

Q-Switch All-Fiber Laser Pulsed by High Order Modes

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Abstract—In this letter, we demonstrate an all-fiber Q-switch laser in erbium-doped fiber using an intracavity loss modulator that controls the power transmitted by a cladding mode. The cladding mode is coupled by a pair of concatenated long period gratings; pulsed regime is achieved by dynamic attenuation of the power transmitted by the cladding mode, and attenuation is caused by lateral compression with a piezoelectric transducer. The pulse sequence can be controlled from a single shot up to repetition rates of 2 kHz. The laser performance is analyzed as a function of the pump power and emission frequency; pulses having a peak power of 4 W and a duration of ~80 ns can be generated with an absorbed pump of 100 mW.

Index Terms—Long period fiber grating, Q-Switch, fiber laser, piezoelectric transducer.

I. INTRODUCTION

In long period gratings (LPGs) a modal coupling occurs between fiber modes traveling to the same direction. Since LPGs' pitch is usually within the range from 100 to 1000 μm , several notches in near-infrared transmission spectrum that correspond to coupling between the core mode and different cladding modes [1] are observed. The spectral position and the depth of the notches are sensitive to strain, temperature variation, refractive index of the surrounding medium, and fiber bending. As a result of these features, LPGs found a number of applications in sensors and actuators [2]–[5], in optic communications [6], [7], and in laser technology [8]–[10].

Since LPG length to pitch ratio is much less as compared to that of fiber Bragg gratings (FBG), the LPG attenuation bands that correspond to the fundamental fiber mode are relatively broad. This feature makes it possible to incorporate LPG into a fiber laser (FL) cavity as an in-fiber loss element without additional spectral tuning. Direct strain applied to LPG placed into a FL cavity permits effective tuning of intra-cavity loss. Hypothetically, a rapid periodical strain applied to LPG produces fast loss modulation that would permit FL to operate in Q-switch regime in an all-fiber configuration.

Manuscript received February 27, 2013; revised April 2, 2013; accepted April 6, 2013. Date of publication April 24, 2013; date of current version May 15, 2013. This work was supported in part by the Ministerio de Economía y Competitividad and the Generalitat Valenciana of Spain under Projects TEC2008-05490 and PROMETEO/2009/077, respectively.

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Digital Object Identifier 10.1109/LPT.2013.2257727

Experimentally, a direct tuning of LPG with strain, from transmission maximum to minimum, is not attainable at high frequency because of the slow response of large displacement transducers. In order to solve this problem, a modal interferometer composed of two LPGs was proposed [11], where intra-cavity loss was controlled by modulating the phase of the modes with a piezo-electric transducer (PZ). Although this type of modulator is capable to change strongly a Q-factor of FL cavity [9], the Q-switch pulses observed in this case are too long because of large rise time of the modulator. To solve this problem, Luo and Yeh proposed to modulate the LPG coupling efficiency by lateral compression [12], however the energy transfer between the core and the cladding modes was not completely suppressed, hence the insertion loss of the modulator exceeds 3 dB in the “open” state, which decreases FL efficiency.

Recently, Q-switched operation of a Thulium-doped FL has been demonstrated by fundamental mode loss modulation with periodic microbends introduced by means of a piezoelectric actuator [13]. However, this approach is relatively bulky and slow, producing microsecond pulses. It is known that the cladding modes have higher sensitivity to curvature than the fundamental fiber mode [5]. Based on this fact, we recently proposed and experimentally demonstrated that dynamic bending of the fiber located between two concatenated LPGs produces fast intensity modulation of the guided light, with low insertion loss in the modulator high transmission level [14]. In this letter we report on the efficient operation of a Q-switched FL by inserting this kind of cladding mode modulator into the laser cavity, obtaining pulses shorter than 80 ns.

II. FIBER LASER SETUP

The experimental setup of the erbium-doped fiber laser (EDFL) is shown in Fig. 1 (the upper part). The laser is built in a standard Fabry-Perot geometry. A piece of erbium doped fiber (*Fibercore M12-980-125*) with length of 67 cm was used as an active fiber. The fiber length was chosen so that the downstream end of the fiber had sufficient pump level with the available pump power. The fiber had a numerical aperture of 0.22 and a cut-off wavelength of 904 nm, the absorption peaks were measured to be 11.7 dB/m at 979 nm (pump band) and 17.3 dB/m at 1531 nm (emission band).

The modulator was formed by two concatenated LPGs. A boron co-doped germanosilicate fiber provided by *Fibercore (PS1200/1500)* was used for LPGs inscription. The fiber had a cutoff wavelength of 1234 nm and a numerical aperture

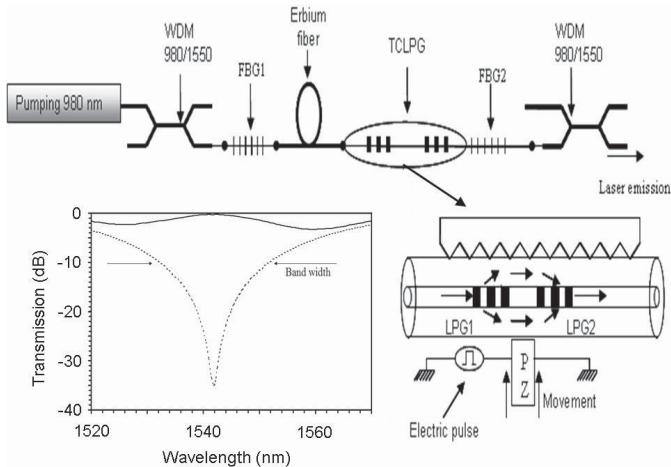


Fig. 1. Experimental setup of the Q-switch FL (upper picture) and details of the intra-cavity loss modulator (bottom pictures). Transmission spectra of one LPG (dotted line) and of two concatenated LPGs (solid line) are shown in the left bottom corner.

of 0.12. This fiber is intrinsically photosensitive to UV radiation. The LPGs were written using a frequency-doubled argon laser operating at 244 nm by scanning the fiber point by point. The gratings' period was 376 μm , both LPGs had a length of 2.33 cm with a gap between them of 3.3 mm. The spectra of a single LPG and of the pair of LPGs are shown in Fig. 1 (the left bottom corner). In the high transmission level, the static and the dynamic insertion losses of the modulator were 0.3 and 1 dB, respectively. The modulator introduced 20 dB of peak attenuation at 1542 nm within a bandwidth of 29 nm measured at 10 dB level. It was capable to operate within the repetition rate interval from 0 kHz to 2 kHz with the rise time of 7.5 μs [14].

Two FBGs with reflection peaks centered at approximately 1541 nm were used as the FL cavity couplers. In order to reduce intra-cavity loss FBG1 (rear mirror) was inscribed in the erbium doped fiber, the fiber length between the grating and the splice to the WDM was less than 1 cm that reduces unwanted pump absorption and ASE generation outside the cavity. This grating had a length of 8.75 mm, a reflectivity of 99.5%, and a bandwidth of 250 pm measured at 3 dB. FBG2 (output mirror) was inscribed in the same fiber that was used for the modulator. It had a length of 1.42 mm and reflectivity of 53%. The spectrum bandwidth was 580 pm at 3 dB-level. The laser cavity was 1.3 m long. The intra-cavity loss defined by the splice between the low NA photosensitive fiber and the high NA erbium doped fiber was estimated to be ≈ 1.1 dB. Two wavelength division multiplexers (WDM) were spliced to the laser, the up-stream WDM isolates the pump laser at the entrance and the down-stream WDM separates the residual pump and the signal at the output.

III. EXPERIMENTS AND RESULTS

First, we characterized the laser performance in continuous wave regime. In this case, the PZ modulator did not press the gap between two LPGs so that it did not introduce attenuation. The two FBGs were slightly strained to tune

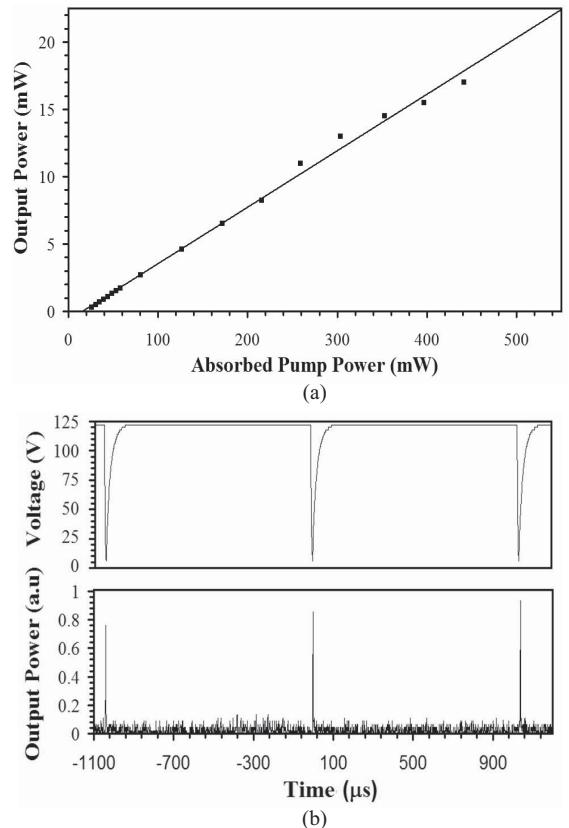


Fig. 2. (a) Continuous output power of the laser versus absorbed pump power. (b) Train of electrical pulses (top), and corresponding train of optical pulses (bottom); both at 1 kHz (absorbed pump 171 mW).

its Bragg wavelength at 1542 nm where the modulator has maximum loss modulation. The output power of the laser was measured as a function of the absorbed pump power (power delivered by the pump laser minus residual power at the output WDM). Fig. 2(a) shows that the threshold of the laser was 15.9 mW and the maximum output power was 17 mW for 441 mW of absorbed pump power (the latter corresponds to a pump of 525 mW at the FBG1 input and a residual pump of 84 mW at the EDL output). The laser line-width was below the resolution of the optical spectrum analyzer (50 pm).

When the modulator was switched on and off, the laser emitted in a pulsed regime at frequencies ranging from 0 kHz to 2 kHz. A train of electrical driving pulses at 1 kHz and the output laser emission are shown in Fig. 2 (b). The Q-switching mechanism operates as follows: when the PZ remains poled with a voltage of 120 V, it compresses the fiber between LPGs against the corrugated surface therefore introducing an attenuation of 20 dB in the cladding mode coupled by the LPG. In this situation, the Q factor of the cavity is low and there is no laser emission. When the electric voltage is switched to zero, the PZ releases the fiber and allows the cladding mode to travel between the LPGs, hence, the Q factor becomes high and the laser emits a pulse of light.

The characteristics of the peak power and pulse width versus the operation frequency are shown in Fig. 3 for an absorbed pump level of 171 mW. In this figure, the peak power decreases with frequency from 4.1 W to 1.34 W when the

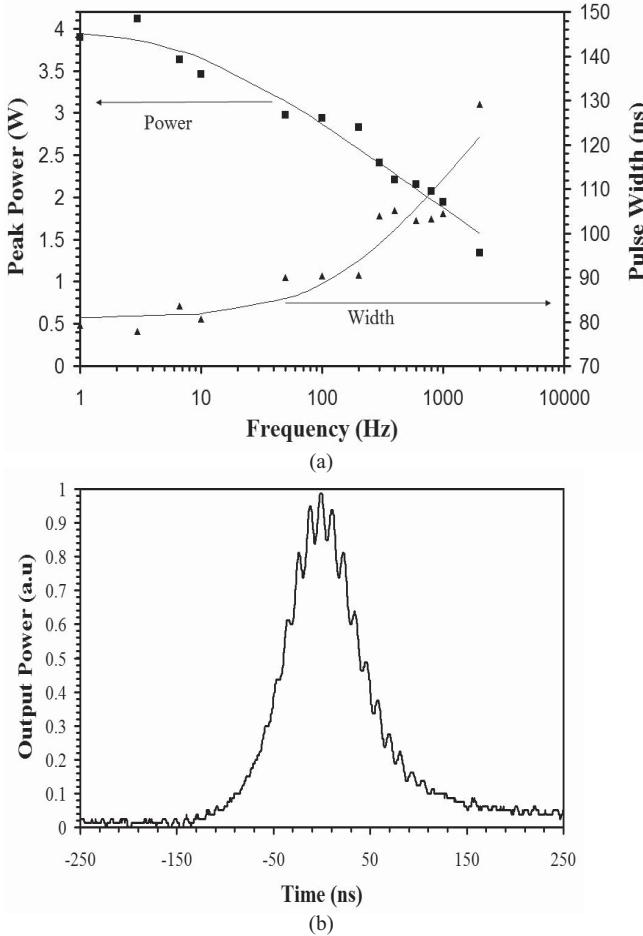


Fig. 3. (a) Pulse peak power and pulse width versus frequency at 171 mW of absorbed pump power. (b) Detail of an 80 ns optical pulse at 10 Hz.

repetition rate rises from 1 Hz to 2 kHz; meanwhile, the pulse broadens from 78 ns to 129 ns. As an example, Fig. 3(b) depicts a Q-switch pulse at 10 Hz, having a peak power of 3.5 W and a width of 80 ns. The pulse shape was measured with a DC-coupled photodetector which had a transimpedance gain of 40 kV/W, a rise time of 3 ns and an output impedance of 50 Ω ; the laser signal was attenuated by 50 dB before detection. The pulse peak power was calculated from the peak-to-offset voltage of the oscilloscope trace taking into account the detector gain and the attenuation. It was verified that the peak power was consistent with the energy per pulse measured with a pulse energy meter and with the average power of the train of pulses measured with an optical power meter. The pulse has a periodic ripple of 12.5 ns in agreement with the cavity round trip time; the pulse shape is not completely symmetrical: it has a long weak tail caused mainly by the remaining emission during the time that the cavity is in the high transmission state (which lasts 30 μ s according to [14]). It must be noticed that the DC offset of the photoreceiver has not been corrected in figure 3(b); the offset is about 1.8% of the maximum level as it can be observed in the pre-pulse interval. The pulse tail tends to zero and falls to 2.5% in 250 ns after the pulse peak and then to 0 in approximately 10 μ s.

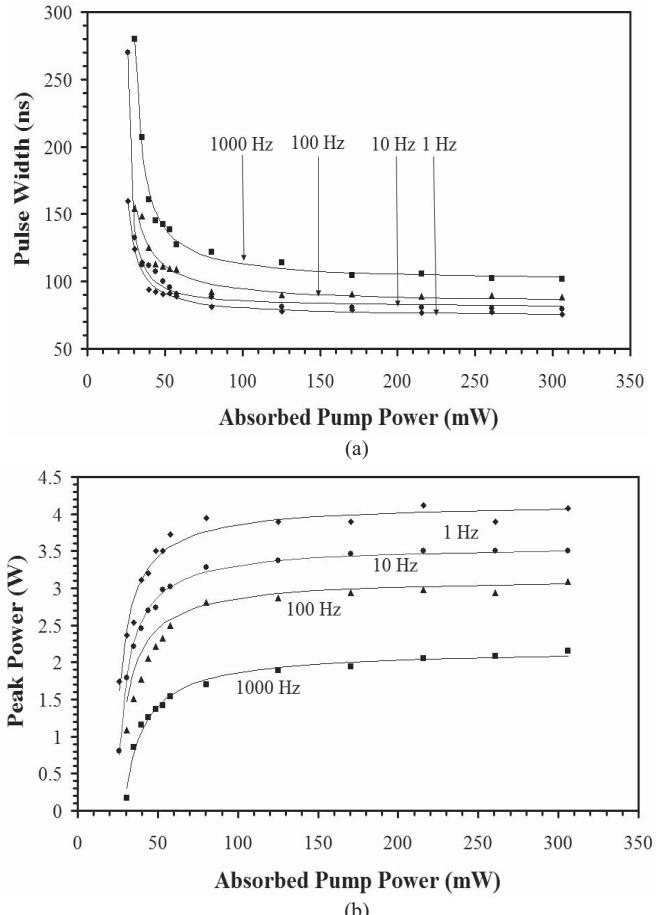


Fig. 4. Laser response versus absorbed pump power at different frequencies: (a) pulse width and (b) peak power.

The dependence of the peak power and the pulse width with the absorbed pump power at different frequencies was also studied. The results are plotted in Fig. 4. When the absorbed pump power rises, from threshold to around 80 mW, the peak power increases and the pulse duration shortens, as a consequence of the higher population of the excited state of the Er-doped fiber. If the absorbed pump power exceeds 80 mW the laser pulses saturate and the pulse width reaches a steady level. The optimum regime is achieved for an absorbed pump power comprised between 125 mW and 306 mW, when the output peak power ranges from 1.9 to 4.1 W and the pulse width between 75.8 ns and 114 ns.

The laser started to emit two pulses per cycle when the absorbed pump power was over 306 mW. Q-switched lasers can emit two or more pulses per period, depending on the time that the cavity remains in the low loss state and the population inversion of emitting ions. If the pump and the time in low loss level are big enough, after a first optical pulse it can appear a second one in the same cycle [15].

Finally, we must point out that a better performance could be achieved by improving the fibers compatibility; notice that the cavity has a high loss splice (about 1.1 dB) between the erbium doped fiber and the LPGs fiber, these fibers have very different NA and modal diameters at the emission wavelength.

The fabrication of all the gratings in the same fiber would result in higher efficiency and shorter cavity length, hence in strengthened and narrowed pulses.

IV. CONCLUSION

We have demonstrated that a non interferometric all-fiber device based on two concatenated long period gratings, with piezoelectric modulation of the cladding mode losses, can modulate efficiently the Q factor of an all-fiber laser. The fiber laser works in Q-Switch regime and it can be operated at frequencies from 0 to 2 kHz. The peak power and pulse width were measured to be over 4 W and approximately 80 ns, respectively, at a repetition rate of 1Hz.

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