CARTA REVISTA MEXICANA DE FÍSICA **54** (1) 1–4 FEBRERO 2008

Experimental study of a Q-switched ytterbium-doped double-clad fiber laser

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Recibido el 15 de agosto de 2007; aceptado el 10 de diciembre de 2007

We report an experimental characterization of a Q-switched operation of an all-fiber laser using $\sim$ 30 m of a double-clad ytterbium-doped fiber spliced to a piece of single-mode un-doped holey fiber. Loss modulation in the splicing point between the active and un-doped fiber due to a substantial coupling of light into lossy cladding modes stimulates pulsed operation of the fiber laser. Pulse energy of ~ 2.5 μJ was estimated and the repetition rate was measured in the range of 4-16 KHz.

Keywords: Q-switched; fiber laser; ytterbium-doped fiber.

Reportamos una caracterización experimental de la operación en conmutación Q de un láser de fibra óptica de doble revestimiento dopada con iones de iterbio usando 30 m de fibra dopada empalmados a una pieza de fibra hueca monomodal. Modulación de pérdidas en el empalme entre la fibra activa y la fibra hueca no dopada debido a acoplamiento de luz a modos que viajan en el recubrimiento estimula la operación pulsada del láser de fibra. Pulsos máximos de ~ 2.5 μJ fueron estimados y una taza de repetición del pulso en un rango de 4-16 KHz fue medida.

Descriptores: Conmutación Q; láser de fibra; fibra dopada con iones de iterbio.

PACS: 42.55.Wd; 42.55.Xi; 42.60.Gd

1. Introduction

Q-switching of a laser oscillator cavity is a powerful method to produce short, high-energy pulses and in general, different techniques have been used to Q-switch a fiber laser. Q-switching can be achieved actively through the action of a controlled loss modulator or it can also be carried out passively. Active Q-switching of fiber lasers has been demonstrated in a variety of forms, including all-fiber elements as modulators, which are desirable for some applications. Chandonnet *et al.* [1] used a side-polished coupler as an efficient intra-cavity switching element. In interesting works, an acoustically modulated fiber attenuator was combined with a fiber Bragg grating to produce Q-switched pulses [2] and recently, Q-switching of an all-fiber laser was implemented by acousto-optic modulation of a fiber Bragg grating [3,4]. Moreover, by modulating a fiber Bragg grating via a magnetostrictive rod which is fixed to the fiber at the position of the grating, another exciting q-switched laser was demonstrated [5].

Q-switching is also achieved passively. For instance, a saturable absorber placed in the laser cavity acts as loss modulator [6,7]; Brillouin scattering can cause passive Q-switching in fiber lasers [8], or the stimulated Raman scattering can provide the saturation mechanism necessary for passive switching [9]. Recently, self-Q-switching of fiber lasers has been demonstrated in a diode pumped, all-fiber ytterbium fiber laser using a few meters of heavily-doped ytterbium silica fiber and a fiber Bragg grating spliced to one of the active fiber ends pumped at 978 nm with a stabilized output at $\sim$1060 nm [10]. In any case, from an assembly and robustness perspective, all-fiber configurations are preferred.

In this letter, we report an experimental characterization of a Q-switched, fiber laser using $\sim$ 30 m of a double-clad ytterbium-doped fiber spliced to a piece of single-mode un-doped holey fiber. Loss modulation at the splicing point stimulates pulsed operation of the fiber laser. The stable operation of this proposed q-switched laser becomes an attractive approach for a low-cost and effective q-switched fiber laser system.

2. Experimental setup

Figure 1 shows the experimental setup of the pulsed fiber laser. It consists of $\sim$30 m long double-clad ytterbium-doped fiber (DCYDF) with core/cladding dimensions of 6/125 μm and 0.14/0.45 of numerical aperture. The DCYDF is end pumped by a **915** nm pigtailed diode laser connected to a fiber collimator via a bare fiber adapter. The measured pump absorption is $\sim$0.4 dB/m. The collimated pump is coupled to the input end of the DCYDF by an aspheric coated-lens. Between the fiber collimator and the aspheric lens, there is a 45° dichroic mirror with a high transmission at the pump wavelength and a high reflection from $\sim$1050-1100 nm, which prevents back reflection to the pump diode and serves as output coupler for the laser signal. The other end of the DCYDF is spliced to a 1-m length single mode, un-doped holey fiber which has a core/cladding diameter of 11/125 μm. The cladding shape of this fiber has an hexagonal pattern of holes with a lattice pitch of 11 μm and hole diameter of 5 μm. In this way, the fiber laser cavity is defined by: the DCYDF, the spliced holey fiber, and each of the two perpendicular cleaved ends at the sides of the cavity, which gives $\sim$4% of Fresnel reflection. The output laser radiation is measured from the output end of the holey fiber and the reflected light at the dichroic mirror. The output characteristics of the pulsed fiber laser were detected using a photo-detector, oscilloscope, power-meter and an optical spectrum analyser.

The Q-switching element of the fiber laser was produced by applying a periodic excited transverse vibration close to

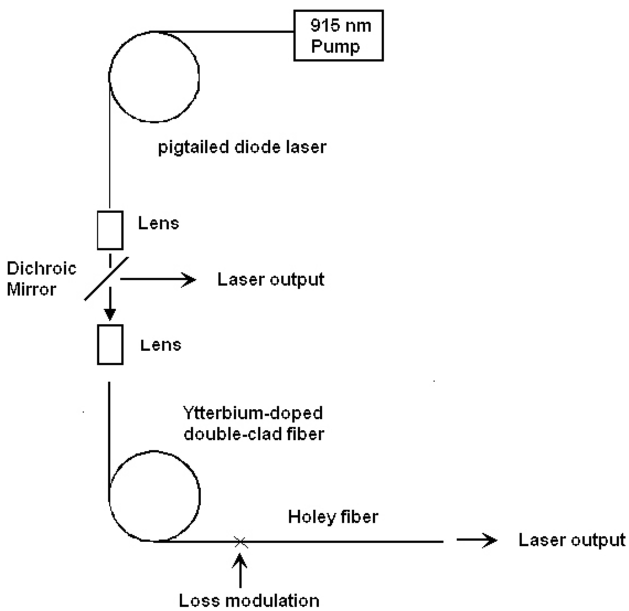

FIGURE 1. Schematic diagram of the Q-switched fiber laser setup.

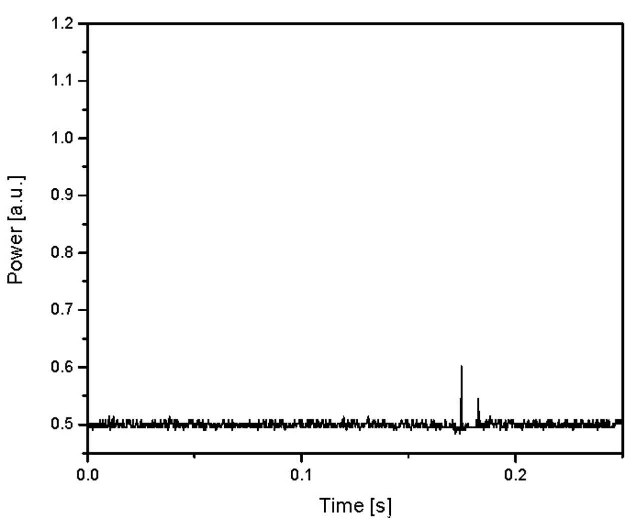

FIGURE 2. Temporal response of the fiber laser in CW regime.

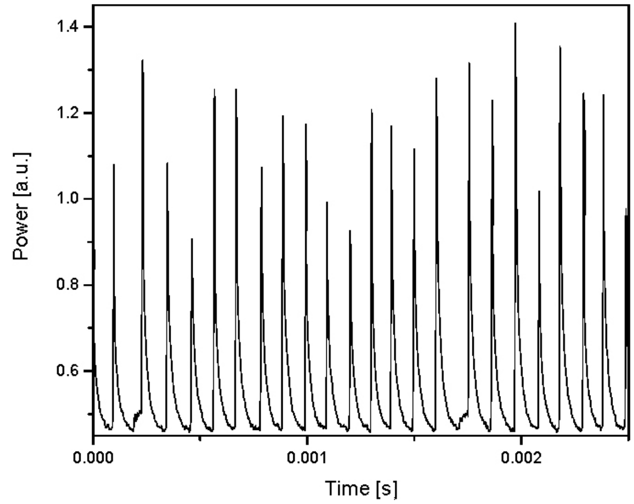

FIGURE 3. Snapshot of a pulse train of the Q-switched fiber laser at 1.7 W of launched pump power.

the splicing point. The splicing point was laterally glued to a tweeter driven by a voltage function generator to receive mechanical vibration. The vibration results in loss modulation due to out-coupling of the core-mode power into cladding modes and consequently, pulsed operation was detected. So we figure out that the pulsation behaviour was stimulated by addition of a piece of holey fiber via loss modulation.

In addition, the fiber laser can operate in a continuous-wave (CW) regimen when no perturbation is applied at the splicing point.

3. Results and discussion

In order to determine the origin of the pulsing behavior, we measure the transmission of light through the fiber core using a laser source operating at 632 nm, (He-Ne laser) which is a light wavelength outside of the absorption and emission bands of the ytterbium ions, and we observe that transmission loss was so high at the splicing point. This means that the out-coupling of the core-mode signal into cladding-modes is due to the bad splicing between the double-clad fiber and the un-doped holey fiber. The splice loss between the DCYDF and the holey fiber was measured as high as 3.97dB. When mechanical vibration is applied close to the splicing point, the transmission loss is unstable and therefore loss modulation is produced. In order to determine the best fiber to use for our purpose, we compare the splicing with three different fibers: un-doped holey fiber, conventional fiber and a dispersion shift fiber. By means of a splicing between a double-clad fiber and an un-doped holey fiber, we get a substantial coupling of light into lossy cladding modes, such as those observed in air-silica microstructured optical fibers [11], which is basically the loss mechanism.

We were able to launch into the fiber laser cavity a maximum of 2.7 W of the available pump power at 915 nm. The laser threshold in the CW operation was $\sim$ 535 mW of the launched pump power, and a slope efficiency of $\sim$45% was measured. The temporal response was measured at 1 W of the launched pump power when no perturbation was applied at the splicing point. Figure 2 shows the continuous wave (CW) operation of the fiber laser. The high laser threshold is primarily due to the bad cavity.

Relaxation oscillations appear at 840 mW of the launched pump power, and the Q-switched laser threshold is around 1.2 W of the launched pump power. After 1.2 W of the launched pump power, a stable pulsed operation was registered.

The pulsed characteristics of the fiber laser are shown in Figures 3-6.

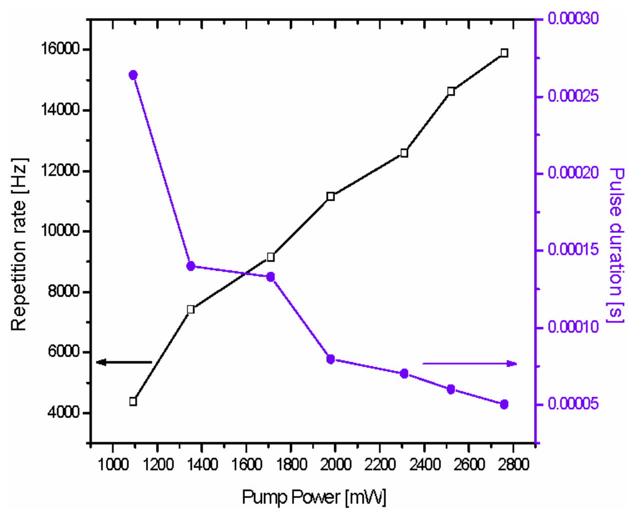

FIGURE 4. Repetition rate and pulse duration versus launched pump power.

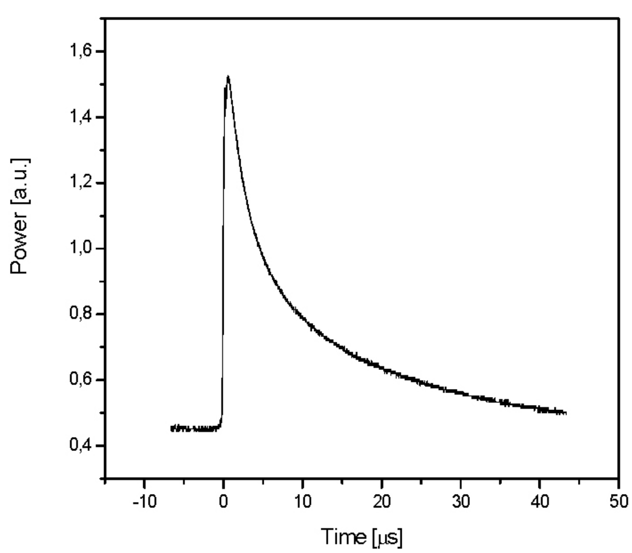

FIGURE 5. Pulse shape at 1.7 W of launched pump power.

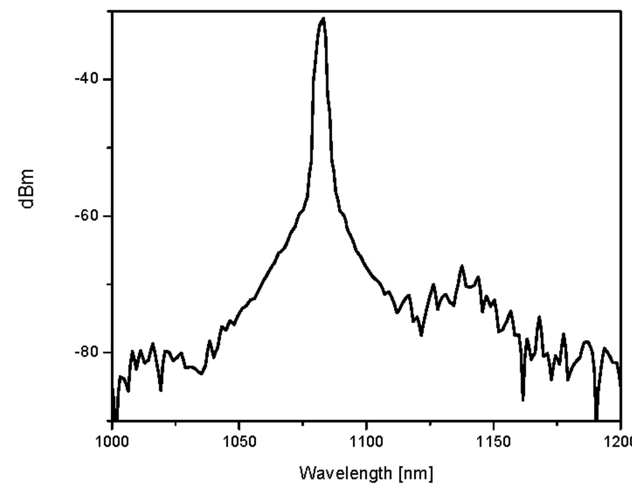

FIGURE 6. Optical spectrum of the pulsed fiber laser.

Oscilloscope traces of a train of pulses of the Q-switched laser output at different launched pump power were measured to analyse the pulse operation behaviour of the fiber laser. A snapshot of a pulse train at 1.7 W of launched pump power is shown in Fig. 3.

The repetition rate of the Q-switched fiber laser was measured in the range of 4 to 16 KHz, as can be observed in Fig. 4. When the launched pump power was increased, the repetition rate of the pulsed laser was decreased, and the average power of the pulses became higher. At low-repetition rates, we obtain a maximum average power, because the pump has enough time between pulses to replenish the population inversion. At a lower pump power, when the repetition rate is high, the available gain decreases, which results in a reduced inversion ratio and less energetic laser beams with longer pulses, as can be seen in Figure 4. This repetition rate behaviour has also been reported in a Q-switched neodymium-doped phosphate glass fiber laser and a diode-pumped fiber laser [12-14]. Despite the low slope efficiency due to high splicing loss, we reach an output average power in Q-switched operation $\sim$ 80 % of that of the CW operation lasing power.

Figure 5 shows the pulse shape of the laser output when 1.7 W of the power is launched into the laser cavity. According to the Q-switching theory, pulse duration is directly proportional to the cavity length, and consequently, to generate short pulses, doped fiber length must be reduced, but short fibres must be made with a highly doped concentration. For this reason, our fiber laser setup requires a length of at least $\sim$30 m of doped fiber, because of the low absorption coefficient measured as 0.4 dB/m of the pump power, which is caused by the low core-to-clad area ratio. There is a special trade-off between the fiber lengths and the pulse duration. The Full Width at Half Maximum (FWHM) pulse duration was measured on the order of $\sim$2-8 μs. It is important to mention that the response time of the detector was fast enough in our measurements (125 MHz, Near IR Model 1811 New Focus).

Energy pulse was estimated indirectly with the consideration that Amplified Spontaneous Emission (ASE) is almost negligible. Figure 6 shows the optical spectrum of the Q-switched fiber laser (lasing wavelength was 1084.4 nm). According to Renaud *et al.* [15], to calculate the pulse energy we can use a simple equation as a function of the repetition rate and the average output power:

$$E = (P\cdot\tau_{21} + N_{th}\cdot h\cdot\upsilon\cdot v)\cdot\left(1 - \exp\left(-\frac{1}{\tau_{21}\cdot f_r}\right)\right), \quad (1)$$

where $P$is the average output power, $\tau_{21}$is the upper level lifetime of Yb^{3+}, $N_{th}$is the population inversion at the laser threshold (ions/m^3), $h\cdot\upsilon$ is the photon energy, $v$is the gain volume and $f_r$is the repetition rate. The maximum pulse energy of this fiber laser was estimated to be $\sim$ 2.5 μJ.

4. Conclusions

We reported an experimental characterization of a Q-switched operation of an ytterbium-doped double-clad fiber laser using $\sim$ 30 m of a double-clad ytterbium-doped fiber spliced to a piece of single-mode un-doped holey fiber. Loss modulation at the splicing point between the active and un-doped fiber stimulates pulsed operation of the fiber laser. By means of a splicing between a double-clad fiber and an un-doped holey fiber, we get a substantial coupling of light into lossy “cladding modes”. The vibration applied at the splicing point results in loss modulation due to out-coupling of the core-mode power into cladding modes, and pulsed operation was detected. So we conclude that the pulsation behaviour was stimulated by addition of a piece of holey fiber via loss modulation.

Pulse energy of $\sim 2.5\ \mu$J was estimated and the repetition rate was measured in the range of 4-16 KHz.

Acknowledgements

This work was supported by the Mexican Council of Science and Technology, CONACYT, under project CONACYT SEP-2004-C01-47237/A-1, and by the Council of Science and Technology of Guanajuato, CONCYTEG, with project 07-16-K662-061. Also, G. Anzueto-Sánchez wishes to thank the CONACYT program “Retención de Investigadores Mexicanos” for their support.

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