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Yb-Doped Strictly All-Fiber Laser Actively Q-Switched by Intermodal Acousto-Optic Modulation[1]

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Abstract—We show an actively Q-switched ytterbium-doped strictly all-fiber laser. Cavity loss modulation is achieved in a tapered optical fiber by core-to-cladding mode-coupling induced by travelling flexural acoustic waves. When the acoustical signal is switched-off, the optical power losses within the cavity are reduced, and then a laser pulse is emitted. Trains of Q-switched pulses were successfully obtained at repetition rates in the range 1–10 kHz, with pump powers between 59 and 88 mW, at the optical wavelength of 1064.1 nm. Best results were for laser pulses of 118 mW peak power, 1.8 μs of time width, with a pump power of 79 mW, at 7 kHz repetition rate.

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1. INTRODUCTION

Q-switched fiber lasers have attractive applications in different fields, such as in medicine, remote sensing and material processing [1]. The mechanism of short pulse emission is based on the modulation of the Q factor of the cavity [2, 3], which can be done either passively or actively. In the former the setups are simpler, but the repetition rate only varies with the pump power of the medium gain [4, 5]. Further, they usually show long-term instability, and frequently the amplitudes of the pulses are randomly modulated in time [6]. On the other hand, active Q-switching is independently and accurately controlled by an electrical signal, which triggers the modulator. The bulk approach, such as by electro-optic [7] or acousto-optic modulators [8], is not adapted to compact fiber laser systems required nowadays; further they have large optical coupling losses and stringent alignment requirements [9]. It is also true that fiber-pigtailed packaged electro-optic or acoustooptic modulators [10–12] could be used; with consequently lower power insertion losses, but still remaining relatively high (typically higher than 3 dB). For these reasons, the all-fiber approach is of permanent interest, being advantageous in terms of cost, loss, packaging, robustness, and simplicity. One solution widely investigated has been enabled by the use of fiber Bragg gratings (FBGs) as cavity mirrors [13]. In this way, the tuning of the wavelength of one of the FBGs has been used to achieve active Q-switching [14]. Among the typical tuning methods, we could mention the stretching of fiber Bragg gratings by magnetostrictive materials [15, 16], by piezoelectric actuators [17, 18], or by the interaction of longitudinal acoustic waves with the FBG [19, 20]. Other technique used for active Q-switching relied in the cavity loss modulation by the core-to-cladding mode-coupling in optical fibers induced by travelling flexural acoustic waves [21, 22].

In this work we present an actively Q-switched strictly all-fiber laser, where cavity loss modulation is achieved by intermodal modulation induced by travelling flexural acoustic waves in a tapered optical fiber. As opposed to [21, 22] which were focused at the erbium lasing wavelength, here we experimentally demonstrate the possibility of using this modulating technique at the technologically relevant ytterbium lasing wavelength [10–12, 23–25]. The use of ytterbium-doped fiber as a medium gain in fiber lasers is an important subject of research also, among other reasons, because it has a high absorption at 976 nm, and for this wavelength there is available a large range of fiber-pigtailed diode pump lasers with different characteristics. As the lasing band is very close to the pump wavelength, then it also has among the highest quantum efficiencies (~95%). Very high doping concentrations are possible also, enabling very high single pass gains and high slope efficiencies. However, very few actively Q-switched ytterbium-doped lasers with an all-fiber configuration have been reported [16]. The main difficulties arise from a relatively long time response and a limited modulation depth of all-fiber amplitude modulators. Here, we present the experi-

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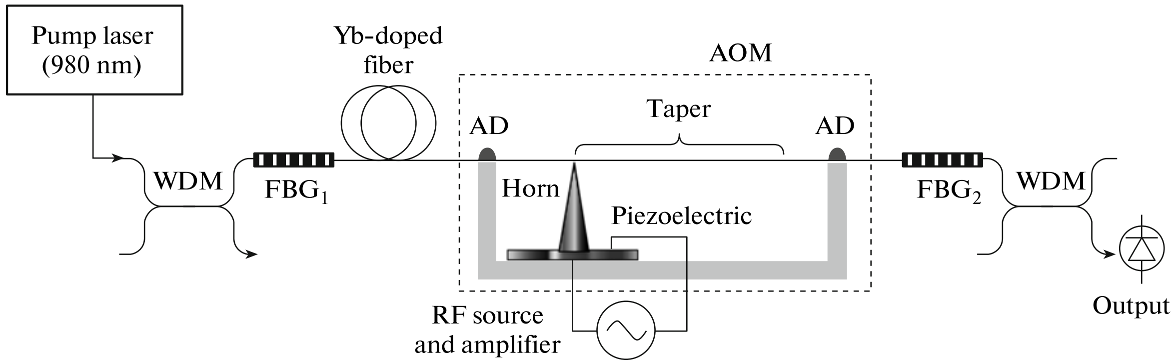

Fig. 1. Q-switched fiber-laser setup. The acousto-optic modulator (AOM) is defined by the elements inside the dashed line; AD stands for acoustic dumper.

mental results that we have obtained in a research work focused on the exploitation of in-fiber acousto-optics. In our proposed Q-switched fiber laser, when the acoustical signal is switched-off, the optical power losses within the cavity are reduced, and then a laser pulse is emitted. With this configuration we obtained trains of Q-switched pulses in the range 1–10 kHz at 1064.1 nm. Best results were for laser pulses of 120 mW peak power, 1.8 μs of time width, for a pump power of 83 mW, and 7 kHz of repetition rate.

2. LASER SETUP AND Q-SWITCHING TECHNIQUE

The setup used for our Q-switched fiber laser is schematically illustrated in Fig. 1. The gain was provided by 0.65 m of a heavily-doped ytterbium-doped single-mode fiber—Nufern SM-YSF-HI, cut-off wavelength of 860 ± 70 nm, numerical aperture of 0.11, and core absorption of 250 dB/m at 975 nm. The active fiber was pumped through a WDM coupler by a pigtailed laser diode emitting at 980 nm, providing a maximum pump power of 110 mW. The in-fiber acousto-optic modulator (AOM) was spliced between FBG_1—Bragg wavelength at 1064 nm, FWHM of 0.23 nm, and 99.6% of maximum reflectivity—and FBG_2—Bragg wavelength at 1064 nm, FWHM of 70 pm, and 44% of maximum reflectivity, defining in this way a Fabry–Perot cavity. The AOM in turn is composed of an RF source, a transversal-mode piezoelectric disk, an aluminum horn, and a tapered single-mode optical fiber—Fibercore SM980 of low numerical aperture (0.13–0.15). The optical fiber was tapered down by the fusion and pulling technique using a travelling flame, to obtain a taper waist with a uniform diameter of 76 μm and 0.1 m length, for this specific case. The tip of the aluminum cone—with the piezoelectric disc fixed to its base—was glued to an uncoated section of fiber near the taper, see Fig. 1. Finally, the optical fiber in the AOM was acoustically dumped in both extremes, in order to prevent unwanted acoustical reflections.

When an RF signal is applied to the piezoelectric disc, a travelling flexural acoustic wave is launched through the taper. If the acoustic wavelength matches the beat-length between the fundamental mode guided by the core and one of the optical modes supported by the cladding, then light coupled to the later remains in the cladding downstream of the taper, being finally absorbed by the fiber coating [26]. Thus, the coupling of power from the fundamental mode to a cladding mode results in the appearance of an attenuation notch in the spectrum. When the acoustic frequency is varied, the periodicity of the perturbation also does, and hence the phase-matching condition is shifted to a different optical wavelength. Figure 2a shows the tunability of the notches caused by the coupling between the fundamental core mode and the first three cladding modes LP_{1m}. The selected operating point was at an optical wavelength of 1064.1 nm for an RF signal applied to the piezoelectric of 825 kHz. These measurements were made by illuminating the taper with a broadband light source and detecting the light transmitted through the taper with an optical spectrum analyzer. As an example, the inset of Fig. 2a shows one of the measured transmission spectra for an applied voltage to the piezoelectric of 26 V and a frequency of 885 kHz. The transfer of optical power from the fundamental core mode to one of the cladding modes behaves periodically as a function of the acoustic power, which in turn is a function of the applied voltage to the piezoelectric. Figure 2b shows this effect for the selected operation point marked in Fig. 2a. As it can be observed, the transmittance decays by a maximum of 12 dB for an applied voltage to the piezoelectric of 50 V (peak-to-peak measurement). Beyond this point, further increment in the applied voltage raises the transmittance again. Therefore, and bearing in mind its use as a Q-switching device, cavity loss modulation between 0 and 12 dB can be achieved by applying to the piezoelectric a sinusoidal signal at the fre-

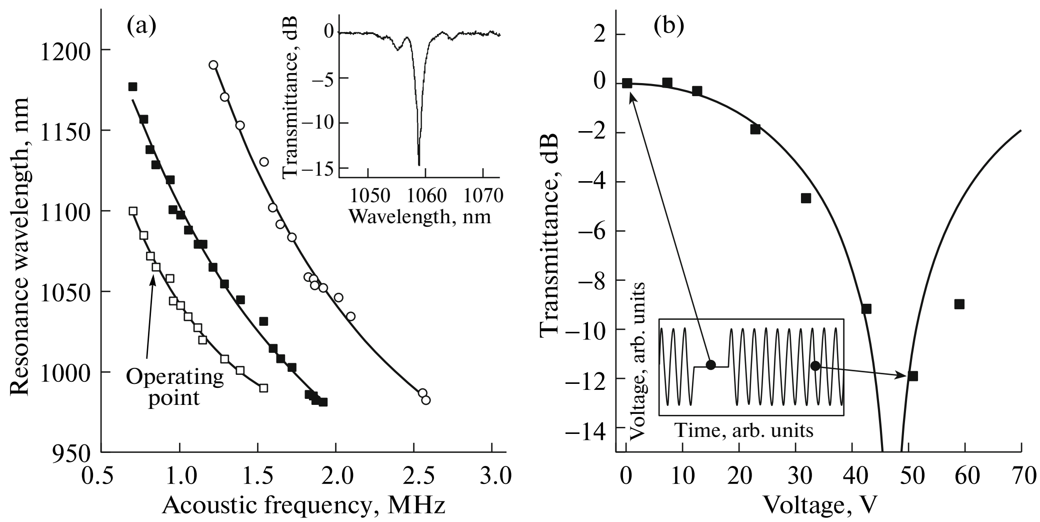

Fig. 2. (a) Resonant optical wavelengths as a function of the acoustic frequency for the first three mode-couplings. The inset shows a typical transmission notch caused by the first mode-coupling by applying to the piezoelectric a sinusoidal signal at 885 kHz and 26 V. (b) Transmittance at the selected operation point marked in (a)—i.e., 1064.1 nm and 825 kHz—as a function of the applied voltage to the piezoelectric (solid scatter points), the curve represents a theoretical fitting according to a square sine function.

quency of 825 kHz fully-modulated by a rectangular signal, see the inset of Fig. 2b. This modulation produced on-off periods of the acoustic wave travel down the fiber, which results in a modulation of the cavity losses at the resonance wavelength. In passing, we should mention that several tapers were fabricated in order to better optimize this laser system, by using Fibercore SM980 of high numerical aperture (0.17–0.19), and Nufern SM-YSF-LO (a moderately ytterbium-doped fiber), and in turn with different taper waists. Despite this, the minimal decay in transmittance was always around the reported values, i.e., between 10 and 16 dB.

The switching time is one of the key parameters for any modulator intended to be used as a Q-switching device in a fiber laser. Preferably, it should be as short as possible. For this reason we measured the temporal response of this device, by detecting the transmitted light, while simultaneously registering the modulating signal in an oscilloscope. It takes 25 μs to increase/decrease the transmitted optical power through the taper when the RF voltage applied to the piezoelectric is switched-off/on, respectively. This time corresponds reasonably well with the time it takes a flexural acoustical wave to travel down the taper, i.e., 0.1 m/3764 m/s $\cong$ 26 μs. This value is short enough to allow the use of this modulator as a Q-switching device in a fiber laser, as it will be demonstrated in the following section. In principle, and for a given taper waist, shorter switching times could be achieved by decreasing the interaction length. Unfortunately, this simultaneously increases the acoustical power needed to reach the same optical coupling power, therefore there is a trade-off between both parameters.

In summary, the basic parameters of the acousto-optic modulator are a time response of 25 μs and a modulation depth of about 12 dB. Although these values are modest for Q-switching applications, we decided to set up the laser and investigate the characteristics of the optical pulses achievable with this type of modulator when using an ytterbium-doped fiber.

3. THE ACTIVELY Q-SWITCHED Yb-DOPED ALL-FIBER LASER

In this setup, both gratings are permanently tuned to the same wavelength by using two translational stages, one for each FBG; see the setup in Fig. 1. In this way, for zero voltage applied to the piezoelectric, this laser emits in CW, since then the cavity losses are minimal, see the transmittance in Fig. 2b for 0 V. Figure 3 shows the optical power in CW emission as a function of the pump power. There is a pump power threshold of 56 mW, about which the laser starts to emit, reaching a maximum output power of 3.4 mW, which in turn is determined by the maximum pump power available in our setup (110 mW). The inset shows the spectrum of CW emission; its linewidth is of 0.21 nm at a center optical wavelength of 1064.1 nm.

Now, we discuss the Q-switched operation of this laser. To this end, we modulated the cavity losses by applying to the piezoelectric a fully-modulated sinusoidal signal at the frequency of 825 kHz and 50 V. A rectangular wave was used to modulate the RF voltage that generates the acoustic wave. At a given frequency of the modulating signal, we found always a maximal duty cycle—i.e., the fraction of time that the signal is in its high level—able to perform Q-switch correctly.

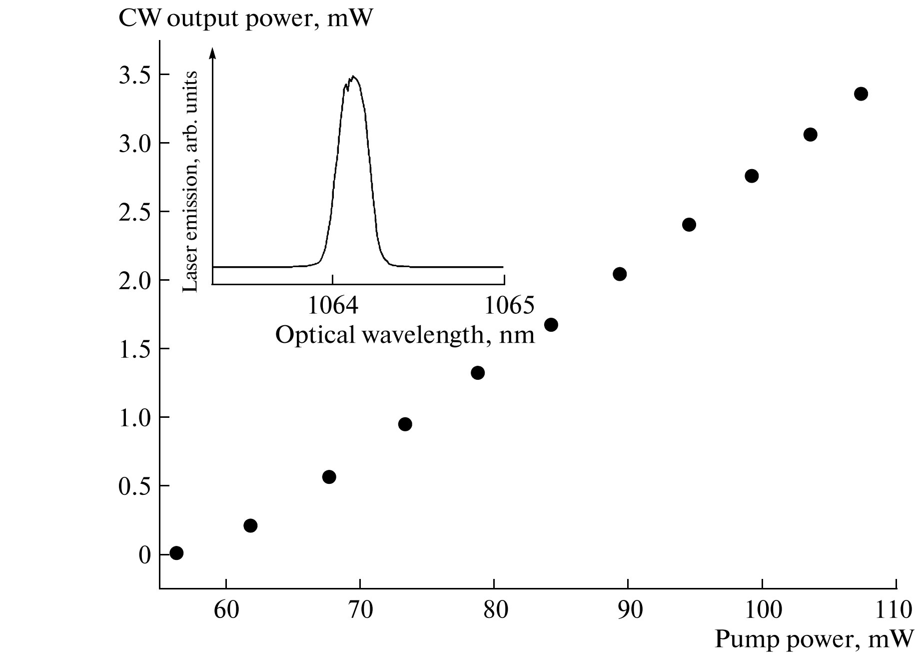

Fig. 3. Output optical power in CW emission as a function of the pump power. The inset shows the emission spectrum.

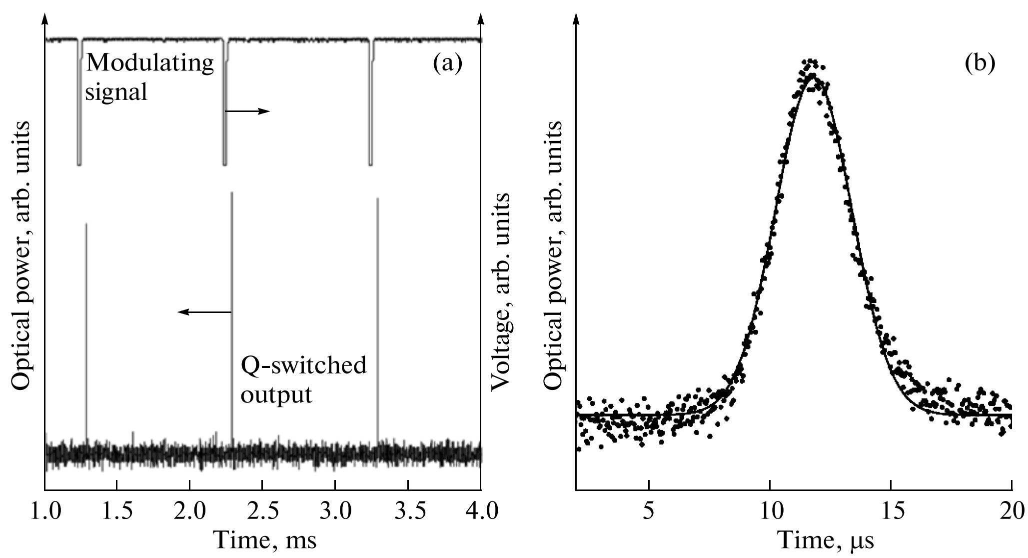

Fig. 4. (a) Modulating signal (above) at 1 kHz repetition rate together with the generated Q-switched laser output (below). (b) Detail of a single Q-switched pulse of (a) (scatter points) together with its corresponding fitting by a Gaussian function (solid curve).

If we decrease this duty cycle, then the cavity would stay in its high Q state longer, and more than one Q-switched pulse would be emitted in each time slot. The Q-switch repetition rate becomes determined by the frequency of the modulating signal; with this configuration we reached continuous tuning of the Q-switch repetition rate in the range 1–10 kHz. Figure 4a shows, as an example, a Q-switched optical pulses train at 1 kHz, together with the corresponding modulating signal, for a pump power of 59 mW. Figure 4b shows a detail of a single Q-switched optical pulse of the train shown in Fig. 4a with a time width (FWHM) of 3.72 μs. The pulses have a quasi-Gaussian profile; the fitting by this function is also shown in Fig. 4b. The effect of pump power on the Q-switched pulses, for different repetition rates in the range 1–10 kHz, is

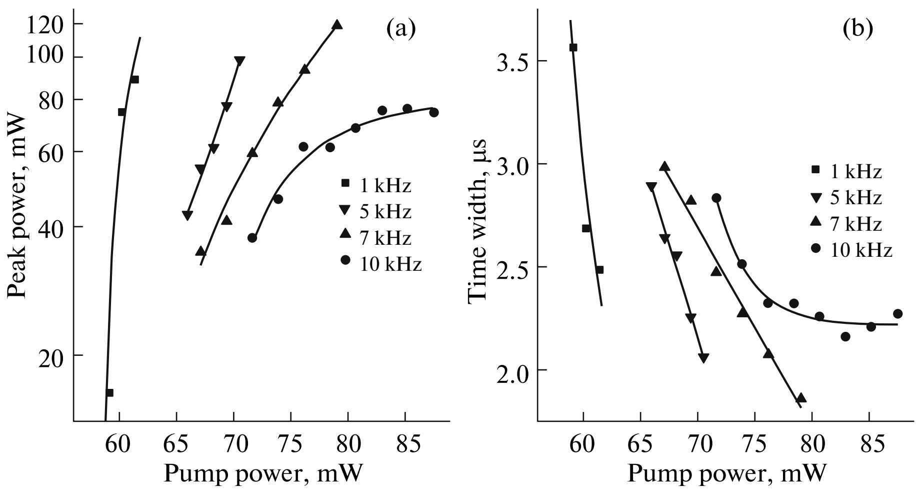

Fig. 5. Peak power and time width in Q-switched operation as a function of the pump power, (a) and (b), respectively, for several repetition rates.

shown in Fig. 5. For each Q-switching frequency there is a pump power threshold. Above threshold, the peak power increases with pump power, and there is a corresponding reduction of pulse width. For a given frequency there is also a pump power level beyond which the emission is not stable and extra pulses appear; the curves are truncated at that point. In order to overtake this limitation, a modulator with improved modulation depth is required. In addition, our laser produces easily multiple pulse emission, which is a well-known problem in actively Q-switched lasers with relatively large time responses. A large time response makes critical the adjustment of the duty cycle of the modulation voltage when the pump power is increased, particularly at low repetition rates. Consequently, a faster switching response of the acousto-optic modulator is required in order to improve the operation of the laser.

4. CONCLUSIONS

We have reported an actively Q-switched ytterbium-doped strictly all-fiber laser. Q-switching modulation is achieved by intermodal modulation induced by flexural acoustic waves travelling in a tapered optical fiber. Q-switched pulses at 1064.1 nm were successfully obtained at repetition rates in the range 1–10 kHz, with pump powers between 59 and 88 mW. Best results were for laser pulses of 118 mW peak power, 1.8 μs of time width, with a pump power of 79 mW, at 7 kHz repetition rate.

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