Cladding-pumped Er/Yb co-doped *Q*-switched all fiber laser

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A compact Q-switched laser based on Er/Yb co-doped fiber is demonstrated. Operating in repetition rate of 10−100 kHz and Q-switching window time of 100 ns−2 μs, the laser is optimized in the amplitude and stability of the pulses. At the repetition rate of 100 kHz, and maximum power of 1.75 W, average output power of 264 mW and a slope efficiency of 14% were obtained. The maximum pulse energy reached to 2.6 μJ at the repetition rate of 100 kHz.

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Q-switched lasers find widespread applications in laser trimming, marking and welding of various solid materials. Further applications can be found in different areas of science and technology. Laser systems based on double-clad rare-earth-doped fibers are attractive for compact and very efficient high-power and high-energy short pulse generation. Their main performance advantages, compared with conventional bulk solid-state lasers, result from the combination of beam confinement and excellent heat dissipation. The development of new fiber optic laser systems is of permanent interest in the optical field, especially on the communication spectral window. Operating in the communication and eye-safe band, erbium-doped fiber lasers and amplifiers have received much attention in recently years. In particular, erbium-doped fiber lasers have shown a variety of potential applications, such as sources for wave divided multiplexing and soliton communications systems, medicine, sensing and spectroscopy. In order to produce an erbium-doped Q-switched laser many different approaches are employed. Passive Q-switching can be obtained with a saturable absorber constructed by inserting a segment of samarium-doped fiber into a ring cavity[1]. Active Q-switching was performed by an electro-optic modulator, an acousto-optic modulator (AOM), or an intensity modulator based on the transmission of a coupler in the cavity[2−3].

However, erbium-doped fiber laser is a three-level laser system, in which the upper lasing level is connected to its ground state. Therefore, the ground-state population must be bleached completely in order to reach the lasing threshold for laser operation. The use of high Er^{3+} concentrations can increase the pump photon absorption and provide higher gain coefficients, and ion-ion interactions by uniform and pair-induced up-conversion mechanisms can lead to degradation in the efficiency. One of the easy and effective ways to solve this problem is to co-dope Yb^{3+} with Er^{3+} in fibers. The Yb^{3+} ions with large peak absorption cross-section can provide a highly efficient means of indirect pumping for Er^{3+} ions, so one can decrease the Er^{3+} ion doping concentration owing to the strong sensitization of Yb^{3+} ions in the Er^{3+}-doped fibers. Thus, the ion-pair-induced self-pulsing in Er^{3+}-doped fiber lasers can be effectively suppressed, and the output stability can be increased. Meanwhile, a much higher pump absorption efficiency will be achieved[4−8]. Today diode-pumped rod solid-state lasers are well established in the low-power regime, due to their inherent stability, efficiency and robustness. In this paper, we present a compact Er^{3+}/Yb^{3+} co-doped double cladding all fiber Q-switched laser source operating at 1550 nm.

The schematic diagram of the compact Q-switched Er/Yb co-doped double cladding fiber (EYDF) laser is shown in Fig. 1. The gain medium of the laser was a 9-m EYDF, which has a core diameter of 7-μm, an inner cladding diameter of 130-μm, an outer cladding diameter of 245-μm, and numerical apertures of the core to the inner cladding and the inner cladding to the outer cladding are 0.14 and 0.46 respectively. The concentrations of Yb^{3+} and Er^{3+} are $N_{\rm Yb}=1.2\times10^{26}$ m^{-3}, $N_{\rm Er}=1.0\times10^{25}$ m^{-3}. Two Bragg gratings (FBG1 and FBG2), written on hydrogen loaded double cladding fiber with core diameter of 9 μm, inner cladding diameter of 85 μm, and outer cladding diameter of 125-μm, were employed as the cavity mirrors. Bragg wavelengths of both gratings are very close (less than 0.2 nm of spectral difference) at 1550-nm wavelength. And the bandwidth of the FBGs is less than 0.3-nm, which can ensure the narrow bandwidth of output spectrum. The reflectivities of FBG1 and FBG2 were 99.8% and 20%, respectively. The transmission spectrum of FBG1 is shown in Fig. 2. The laser was pumped by a 975-nm pig-tailed laser diode (LD) module with maximum power of 4 W and multimode

Fig. 1. Schematic diagram of the Q-switched EYDF fiber laser.

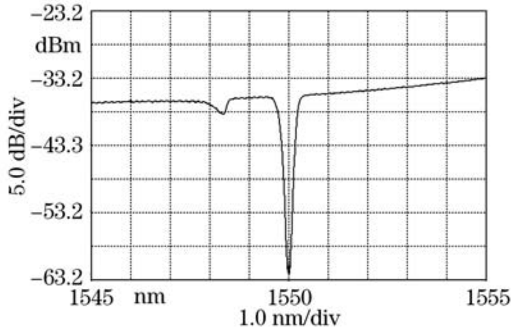

Fig. 2. Transmission spectrum of FBG1 with the reflectivity of 99.8%.

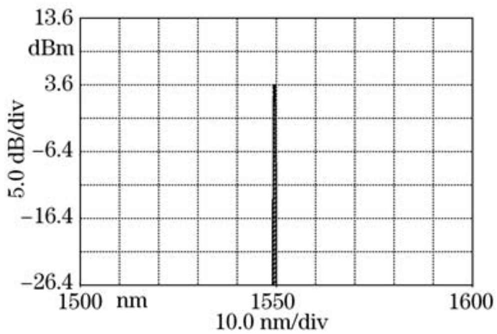

Fig. 3. Output spectrum with the spectrum bandwidth of 0.499 nm.

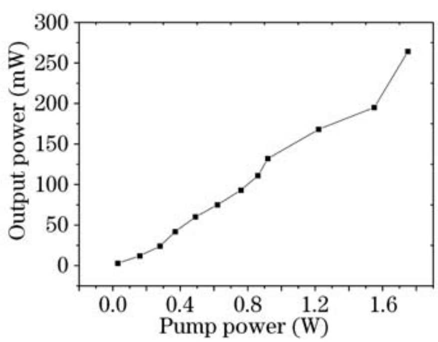

Fig. 4. Average output power versus pump power at the repetition rate of 100 kHz.

fiber pig-tail with core diameter of 100-μm. A pig-tailed AOM with a diffraction efficiency of 90% at its first order was inserted in the cavity. To perform Q-switching, a 5-V transistor-transistor-logic (TTL) variable frequency and duty cycle electric signal was employed as the outer modulation signal for the AOM. A power meter, a high speed 1.5-μm photo-detector, and an optical spectrum analyzer were used to measure the average power, temporal pulse shape and optical spectrum simultaneously. A 200-MHz and 1-GS/s digital oscilloscope was used to sample the temporal pulses.

The output spectrum of the fiber laser is shown in Fig. 3. The spectrum bandwidth (full width at half maximum) is 0.5 nm, which is wider than the FBG2's bandwidth. This can be attributed to the center wave difference of the two FBGs. Figure 4 shows the output power characteristic of the laser. At 100-kHz repetition rate, pumped at maximum power of 1.75-W, the pulse energy

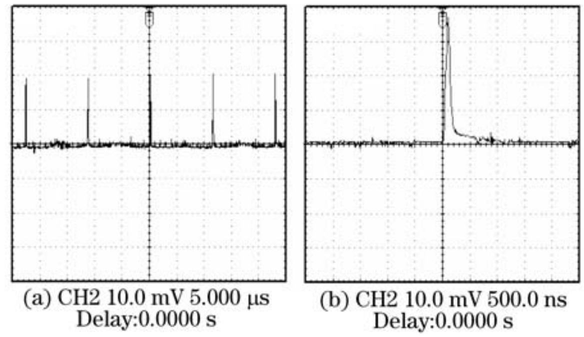

Fig. 5. (a) Q-switched Er-doped fiber laser operating at 100-kHz, (b) profile of a single pulse.

of 2.6 μJ was obtained. The average output power was 264 mW at a maximum pump power of 1.75 W with a slope efficiency of 14%. Operating at 10−100 kHz and Q-switching window time holding in 100 ns−2 μs, the laser is optimized in the amplitude and stability of the pulses. Figure 5(a) shows an example of the laser system running at 100-kHz. Figure 5(b) shows the profile of a single pulse with pulse duration of 100 ns.

We can estimate the maximum energy from this Q-switched fiber laser by[9]

$$E = (P_{\rm cw}\tau_{21} + n_{\rm th}h\nu V)\{1 - \exp[-1/(\tau_{21}f_{\rm r})]\}. \quad (1)$$

Since in the Er/Yb co-doped system, we can consider that Yb^{3+} ions transfer energy in the fiber, and signal emitting is mainly caused by Er^{3+}. $n_{\rm th}$ is the population inversion at the laser threshold,

$$n_{\rm th} = \frac{-\ln(R_1R_2) + N_{\rm Er}\sigma_{\rm aEr}L}{2L(\sigma_{\rm eEr} + \sigma_{\rm aEr})}. \quad (2)$$

$P_{\rm cw} = 560$ mW is the output power at a pump power of 1.75 W in continuous wave regime with the AOM removed, $\tau_{21} = 11$ ms is the upper level lifetime of Er^{3+}, $N_{\rm Er}$ is the concentration of Er^{3+}, V is the gain volume, $f_{\rm r} = 100$ kHz is the repetition rate, $R_1 = 98\%$ and $R_2 = 20\%$ are the reflectivities of the gratings, and $\sigma_{\rm aEr} = 7 \times 10^{-25}$ m^2 and $\sigma_{\rm eEr} = 6.5 \times 10^{-25}$ m^2 are the absorption cross section and emitting section of Er^{3+} at 1550 nm. The cavity length is 10 m. Then we can get the theoretical value of the energy is 5.61 μJ, which is much higher than experimental results, and we attribute this to insert loss of the AOM.

In conclusion, we used a double-clad FBG as input coupler and a pig-tailed AOM as Q switch to set up a compact all fiber Q-switched fiber laser. The laser was optimized in the regime of repetition rate of 10−100 kHz and Q-switching window of time 100 ns−2 μs. Average output power of the laser was 264 mW at a maximum pump power of 1.75 W with a slope efficiency of 14%. At the repetition rate of 100 kHz and maximum pump power of 1.75 W, the laser pulse with duration of 100 ns and energy of 2.6 μJ was obtained. The further work of laser seeded Er/Yb co-doped double-cladding fiber based master oscillation power amplifier is going on.

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