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Single-frequency active Q-switched distributed fiber laser using acoustic waves

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This letter presents a single mode, actively Q-switched distributed feedback fiber laser. Acoustic pulses are launched into an erbium-doped fiber Bragg grating, resulting in the introduction of a traveling defect. Thus, a transmission peak appears in the reflection band while the pulse travels along the grating. This effect allows the laser to operate in a Q-switched regime, providing optical pulses which repetition rate was continuously tuned up to 10 kHz. Pulses of 168 mW of peak power and 73 ns of temporal width were obtained at low repetition rate. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2732832]

Single-frequency erbium Er^{3+}-doped fiber lasers show a wide range of applications in optical telecommunications, sensors, spectroscopy, and interferometry because of their narrow linewidth and high signal-to-noise ratio. They are a reliable alternative to semiconductor distributed feedback (DFB) lasers.

The use of fiber Bragg gratings (FBGs) to prepare these lasers allows tuning the emission wavelength over the whole Er^{3+} band by designing properly the gratings and it awards the structure simplicity and compact nature. In addition, wavelength sensitivity to temperature is dictated by that of the grating, which is over an order of magnitude lower than that for semiconductor lasers.

Different approaches to fabricate single-frequency all-fiber lasers have been demonstrated. Distributed Bragg reflector (DBR) configurations, where a short-length cavity is defined by two fiber gratings spliced together, have been reported, showing very narrow spectral linewidth and low noise.[1–3] DFB configurations, where the feedback is provided by a single fiber grating, have demonstrated to have similar properties, with the advantage of a more simple and compact structure for the laser.[4,5]

To obtain a DFB laser based on a FBG, a phase shift must be introduced in the grating. Different techniques have been employed for this: temperature,[4] strain,[6] or a photoinduced defect.[5] The static characteristics of the defects introduced with these methods lead the laser to operate in cw regime. However, several approaches have been reported to obtain single-frequency pulsed lasers, both in the DBR (Refs. 3 and 7) or DFB (Ref. 8) configurations.

Acoustic waves have been demonstrated to be suitable for controlling dynamically the spectral properties of the FBGs (Ref. 9) and have been applied to perform different all-fiber Q-switched fiber lasers.[10,11] The Q-switched DFB laser presented in this letter is based on the dynamic generation of a defect in a FBG by means of the propagation of an acoustic pulse along it. The acoustic pulse opens a transmission peak in the reflection band of the grating during the time that it takes to travel along the FBG. We apply this effect to realize a single mode, single polarization Q-switched DFB laser.

It is well known that introducing a defect in a FBG, by lengthening a short section of it, leads to the appearance of a transmission peak within the reflection band of the grating. The central wavelength of the transmission window depends on the strength of the local perturbation, and it moves towards longer wavelengths when increasing the phase shift introduced by the defect.

In our Q-switched DFB laser the local perturbation is introduced by means of a short longitudinal acoustic pulse that strains a section of the FBG. This defect is not at a fixed position but it travels along the grating as the pulse does. As in the static case, a transmission peak opens up when the pulse is traveling along the grating.

Figure 1 summarizes the simulations that we have carried out. We take similar parameters to the ones of the experiments: a 12 cm long uniform FBG with 23 pm bandwidth and −34 dB transmittance at the Bragg wavelength (λ_B). The static defect consisted on a 2.8 cm long perturbation of the grating pitch to generate a π-phase shift. Figure 1(a) shows the transmission spectrum of the FBG before introducing the defect, while Fig. 1(b) depicts the spectrum when the defect is located at the center of the grating. Figures 1(c) and 1(d) show the wavelength position and the transmittance of the transmission peak generated by the defect as a function of its position along the grating. From these simulations it can be observed that the wavelength of the transmission peak is not affected by the position of the

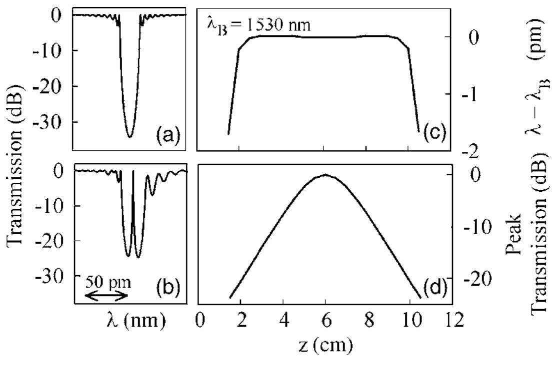

FIG. 1. Transmission spectra of (a) the original FBG and (b) the same FBG when the perturbation is located at $z=6$ cm. (c) Central wavelength and (d) transmission of the peak as the acoustic pulse travels along the grating.

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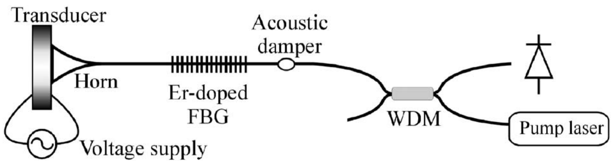

FIG. 2. Scheme of the distributed feedback erbium fiber laser.

defect along the grating, except when it is close to the ends of the FBG. However, the transmittance of the transmission peak (and, consequently, the Q value of the resonance) does change, showing its maximum value when the position of the defect is around the center of the FBG.

In summary, by launching acoustic pulses into the fiber, it is possible to switch on and off the transmission peak, according to the repetition rate of the pulses. We applied this effect to demonstrate a Q-switched erbium DFB fiber laser: when the FBG is undisturbed, there is no feedback for the optical signal and laser emission is not allowed, whereas an optical pulse is emitted when an acoustic pulse forces the appearance of a transmission peak.

Figure 2 shows a scheme of the Q-switched DFB fiber laser. The FBG used in the experiment was 12 cm long and was written in a 1000 ppm erbium codoped germanosilicate fiber, using a doubled argon laser and a uniform period mask. The FBG presented a 30 pm bandwidth and more than 30 dB attenuation at the Bragg wavelength, 1532.4 nm. The length of the erbium fiber was not longer than the active FBG itself, and it was pumped through a WDM coupler with a 980 nm pigtailed laser diode, providing a maximum pump power of 140 mW.

The longitudinal acoustic pulse was generated by a piezoelectric disk driven by an ac signal generator and launched into the fiber using a silica horn. The tip of the horn was reduced to 125 μm in diameter and fusion spliced to the optical fiber.

The electric pulse applied to the transducer consisted of one cycle of a harmonic signal of frequency of 200 kHz, phase shifted to start at one minimum. This frequency corresponds to one of the resonances of the piezoelectric disk. The repetition rate of the electric pulses was varied up to 10 kHz (this limitation arises from the generator used in the experiment). According to the velocity of the lowest longitudinal elastic mode in an optical fiber,[12] 5760 m/s, the perturbation generated by the transducer consisted of an acoustic pulse of 28 mm long, and the time that it takes to travel along the entire length of the grating was 21 μs.

Figures 3(a) and 3(b) show an example of the laser operating at 10 kHz repetition rate. The amplitude of the electric pulse applied to the transducer was 2.8 V and the pump power was 35 mW.

The linewidth of the emission was narrower than 0.08 pm, which was the resolution of the technique we used to measure the spectrum.[13] A typical pulse is shown in Fig. 3(c). In this example, the laser was running at 200 Hz and pumped with 10.6 mW. This trace was recorded with a 1 GHz bandwidth optical detector and a 500 MHz oscilloscope without using any averaging. No evidences of beating between modes were observed, neither longitudinal nor polarization modes, in agreement with the observed spectrum. Furthermore, the single polarization nature of the emission was verified by using a polarization analyzer at the output of the laser. We assume that the single polarization emission results from some weak birefringence of the FBG.

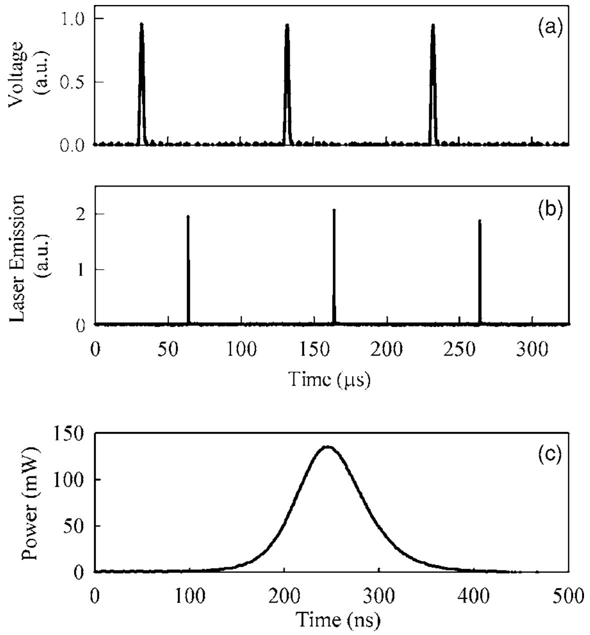

FIG. 3. (a) Electric signal applied to the piezoelectric disk. (b) Optical pulses emitted at 10 kHz repetition rate. (c) Optical pulse emitted at 200 Hz repetition rate. Pump power: 10.6 mW.

Figure 4 illustrates the evolution of the laser peak power when increasing the amplitude of the acoustic pulse. Below 0.5 V, there was no laser emission since the Q value of the resonance was not high enough to reach the threshold condition. Above this voltage, the laser emitted an optical pulse per acoustic pulse. Increasing the amplitude of the electric signal led to better Q values and, as a result, optical pulses with higher peak power were obtained. In this example, the optimum voltage amplitude is reached at 2.8 V. Further this value, the peak power decreased as the voltage amplitude was increased up to an upper limit beyond which a second optical pulse per electric pulse was emitted. It was observed that, as the voltage amplitude increased, the delay time between the electric pulse and the laser pulse decreased. This indicates that, as the voltage amplitude increases, the laser pulse is emitted when the acoustic pulse is located at an earlier point of the grating. Since the detector is placed at the opposite end to the horn, the emission of the laser pulse when the defect is nearer from the horn leads to a poorer output coupling factor, which results in a decrease of the peak power. Thus, a balance between a high Q value of the resonance and a good output coupling factor must be accomplished to optimize the performance of the laser. As it was pointed out, a second laser pulse per electric pulse was emitted when the voltage amplitude is higher than 4.8 V. The delay between the two optical pulses was about 2 μs so,

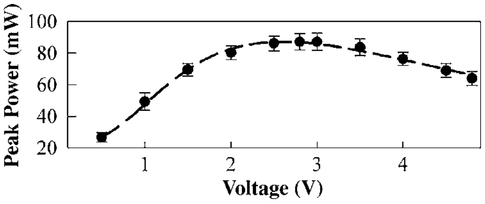

FIG. 4. Dependance of the peak power of the optical pulses with the amplitude of the electric signal. Pump power: 33 mW; repetition rate: 10 kHz.

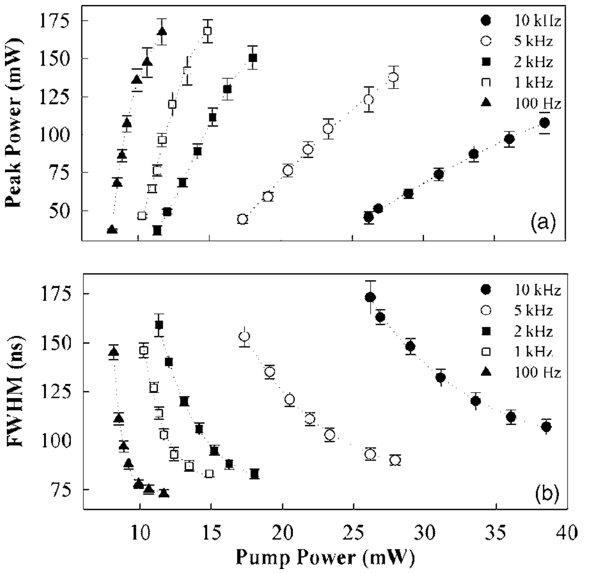

FIG. 5. (a) Peak power and (b) temporal width of the optical pulses as a function of the pump power.

according to propagation velocity of the acoustic pulse in the fiber, it travels a distance of about 12 mm. For the conditions of pump power and repetition rate used in these measurements, this time results to be enough to allow the laser building up and emitting a second laser pulse.

Figure 5 shows the effect of pump power on the *Q*-switched laser pulses for different repetition rates. As expected, the peak power increases with pump power, while the temporal width decreases. Temporal width and peak power jitters are shown by means of error bars and are estimated to be about 5%. At 1 kHz repetition rate, pulses of 168 mW of peak power and 83 ns of temporal width (14 nJ pulse energy) were obtained by pumping with 15 mW. The pump threshold increased with the repetition rate, as shown in the figure. For pump powers below the threshold, it was not possible to obtain the emission of an optical pulse every acoustic pulse. For each repetition rate, there is also an upper pump limit. Beyond it, the laser emitted more than one optical pulse per cycle. The maximum peak power varied from 168 mW at 100 Hz to 107 mW at 10 kHz, and the corresponding temporal widths were 73 and 107 ns, respectively.

As a summary, we have reported a single-frequency, actively *Q*-switched DFB erbium fiber laser using acoustic waves. By means of the propagation of a longitudinal acoustic pulse, a transmission peak appears in the reflection band of the FBG as the acoustic pulse travels along the grating. The transmission peak is switched on and off, leading to the laser to operate in an active *Q*-switch regime. We observed the single-mode, single polarization nature of the emission; its bandwidth was narrower than 0.08 pm and the repetition rate was continuously tunable up to 10 kHz. At 1 kHz, pulses of 168 mW of peak power and 83 ns width were obtained by pumping with 15 mW. More experiments are in progress to improve the performance of the *Q*-switched DFB fiber laser in terms of peak power and repetition rate.

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