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Self-balanced Q- and gain-switched erbium all-fiber laser

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We demonstrate a 980-nm CW-pumped fully passive pulsed all-Er3+ all-fiber laser, self-balancing between being Q- and gain-switched at S and L bands. The laser was passively Q-switched at 1510 nm with the saturable absorber in an intra-cavity gain-switched at 1570 nm. The time spacing between the Q- and gain-switched pulse peaks was steadily 0.92 or 2.75 μs depending on the absorber lengths. Sequential 1510-nm pulsing with a pulse energy of 3.8 μJ and a pulse width of 280 ns at a repetition rate of 1.7 kHz was achieved with a pump power of 175 mW.

An all-fiber laser scheme with no air gap requiring no signal coupling into and out of fiber cores and long-term maintenance has an inherent low cavity loss that favors the efficiency of a Q-switching operation. Q-switching in an all-fiber laser scheme could be realized using active devices, such as piezoelectric transducers (PZT)1,2 and a polarization switch in a micro-structured fiber,3 or using a passive saturable-absorber Q-switch (SAQS) fiber.4–14 Passive Q-switching using a SAQS fiber requiring no external circuitry is a relatively compact and economic technology for producing nanosecond high-intensity pulses. In the last decade, the technology of passively Q-switched all-fiber laser has been realized mostly in Yb3+ lasers, Q-switched by the fibers doped with Tm3+5, Sm3+6, Ho3+7 and Bi8 at the wavelength region of 1050-1125 μm. Lately we demonstrated an erbium all-fiber laser passively Q-switched by thulium fiber.9 Thulium doped fiber is, thus far, the only fiber-type SAQS capable of directly Q-switching erbium fiber lasers without using the mode-field-area (MFA) mismatch method.10 The laser was soon realized in a cladding-pumped large-core all-fiber system by Kurkov et al., providing a higher average output power of 0.8 W at a repetition rate of 2 kHz.11 In spite of the superior Q-switching performance with thulium fiber, the operation of Q-switching is restricted to wavelengths longer than 1570 nm, referred to as the L band in optical communications. Besides, in order to have a full absorption population of Tm3+ relaxed back to the ground state (3Ho) for next Q-switching, the pulse repetition rate is limited by the inversion of the relaxation lifetime (3Fa) of Tm3+, 1/τa, about 2 kHz. Thus far, a passively Q-switched Er3+ all-fiber laser capable of operating at a broad band and high repetition rates with pulse energy independent of the repetition rate has not been reported in the literature.

In principle, to activate saturable-absorber Q-switching, the general criterion is that the critical ratio, Cq, defined to be (σsa,e+σsa,a)/(σg,e+σg,a), should be larger than 1, where σsa,a and σsa,e (or σg,a and σg,e) are the absorption and emission cross sections of the saturable absorber (or gain medium) respectively. A large Cq also indicates a high Q-switching speed. In the case of self Q-switching (i.e. the SAQS and the gain medium are the same material), the critical ratio Cq is always 1. Therefore, a three-level laser medium such as Er3+ could ideally be self Q-switched using the MFA mismatch method at a broad range from 1.48 to 1.62 μm, thereby providing a more flexible alternative than

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FIG. 1. The schematic design of a dual-wavelength passively pulsed erbium all-fiber laser, self-balancing between Q-switching at 1510 nm and gain-switching at 1570 nm.

the laser using thulium SAQS fiber. The relaxation time of the SAQS could be shortened using an auxiliary light source,12 or simply by a high-Q gain-switched intra-cavity confining the SAQS.8, 13 With the gain-switched intra-cavity, the repetition rate of Q-switched pulses was no longer restricted by the relaxation lifetime of the SAQS but only limited by the maximum pump power.

The energy transition between 4I_{13/2} and 4I_{15/2} of Er^{3+} has the absorption band slightly blue-shifted from the emission band. The spectral mismatch of $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ results in a variation of gain population, $N_g(\lambda) = N_2 - g_r(\lambda)N_1$, with the wavelength, $\lambda$, where $g_r(\lambda)$ is the ratio of $\sigma_a(\lambda)$ to $\sigma_r(\lambda)$. Because of the variation of $g_r(\lambda)$, an Er^{3+} fiber saturated at the 1510 nm provides a positive gain at 1570 nm, and on the contrary, the saturation of an Er^{3+} fiber at 1570 nm gives rise to an absorption loss at 1510 nm. Using these characteristics, we demonstrate a fully passive CW-pumped pulsed erbium all-fiber laser, self-balancing between being Q-switched at the 1510 nm and being gain-switched at 1570 nm. To our knowledge, the erbium laser is, for the first time, passively Q-switched at the S-band region.

Figure 1 shows the schematic design of the self-balanced Q- and gain-switched erbium all-fiber laser system. The Q-switched laser cavity consisted of a pair of 1510-nm fiber Bragg gratings (FBG), an erbium gain fiber, an erbium SAQS fiber and an internal 980/1550-nm WDM that left the SAQS unexcited. The gain fiber, manufactured by CorActive Inc., was multi-mode erbium fiber with a core diameter of 13.7 $\mu$m and an absorption of 19 dB/m at 1530 nm. Correspondingly, the SAQS fiber, manufactured by the OFS company, was single-moded with a relatively small fundamental mode field diameter of 4.3 $\mu$m and an absorption loss of 150 dB/m at 1530 nm. The SAQS fiber was confined in an intra-cavity formed by a pair of 1570-nm FBGs. The lengths of the SAQS fiber were 10.8 and 15.5 cm tested with a 360-cm long gain fiber. The lengths of the 1510-nm and 1570-nm resonators were about 10 and 3 meters, respectively.

The values of $\sigma_a(\lambda)$ and $\sigma_r(\lambda)$ of Er^{3+} doped silica fiber have been well-studied in research literature. For simplification of discussion, we consider $\sigma_a = 3.56 \times 10^{-21}, 6.5 \times 10^{-21}, 1.23 \times 10^{-21}$ cm$^2$ and $\sigma_r = 2.17 \times 10^{-21}, 6 \times 10^{-21}, 2.62 \times 10^{-21}$ cm$^2$ at the wavelengths of 1510, 1530, 1570 nm respectively, and assume a constant summation of the populations on the levels 4I_{13/2} and 4I_{15/2} of Er^{3+}. With the given parameters above, it could be calculated that the achievable one-trip gain of the 15.5-cm SAQS switched by an efficient Q-switching action (i.e. full bleaching of the SAQS at 1510 nm) is about 4 dB at 1570 nm, sufficient to produce a gain-switched pulse that soon saturates the SAQS at 1570 nm to have an absorption loss of 6 dB at 1510 nm for the next Q-switching. Figure 2 shows the Q- and gain-switched pulses detected by an oscilloscope and the corresponding spectrum measured by a monochromator.

The pulses were further distinguished using a S/L-band WDM, and verified to be a Q-switched pulse at 1510 nm and a gain-switched one at 1570 nm, individually. Due to the MFA mismatch method employed to activate the Q-switching operation, the smaller core diameter of the SAQS fiber gave rise to relatively small output power of 1570 nm. The pulse energy of 1510 nm was measured to be about 5 times that of 1570 nm. Figure 3 shows the characteristics of the Q- and gain-switched
FIG. 2. (a) Q- and gain-switched pulses with a time spacing of 0.92 μs, and (b) the corresponding spectra from 1500 to 1580 nm.

Lasers, such as the average output power (1510 nm only), the full width at half maximum (FWHM) of 1510-nm pulse, the repetition rate and the time spacing between the Q- and gain-switching pulse peaks \( (t_s) \), related to the pump power. The maximum applied pump power of the 980-nm laser diode was about 175 mW. It can be calculated correspondingly that the optimal switching gain and loss in a 10.8-cm SAQS fiber was respectively about 2.8 and 4.2 dB, which leads to lower pulse energies, longer pulse FWHMs, longer time spacings, \( t_s \), and higher repetition rates. The repetition rate was stable and linearly proportional to the pump power. Figure 4 shows a stable pulsing chain at the repetition rate of 3.3 kHz with a constant spacing between the 1510-nm pulses. The standard deviation of the repetition rate was calculated to be 19 Hz at the repetition rate of 3.3 kHz. In addition, by observing the pulse peak magnitudes detected on the oscilloscope, the deviation normalized by the average magnitude was calculated to be \( 6.2 \times 10^{-3} \).

The self-balancing mechanism could be modeled using the modified four rate equations of the gain population of the gain fiber, \( N_g \), the absorption population of the SAQS, \( N_a \), and the two photon numbers of \( n_1, n_2 \) at the Q- and gain-switching wavelengths \( \lambda_1 \) and \( \lambda_2 \). With the 10.8-cm SAQS fiber and the parameters employed in the experiment, the self-balanced pulsing mechanism is simulated and shown in Fig. 5, where \( N_g \) is normalized by the total Er\(^{3+} \) populations in the SAQS fibers, \( N_{aT} \), and \( N_a \) by the threshold \( N_{ghv} \), and the pulses by the maximum peak power. The pulse energies of 1510 and 1570 nm are calculated to be 5.2 and 0.9 μJ with the corresponding pulse FWHMs of 250 and 180 ns. As depicted in Fig. 5(a), the absorption population of the SAQS, \( N_a \),
FIG. 3. The characteristics of Q- and gain-switched lasers with the SAQS lengths of 10.8 and 15.5 cm, as (a) the average output powers of 1510 nm, (b) the pulse repetition rates, (c) the pulse widths of 1510 nm and (d) the time spacings between Q- and gain-switched pulses.

FIG. 4. Stable pulsing chain at the repetition rate of 3.3 kHz was achieved with a pump power of 175 mW. Each pulsing contained a Q-switched pulse and a gain-switched one.

starts from the total population, $N_{aT}$, and is slightly decreased by the spontaneous emission of the pumped $N_g$ until the first Q-switched pulse occurs. Then, $N_a$ is switched into the two states of saturation at 1510 and 1570 nm, ideally 0 and $N_{ai}$, where

$$N_{ai} = \frac{1 - g_e(\lambda_2) / g_r(\lambda_1)}{1 + g_r(\lambda_2)} N_{aT}. \quad (1)$$

The ratio of $N_{ai}$ to $N_{aT}$ is about 0.48 for the case of 1510 and 1570 nm. The $N_{ai}$ less than $N_{aT}$ would result in relatively small pulse energy of the subsequent 1510-nm pulses compared with the energy of the first Q-switched pulse. As shown in Fig. 5(b), $N_a$ is reset back by the 1570-nm gain-switched pulses to $0.42 \times N_{aT}$. Although the first Q-switched pulse with a relatively high threshold exhibits a better Q-switching performance compared to the succeeding ones, the succeeding pulses are the ones observed and measured in the experiment. It should be noted that the self-balancing mechanism is based on the $g_\ell(\lambda)$ of erbium varying with the wavelength (i.e. decreasing from 1480 to 1620 nm).
FIG. 5. (a) Normalized $N_a$, $N_g$ and output Q-switched pulses of 1510 nm and gain-switched pulses of 1570 nm. $N_a$ is normalized by $N_{aT}$, $N_g$ by the threshold $N_{gth}$, and the pulses by the first Q-switched pulse peak power, (b) the performance of the succeeding pulsing in a minor time scale.

As clearly indicated in Eq. (1), when $\lambda_2$ and $\lambda_1$ are getting close, the ratio of $g_r(\lambda_2)/g_r(\lambda_1)$ increases and a longer SAQS fiber (i.e. a larger $N_{aT}$) is required in order to have a desired initial absorption population, $N_a$.

The complete bleaching of $N_a$ to zero by each Q-switched pulse shown in Fig. 5 indicates the steady maximum gain for each gain-switching. Such a constant gain leads to a stable gain-switching operation and a constant time spacing between the Q- and gain-switched pulses as observed in Fig. 3(d). Furthermore, it is interesting to notice that during the period from gain-switching to next Q-switching, $N_a$ increases slightly due to the population relaxation from $^{4}I_{13/2}$ to $^{4}I_{15/2}$. The increased amount of $N_a$ could slightly benefit the Q-switching performance at a lower repetition rate, such as the shorter pulse widths that were observed in Fig. 3(c).

In summary, we have demonstrated a passively Q- and gain-switched all-Er$^{3+}$ all-fiber laser at 1510 and 1570 nm. The laser was self-Q-switched at 1510 nm using the MFA mismatch method, and balanced with gain-switching in an intra-cavity of 1570 nm. The lasing of 1510 and 1570 nm resulted from the same energy transition between $^{4}I_{13/2}$ and $^{4}I_{15/2}$ of Er$^{3+}$. The pulse energy was independent of the repetition rate that was proportional to the pump power. Q-switching at high repetition rates could be achieved using high pump power, and the performance was not restricted by the long relaxation lifetime of erbium. With a 980-nm CW pump power of 175 mW, sequentially Q-switched pulses with a pulse energy of 3.8 $\mu$J and a pulse width of 280 ns at a repetition rate of 1.7 kHz were achieved.

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