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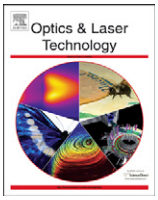

Review

# High efficiency, actively Q-switched Er/Yb fiber laser

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## ABSTRACT

We report the efficient and stable operation at 1549 nm of an actively Q-switched fiber laser based on an $Er^{3+}/Yb^{3+}$ doped double-clad single mode fiber. It operates with a repetition rate from 45 to 120 kHz and pulse duration from 34 to 80 ns; the output pulse shape and peak pulse intensity are stable over hours of operation. For a repetition rate of 120 kHz and a maximum pump power of 8.1 W we obtained an average output power of 4.0 W with an overall efficiency of 50% and with a minimum pulse duration of 34 ns.

**Contents**

## 1. Introduction

Q-switched fiber lasers have found widespread applications in laser trimming, marking and welding of various solid materials. These lasers are characterized by short pulse duration and high peak power of the output pulses. Many techniques have been demonstrated for Q-switched lasers [1], but there are many more applications covering other fields of science and technology that require different laser characteristics (beam quality, system compactness and quantum efficiency). Laser systems based on double clad, rare earth-doped fibers are attractive for compact and very efficient high power and short pulse generation. Their main performance advantage, compared with conventional bulk solid state lasers, results from the combination of beam confinement and excellent heat dissipation. Mostly Yb-doped high power systems are reported. Nevertheless the development of new fiber optic laser systems for eye save applications is of great interest for specific applications especially for atmospheric transmission in free space optical communication and active remote sensing, medical applications [2], and spectroscopy [3]. In some cases a longer wavelength is better suited for phase matching nonlinear conversion to longer wavelengths.

Many techniques are available for Q-switched laser operation; for example passively Q-switched lasers were demonstrated using an external cavity configuration containing elements with a $Co^{2+}/ZnS$ crystal as a saturable absorber [4], and polymer

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composites have already demonstrated saturable absorber properties on including carbon nanotubes [5] and graphene [6] in the matrix.

Novel active Q-switch devices [7–11] were proposed to provide pulsed laser operation; for example a fiber Bragg grating was used to eliminate the need for bulk-optics components [8], yielding Q-switched pulsing at MHz frequencies. A single-frequency, all fiber laser at a wavelength of 1550 nm was demonstrated with a reported peak power of 25 W and a pulse width of 12 ns (0.3 μJ/pulse) at a repetition rate of 80 kHz [9]. In several publications, Q-switching devices based on MOEMS [10,11] technologies were reported. On the other hand, acousto-optics modulators (AOMs) [12] are commonly available devices used to produce actively Q-switched lasers and they have excellent damage thresholds, good extinction ratio, and stable operating characteristics that are not available in other devices.

For cladding pumped fiber laser operation, the Erbium absorption is low. Doping the fiber with high $Er^{3+}$ concentration is limited by ion–ion interactions that lead to dimer formations that degrade the pump efficiency. This problem has been solved by co-doping the fibers with $Yb^{3+}$ ions. Ytterbium absorbs the pump energy and transfers it to the Erbium ions. $Er^{3+}/Yb^{3+}$ co-doping technique allows pumping of $Yb^{3+}$ ions using broad-stripe, high-power sources to reach much higher output power levels. $Yb^{3+}$ ions exhibit a strong absorption centered at a wavelength of 980 nm, but they can be pumped over a wavelength range extending from 800 to 1110 nm. $Yb^{3+}$ excited ions then transfer their energy to $Er^{3+}$ ions. The absorbed photons facilitate the transfer of population between the $^2F_{7/2}$ level and the $^2F_{5/2}$ level of the $Yb^{3+}$ ion. A cooperative energy transfer process between the excited state of $Yb^{3+}$ and the ground state of $Er^{3+}$ in the $^4I_{15/2}$ level excites the $Er^{3+}$ to the $^4I_{11/2}$ level while the $Yb^{3+}$ returns to its ground state. Much higher pump absorption efficiency is achieved this way [13–16]. Previous publications on the operation of high power lasers show that an important aspect is doped-core design [17,18]. The highest energy per pulse in a fiber laser was reported using a large mode area fiber for a high brightness output beam [19]. In this work, we exploit the Q-switched single mode operation to increase the peak intensity by designing a stable pump configuration that produces high average output power and short pulses using an $Er^{3+}/Yb^{3+}$ co-doped double clad single-mode fiber and we minimize heating of the fiber end.

We report stable Q-switched operation of a single-mode fiber laser with high pump slope efficiency operating at a wavelength around 1.5 μm. The main motivation for our work is its potential applications in coherent laser radar and tunable sources for down-conversion, for example to develop tunable THz sources with mW output power. In the next section we present the experimental setup and examine the operational design characteristics of our Q-switched fiber laser. The laser was operated under varying conditions and the results are presented and discussed in Section 3. In Section 4 we conclude by summarizing our most relevant results.

## 2. Experimental setup

A schematic diagram of the actively Q-switched $Er^{3+}/Yb^{3+}$ co-doped, double-clad fiber laser is shown in Fig. 1. The optical setup is a combination of two optical sub-systems operating at different wavelengths. One of them is the pump system for 980 nm and the other one is the laser system for 1550 nm. The arrangement consists of an end pumped Fabry–Perot cavity with an intra-cavity acousto-optic Q-switch element. The dichroic mirror (DM2) and Sagnac loop mirror are employed as cavity end mirrors. The Sagnac loop mirror consists of a fused fiber coupler, in our case a 3 dB coupler whose output ports are spliced to ~50 cm of Corning SMF-28 fiber, forming a short loop. This is a cheap and rugged device and the coupling ratio $\alpha$ of the coupler can be set to produce any desired reflectivity $R$. The properties of the Sagnac loop mirror were investigated in detail in [20]. In this laser the fiber loop is a convenient all-fiber mirror. The gain medium of the laser is a 3 m length of $Er^{3+}/Yb^{3+}$ co-doped, double clad fiber, which has a core diameter of 7 μm, an inner cladding diameter of 130 μm, and an outer cladding diameter of 245 μm. The numerical aperture for the signal is 0.17 and the inner cladding to the outer cladding ratio is 0.46. The end of the $Er^{3+}/Yb^{3+}$ doped fiber was spliced to a 1 m length of Corning SMF-28 fiber, which is single mode at 1550 nm, in order to attenuate the residual pump signal and also the 1064 nm signal due to the Ytterbium emission. The optical components in the system were carefully optimized through optical design software (ZEMAX) to reduce the spherical aberrations caused by the large numerical aperture of the fibers. Two aspherical lenses, L1 of 18 mm

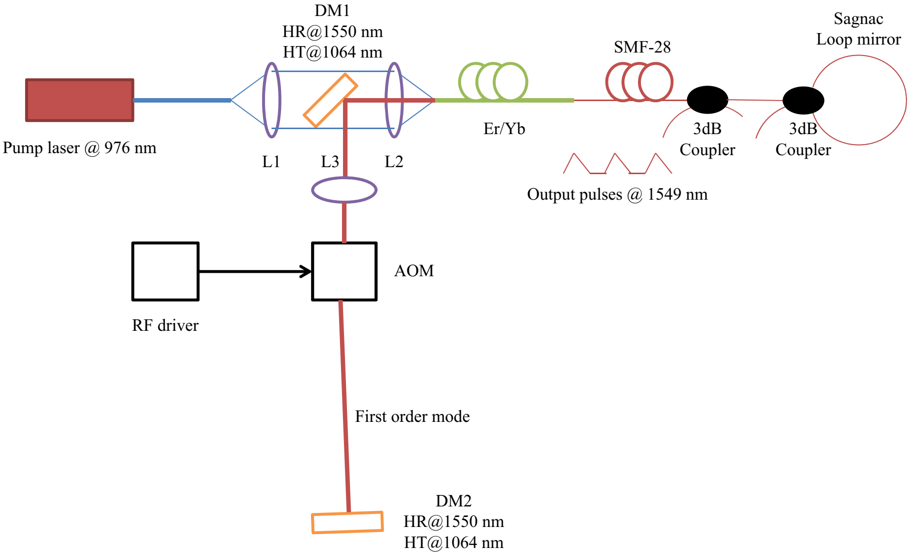

**Fig. 1.** Schematic diagram of the actively Q-switched $Er^{3+}/Yb^{3+}$ doped double clad fiber laser. The elements in the design are discussed in the text.

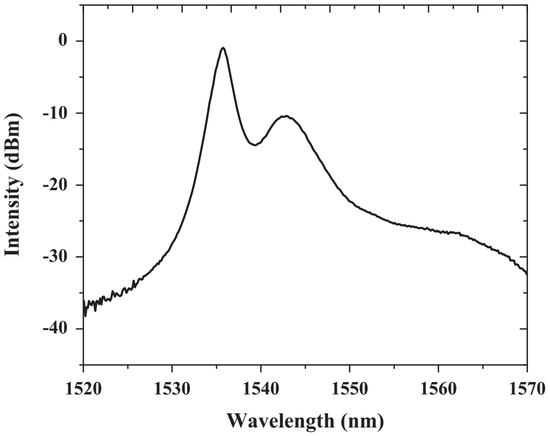

**Fig. 2.** Spontaneous emission spectrum of the $Er^{3+}/Yb^{3+}$ co-doped double-clad fiber.

focal length and L2 of 8 mm focal length, were used to efficiently relay and focus the pump and signal into the $Er^{3+}/Yb^{3+}$ co-doped, double-clad fiber. A lens L3 with a focal length of 150 mm was used in the system to make the beam diameter smaller than the Q-switch crystal size and at the same time to increase the stability of the cavity. The experimental setup includes two short wave pass (SWP) dichroic mirrors DM1 and DM2 with high reflectivity ($>99.5\%$) at 1550 nm and high transmission ($>90\%$) at 1064 nm, at 45° and 0° incident angles, respectively. The $Er^{3+}/Yb^{3+}$ co-doped, double-clad fiber was pumped by a high power diode laser (JOLD-30-FC-12-976); the diode laser has its output fiber coupled with a core diameter of 200 μm and numerical aperture of 0.22. The pump beam was coupled into the doped fiber through a 7.5° cleave at one end of the doped fiber. In experiments pump power was limited to a maximum pump power of 8.1 W.

To perform Q-switching an acousto-optic modulator (AOM) with a diffraction efficiency of $>60\%$ at first order was inserted in the cavity. A 5 V transistor–transistor-logic (TTL) variable repetition rate and duty cycle electrical signal was applied to the AOM driver. Several instruments were used to characterize the laser. To measure the output power of the Q-switched laser we used a power meter at a second 3 dB coupler that was inserted close to the Sagnac loop mirror in the cavity, an InGaAs photodetector with a spectral range from 800 to 1700 nm and a bandwidth of 1.2 GHz, and an oscilloscope of 100 MHz analog bandwidth with a sampling rate of 1.25 GS/s were used to measure the pulse shape; a monochromator was also used to measure the optical spectrum of the output signal; these measurements were made simultaneously. The DM2 was adjusted to the position of the waist of the lasing signal. The distance between L3 and DM2 was very close to 230 mm, in fact much longer than the focal length of 150 mm for L3. This is necessary because both pump and lasing signal with different wavelengths share the same lens L2. Fine-tuning of DM2 position guarantees a better coupling of the lasing signal into the core at the extremity of the doped fiber, forming a good cavity.

## 3. Experimental results and discussion

The spontaneous emission profile of our $Er^{3+}/Yb^{3+}$ fiber covers the wavelength range from 1520 to 1570 nm. This profile of the $Er^{3+}/Yb^{3+}$ fiber allows a laser to operate within this region depending upon the cavity configuration. Fig. 2 shows a spectrum measured with the monochromator in which we observe a strong peak at 1535 nm, in agreement with data sheet specifications.

The fiber length is a critical parameter in a laser. A laser with a longer $Er^{3+}/Yb^{3+}$ fiber length will operate at a longer wavelength due to the preferential re-absorption of the shorter wavelengths in the un-pumped section of fiber. We measured the average output power for six lengths of the $Er^{3+}/Yb^{3+}$ doped fiber. The result is shown in Fig. 3.

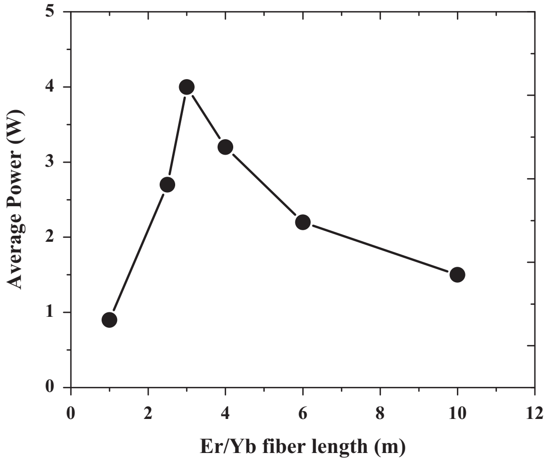

**Fig. 3.** Variations of the average output power of the Q-switched laser with the $Er^{3+}/Yb^{3+}$ co-doped double clad fiber length.

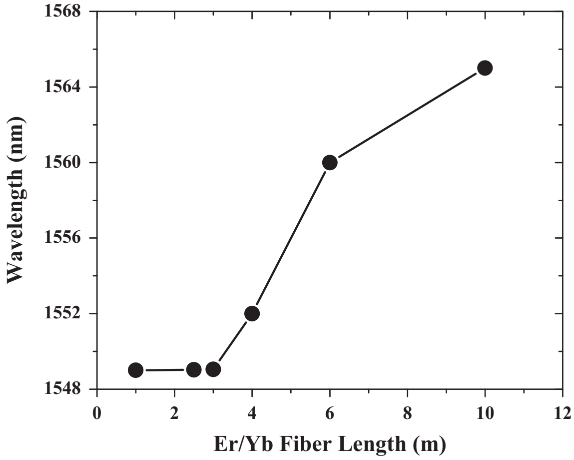

**Fig. 4.** Variation of the wavelength of the Q-switched laser with the $Er^{+3}/Yb^{+3}$ co-doped double clad fiber length.

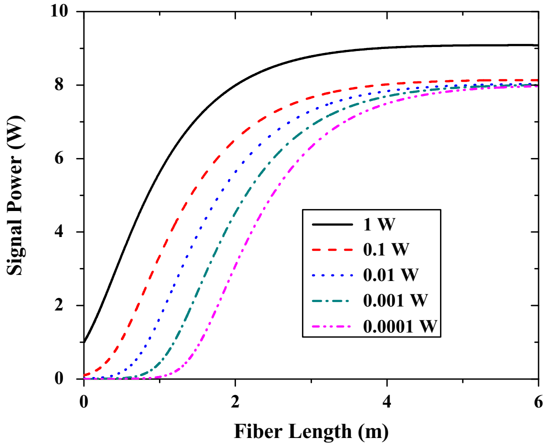

**Fig. 5.** Variation of the signal power along the amplifier length for various input powers.

It can be seen that there exists an optimal doped fiber length of 3 m for which we obtain the maximum average power from our laser; away from that optimal length the average output power falls off rapidly as shown in Fig. 3. The initial increase of the average output power with $Er^{3+}/Yb^{3+}$ co-doped fiber length is due to the increase in the magnitude of the stored energy in the fiber. Beyond the optimum fiber length a drop in average output power occurs due to the re-absorption of the signal from the unpumped section of the fiber. Increasing of $Er^{3+}/Yb^{3+}$ doped fiber length causes the operation wavelength shift to longer wavelengths as shown in Fig. 4. We can observe that for fiber lengths shorter than 3 m, the wavelength of operation of the laser is stabilized at 1549 nm.

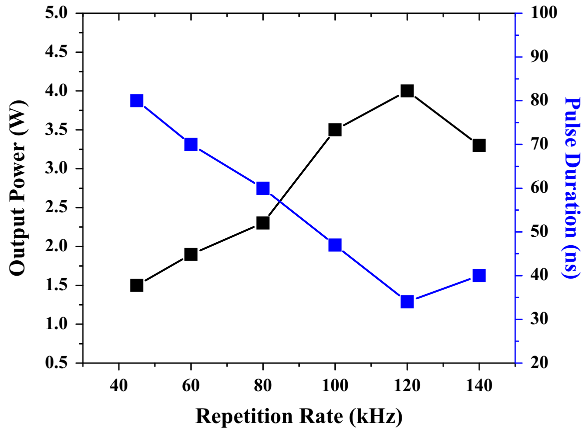

**Fig. 6.** Variation of average output power and pulse duration with repetition rate.

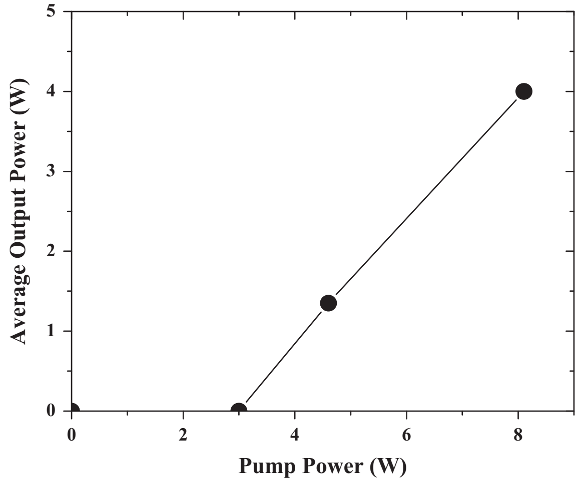

**Fig. 7.** Average output power against pump power into the fiber for 3 m span of $Er^{3+}/Yb^{3+}$ co-doped, double-clad fiber laser at the repetition rate of 120 kHz.

An analytical analysis for Ytterbium fiber amplifiers was previously published [21]; we adopted that analysis to calculate the optimum doped fiber length and saturation power for our pumping scheme. Using the results presented in that reference we can demonstrate that the optimum fiber length is around 3 m for input signal powers from $10^{-4}$ to 1 W at constant pumping power (see Fig. 5). We can observe that for a length longer than 3 m, the gains are saturated for any value of the pump power.

Both theoretical and experimental results show that the 3 m length of Er/Yb fiber can be considered as an optimum length. The variations of the output power and pulse duration were measured as a function of repetition rate and the results are shown in Fig. 6. These results were obtained experimentally (using 3 m of fiber as an optimum length). For this length the output power starts to increase at repetition rates above approximately 80 kHz as shown in Fig. 6. Shorter pulse duration can be achieved with shorter lengths of fiber but at the expense of output power. The laser operation is optimal for repetition rates from 40 to 140 kHz; pulse durations were obtained between 80 and 34 ns. Once the laser operating conditions are determined the pulse train exhibits small fluctuations in peak power over hours of operation.

The output power of the laser increases for high repetition rates because the time-averaged excited state population is reduced, which decreases the energy lost due to spontaneous emission. Fig. 6 shows that the $Er^{3+}/Yb^{3+}$ co-doped double clad fiber allows high output powers to be maintained at high repetition rates because the pump light absorbed by Ytterbium ions is transferred to the adjacent Erbium ions by a fast cross-relaxation process; hence the Erbium ions experience higher pump intensity than in the absence of Ytterbium. This ability of actively $Er^{3+}/Yb^{3+}$ Q-switched fiber lasers to operate at high repetition rates makes them suitable for applications which require high repetition rate. The average output power at a repetition rate of 120 kHz for several pump powers is plotted in Fig. 7. The line drawn shows that the lasing threshold is 3 W.

An average output power of 4.0 W at a wavelength of 1549 nm was obtained for a pump power of 8.1 W; this corresponds to a laser efficiency of ~50%. Fig. 8 shows a train of pulses and a single pulse of the Q-switched laser using 3 m of doped fiber.

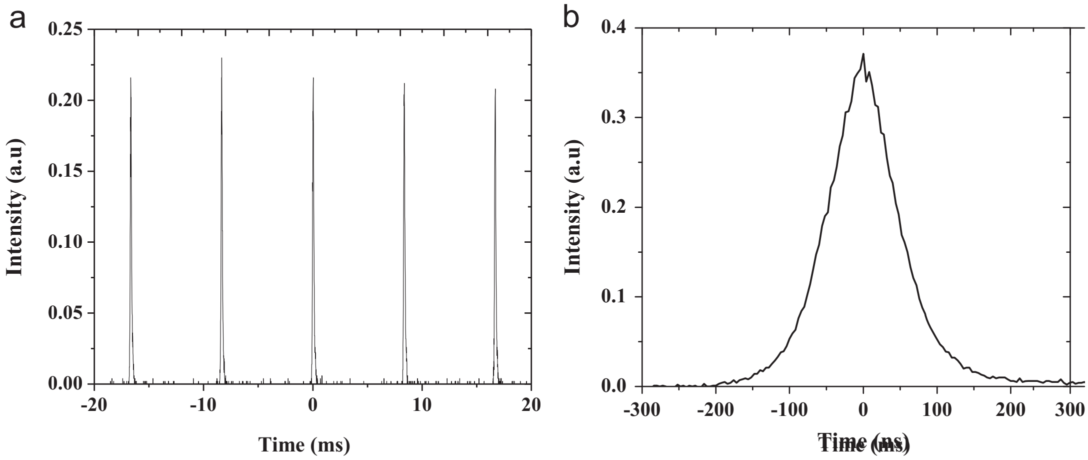

**Fig. 8.** (a) Scope trace of the pulse train from Q-switched $Er^{3+}/Y^{3+}$ co-doped, double-clad fiber laser operating at 120 kHz, (b) profile of a single pulse.

One of the theoretical models used to calculate the pulse energy is reported in Ref. [22] which provides an approximate expression to calculate the maximum energy of a Q-switched fiber laser. The maximum energy is expressed as a function of several variables as

$$E=(P_{CW}\tau_{21}+n_{th}h\nu V)\left(1-e^{-1/(\tau_{21}f_r)}\right) \tag{1}$$

where $P_{CW}$ is the output power in CW, $\tau_{21}$ is the upper level lifetime of $\mathrm{Er}^{3+}$, $n_{th}$ is the population inversion at the laser threshold, $h$ is Planck's, constant, $\nu$ is the frequency, $V$ is the gain volume, and $f_r$ is the repetition rate. The population inversion $n_{th}$ is given by

$$n_{th}=\frac{-\log(R_1R_2)+N_{Er}\sigma_{aEr}L}{2L(\sigma_{eEr}+\sigma_{aEr})} \tag{2}$$

where $R_1$ and $R_2$ are the reflectivities of the end mirrors, in this case the DM2 and Sagnac loop mirror, $\sigma_{aEr}$ and $\sigma_{eEr}$ are the absorption and emission cross sections of $\mathrm{Er}^{3+}$, $N_{Er}$ is the $\mathrm{Er}^{3+}$ concentration and $L$ is the cavity length. The one remaining issue to be addressed is to estimate the pulse duration, but a reasonable estimate can be obtained by dividing the energy by the maximum power: $\Delta t \approx E/P_{peak}$. For the following parameter choices: $P_{CW}=1.5$ W, $\tau_{21}=11$ ms, $f_r=120$ kHz, $R_1=99.5\%$, $R_2=100\%$, $\sigma_{aEr}=7\times10^{-25}\ \mathrm{m}^2$, $\sigma_{eEr}=6.5\times10^{-25}\ \mathrm{m}^2$, $\lambda=1549$ nm, $L=5$ m, $N_{Er}=1.716\times10^{25}\ \mathrm{m}^{-3}$, we obtain a theoretical value of the pulse energy around 33.5 μJ that is in good agreement with the experimental result of 34 μJ (this value was obtained from Fig. 6).

## 4. Conclusion

In conclusion, we used an $\mathrm{Er}^{3+}/\mathrm{Yb}^{3+}$ co-doped, double-clad, single-mode fiber as the gain medium and an AOM as Q-switching element to setup a Q-switched fiber laser. Optical design software Zemax was used to choose the focal distance of aspherical lenses for maximization of the pump and signal coupling. The average output power of the laser was 4.0 W at maximum pump power of 8.1 W, showing an overall efficiency of ~50%. For a pulse repetition rate of 120 kHz, laser pulses with pulse duration of 34 ns were obtained.

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