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# High-repetition rate acoustic-induced Q-switched all-fiber laser

D. Zalvidea [a], N.A. Russo [a], R. Duchowicz [a,b], M. Delgado-Pinar [c], A. Díez [c,*], J.L. Cruz [c], M.V. Andrés [c]

[a] *Centro de Investigaciones Opticas, CIOp (CONICET, CIC), La Plata, Argentina*
[b] *Departamento de Física, Fac. Ciencias Exactas, UNLP, La Plata, Argentina*
[c] *Departamento de Física Aplicada, ICMUV, Universidad. de Valencia, Dr. Moliner 50, 46100 Burjassot, Spain*

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## Abstract

We report a high-repetition rate actively Q-switched all-fiber laser. The acousto-optic interaction controls the coupling between co-propagating core and cladding modes and is used to modulate the optical losses of the cavity, which permits to perform active Q-switching. Using 1.4 m of 300 ppm Er-doped fiber and a maximum pump power of 120 mW, we have obtained up to 1 W peak power pulses, with a pulse repetition rate that can be continuously varied from 1 Hz to 120 kHz and a pulse width that changes from 70 ns to 2.2 µs.

*PACS:* 42.55.W; 42.60.G
*Keywords:* Fiber lasers; Q-switching

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## 1. Introduction

The development of new fiber optic laser systems is of permanent interest in the optical field, especially on the communication spectral window. In particular, erbium-doped fiber lasers have shown a variety of potential applications, such as sources for WDM and soliton communications systems, medicine, sensing and spectroscopy. In order to produce an erbium-doped Q-switched laser many different approaches can be employed. Passive Q-switching can be obtained by using a saturable absorber constructed by inserting a segment of samarium-doped fiber into a ring cavity [1]. Active Q-switching was performed using an electro-optic modulator, an acousto-optic modulator (AOM), or an intensity modulator based in the transmission of a coupler in the cavity [2–4].

On the other hand, U-V written fiber Bragg gratings (FBGs) as a reliable fiber technology has

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[*] Corresponding author. Tel.: 34 963983431; fax: 34 963983146.
*E-mail address:* antonio.diez@uv.es (A. Díez).

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generated very important advances in the development of fiber-based devices and systems. In particular, FBGs can be used as all-fiber mirrors to define a Fabry–Perot cavity. The laser emission wavelength is, in this case, determined by the Bragg wavelengths of the fiber gratings. Many designs of fiber lasers for optical communications, making use of fiber gratings to the resonant cavity, have been previously reported [5].

In a previous work, we demonstrated active Q-switching of an erbium-doped fiber laser that employs a pair of fiber Bragg gratings as reflective mirrors. The laser operation was based on modulating the Bragg wavelength of one grating fixed to a piezoelectric ceramic tube. By using this very simple scheme, we obtained a Q-switched laser in the erbium spectral gain region with a high laser efficiency of energy conversion. Pumping at 76 mW and operating the laser at 18.5 kHz, an efficiency of 26% was achieved [6,7].

Recently, Liu and co-workers [8] demonstrated an actively Q-switched fiber laser in which an acousto-optic-based fiber attenuator [9,10] placed inside the cavity was employed to actively control the cavity losses. Microbending induced in the fiber by a flexural acoustic wave produces resonant coupling between the fundamental core mode and cladding modes, which are rapidly attenuated by the fiber coating [11]. Pulses of several μJ per pulse, 150 ns wide and a repetition rate of up to 5 kHz was reported.

In this paper, we report an optimized design of a Q-switched all-fiber laser based on the idea reported by Liu and co-workers [8]. We have included two modifications to Liu's design to improve the performance of the system. First, we used photosensitive erbium-doped fiber, so that the FBG used as reflective elements were written in the active fiber itself, giving rise to a splice-less laser cavity. Second, to enhance the efficiency of the acousto-optic attenuator, it was made on a section of fiber that was tapered down using a fusion-and-pulling technique. This allows making acousto-optic attenuators as efficient as the one used in [8], which was made using HF etching, but with smaller reductions of the fiber diameter. This is relevant to the performance of the Q-switched laser, i.e. the maximum repetition rate achievable, since the time response of the attenuator shortens as the fiber diameter increases due to the dependence of the acoustic velocity with the diameter [11].

We demonstrate a Q-switched laser with up to 1 W peak power, pulses from 70 ns to 2.2 μs wide, and a pulse repetition rate that can be continuously varied from 1 Hz to 120 kHz.

## 2. Experimental setup and results

Fig. 1 shows a schematic diagram of the Q-switched erbium-doped fiber laser. The fiber used in the experiments was an erbium-doped germanosilicate fiber containing 300 ppm $Er^{3+}$, with a cut-off wavelength of 965 nm, and a numerical aperture (NA) of 0.23. Two Bragg gratings, FBG1 and FBG2, were written on the core of the $Er^{3+}$-doped fiber by UV exposure using a doubled argon laser and a uniform period phase mask, to define a cavity of 140 cm in length. The fiber was hydrogen loaded to enhance its photosensitivity. The Bragg wavelength of both FBGs was 1546.6 nm. The reflectivity of FBG1 and FBG2 was 60% and 99%, respectively, and the bandwidth was 0.15 and 0.25 nm.

The acousto-optic attenuator was implemented on the $Er^{3+}$-doped fiber itself. Flexural acoustic waves were imposed on the fiber using a piezoelec-

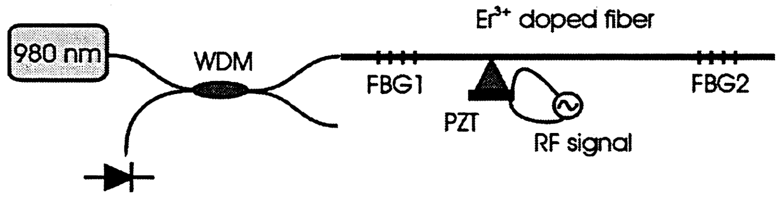

Fig. 1. Experimental setup.

tric transducer (a PZT ceramic disc of 1 cm diameter) driven by a RF signal, and an aluminum horn (see Fig. 1). The acousto-optic interaction takes place in a section of 8 cm long of the $Er^{3+}$ fiber. To enhance the acousto-optic interaction, this section of fiber was tapered down from 125 to 80 μm in diameter using a standard fusion-and-pulling tapering technique [12]. We found that resonant coupling between the fundamental core mode $LP_{01}$ and the $LP_{12}$ cladding mode occurred at around 1.55 μm when the frequency of the RF signal was 1.2 MHz. Fig. 2 shows an example of the transmission spectrum of the fiber when an RF signal of 1.201 MHz and an amplitude of 15 V was applied to the piezoelectric. An attenuation peak centered at 1546.6 nm (i.e., the Bragg wavelength of the FBGs) as deep as 16 dB is observed. The inset of Fig. 2 shows the tunability of the dip with the frequency of the RF signal. Coupling from the $LP_{01}$ to other cladding modes was also observed for other frequencies. Measurements shown in Fig. 2 were done before the FBGs were written.

Fig. 3 shows the time response of the acousto-optic attenuator. For this experiment, the fiber was illuminated using a laser diode tuned at the acousto-optic resonant wavelength and the FBGs were detuned to avoid reflections from them. Fig. 3(a) shows the electrical signal applied to the piezoelectric transducer and Fig. 3(b) shows the corresponding optical transmission. The switching time, i.e., the time that the signal takes to change from 100% to 0%, is about 50 μs. This value is an order of magnitude shorter than the best value reported in [8]. A delay of 30 μs between the electrical and the optical signals is also observed, which is caused by the overall system that generates the acoustic wave.

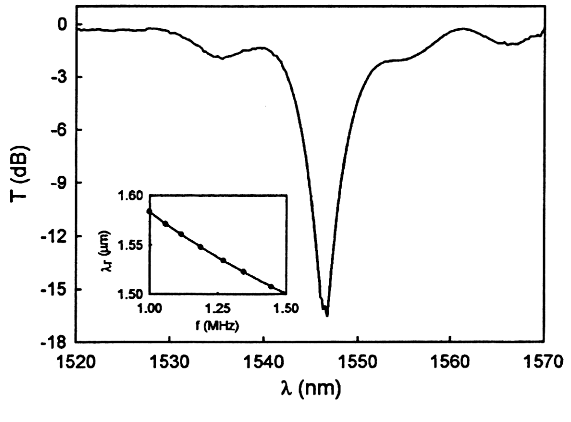

Fig. 2. Transmission spectrum when an electrical signal of 15 V and 1.201 MHz is applied to the piezoelectric. The dip is caused by the resonant coupling between the $LP_{01}$ core mode and the $LP_{12}$ cladding mode. Inset: acousto-optic resonant wavelength $\lambda_r$ as a function of the RF frequency.

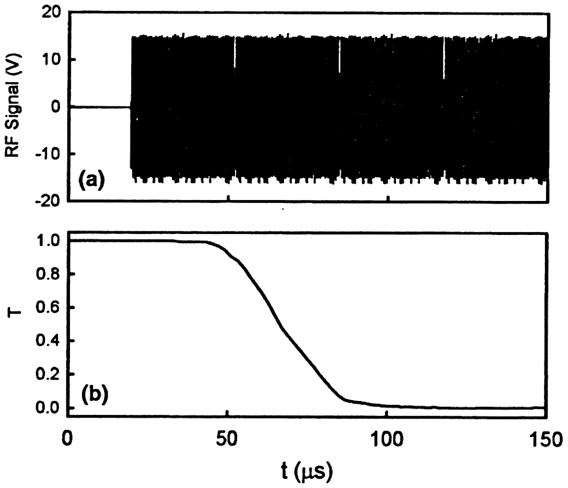

Fig. 3. Time response of the acousto-optic process. (a) Electrical signal applied to the piezoelectric and (b) light transmission.

The active medium was pumped through a WDM coupler using a pigtailed semiconductor laser diode (980 nm, 125 mW of maximum optical power). The optical output from FBG1 was detected using a 125 MHz bandwidth InGaAs photodetector. The efficiency of the fiber laser in CW operation (without acoustic excitation) was about 5% and the threshold was 4 mW.

To perform Q-switching, the RF signal was amplitude modulated by a rectangular wave of variable frequency and duty cycle. This modulation produced on–off periods of the acoustic wave being imposed to the fiber, which results in a modulation of the cavity losses at the laser emission wavelength.

Fig. 4 shows an example of the laser system running at 10 kHz. Fig. 4(a) is the laser signal and Fig. 4(b) shows the modulation signal. The duty cycle was adjusted to optimize the amplitude and the stability of the pulses. Fig. 4(c) shows the performance of the fiber attenuator under the same

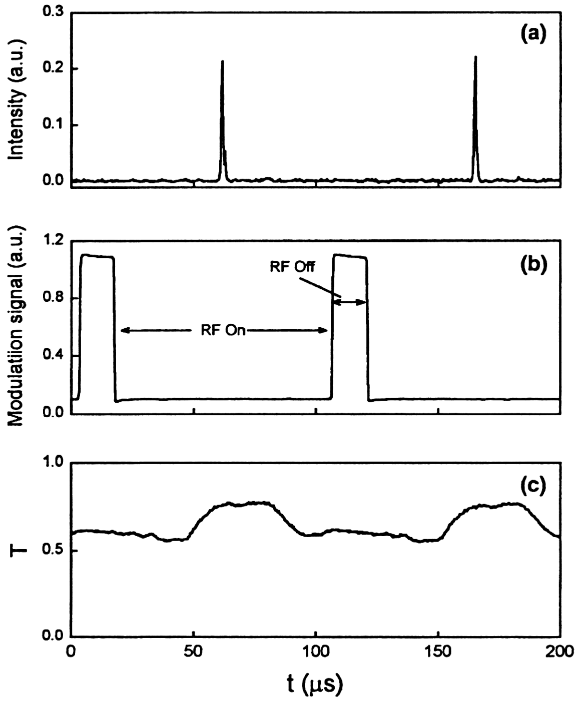

Fig. 4. (a) Laser output when operating at 10 kHz. (b) Corresponding modulation signal. (c) Light transmission under the same piezoelectric excitation.

piezoelectric excitation. This measurement was done in a similar way as in Fig. 3 (with no pump and detuning the FBGs to avoid reflections), and it shows that just a few percent of attenuation change is enough to generate Q-switching. Fig. 5 shows an example of the laser operating at 120 kHz. Higher repetition rates could be attainable by reducing the time response of the acousto-optic attenuator. This could be achieved, for example, by shortening the length of the acousto-optic attenuator, provided that enough acoustic power is available to obtain the required attenuation level to perform Q-switching.

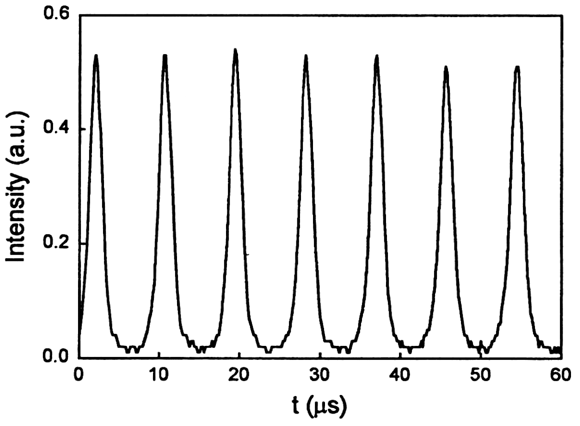

Fig. 5. Laser output when operating at 120 kHz.

Fig. 6(a) gives the output peak power of the Q-switched laser pulses against the continuous pump power, for several repetition frequencies. Pulses of up to 1 W were obtained at low frequencies. Pulse-to-pulse fluctuation of the peak power was typically about 5%. Fig. 6(b) gives the peak power and the pulse width as a function of the repetition rate, when pumping at 85 mW. Around 1–2 kHz the peak power starts to decrease significantly and the pulse width to increase, as expected for a medium with an upper-level effective lifetime of 1 ms. Pulses from 70 ns to 2.2 μs wide were obtained. The long microsecond pulses at high-repetition rates may limit the use of the system in some applications. Shorter pulses could be obtained by reducing the length of the laser cavity and also by improving the time response of the acousto-optic modulator.

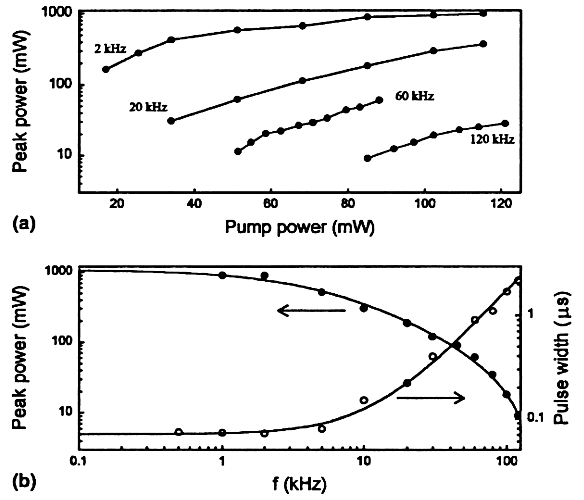

Fig. 6. (a) Optical peak power versus continuous pump power, for several pulse repetition frequencies. (b) Optical peak power and pulse width against pulse repetition frequency when pumping at 85 mW.

## 3. Summary

In summary, we have reported a high-repetition rate acoustic-induced Q-switched all-fiber laser. A single piece of $Er^{3+}$-doped germanosilicate fiber has been employed to make the laser, writing the FBGs and performing the modulation of the cavity losses in the fiber itself. Q-switching was performed by controlling the optical losses in the $Er^{3+}$ fiber by coupling light from the core mode to cladding modes using flexural acoustic waves. The active Q-switching can be operated continuously from 1 Hz to 120 kHz and the pulse width changes from 70 ns to 2.2 μs. Using 1.4 m of 300 ppm Er-doped fiber and pumping powers lower than 120 mW, up to 1 W peak power pulses were achieved at 2 kHz repetition rate.

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