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A self-Q-switched all-fiber erbium laser at 1530 nm using an auxiliary 1570-nm erbium laser

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1. Introduction

Fiber lasers have been Q-switched using traditional bulk Q-switches and fiber-pigtailed ones. Sophisticated alignment techniques were necessary for reducing the coupling losses between the bulk Q-switches and the fiber cores. All-fiber Q-switched lasers with fiber-pigtailed Q-switches are of great interest because of their alignment-free characteristics and low cavity loss that is essential for efficient Q-switching performance. The fiber-pigtail Q-switches can be active devices as acousto-optical modulators [1-3] , or passive ones as saturable-absorber fibers [4-8] . Passive Q-switching with a saturable absorber fiber is the simplest and most economical approach for producing high-power laser pulses. In addition, a solid-state saturable absorber Q-switch (SAQS) fiber has a high damage threshold and can hold an enormous laser gain for energy release into one Q-switched laser pulse. In spite of these advantages, the SAQS fibers are seldom considered in the literature. One of the criteria for a SAQS laser is that the absorption cross section, σ_a, of the SAQS should be larger that the emission cross section, σ_e, of the gain medium. Furthermore, to achieve sequentially Q-switched pulses using a continuous-wave (CW) pump source, the relaxation lifetime of the SAQS, τ_{a2}, should be shorter than that of the gain medium, τ_{g2}.

Erbium fiber lasers emitting at the so-called eye-safe wavelength of 1.5-1.6 μm are the preferred laser devices for light detection and ranging (LIDAR) and other applications that require Q-switched operation. There has been no fiber-type SAQS material demonstrated for erbium fiber lasers except for erbium fiber itself. Recently, we demonstrated self-Q-switched, all-fiber erbium lasers in a ring scheme [9] and a standing-wave resonator [10] , where erbium fibers served as both 3-level lasers and 2-level saturable absorbers. Since the cross sections, σ_a and σ_e, of erbium are comparable, techniques of photon density enhancement in the SAQS fibers, such as double-passing routes and mismatch of mode field areas (MFA), were developed to activate SAQSing functions. Due to lifetime matching, $\tau_{a2}=\tau_{g2}$, in a self-Q-switched laser, a saturable-amplifier pump switch (SAPS) was introduced for acquiring sequentially Q-switched pulses [10] .

In this paper, we demonstrate a self-Q-switched, all-fiber, erbium laser that emits at 1530 nm using an auxiliary 1570 nm erbium laser applied to the SAQS erbium fiber. Both wavelengths, 1530 and 1570 nm, are in the same transition band of erbium. The dopant Er^{3+} has a broad band of energy transition between $^4I_{13/2}$ and $^4I_{15/2}$, which corresponds to an emission and absorption wavelength range from 1.48 to 1.6 μm. According to the specifications of the SAQS erbium fiber provided by the manufacturer nLight, the emission and absorption cross sections are about the same: $6\text{X}10^{-21}$ cm^2 at 1530 nm. They are $2.6\text{X}10^{-21}$ cm^2 and $1.3\text{X}10^{-21}$ cm^2 at 1570 nm, correspondingly. These values might differ slightly for different products and manufacturers. The cross-section ratio, σ_a/σ_e, is also the population ratio of N_{a2} to N_{a1} in the state of full saturation. When a large laser power at 1570 nm, $I_{a,1570}$, saturates the SAQS, the absorption population at 1570 nm, defined as $N_{a,1570}$=[N_{a1}-(σ_e/σ_a)N_{a2}], becomes zero and the population ratio of N_{a2} to N_{a1} is about 0.5. Such a population ratio indicates a reduction of the absorption population at 1530 nm, $N_{a,1530}$, by the $I_{a,1570}$ to a value of one-third of the total erbium dopants of the SAQS fiber, N_{aT}. Therefore, the initial value of $N_{a,1530}$, called N_{ai}, for Q-switching is tunable with an $I_{a,1570}$ applied on the SAQS fiber. More importantly, an $I_{a,1570}$ can shorten the relaxation lifetime of $N_{a,1530}$. When the SAQS fiber is fully bleached by a Q-switched pulse at 1530nm, N_{a2} is equal to N_{a1} instantly. Here, $N_{a,1530}$ will soon be modified by the $I_{a,1570}$ back to the initial N_{ai} for next Q-switching. To simplify the discussion on the effect of $I_{a,1570}$ on the erbium lifetime, we assumed uniform distribution of N_{a2}, N_{a1} and $I_{a,1570}$ in the SAQS and derived the effective lifetime of $N_{a,1530}$ as:

$$\tau_{a2}' = \frac{\tau_{a2}}{1+\left(1+\frac{\sigma_{a,1570}}{\sigma_{e,1570}}\right)\frac{I_{a,1570}}{I_{s,1570}}}, \; where\ I_{s,1570} = \frac{h\nu}{\tau_{a2}\sigma_{e,1570}}\frac{A_a}{\Gamma}. \quad (1)$$

A_a is the cross sectional area of the fiber core, Γ the confinement factor and $I_{s,1570}$ is the saturation power of the SAQS fiber. Therefore, with the known ratio$\sigma_{a,1570}$ / $\sigma_{e,1570}$~0.5, the effective lifetime, τ_{a2}', could be one order of magnitude shorter than the real lifetime τ_{a2} when the ratio $I_{a,1570}/I_{s,1570}$ is larger than 6.

2. Experiments

Fig. 1 shows the schematic design of a self-Q-switched, erbium, all-fiber laser, pumped with a continuous-wave (CW) 980-nm laser diode (LD). The Q-switched laser was stabilized, and the pulse repetition rate was tunable using a 1570-nm laser that was also an erbium fiber laser pumped with a 980-nm LD (not shown). Therefore, the laser system could be simplified using only one high-power pump LD and a pump splitter with a properly designed ratio. The gain medium was a 210-cm erbium-doped fiber with a core diameter of 14 μm and an absorption loss of 19 dB m^{-1} at 1530 nm, manufactured by the company Coractive. The SAQS was a 20-cm Er fiber, made by the manufacturer nLight, with a relatively smaller core diameter of 4 μm and an absorption loss of 110 dB m^{-1} at 1530 nm. The mismatch of the mode field areas (MFA) between the gain and the SAQS resulted in high photon density and fast absorption saturation in the SAQS fiber, thereby giving rise to Q-switching action. The numerical aperture (NA) number and the mode field diameter of the SAQS were 0.2 and 6.5 μm, indicating a confinement factor Γ of about 0.53. Thus, the saturation power, $I_{s,1570}$, was determined by Eq. (1) to be 1.2 mW. The 980/1530 nm WDM inside the resonator was used to protect the SAQS from the pump power. Similarly, a 1530/1570 nm WDM was employed to prevent the gain fiber from being stimulated by the 1570-nm laser. All components were core-fusion spliced. The length of the resonator was about 4 meters.

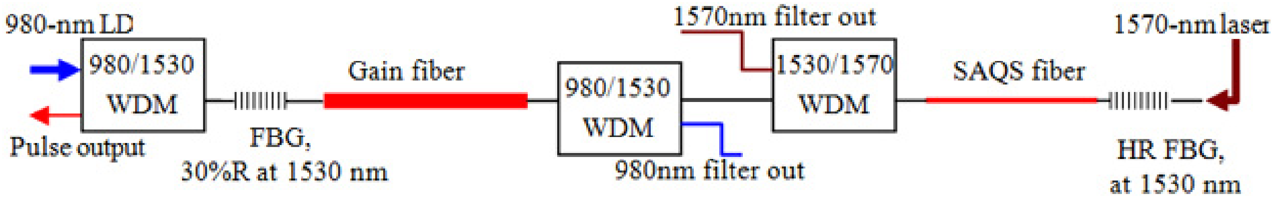
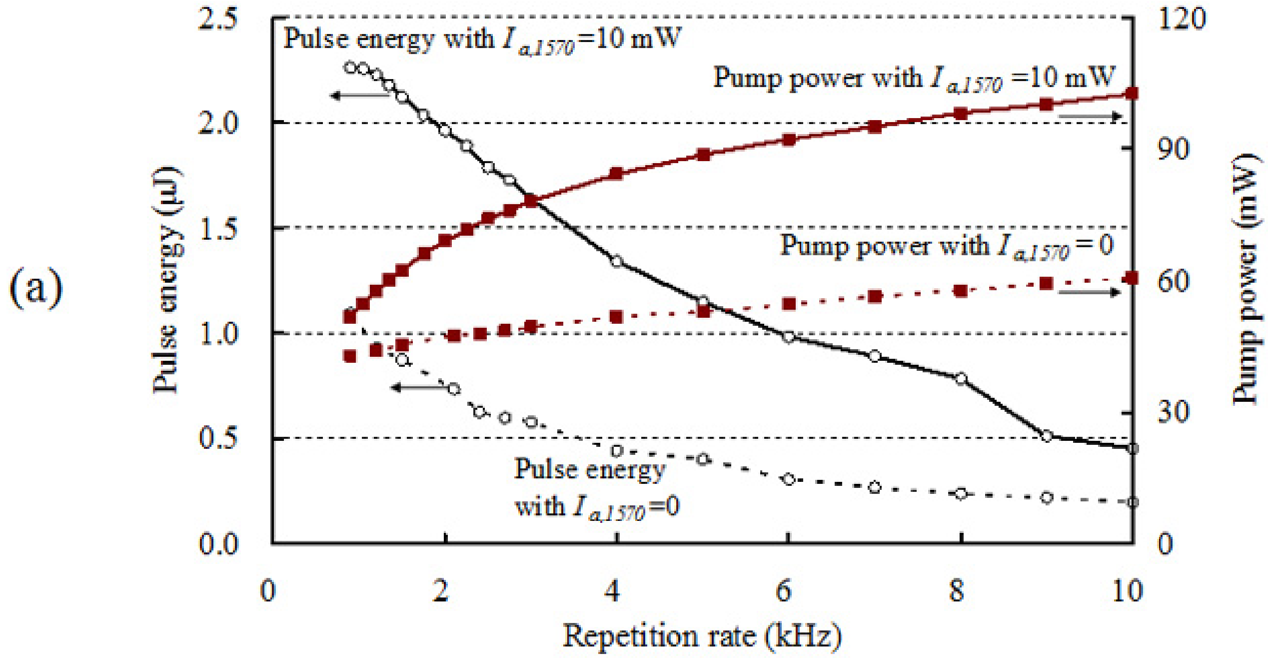


Fig. 1. Schematic diagram of a self-Q-switched, all-fiber erbium laser at 1530 nm with a tunable repetition rate using an auxiliary 1570 nm laser.

The Q-switching performances related to the pulse repetition rate, R_{pr}, with $I_{a,1570}$=0 and $I_{a,1570}$=10 mW are compared and shown in Fig. 2 (a) and (b). Both the cases with and without $I_{a,1570}$ were stable when R_{pr} was within 0.9-10 kHz and unsteady when R_{pr} was below 0.9 kHz. At the end of the experiment, the case with the $I_{a,1570}$ was stabilized in a low-R_{pr} operation of 0.1-1.5 kHz by doubling the length of the SAQS fiber. Instead of stabilizing the laser at low R_{pr} (<1 kHz) as the function of a saturable-amplifier pump switch (SAPS) [10], the tuning source, $I_{a,1570}$, primarily improved the Q-switching efficiency at high R_{pr} by affecting the relaxation lifetime. Without the $I_{a,1570}$, a pulse had a full-width-at-half-magnitude (FWHM) of about 0.9 μs and an energy of 1.1 μJ at a repetition rate, R_{pr}, of 0.9 kHz near the laser threshold. The 0.9 kHz value of R_{pr} indicated a 1.1-ms recovery time (i.e. τ_{a2}/9) for $N_{a,1530}$ after being bleached by a Q-switched pulse. Assuming the SAQS was fully bleached by each pulse, it can be calculated that $N_{a,1530}$ switched between 0 to about 0.1N_{aT}. A higher pump power would give less time for $N_{a,1530}$ recovery, leading to a higher repetition rate and smaller pulse energy. The pulsing output still remained with a pump power larger than 100 mW where the pulse had a pulse width of microseconds and a very low pulse energy. Such low-efficiency Q-switching is referred to as “Q-fluctuation” and can only hold a small amount of energy in the gain medium and will have low extraction efficiency of the gain population.



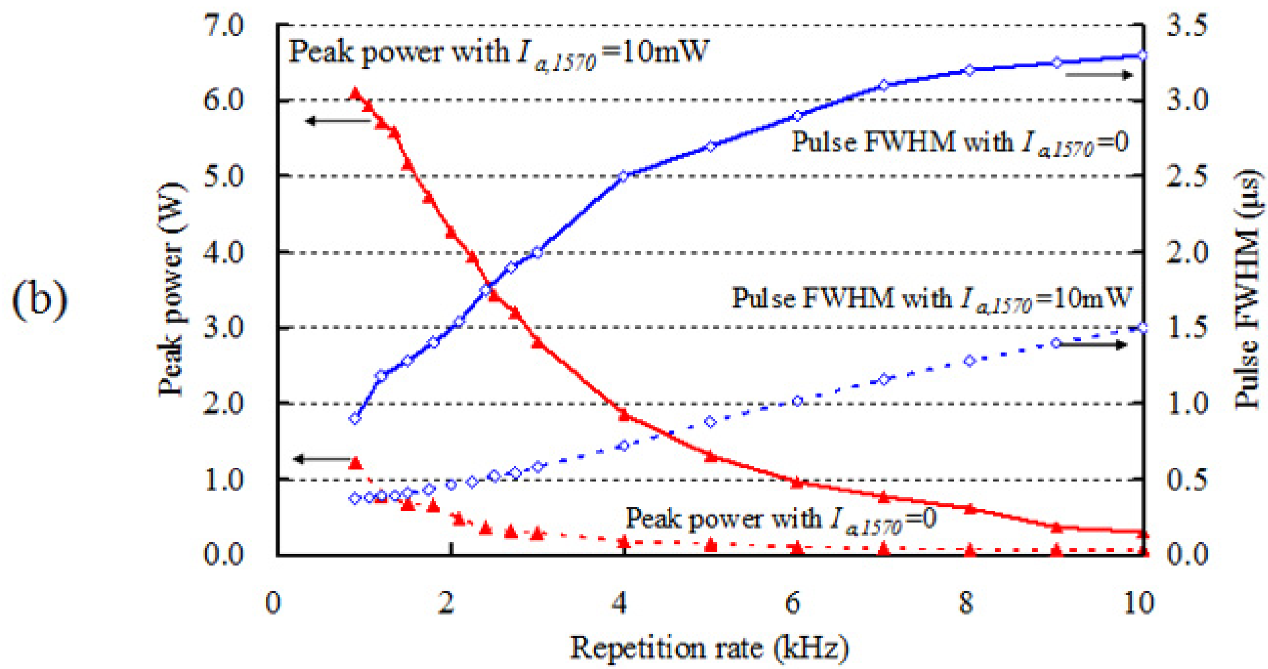


Fig. 2. The Q-switching performances with $I_{a,1570}$=0 and $I_{a,1570}$=10 mW. (a) Pulse energy and pump power related to pulse repetition rate, (b) pulse peak power and pulse FWHM related to pulse repetition rate.

When the 1570-nm laser was turned on, the Q-switching performance was much improved. By comparing the two cases (i.e. with and without $I_{a,1570}$) at the same R_{pr} in Fig. 2(a), the improved pulse energy with the $I_{a,1570}$ demonstrates faster and more extensive recovery of $N_{a,1530}$. Due to this increased $N_{a,1530}$ recovery, a higher pump power was required with the $I_{a,1570}$. Furthermore, the improved recovery of $N_{a,1530}$ denoted a higher hold-off ratio of the gain population in the gain fiber, in turn leading to a better Q-switching performance with a shorter pulse width and higher peak power as clearly demonstrated in Fig. 2(b).

We further improved the Q-switching performance by doubling the length of a SAQS fiber. The SAQS had an absorption loss of 44 dB at 1530 nm that was even larger than that of the gain fiber. Thus, the laser could not reach the threshold by pumping alone without the assistant of the $I_{a,1570}$. Stable, sequential, Q-switched pulses were achieved using a 10-mW $I_{a,1570}$, as shown in Fig. 3. The pulse had a very stable shape, a FWHM of about 40 ns, and a peak power of larger than 100 W along the pump range from 75-200 mW. The maximum pulse energy of 6 μJ and peak power of 165 W was achieved at the lowest R_{pr} of 0.1 kHz. The R_{pr} was steadily proportional to the pump power and limited by the maximum 980-nm LD output. The high Q-switching efficiency was attributed to the high hold-off ratio of the gain population by the large N_{ai}, which, in turn, lead to a high extraction efficiency of the pumped gain. Since more pumping time was needed for the large gain population, the Q-switching was stabilized into a low-R_{pr} range from 0.1-1.5 kHz. Efficient Q-switching at higher R_{pr} should be achievable using a more intense pump LD. The results demonstrated here were better and more stable than what can be achieved using a saturable-amplifier pump switch [10].

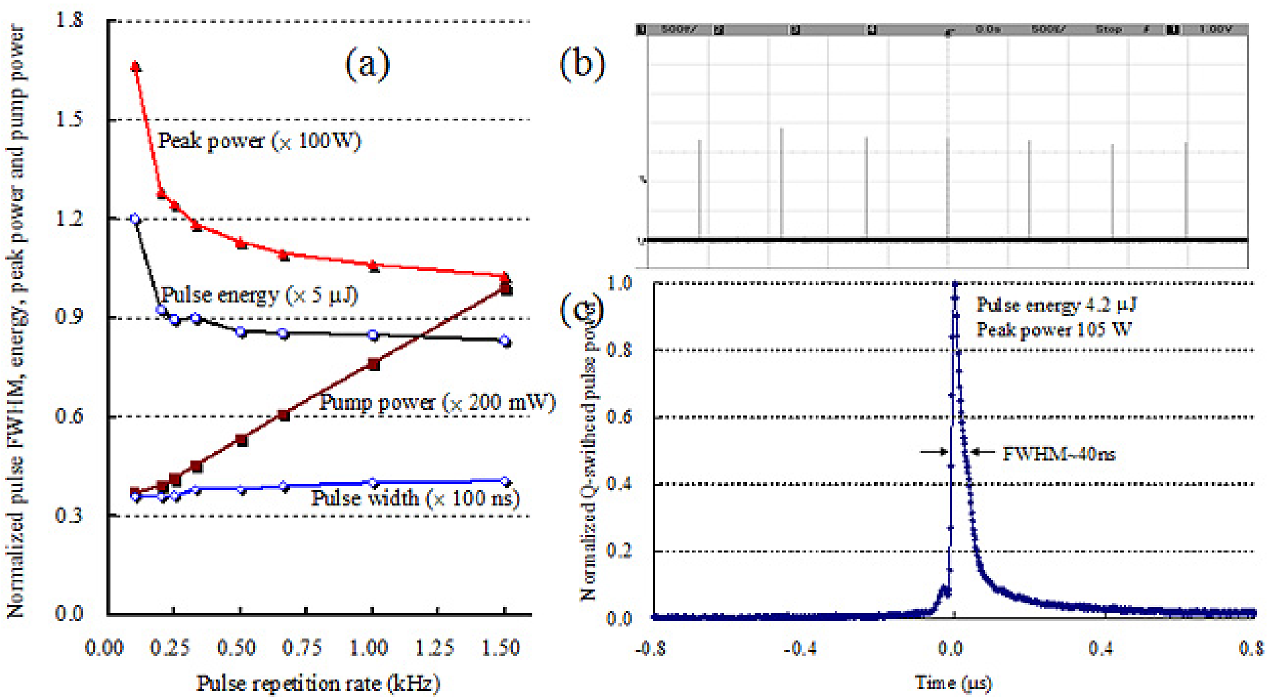


Fig. 3. (a) Q-switching performance using a 10-mW $I_{a,1570}$ and a SAQS erbium fiber with an absorption loss of 44 dB at 1530nm. (b) Sequential Q-switched pulses at 1.5 kHz captured on an oscilloscope, and (c) the corresponding pulse with a peak power of 105 W.

2.Conclusion

We have demonstrated a self-Q-switched, all-fiber erbium laser emitting at 1530 nm through the use of an auxiliary laser at 1570 nm, $I_{a,1570}$, that allowed tunable and optimizable Q-switching performance. The $I_{a,1570}$ was applied to a SAQS erbium fiber to shorten the relaxation lifetime. The wavelengths of 1530 and 1570 nm are in the same band of energy transition between $^4I_{13/2}$ and $^4I_{15/2}$. A SAQS fiber with a 22-dB absorption loss was employed for demonstrating the effect of lifetime shortening, and the improvement on Q-switching at the repetition rate from 0.9 to 10 kHz. By doubling the length of the SAQS fiber and applying a 10-mW $I_{a,1570}$, sequential pulses with pulse energy of 6-4 μJ, steady pulse width of 38-40 ns and peak power of 165-105 W were achieved at repetition rate of 0.1-1.5 kHz. Efficient Q-switching at higher repetition rates is expected when a more intense pump source is employed.

Reference

1. D. W. Huang, W. F. Liu and C. C. Yang, “Q-switched all-fiber laser with an acoustically modulated fiber attenuator,” IEEE Photonics Technol. Lett. **12**, 1153-1155 (2000).
2. D. Zalvidea, N. A. Russo, R. Duchowicz, M. Delgado-Pinar, A. Díez, J.L. Cruz and M.V. Andrés, “High repetition rate acoustic-induced Q-switched all-fiber laser,” Opt. Commun. **244**, 315-319 (2005).
3. M. Delgado-Pinar , D. Zalvidea, A. Díez, P. Pérez-Millán and M. V. Andrés, “Q-switching of an all-fiber laser by acousto-optic modulation of a fiber Bragg grating,” Opt. Express **14**, 1106 (2006).
4. V. V. Dvoyrin, V. M. Mashinsky, and E. M. Dianov, "Yb–Bi pulsed fiber lasers," Opt. Lett. 32, 451-453 (2007).
5. A. A. Fotiadi, A. S. Kurkov and I. M. Razdobreev, “All-fiber passively Q-switched Ytterbium laser,” 2005 Conference on Lasers and Electro-Optics Europe, p. 515.
6. P. Adel, M. Auerbach, C. Fallnich, S. Unger, H.-R. Müller and J. Kirchhof, "Passive Q-switching by Tm3+ co-doping of a Yb3+ fiber laser," Opt. Express 11, 2730-2735 (2003).
7. A.S. Kurkov, E.M. Sholokhov and O.I. Medvedkov, "All fiber Yb-Ho pulsed laser," Laser Phys. Lett. 6, 2, 135–138 (2009).
8. S. D. Jackson, "Passively Q-switched Tm3+-doped silica fiber lasers," Appl. Opt. 46, 16, 3311-3317 (2007).
9. T. -Y. Tsai and Y. -C. Fang, "A saturable absorber Q-switched all-fiber ring laser," Opt. Express 17, 1429–1434 (2009).
10. T. -Y. Tsai, Y. -C. Fang, Z. -C. Lee and H. –X. Tsao, "All-fiber passively Q-switched erbium laser using mismatch of mode field areas and a saturable-amplifier pump switch," Opt. Lett. 34, 19, 2891-2893 (2009).