Passive Q switching of Er-Yb fiber laser with semiconductor saturable absorber

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Abstract: A high-performance AlGaInAs quantum-well saturable absorber is developed for passively Q-switched Er-Yb double-clad fiber lasers at 1560 nm. With an incident pump power of 13.5 W, an average output power of 1.26 W with a pulse repetition rate of 12 kHz is obtained. The maximum peak power is greater than 500 W.

OCIS codes: (140.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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1. Introduction

High-power light sources in the eye-safe wavelength regime near 1.55-μm have many potential applications in free-space communication, range finding, nonlinear frequency conversion, and medical surgery [1-4]. These prospective applications have led to the erbium-ytterbium-codoped double-clad fiber laser (EYDFL) to receive a great deal of interest during the past years [5-8]. Er^{3+} and Yb^{3+} codoped gain materials are generally significantly superior to Er^{3+}-doped gain media because the incorporation of Yb^{3+} ions considerably enhances the pump absorption, reduces the clustering of Er^{3+} ions, and allows for higher Er^{3+} concentrations without strong quenching effects [8].

Q Switching is an effective approach to intensify the laser peak power. Among various Q switching methods, passive Q switching by use of a saturable absorber is a simple, convenient, and efficient way to achieve high-peak-power pulses [9-12]. Nowadays, the most used saturable absorbers in the eye-safe wavelength regime are the transition metal-doped crystals that comprise $Co^{2+}:ZnSe$ [13], $Co^{2+}:ZnS$ [14], $Cr^{2+}:ZnSe$ [15], $Co^{2+}:MgAl_2O_4$ [15]. In addition to the transition metal-doped crystals, the semiconductor saturable-absorber mirror (SESAM) [16] is an alternative material for the passively Q-switched eye-safe laser. However, the pulse energy with the SESAM has been limited to 17 μJ.

So far, the semiconductor saturable-absorber materials for passively Q-switched fiber lasers in the range of 1.5-1.6 μm have only been based on the InGaAsP thick layer [16] and the InGaAs quantum-well (QW) structure [17]. Recently, an AlGaInAs material with a periodic QW/barrier structure has been used as a saturable absorber to achieve an efficient passively Q-switched 1.06-μm laser [18]. Compared with InGaAsP materials, the AlGaInAs quaternary alloy with a larger conduction band offset can provide a better electron confinement covering the same wavelength region [19-21]. However, AlGaInAs/InP QWs have not been developed to be saturable absorbers in eye-safe lasers. Therefore, it is of practical importance to employ AlGaInAs QWs as saturable absorbers for high-power Q-switched eye-safe lasers.

In this work we report, for the first time to our knowledge, a passively Q-switched EYDFL with a periodic AlGaInAs QW/barrier structure as a saturable absorber. As the result of the rather low nonsaturable loss, the overall Q-switching efficiency could be up to 84%. With an incident pump power of 13.5 W, the passively Q-switched fiber laser, operating at 12 kHz, produces an average output power up to 1.26 W with a pulse energy of 100~110 μJ. The maximum peak power is generally higher than 500 W.

2. Experimental setup

An AlGaInAs QW/barrier structure was grown on a Fe-doped InP substrate by metalorganic chemical-vapor deposition. The region of the saturable absorber consists of 30 groups of two QWs with the luminescence wavelength around 1560 nm, spaced at half-wavelength intervals by AlGaInAs barrier layers with the band-gap wavelength around 1070 nm. Note that the

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structure of the semiconductor saturable absorber (SESA) was essentially similar to that used in the passively Q-switched 1.06-μm laser reported in Ref. [18]. However, the composition for the AlGaInAs alloy has been changed to design the band gap from 1.17 eV (1.06 μm) to 0.79 eV (1.56 μm) for the QWs. Even so, there is very little difference in the fluorescence efficiency and response time for these two saturable absorbers.

Compared to a conventional SESAM structure, the missing DBR considerably simplifies the structure of growth. Since the cavity modes with lower losses always dominate the lasing output, the lasing modes are naturally the modes with the electric field minima in the vicinity of the periodic QWs. In other words, the barrier layers are used not only to confine the carriers but also to locate the QW groups nearby the region of the nodes of the lasing standing wave [18]. Consequently, damage to the absorber can be effectively avoided by the periodic QW/barrier structure. An InP window layer was deposited on the QW/barrier structure to avoid surface recombination and oxidation. The backside of the substrate was mechanically polished after growth. The both sides of the semiconductor saturable absorber were antireflection (AR) coated to reduce back reflections and the couple-cavity effects. The total residual reflectivity of the AR-coated sample is approximately 8%.

Figure 1 shows the transmittance spectrum at room temperature for the AR-coated AlGaInAs/InP SESA device. It can be seen that the strong absorption of the AlGaInAs QWs leads to the initial transmission at the wavelength of 1560 nm to be approximately 40%. A pulsed semiconductor laser at 1.56 μm was used to measure the modulation depth of the QW saturable absorber with the z-scan method. The pump pulse energy and pulse width were 3 μJ and 50 ns, respectively. The pump radius was varied from 0.1 to 1 mm. Therefore, the pump fluence was in the range of 0.1~10 mJ/cm^2 and was comparable to the intra-cavity fluence in the present fiber laser. Experimental results revealed that the maximum transmission was up to 90%. Consequently, the modulation depth was deduced to be approximately 50% in a single pass. Considering the 8% residual reflectivity of the AR-coating, the total nonsaturable loss introduced by the SESA was estimated to be approximately 2%. In the z-scan experiment, there are no noticeable nonlinear index modifications to be observed except for amplitude effects.

Figure 2 depicts the schematic of the experimental setup for EYDFL that comprises a 7-m Er-Yb codoped fiber and an external feedback cavity with a periodic AlGaInAs QW/barrier structure as a saturable absorber. The fiber has an absorption coefficient of 3.0 dB/m at 976 nm and a double-clad structure with a diameter of 450-μm octagonal outer cladding, diameter of 300-μm octagonal inner cladding with a numerical aperture (NA) of 0.46, and 25-μm circular core with a NA of 0.07. Note that the large mode area (LMA) fiber featuring a unique low NA core design is used to achieve the nearly single-mode output beam quality with high pulse energies. The external cavity consists of a focusing lens of 25-mm focal length to focus the fiber output into the SESA device and a highly reflective mirror for feedback. The focusing lens was arranged to have a beam waist of 50 μm inside the SESA. The SESA was mounted in a copper block without active cooling. The pump source was a 16-W 976-nm fiber-coupled laser diode with a core diameter of 400 μm and a NA of 0.22. A focusing lens with 25 mm focal length and 85% coupling efficiency was used to re-image the pump beam into the fiber through a dichroic mirror with high transmission (>90%) at 976 nm and high reflectivity (>99.8%) at 1560 nm. The pump spot radius was approximately 200 μm. The fiber end on the pump side was perpendicularly cleaved, which acted as the cavity output coupler with about 4% Fresnel reflection.

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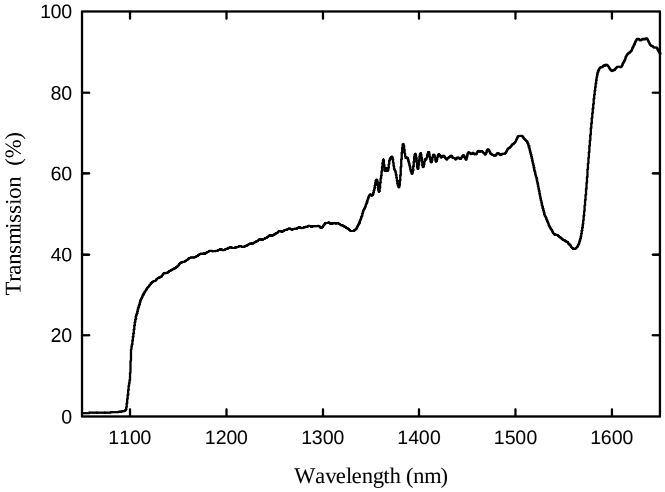

Fig. 1. Transmittance spectrum at room temperature for the AR-coated AlGaInAs/InP SESA device.

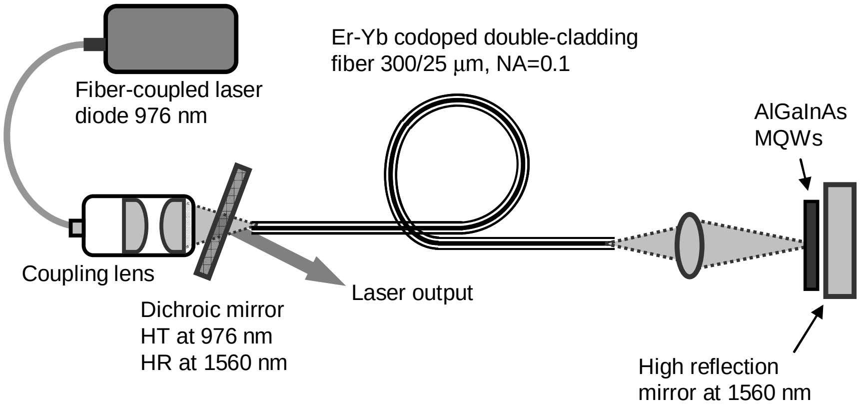

Fig. 2. Schematic of the experimental setup for EYDFL comprising a 7-m Er-Yb codoped fiber and an external feedback cavity with a periodic AlGaInAs QW/barrier structure as a saturable absorber. HR, high reflection; HT, high transmission.

3. Results and discussions

Figure 3 shows the average output powers at 1560 nm with respect to the incident pump power in cw and passively Q-switching operations. The cw performance at 1560 nm provides the baseline for evaluating the passively Q-switched efficiency. Without the SESA in the cavity, the cw laser at 1560 nm had an output power of 1.50 W at an incident pump power of 13.5 W. In the passively Q-switching regime, an average output power of 1.26 W was obtained at an incident pump power of 13.5 W. As a consequence, the Q-switching efficiency (ratio of the Q-switched output power to the cw power at the maximum pump power) was found to be as high as 84%. This Q-switching efficiency is significantly superior to those of eye-safe lasers with Co^{2+} or Cr^{2+} doped crystals as saturable absorbers [9-11] up to 50%. The M^2 beam-quality factor was measured to be <1.5 over the complete output power range. On the other hand, no damage to the fiber was observed over several hours of operation, and the laser performance was reproducible on a day-to-day basis.

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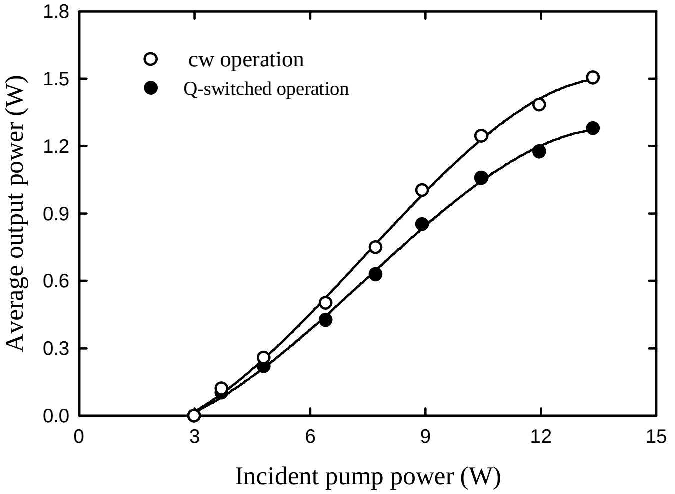

Fig. 3. Dependence of the average output power on the incident pump power for the cw and passive Q-switching operations.

The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10G samples/sec; 1 GHz bandwidth) with a fast InGaAs photodiode. Figure 4 shows the pulse repetition rate and the pulse energy versus the incident pump power. The pulse repetition rate increases monotonically with the pump power up to 12 kHz. Like typical passively Q-switched lasers, the pulse energy is almost unrelated to the pump power and its value is 105 μJ on average.

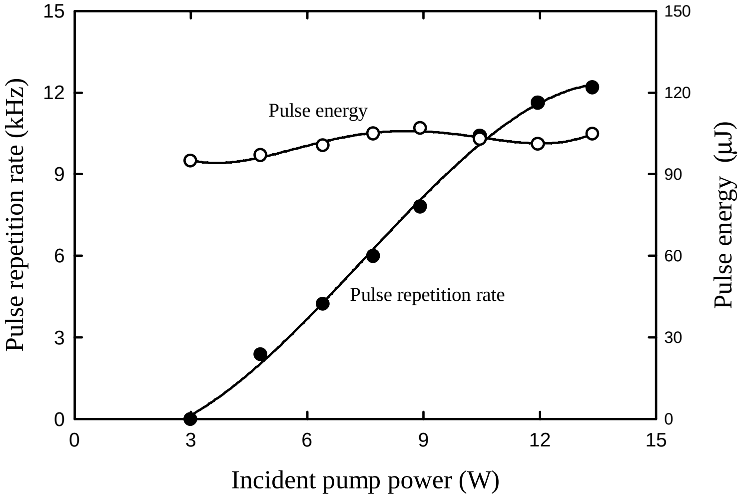

Fig. 4. Pulse repetition rate and the pulse energy versus the incident pump power.

Figure 5(a) shows the temporal shape of a single Q-switched pulse envelope, which was recorded at the maximum pump power. It can be seen that the self-mode-locking effect [22,23] leads to the formation of the mode-locked pulses inside the Q-switched pulse envelope. The separation of the mode-locked pulses was found to be 80 ns, which matched exactly with the cavity roundtrip time and corresponded to a repetition rate of 12.4 MHz. The estimated energy of the highest pulse inside envelope was found to be close to 17μJ. The

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expanded oscilloscope traces reveal that the mode-locked pulse width is approximately 33 ns. As a result, the peak power can be found to be greater than 500 W.

A typical oscilloscope trace of Q-switched pulse train is shown in Fig. 5(b). With the optimum alignment, the pulse-to-pulse stability was found to be approximately ±10% for the pump power higher than 8 W. The pulse-to-pulse instability mainly arises from the mode-locking effect, even though this effect can enhance the output peak power. Experimental results reveal that slightly tilting the SESA (10-30 mrad) or inserting an etalon can usefully suppress the mode-locking effect. However, the overall peak power is reduced by two times.

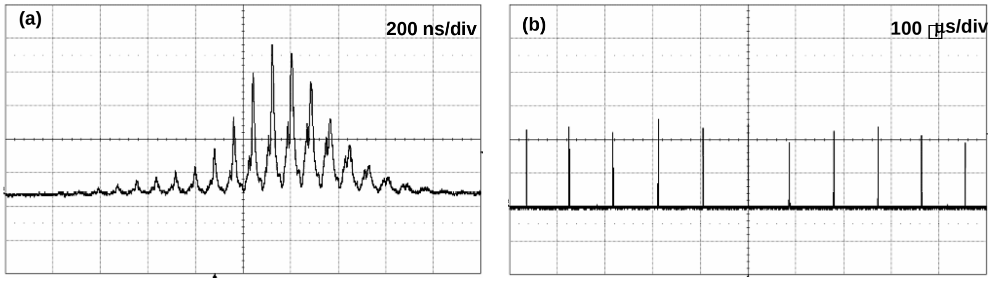

Fig. 5. (a). Oscilloscope traces of a typical Q-switched envelope., (b) Oscilloscope traces of a train of Q-switched pulses.

4. Conclusion

In summary, we have demonstrated an efficient passively Q-switched EYDFL at 1560 nm with a periodic AlGaInAs QW/barrier structure as a saturable absorber in an external-resonator configuration. Greater than 1.26 W of an average output power at a repetition rate of 12 kHz was generated with a 13.5-W diode pump power. The maximum peak power is higher than 500 W. The remarkable performance confirms the prospect of using AlGaInAs QWs as saturable absorbers in passively Q-switched eye-safe lasers. Moreover, the present result indicates that the output peak power can be significantly enhanced by using a fiber with a larger core size and a saturable absorber with a lower initial transmission.

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