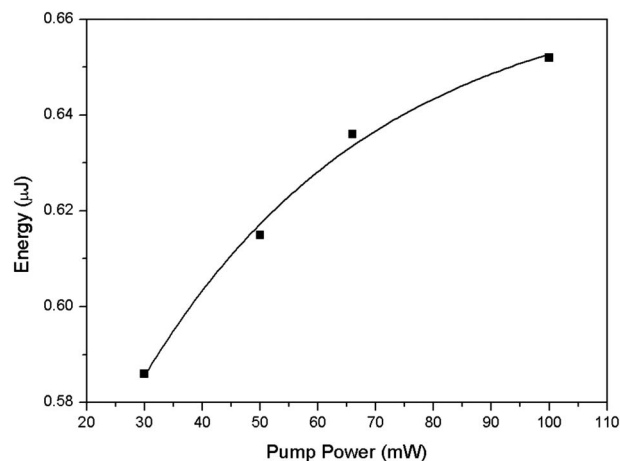


Fig. 4. Energy of QML pulses as a function of the pump power for a repetition rate of 500 Hz.

improved performance of the laser in terms of peak power when both Q -switching and mode locking are operating.

The energy of a Q -switched train of pulses, as that reported in Fig. 3(b), as a function of the pump power is shown in Fig. 4. This energy was measured directly with a pyroelectric detector. At high pump powers, the energy of the QML train of pulses reach gain saturation. Thus, a peak power higher than 250 W can be calculated for the central pulses of a train with energy of $0.65 \mu\text{J}$, assuming that the mode-locked pulses are 1 ns width. This result demonstrates a dramatic enhancement in comparison with the peak power achieved when the laser was operated in CW mode-locking regime [10], since the ratio is higher than 2×10^3 .

In conclusion, we have reported an actively Q -switched AM mode-locked all-fiber laser. This doubly active design—for both mode locking and Q switching—has the advantage of increasing the peak power of the mode-locked pulses, generating trains of pulses at a tunable repetition rate. The laser generates a QML train of ~ 12 pulses, about 1 ns duration each, with an envelope of 550 ns.

This work has been financially supported by the Ministerio de Educación y Ciencia and the Generalitat Valenciana of Spain (projects TEC 2008-05490 and PROMETEO/2009/077, respectively). C. Cuadrado-Laborde acknowledges the Secretaría de Estado de Universidades e Investigación del Ministerio de Investigación y Ciencia (Spain).

References

- H. A. Haus, *IEEE J. Sel. Top. Quantum Electron.* **6**, 1173 (2000).
- S. Kobtsev, S. Kukarin, and Y. Fedotov, *Opt. Express* **16**, 21936 (2008).
- Y. Gan, W. H. Xiang, and G. Z. Zhang, *Laser Phys.* **19**, 445 (2009).
- J. K. Jabczyński, W. Zendzian, and J. Kwiatkowski, *Opt. Express* **14**, 2184 (2006).
- J. H. Lin, H. R. Chen, H. H. Hsu, M. D. Wei, K. H. Lin, and W. F. Hsieh, *Opt. Express* **16**, 16538 (2008).
- D. O. Culverhouse, D. J. Richardson, T. A. Birks, and P. St. J. Russell, *Opt. Lett.* **20**, 2381 (1995).
- M. Y. Jeon, H. K. Lee, K. H. Kim, E. H. Lee, W. Y. Oh, B. Y. Kim, H. W. Lee, and Y. W. Koh, *Opt. Commun.* **149**, 312 (1998).
- N. Myren and W. Margulis, *IEEE Photon. Technol. Lett.* **17**, 2047 (2005).
- M. W. Phillips, A. I. Ferguson, G. S. Kino, and D. B. Patterson, *Opt. Lett.* **14**, 680 (1989).
- C. Cuadrado-Laborde, A. Díez, M. Delgado-Pinar, J. L. Cruz, and M. V. Andrés, *Opt. Lett.* **34**, 1111 (2009).
- P. Pérez-Millán, A. Díez, M. V. Andrés, D. Zalvidea, and R. Duchowicz, *Opt. Express* **13**, 5046 (2005).
- T. Imai, T. Komukai, T. Yamamoto, and M. Nakazawa, *Jpn. J. Appl. Phys.* **35**, 1275 (1996).
- W. F. Liu, P. St. J. Russell, and L. Dong, *Opt. Lett.* **22**, 1515 (1997).
- W. F. Liu, P. St. J. Russell, and L. Dong, *J. Lightwave Technol.* **16**, 2006 (1998).
- J. L. Proctor and J. N. Kutz, *J. Opt. Soc. Am. B* **23**, 652 (2006).