Q-switched all-fiber laser based on magnetostriction modulation of a Bragg grating

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Abstract: We report an actively Q-switched all-fiber laser based on magnetostriction modulation of a Bragg grating. The laser employs a pair of Bragg gratings as reflective mirrors, one of which is bonded to a magnetostrictive element. Lengthening of the magnetostrictive element when a magnetic field is applied shifts the Bragg wavelength of the grating, allowing control of the Q-factor of the cavity and, thus, performing active Q-switching. The magnetostrictive modulator is small, compact and requires less than 300 mW electrical drive power. Using erbium-doped fiber and a maximum pump power of 120 mW, Q-switch pulses of more than 1 W peak power were obtained, with a pulse repetition rate that can be continuously varied from 1 Hz to 125 kHz.

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1. Introduction

The development of new fiber optic laser systems is of permanent interest in the optical field, especially within 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. The development of fiber lasers experienced very important advances since fiber Bragg gratings (FBGs) came out. In particular, FBGs are used as laser cavity reflective elements and many designs of fiber lasers for optical communications making use of FBGs have been reported [1].

Q-switching of fiber lasers is a suitable technique to obtain short and powerful pulses, which are required in many applications such as optical time-domain reflectometry (OTDR), sensing and materials processing. Many different approaches can be employed to develop an erbium-doped Q-switched laser. Passive Q-switching can be obtained by using a saturable absorber element placed inside the laser cavity. Different crystalline materials have been used as saturable absorbers, as Co^{2+}:ZnS [2] and Co^{2+}:ZnSe [3]. Passive Q-switched fiber lasers have also been demonstrated using semiconductor saturable-absorber mirrors (SESAM) [4]. An all-fiber scheme of a passive Q-switched laser has been proposed [5]; it includes a section of samarium-doped fiber as saturable absorber, although, to our knowledge, an experimental demonstration of such a laser has not been reported.

Active Q-switching is performed by modulating the cavity losses using typically bulk components as electro-optic modulators [6] and acousto-optic modulators [7]. The use of bulk intracavity switching elements causes degradation of the beam quality and it is at the origin of high cavity losses, which results in a decrease of the overall performance of the laser, often forcing the use of higher pump powers. Moreover, bulk components require fine alignment and good mechanical stability, which really complicates the design of a practical device. Very few all-fiber approaches have been reported. Chandonnet et al. [8] demonstrated Q-switching of a fiber laser using an all-fiber intensity modulator, Liu et al. [9] employed an all-fiber acoustooptic-based attenuator as cavity loss modulator.

Recently, Q-switching of an erbium-doped fiber laser (that used a pair of FBGs as cavity mirrors) was demonstrated by tuning the Bragg wavelength of one FBG fixed to a piezoelectric tube [10]. This laser exhibited a high laser efficiency of energy conversion and an efficiency of 26 % was achieved when pumping at 76 mW. The pulse repetition rate of the laser was fixed at 18.5 kHz, being this frequency a resonant frequency of the piezoelectric. At frequencies out of resonance, the deformation of the piezoelectric was not large enough to generate overlapping between both FBGs and Q-switching could not be performed.

In this letter, we present an actively Q-switched all-fiber laser in which a magnetostrictive-based modulator (MM) is used to modulate the Q-factor of the laser cavity. The MM consists of an FBG bonded to a magnetostrictive element (the 'transducer'). When a magnetic field is applied, the transducer increases its length and stretches the FBG, which shifts its Bragg wavelength [11]. This allows optimizing the cavity and producing Q-switching. Since the frequency response of the magnetostrictive transducer is basically flat within a wide range of frequencies, the MM permitted continous tuning of the pulse repetition rate of the Q-switched laser from 1 Hz to 125 kHz.

2. The magnetostrictive modulator

The transducer consisted of a square-shaped bar made of Terfenol-D ($Tb_{0.27}$ $Dy_{0.73}$ Fe_2), a magnetostrictive material that has a giant magnetostriction of the order of 1000 ppm for a magnetizing field of 100 mT when it operates at room temperature free of mechanical stress. The dimensions of the bar were 15 mm in length and 1 mm^2 cross-section. The upper limit of the frequency response of Terfenol-D transducers is generally due to eddy current losses. The critical frequency is inversely proportional to the cross-section area of the bar, thus, it can be increased by reducing the cross-section of the transducer. Nominally, the critical frequency of our transducer was 75 kHz, although significant magnetostriction was observed at frequencies up to 125 kHz with moderate magnetic fields.

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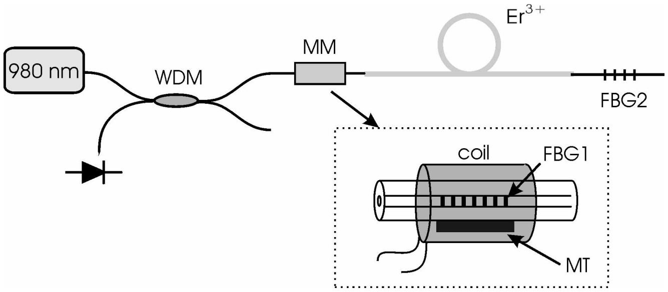

Fig. 1. Q-switched all-fiber laser arrangement. MM: magnetostrictive modulator, MT: magnetostrictive transducer.

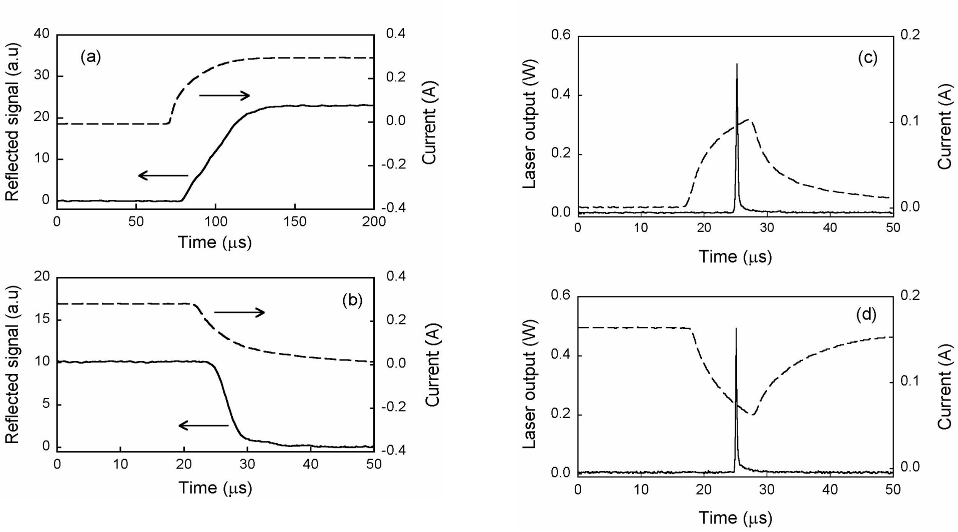

Fig. 2. (left) Time response of the magnetostrictive modulator when the current is switched on (a) and switched off (b). (right) Q-switch laser pulse emitted when the reflection band of the FBGs overlap as the current is switched on (c) and switched off (d). The current applied to the coil is also plotted in all cases (dashed line).

An FBG (labeled as FBG1 in Fig. 1) was bonded to the transducer and placed inside a 15 mm long, 10 mm outer diameter magnetic coil, leading to a really small, light and compact device. The coil consisted of 800 turns, having an electrical resistance of 5.8 ohms. In all the experiments reported in this paper, the magnetic coil was driven simply by a square pulse generator, and no matching circuits were employed. FBG1 was written on conventional photosensitive fiber by UV exposure using a doubled argon laser and a uniform period phase mask. Its Bragg wavelength was 1544 nm, it was 13 mm long, with a reflectivity of 80% and a bandwidth of 0.15 nm.

The MM was operated along all the experiments at moderate magnetic fields, thus, quasi-linear behavior of the transducer was observed. The Bragg wavelength of our device shifts at a rate of 0.4 nm/A applied to the coil. Currents of the order of 200 mA were enough to generate a wavelength shift equivalent to the spectral bandwidth of FBG1, which was sufficient to perform Q-switching. Notice that the requirement of electrical drive power was as low as 230 mW.

Figure 2 contains the typical time response of the MM. For this experiment, the Bragg grating was illuminated using a tunable laser (TL). Figure 2(a) shows the reflected signal when the TL is tuned 0.1 nm away from the Bragg wavelength and initially no electrical current is applied to the coil. When current is applied, the FBG's reflection band shifts and overlaps the TL emission, so the reflected signal goes from zero to its maximum. Figure 2(b) corresponds to the case in which initially the current is on and the FBG's reflection band overlaps the TL. When current is switched off the reflection decays from its maximum to zero. Note that the time response is different, being longer in the first case (about 40 μs) than in the second one (about 10 μs). This effect is caused by the hysteresis of the magnetostrictive material.

The switching speed of the MM is basically limited by two factors: the rise time of the current in the coil due to its self-inductance, and the frequency response of the magnetostrictive transducer. The rise time of the current can be significantly shortened using a proper electric matching circuit. Preliminary results with just a capacitor and a resistance showed that the time response can be reduced down to 1 μs. The second limiting factor, i.e. the frequency response of the magnetostrictive element, can also be improved if thinner transducers are used, as mentioned above.

3. The Q-switched all-fiber laser

To demonstrate the feasibility of the MM to perform Q-switching, we set up a Fabry-Perot type fiber laser, Fig. 1. The active 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 of 0.23. The active fiber was pumped through a WDM coupler with a pigtailed semiconductor laser emitting at 980 nm with 125 mW of maximum optical power. The MM and a second fiber Bragg grating, FBG2 (1544 nm Bragg wavelength, 99% reflectivity and 0.1 nm bandwidth) were spliced at each end of the gain fiber, defining a cavity length of about 1.9 m. The output of the Q-switched fiber laser was taken from FBG1 and the signal was detected with a 125 MHz bandwidth InGaAs photodetector

Both modulation options shown in Fig. 2 (a) and (b) can be exploited to perform Q-switching. Fig. 2 (c) and (d) show two examples of the Q-switched laser running at low frequency, 1 kHz. The current applied to the coil is also shown. In Fig. 2 (c), initially both FBG were detuned by applying some mechanical stress to FBG2, thus, no laser emission happened. Q-switching pulses were obtained by switching on the current, and so that optimizing the laser cavity during a short time. In Fig. 2 (d), initially both FBGs overlap, thus the laser cavity was optimized when the current was off. When pumping, laser emission was avoided by applying current to the coil. When the current wass switched off a pulse was generated. In both cases, the time delay between the current being switched and the laser peak was similar, about 8 μs. Narrower pulses were observed when the laser was operated as in Fig. 2 (d), given that the fast switching mode of the modulator is exploited (Fig. 2 (b)). However, in this case, when the laser system operates at low frequencies, the system requires current to be applied to the coil most of the time, which can cause thermal instabilities of the FBG due to heating of the coil.

The pulses had a quasi-gaussian shape, Fig. 3 (a). Each pulse is splitted on 18 ns pulses with a repetition rate of 53 MHz. This effect is well known in actively Q-switched lasers and it is caused by a self-mode-locking effect [12]. Figure 3 (b) shows an example of the laser operating at 125 kHz, which is the maximum pulse repetition rate achieved with our setup. At such a frequency no evidence of self-mode-locking effect was observed, in accordance with the decrease of pulse energy and elongation of the pulse width.

Fig. 4 (a) gives the output peak power of the Q-switched laser against the continuous pump power, for several pulse repetition frequencies. Pulses of more than 1 W peak power were obtained at low frequencies. It is expected that the laser will perform properly at higher pump powers than the available pump powers for the present experiments. The maximum pump level will be determined by reflections in splices and FBG sidelobes, which can induce lasing when the FBGs are detuned if high gains are involved. Fig. 4 (b) gives the pulse width as a function of the repetition rate when pumping at 76 mW and operating the laser as in Fig.

2 (c). The pulse width runs from 180 ns at low frequencies to up to 1.1 μs at the highest frequency achieved, 125 kHz. Values of pulse peak powers and pulse widths are averaged measurements over the multiple mode-locked peaks of the pulses. Present results are limited by the MM response, as Fig. 2 shows, since the laser pulse is emitted before the MM feeding current reaches a stationary state. Shortening of the switching time of the MM will lead to narrower pulses with higher peak powers, as well as higher pulse repetition rates. The simplicity of the proposed Q-switching technique makes it suitable for being implemented on other family of fiber lasers, as Yb or Er-Yb doped lasers, and cladding-pumped large-mode-area lasers, in order to achieve higher average power and pulse energies.

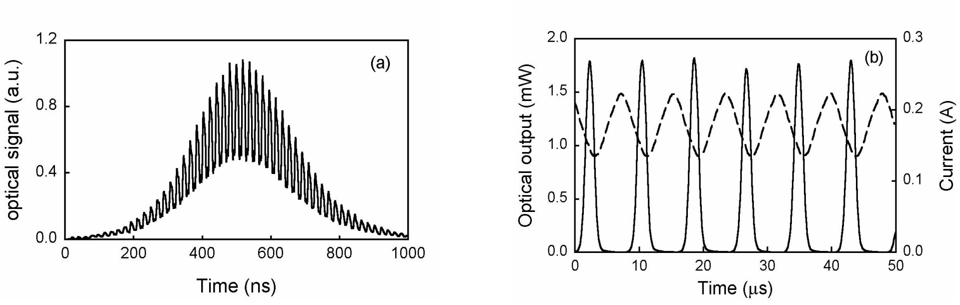

Fig 3. (a) Pulse shape for a 15 mW pump power and 1 kHz pulse repetition rate. (b) Laser output when operating at 125 kHz (solid line) and current applied to the magnetic coil (dashed line).

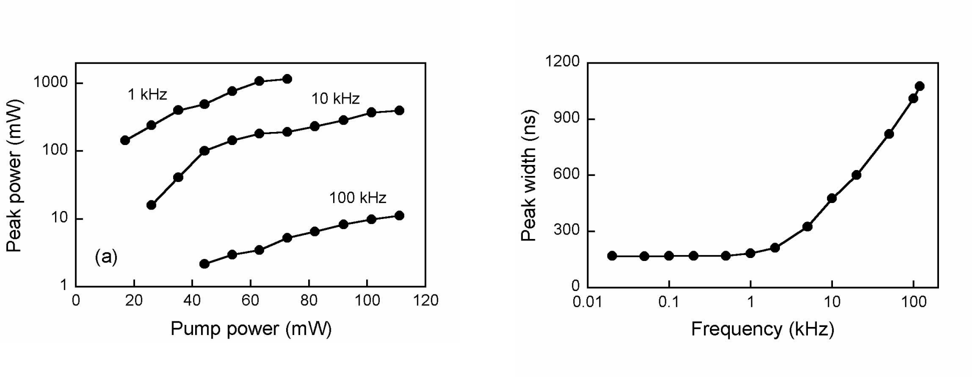

Fig4. (a) Optical peak power versus continuous pump power for several pulse repetition frequencies. (b) Pulse width against pulse repetition frequency when pumping at 76 mW.

4. Summary

In summary, we have reported a suitable technique to produce active Q-switching in an all-fiber laser. The switching device is based on the modulation of the Bragg wavelength of a fiber grating using a magnetostrictive transducer. The magnetostrictive modulator is small, compact and requires low electrical drive power. The repetition rate of the active Q-switching can be tuned continuously from 1 Hz to 125 kHz. Using a pump power of 60 mW, pulses of more than 1 W peak power were obtained at 1 kHz repetition rate, with a pulse width below 200 ns. Improvements in the magnestostrictive modulator to obtain faster responses and tests of the Q-switching technique on Yb-doped fiber lasers to achieve higher peak powers are currently in progress.

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