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Active *Q*-switched distributed feedback erbium-doped fiber lasers

P. Pérez-Millán, J. L. Cruz,[a] and M. V. Andrés
Departamento de Física Aplicada y Electromagnetismo, ICMUV, Universidad de Valencia, C/Dr Moliner 50, Burjassot 46100, Spain

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This letter presents a distributed feedback fiber laser that operates in an actively controlled *Q*-switched regime. The laser is based on a Bragg grating made in an erbium-doped fiber. The grating has a defect induced by a magnetostrictive transducer that configures the distributed feedback laser structure. The phase shift generated by the defect can be dynamically modified by an electric current, permitting active *Q*-switching of the laser. The laser generates pulses of 75 ns duration and the repetition rate can be continuously adjusted from 0 to 10 kHz. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1990252]

Q-switched fiber lasers have attractive applications in medicine, industry, and remote sensing (light detection and ranging, optical time-domain reflectometry, and gas detection). The mechanism of short pulse emission is based on the modulation of the *Q* factor of the cavity. *Q*-switched fiber lasers can be actively controlled by external elements such as acousto-optic or electro-optic modulators.[1,2] Passively *Q*-switched lasers have more simple structures, but the repetition frequency cannot be modified independently of other operation parameters.[3] A small modulation of the pump power can force a fiber laser to operate in pulsed regime.[4] This is a very simple technique to achieve giant optical pulses, but it works only at modulation frequencies around the relaxation frequency of the laser. Lasers having fiber gratings as reflectors open new possibilities to simplify the laser configuration because the *Q* factor of the cavity can be controlled externally with acoustic waves[5] or piezoelectric transducers.[6] Kaneda and co-workers[7] have recently demonstrated a very compact structure, introducing polarization-dependent loss in the cavity between two fiber gratings.

Distributed feedback (DFB) lasers constitute a further degree of improvement and simplification of the structure of fiber lasers. These lasers are promising candidates for dense wavelength division demultiplexing, spectroscopy, remote sensing, and as sources for high-power amplifiers because they provide narrow linewidth and high signal-to-noise ratio. DFB fiber lasers have been fabricated with two fiber gratings spliced together[8] or with a photoinduced defect in a single grating for more accurate control of the phase.[9] The phase shift of these gratings is static and the resulting lasers operate in a continuous regime.

In this letter we present a technique to generate dynamic defects in fiber Bragg gratings and a simplified implementation of an actively *Q*-switched fiber laser made with a single grating in an erbium-doped fiber. The dynamic defect is introduced by a small magnetostrictive actuator that is electronically controlled by a small solenoid with low power consumption. This DFB laser can operate in a continuous wave regime or in an active *Q*-switched regime depending on the wave form of the electric current driving the transducer. The laser can be operated at repetition rates ranging from one single pulse to 10 kHz, generating optical pulses of 75 ns duration.

Magnetostrictive transducers are an efficient tool for tuning and chirping fiber gratings and, as demonstrated here, a small transducer held on the center of a fiber grating can generate a phase shift in the grating when the material is magnetized. The magnetostrictive compound used in this experiment was Terfenol-D, an alloy of composition $Tb_{0.27}Dy_{0.73}Fe_2$ that increases about 0.11% in length when it is subjected to a magnetic field of 4×10^5 A/m.

In order to show the operation principle of the technique to generate dynamic defects, a grating was fabricated in a boron-codoped germanosilicate fiber by irradiation with a doubled argon laser at 244 nm through a phase mask of 1067 nm period. The resulting grating had a 3 dB bandwidth of 0.06 nm and a reflectivity of 30 dB. A piece of Terfenol-D of 2 mm length and 1 mm^2 cross section was glued at the center of the grating and was subjected to a static magnetic field. Figure 1 shows the effect of the phase shift induced by the transducer. A transmission band is generated inside the reflection band of the grating and it can be tuned with the magnetic field intensity.

The laser was made with a single fiber grating fabricated in an erbium-doped fiber. The fiber core codopants were germanium and aluminum and the content of erbium was 1500 ppm. The fiber was loaded with hydrogen at high pressure and a grating was written with a phase mask of 1058 nm period and 140 mm length. The length of the erbium-doped fiber was 340 mm (100 mm before and 100 mm after the

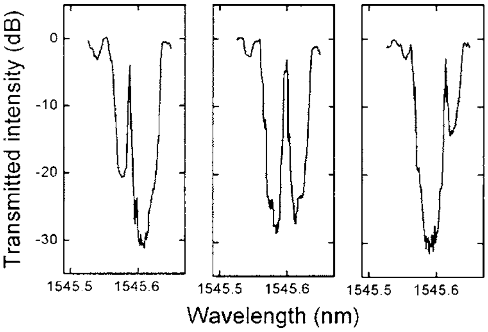

FIG. 1. Transmission spectra of a Bragg grating with a phase shift induced by magnetostriction. From left to right, the curves correspond to magnetic fields of 35, 52, and 105 mT.

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[a] Electronic mail: cruz@uv.es

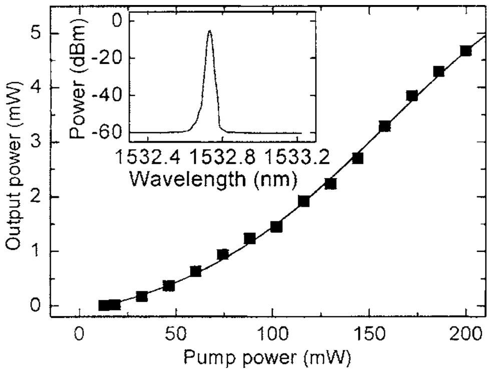

FIG. 2. Power delivered by the laser in cw operation mode as a function of the pump power. The inset shows the laser line measured with 20 pm resolution for a pump power of 41 mW.

grating) and it was pumped by a semiconductor laser at 976 nm through a wavelength multiplexer. The transducer was fixed in the middle point of the grating and subjected to a static stress by a neodymium magnet to generate a defect in the grating. When the phase shift is adequate the system behaves as a DFB laser and continuous emission is observed at 1532.7 nm. The dimensions and the bandwidth of the grating ensure single wavelength operation. The laser could have two polarization modes, one of these modes could be supressed by applying transverse stress to the fiber.[4,10] The output power of the laser in the backward direction is plotted in Fig. 2 as a function of the nominal power of the pump laser (loss in the multiplexer and splices have not been corrected for in the measurements). The laser has a threshold of 15 mW and a maximum output power of 5 mW. The response is not linear, and it also has been observed that the threshold can be reduced to 10 mW by fine adjustment of the phase shift in the defect; however, this improvement implies a reduction of the laser efficiency at high pump levels. The authors think that this is caused by the strong absorption of the fiber that results in thermal effects and an asymmetric variation of the effective refractive index along the grating.[11] The relaxation oscillation frequency of the laser has been measured and it has been observed that it increases from 100 to 200 kHz when the pump power varies between 75 and 270 mW.

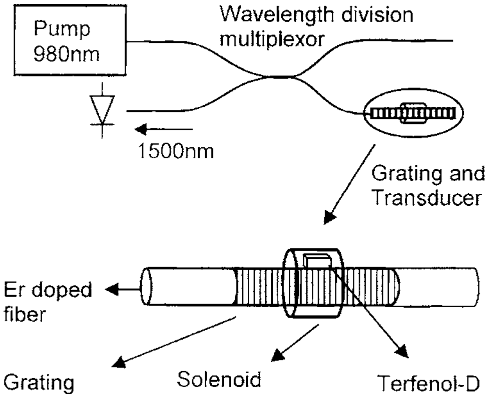

FIG. 3. Setup for Q-switching a fiber laser based on a single fiber grating.

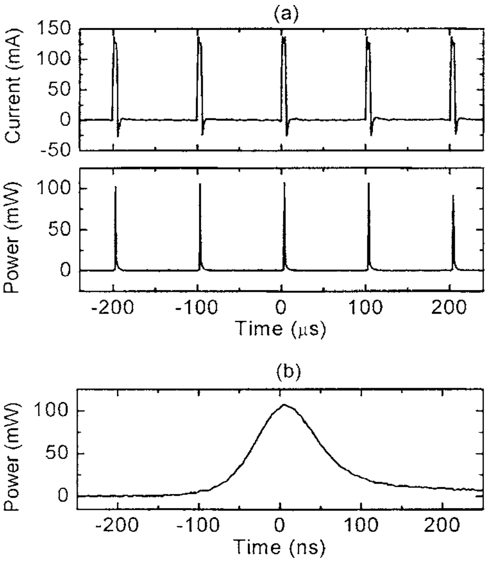

FIG. 4. (a) Electric current in the solenoid and output power of the laser. Repetition rate 10 kHz, pump power 41 mW. (b) Detail of the pulse shape.

To create a dynamic defect in the grating, the transducer was introduced in a solenoid driven by an electrical current as illustrated in Fig. 3. When the current rises in the solenoid the magnetic field generates a local phase shift, i.e., a defect, and consequently a high-Q DFB laser that emits a light pulse. Figure 4 shows the train of pulses excited at a repetition rate of 10 kHz, the duration of each emission pulse is 87 ns, as seen in the detail of the pulse shape. The coil consisted of 800 turns of copper wire, its induction was 1 mH and its resistance 5.8 Ω. The size of the solenoid was 15 mm in length and 10 mm in outer diameter. The driving electric current was a train of rectangular pulses with 5 μs width and 125 mA amplitude; the average power consumed at 10 kHz is about 5 mW. Eddy currents do not generate significant heating at this repetition rate because of the small cross section of the transducer.

Figure 5 represents the characteristics of the pulses at different repetition rates. The peak power decreases with frequency from 0.4 to 0.1 W, while the pulse width increases from 75 to 87 ns. The fall-off in the peak power with the repetition rate is due to the finite recovery time of the population inversion. Figure 6 shows the effect that the pump power has on the pulse. The pulse duration is independent of the pump power above the cw laser threshold (15 mW), while the pulse power experiences a slight increase.

In conclusion, by using a magnetostrictive transducer as a phase shifter element, a DFB laser has been demonstrated in an Er^{3+}-doped fiber. The laser can work in continuous or in active Q-switched mode since the defect can be activated by an electric current. Optical pulses of 75 ns width and 0.2 W power have been generated at frequencies of several

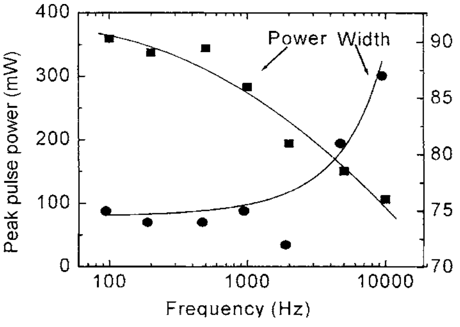

FIG. 5. Pulse width and peak power as a function of the repetition rate. Pump power 41 mW.

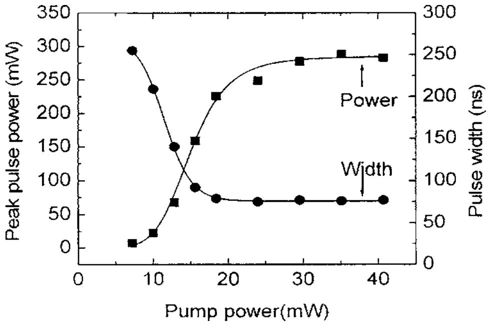

FIG. 6. Pulse width and peak power as a function of the pump power. Repetition rate 1 kHz.

kHz with a compact transducer driven by a small current. This procedure opens a new way to develop high peak power pulsed lasers of very simple structure and narrow linewidth.

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