Q-switching of an all-fiber laser by acousto-optic modulation of a fiber Bragg grating

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Abstract: We report active Q-switching of an all-fiber laser using a Bragg grating based acousto-optic modulator. Q-switching is performed by modulating a fiber Bragg grating with an extensional acoustic wave. The acoustic wave modulates periodically the effective index profile of the FBG and changes its reflection features. This allows controlling the Q-factor of the cavity. Using 1 m of 300 ppm erbium-doped fiber and a maximum pump power of 180 mW, Q-switch pulses of 10 W of peak power and 82 ns wide were generated. The pulse repetition rate of the laser can be continuously varied from few Hz up to 62.5 kHz.

OCIS codes: (060.2310) Fiber optics; (140.3510) Lasers, fiber; (140.3540) Lasers, Q-switched; (230.1040) Acousto-optic devices

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1. Introduction

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), material processing, and remote sensing. Many different approaches can be employed to develop Q-switched fiber lasers. Passively Q-switched lasers have very simple structures but the repetition frequency can not be modified with independence of other operation parameters. Passive Q-switching can be generated by using a saturable absorber placed inside the laser cavity. Different crystalline materials have been used as saturable absorbers, as Co^{2+}:ZnS [1] and Co^{2+}:ZnSe [2]. Recently, a passively Q-switched all-fiber laser that utilizes a section of samarium-doped fiber as saturable absorber has been reported [3]. Passively Q-switched fiber lasers have also been demonstrated using semiconductor saturable-absorber mirrors (SESAM) [4].

Active Q-switching is performed by modulating the quality factor Q of the laser cavity using typically bulk components, as electro-optic [5] and acousto-optic modulators [6]. The use of bulk intracavity switching elements is at the origin of high cavity losses, which results in a decrease of the overall performance of the laser. Moreover, bulk components require fine alignment and good mechanical stability, which makes difficult the design of practical devices.

In the last years, several all-fiber approaches based on different modulation techniques, as all-fiber intensity modulators [7], and all-fiber acoustooptic attenuators [8-9] have been reported. Q-switching of all-fiber lasers by tuning two FBG's using piezoelectric [10] and magnetostrictive transducers [11] have also been demonstrated.

In 1997, Liu *et al*. [12] demonstrated a Bragg grating-based acousto-optic superlattice modulator. An extensional acoustic wave propagating along the grating produces periodic stretching and compression of the FBG. As a result, the effective index profile of the FBG is periodically modulated, which causes that additional bands of reflection appear on both sides of the Bragg wavelength. A full theoretical description of this effect can be found in Ref. [13]. Recently, we demonstrated a wavelength-switchable fiber ring laser that takes advantage of this effect [14].

In this paper we demonstrate active Q-switching of an all-fiber laser by utilizing a Bragg grating-based acousto-optic modulator (BG-AOM). A Fabry-Perot configuration is used for the laser cavity and it is formed by overlapping the reflection wavelength of a fiber Bragg grating and one of the sidebands of the BG-AOM. By means of the acoustic power launched into the fiber, the reflectivity of the BG-AOM reflection band is controlled, so the losses of the cavity can be varied in a dynamic way. Using a short length of 300 ppm erbium-doped fiber and a maximum pump power of 180 mW, Q-switch pulses of 10 W of peak power and 82 ns wide were generated. The pulse repetition rate of the laser can be continuously varied from few Hz up to 62.5 kHz.

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2. The Bragg grating-based acousto-optic modulator

A schematic diagram of the BG-AOM is shown in Fig. 1. The grating, FBG1, was written in the core of a previously tapered fiber. The fiber was tapered to enhance the acousto-optic interaction [12]; the taper had a 55 mm long uniform waist of 100 μm in diameter, and the transitions were 12 mm in length. FBG1 was written along the uniform waist of the taper, its length was L = 5 cm, the bandwidth was 0.1 nm and the reflectivity was higher than 99.9 %. A value of 6 was estimated for the κL factor of the grating, where κ is the coupling coefficient.

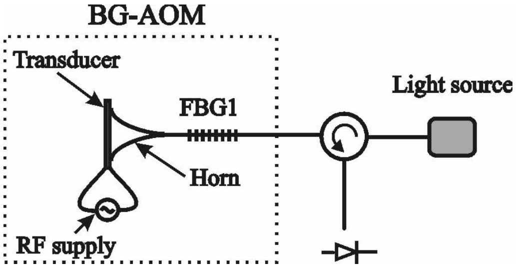

Fig. 1. The Bragg grating-based acousto-optic modulator.

Longitudinal acoustic waves, generated with a piezoelectric disk driven by an RF signal generator, were launched into the fiber Bragg grating using a silica horn. The tip of the horn was reduced down to 125 μm in diameter, and then spliced to the fiber. We paid special attention to the splice between the silica horn and FBG1 in order to avoid acoustic and optical reflections from it.

Figure 2 summarizes the performance of our BG-AOM. Figure 2(a) shows the reflection spectra from the modulator, measured with a resolution of 1 pm, for three RF electric signals of frequency 1 MHz, 2.66 MHz and 5.5 MHz. As it has been reported before [14], the wavelength shift of the sidebands, $\Delta\lambda$, from the Bragg wavelength increases linearly with frequency (see Fig. 2(c)). The experimental separation between two adjacent sidebands increases with frequency at a rate of 0.142 nm/MHz.

Figure 2(b) shows the reflection spectra from the BG-AOM for three amplitudes of the RF signal, and a fixed frequency of 1.017 MHz. These spectra were taken using an OSA, with a spectral resolution of 20 pm. The top one is the original grating. The second shows an example in which three sidebands can be observed; the first-order sideband is of the same amplitude as the central band, i.e., the original band. If the voltage amplitude is increased further, the reflectivity of the central band can be reduced until it practically disappears (bottom). In this example, the reflection band of the original grating is reduced in about 16 dB. Figure 2(d) gives the reflectivity of the first four bands, the central band and three sidebands, as a function of the voltage amplitude applied to the piezoelectric. Lines represent the results obtained from fitting the Eq. (2) given in [12] to our experimental data. When the RF amplitude is around 6 volts, the reflectivity of the first sideband is close to one. A minimum of the central band's reflectivity happens for a voltage amplitude of 16 V.

The time response of the BG-AOM was also investigated, Fig. 3. The BG-AOM was illuminated with a tunable laser diode which wavelength of emission was tuned to match one of the sidebands. The frequency of the RF signal is 2.66 MHz. The optical signal reflected from the BG-AOM takes around 20 μs to reach the steady state. This time corresponds to the time that the acoustic wave takes to travel along the grating length. This measurement was done also at other frequencies of the acoustic wave, 1 MHz and 5.5 MHz, and similar results were obtained. This agrees with the fact that the velocity of the lowest longitudinal elastic mode in an optical fiber is practically constant within this range of frequency [15]. A delay of 50 μs between the electrical and the optical signals is observed. This delay is due to the overall system that generates the acoustic wave, the main contribution coming from the propagation of the acoustic wave through the horn.

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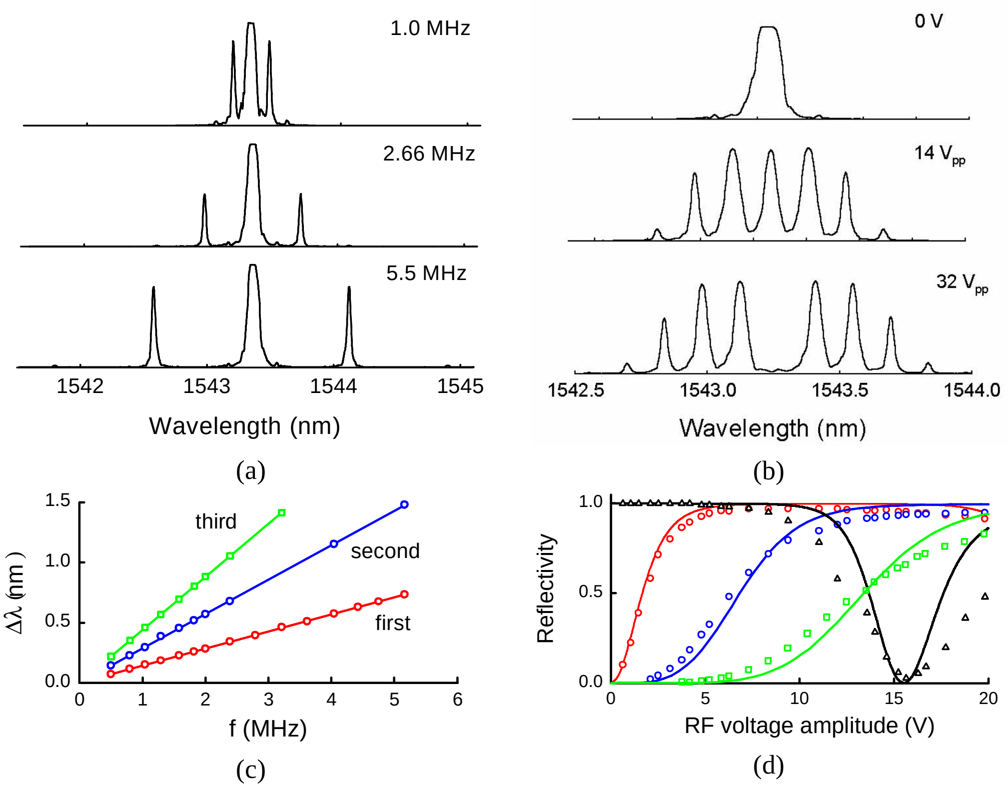

(a) (b)

(c) (d)

Fig. 2. (a) Reflection spectra for three different frequencies of the RF-signal and amplitudes (from top to bottom) of 4, 13 and 38 V. (b) Reflection spectra for three voltage amplitudes of the RF signal and a fixed frequency of 1.017 MHz. (c) Wavelength shift from the Bragg condition of the first-, second- and third-order sidebands, as a function of frequency. (d) Peak reflectivity of the central band (black) and first- (red), second- (blue) and third-order (green) sideband as a function of the RF voltage amplitude applied to the piezoelectric. The scale of vertical axis in (a) and (b) is linear.

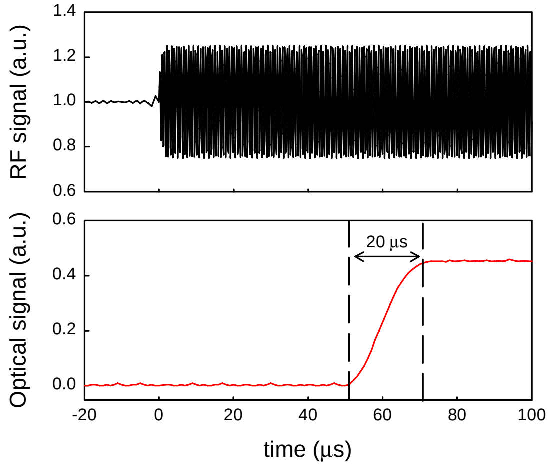

Fig. 3. Time response of the BG-AOM. (top) RF electric signal applied to the piezoelectric disk and (bottom) the optical signal reflected by one of the sidebands of the modulator.

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3. The Q-switched all-fiber laser

A schematic diagram of the Q-switched all-fiber laser is shown in Fig. 4. The gain was provided by 1 m of erbium-doped fiber that was pumped through a WDM coupler with a 980 nm pigtailed laser diode, providing a maximum pump power of 180 mW. The Er^{3+} concentration in the fiber core was 300 ppm, and the absorption at 979 nm was 5.5 dB/m. A fiber Bragg grating spliced to the erbium fiber, FBG2, acts as the output reflector of the laser. The Bragg wavelength was 1543.2 nm, the bandwidth 0.04 nm and the reflectivity was 70 %. A translation stage was used for tuning the Bragg wavelength of this grating to the first sideband of the BG-AOM. At the other end of the erbium-doped fiber, the laser incorporates the BG-AOM. In this arrangement, when the RF signal generator is on, the sideband of the BG-AOM appears and overlaps the reflection band of the output grating. This can be used to optimize the laser cavity for a short period of time and, as a result, laser emission in the form of strong pulses is obtained.

Fig. 4. The Q-switched all-fiber laser arrangement.

Figure 5 shows the CW laser emission spectra, measured with a resolution of 20 pm, for three RF frequencies. For each frequency, the output grating was tuned to overlap the first order right-hand sideband of the BG-AOM. This measurement indicates a signal-to-noise ratio of at least 55 dB. No emission was observed when the RF signal generator was off and the pump power was maximum (red curve). The efficiency of the laser in continuous wave when the RF signal was 1 MHz was 3 % and the threshold 10 mW. Inset of Fig. 5 shows the emission spectrum of the laser measured with high resolution. This result was obtained using a very high-resolution optical spectrometric technique based on filtering and amplification of the measured optical signal by means of stimulated Brillouin scattering (SBS). This technique allows 0.08-pm resolution and more than 80-dB dynamic range. More details can be found in Ref. [16]. The multimode nature of the laser, as well as polarization line splitting can be observed.

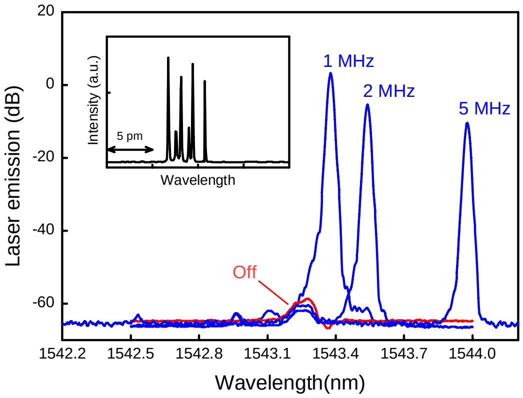

Fig. 5. Laser emission spectra for three frequencies of the acoustic wave (blue). Spectrum when the RF generator was off and the output grating was tuned as in 1 MHz (red). The pump power in all cases was 180 mW. Inset: emission spectrum measured with resolution of 0.08 pm.

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Figure 6 shows a pulse train emitted by the laser at a repetition rate of 20 kHz. The frequency of the RF signal was 1.017 MHz. To obtain on-off periods of the acoustic wave propagating along the grating, the RF signal was modulated in amplitude by a rectangular signal (shown in red). A detailed inspection of the Q-switched pulses reveals that each pulse is split into 5 ns wide pulses, with a repetition rate of 53 MHz. This frequency agrees very well with the round-trip time of the cavity. The self-mode-locking behavior is well known and has been observed in both, passively [2] and actively [17] Q-switched fiber lasers. Myslinski et al. [18] proposed a mechanism in which the self-mode-locking formation is forced through mode beats between axial modes of the cavity and is supported by further more coupling induced by self-phase modulation. A more detailed analysis can be found in [18]. The modulation depth in this example is about 50 %. We observed an increase of the modulation depth with pump power, in accordance with the increase of energy stored in the cavity.

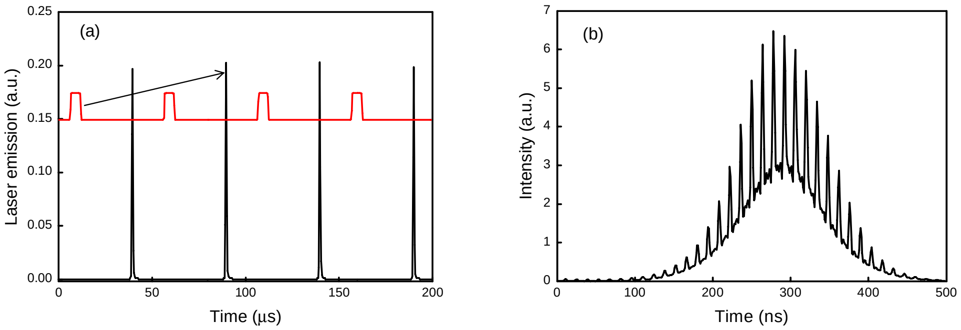

Fig. 6. (a) Laser output when operating at 20 kHz (black). Rectangular electric signal used to modulate the RF signal (red). (b) Typical pulse shape, showing self-mode-locking

The effect of pump power on the Q-switch pulses is shown in Fig. 7(a). As expected, the peak power of the pulses increases with pump power, and there is a corresponding reduction of pulse width. At 1 kHz repetition rate, the pulse width decreases from 157 ns at the lowest pump power, down to 82 ns at the maximum pump power available. Pulses of nearly 10 W of peak power were generated by pumping with 180 mW.

Figure 7(b) shows the effect of the repetition rate on the Q-switch pulses. The peak power starts to fall off and the pulse width to increase for frequencies above 1 kHz, due to the recovery time of the Er^{3+} system. Pumping with 180 mW, the pulse width increases from 82 ns for the strongest peaks generated at low frequency, up to 800 ns at the highest repetition rate achieved, 62.5 kHz.

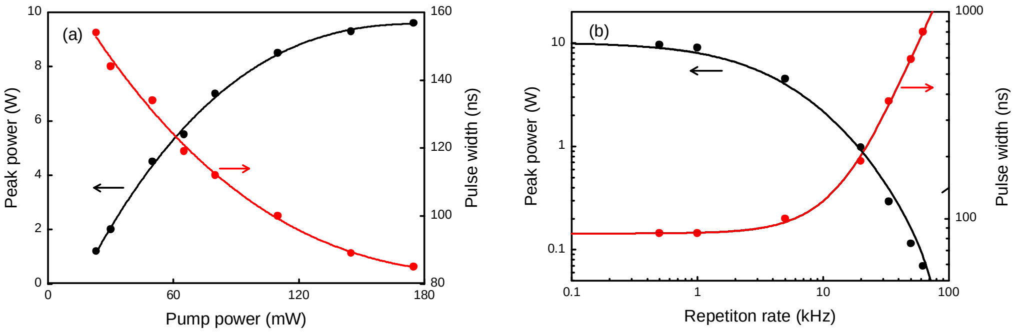

Fig. 7. (a) Peak power and pulse width as a function of pump power. Repetition rate 1 kHz. (b) Peak power and pulse width as a function of repetition rate. Pump power 180 mW.

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As described above, the peak reflectivity of the central band of the BG-AOM can be reduced by the acousto-optic interaction (see Fig. 2(b)). This can also be exploited to modulate the Q factor of the cavity and to generate Q-switching. In this mode, the output grating is tuned to overlap the central band of the BG-AOM. We carried out experiments using this configuration and we found three main disadvantages, (1) more acoustic power is required to reduce the central band than to generate a sideband, (2) at low repetition rates, the RF signal generator is on most of the time, and this can occasionally cause heating of the piezoelectric, and (3) we observed insufficient holdoff of the modulator at high pump powers, which limits the maximum pump power allowed before the occurrence of cw lasing. With 130 mW pump power, pulses of 5 W of peak power and 100 ns wide were obtained at 1 kHz using this configuration.

In order to generate stronger Q-switch pulses, experiments using fibers with higher concentrations of erbium are currently in progress. Preliminary results demonstrate pulses of up to 20 W of peak power at 1 kHz repetition rate using a short length of 20 cm of Er doped fiber with 1500 ppm Er^{3+} concentration.

4. Conclusions

We have reported active Q-switching of an all-fiber laser by acousto-optic interaction in a fiber Bragg grating. As a result of the propagation of a longitudinal elastic wave along a fiber Bragg grating, spectral equally spaced bands of reflection appear on both sides of the Bragg wavelength. Q-switching is achieved by controlling the reflectivity of the reflection bands of the BG-AOM which acts as a laser cavity mirror. Q-switch pulses of 10 W of peak power and 82 ns wide were generated with 1 m of 300 ppm erbium-doped fiber and a pump power of 180 mW. The performance of the laser in terms of peak power and pulse energy is lower than previous reports, and more work should be done to enhance this parameters. The main advantage is the continuous tunability of the laser pulse repetition rate, which was varied from few Hz up to 62.5 kHz.

Acknowledgments

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