Efficient high-peak-power AlGaInAs eye-safe wavelength disk laser with optical in-well pumping

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Abstract: We have demonstrated an efficient high-peak-power AlGaInAs eye-safe wavelength disk laser at 1555 nm. The quantum defect and the thermal load are significantly reduced by pumping the quantum well directly. The overall conversion efficiency is enhanced over three times compared with the barrier pumping method. With a pump peak power of 3.7 kW, an output peak power of 0.52 kW is generated at a pulse repetition rate of 20 kHz.

OCIS codes: (140.3380) Laser materials; (140.3480) diode-pumped; (140.3538) Lasers, pulsed

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1. Introduction

High-peak-power lasers operated at the eye-safe region near 1.5-1.6 µm have been attracting versatile interesting applications including laser radars, range finders, active imaging, and telemetry [1–3]. The radiation within this spectral region is absorbed mainly in the ocular fluid of the eye before the retina such that the damage threshold of the eye is greatly increased. There are several ways in realizing eye-safe laser sources. Directly utilizing gain materials such as Er:Yb:glass [4,5] or Cr^{4+}:YAG [6] in solid-state lasers for generating 1.54-µm radiation are commonly used while the poor thermal conductivity of Erbium glass restricts their use for high power pumping. Stimulated Raman scattering (SRS) lasers pumped by pulsed neodymium (Nd) lasers operating at the 1064 nm or 1340 nm lines [7–9], and optical parametric oscillators (OPO) pumped by high peak power Nd lasers [10–12] are alternative methods for generating high-peak-power eye-safe lasers.

The lasers based on semiconductor quantum-well (QW) materials including InGaAsP, AlGaInAs, and GaInAsSb system [13–18] provide another practical method for generating the radiation at the eye-safe region. Recently, an optically pumped high-peak-power AlGaInAs eye-safe laser at 1.57 µm pumped by an actively-Q-switched 1064-nm laser was demonstrated [19]. In the gain region of AlGaInAs QW/barrier, the electrons are excited from the ground state to an excited state in the barrier region with band-gap wavelength around 1064 nm, and emit photons with wavelength of 1.57 µm in the QW region. Such a scheme could generate high peak power of hundreds of watt with quite low lasing threshold. However, the quantum defect between the pump photon and lasing photon would give rise to heat generation and influence the performance for the operation of high repetition rate and high pump power.

Recently, the quantum defect and the thermal load were confirmed to be significantly reduced by pumping the QW directly [20,21]. In this work, we employ the in-well pumping scheme to excite AlGaInAs QWs for efficient eye-safe emission at 1.56 µm. The gain medium is an AlGaInAs QW structure grown on a Fe-doped InP transparent substrate and is pumped by an actively Q-switched 1342 nm laser which directly excites the electrons to an excited state in the QW region rather than in the barrier region. As depicted in Fig. 1, electrons are excited in the QW region and the quantum defect between pump photon and lasing photon is reduced from 32% to 14% compared with a pump source at 1064 nm. As a result, the thermal effect is significantly reduced. Experimental result shows that the optical conversion efficiency is up to 30% and is enhanced over three times compared with the barrier pumping method. A high peak output power of 0.52 kW can be generated at a pulse repetition rate of 20 kHz and a pump peak power of 3.7 kW.

2. Device fabrication and experimental setup

Figure 2 shows the experimental configuration for the AlGaInAs QWs 1555-nm laser pumped by a diode-pumped actively Q-switched Nd:YVO_4 laser at 1342 nm. The pump source provides 20~110-ns pulse width between 20 kHz and 100 kHz. For comparison, a 1064-nm Q-switched laser was used in barrier-pumping scheme. The pump spot radius was controlled to be 70-100 µm by a focusing lens to maintain the spatial overlapping between lasing mode and

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pump mode. To simplify the cavity structure, the resonator is designed to be a flat-flat cavity stabilized by thermal lens effect of gain medium [22,23]. Although the thermal lens is reduced in in-well pumping, the effect is still strong enough to stabilize the cavity. For the pump power between 0.4 W and 1.7 W, the mode to pump size was experimentally measured to be 0.6-0.9. The front mirror of resonator is a flat mirror coated with anti-reflection coating at pumping wavelength (R<0.2%) on the entrance surface, and with high-reflection coating at 1555 nm (R>90%) as well as high-transmission coating at pumping wavelength (T>80%) on the other surface. The output coupler is a flat mirror with partial refection of 90% at 1555nm and 60% at pumping wavelength. The overall laser cavity length is approximately 5 mm.

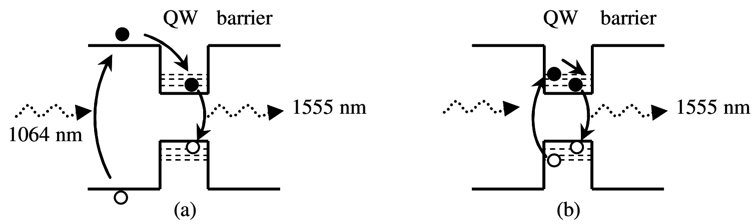

Fig. 1. Schematic explanation of energy diagrams of (a) barrier pumping and (b) in-well pumping.

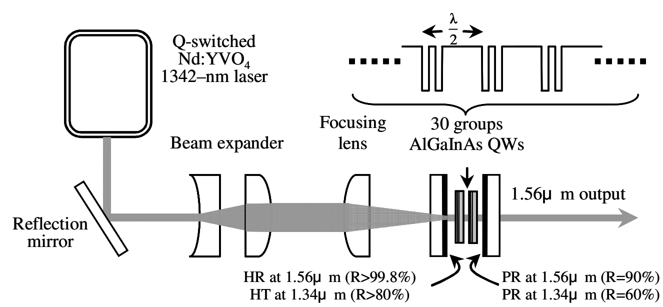

Fig. 2. The schematic of the AlGaInAs/InP eye-safe laser at 1555 nm. HR: high reflection; HT: high transmission; PR: partial reflection.

The gain medium is a structure of AlGaInAs QW/barrier grown on a Fe-doped InP substrate by metalorganic chemical–vapor deposition. The optically active region consists of 30 pairs of AlGaInAs QW/barrier. Each pair contains two 8-nm-thick QWs and 10-nm-thick barrier. The band-gap wavelength of barrier is around 1064 nm and of quantum well is around 1555 nm. In order to get a resonant periodic gain, each group of quantum wells is designed to be located at the antinodes of the lasing mode, or to have intervals of half-wavelength separated by barriers. A window layer of InP was deposited on the gain structure to prevent surface recombination and oxidation. Both surfaces of the gain chip were coated to have anti-reflection coating at pumping and lasing wavelength. The active gain medium was adhered to a water-cooled copper heat sink and the temperature was controlled by water feedback. Figure 3(a) depicts the transmission spectrum of the gain medium and Fig. 3(b) shows the room-temperature spectrum of photoluminescence (PL) obtained by pulse excitation at 1342 nm. It can be seen that there is a high absorption at the pump wavelength of 1342 nm and the spectrum of emission extends more than 200 nm with a peak at the wavelength of 1555 nm.

It is worthwhile to mention that due to the shorter effective thickness of quantum well, the active gain region has lower absorption at 1342-nm pump wavelength than at 1064 nm which has single pass absorption higher than 95%. In order to increase the absorption efficiency, double chips were further used in the serial experiments. The advantage of directly using multiple chips is that could reduce the difficulty of fabrication of gain medium with more quantum wells. The experimental result shown in Fig. 3(c) reveals that the single pass

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absorption efficiency was increased from 45% to 65% when double chips were employed. Total effective absorption efficiency in the cavity could be estimated to be 60% and 79%, respectively. On the other hand, the effective absorption efficiency for single chip could be up to 70% by using an output coupler with retro-reflection at pump wavelength.

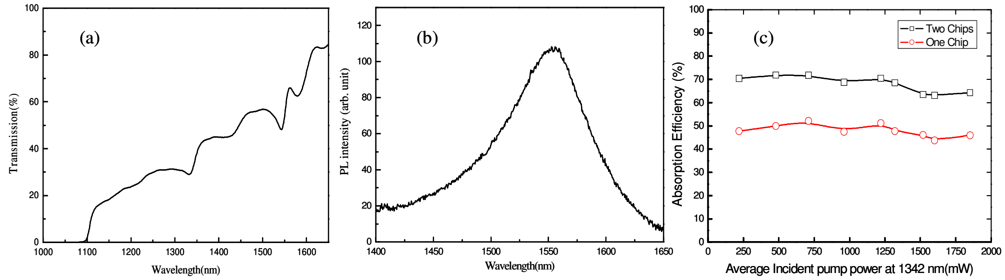

Fig. 3. (a) The transmission spectrum of AlGaInAs QWs. (b) the room-temperature spectrum of photoluminescence pumped by an actively Q-switched Nd:YVO_4 1342-nm laser. (c) The single pass absorption efficiency of single and double AlGaInAs QW chips.

3. Experimental results and discussions

Figure 4 shows the comparison of average output power of single gain chip with in-well and barrier pumping for the operation of 40 kHz repetition rate and 12°C temperature. The maximum values shown in the two curves were measured for the comparable incident pumping power. The solid lines are forth order polynomial fitting curves. It can be seen that employing the 1342-nm laser as a pump source exhibits good performance in conversion efficiency. This significant improvement result is contributed from the heat reduction by lowering the quantum defect which is diminished from 32% to 14%. However, since the absorption efficiency of gain medium at 1342 nm is lower than at 1064 nm, the available pump power is restricted. Double gain chips, accordingly, were investigated to improve the absorption efficiency. The earlier onset of thermal rollover in in-well pumping shows that further thermal management may be desired to delay the thermal rollover such as lower operating temperature or bonding a diamond heat spreader.

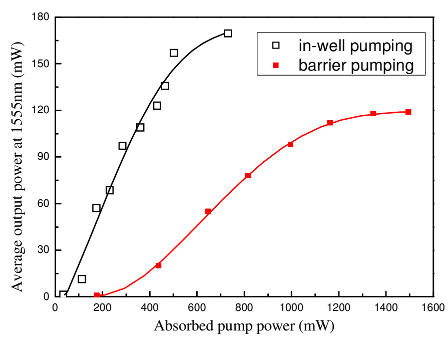

Fig. 4. The performance of single-chip AlGaInAs 1555-nm laser for 40 kHz and 12°C operation in the scheme of barrier and in-well pumping, respectively. The solid lines are forth order polynomial fitting curves. The in-well pumping scheme exhibits good performance in conversion efficiency.

Figure 5(a) shows the performance of the optically pumped AlGaInAs eye-safe laser with double gain chips operated at 12°C for different pump repetition rate from 20 kHz to 100 kHz in 20 kHz interval. The corresponding average pump pulse width ranges from 20 ns to 110 ns with increasing repetition rate and therefore a decreasing peak power of pulse is corresponded. In the process of increasing the repetition rate for the given cavity and absorbed pump power, the conversion efficiency was limited by instantaneous high peak power which resulted in a rapid temperature rise in low repetition rate and limited by high average power

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which resulted in an average temperature rise in high repetition rate. Therefore, there was an optimum repetition rate for obtaining the maximum average output power. This conclusion is coincident to the result of the experiment and the published research [19]. From the experimental results shown in Fig. 5(a), the optimum repetition rate was between 40 kHz and 60 kHz. Figure 5(b) shows the typical lasing spectrum for the operation of 40-kHz repetition rate with average pump power of 0.65 W. The spectral bandwidth was approximately 17 nm. The filamented spectrum may result from multiple interferences between cavity mirrors and chips and it could also be observed in single chip operation.

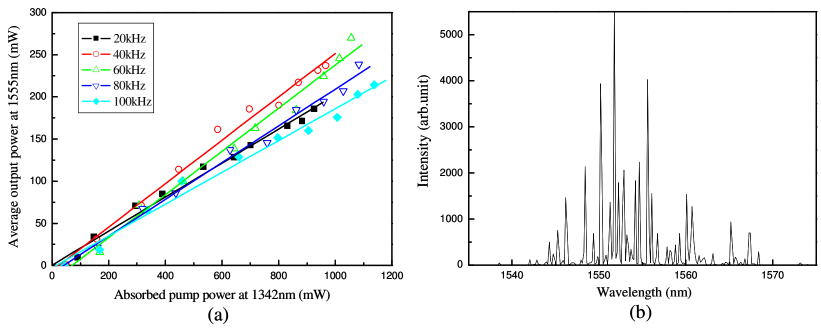

Fig. 5. Performance of double chips: (a) Experimental results for the optically pumped AlGaInAs eye-safe laser operated at 12 °C for several pulse repetition rates. The repetition rate for optimum performance of conversion efficiency was between 40 kHz and 60 kHz. (b) Typical lasing spectrum at repetition rate of 40 kHz and average pump power of 0.65 W

In order to further realize the influence of thermal effect, the average output power versus pump power was measured for different operating temperature, 9°C, 15°C, 20°C, and 25°C, at 50 kHz repetition rate and the result was shown in Fig. 6. Increase of temperature leads to the reduction of conversion efficiency and this result demonstrates the reduction of quantum defect is a practical way to improve optical conversion efficiency. The optical conversion efficiency could be up to 30% under the operating temperature of 9°C. Compared with barrier pumping which shows an optimum efficiency in 30 kHz repetition rate, the optical conversion efficiency exceeds 3 times and over 20% of enhancement was obtained.

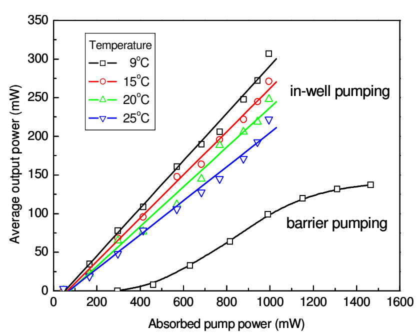

Fig. 6. The output characteristics of double chips in in-well pumping and of single chip in barrier pumping were measured for the operation of different temperature. In-well pumping was operated in 50 kHz repetition rate, while barrier pumping in 30 kHz for optimum conversion efficiency. The result shows the influence of thermal effect on conversion efficiency.

The operation of 20-kHz pulse repetition rate was chosen to evaluate the performance of output peak power due to shorter pulse and available maximum pump peak power. For the operation at the temperature of 9 °C, the output peak power from double chips at 1555 nm versus the absorbed pump power at pulse repetition rate of 20 kHz was measured and shown in Fig. 7. At the pump peak power of 3.7 kW, the maximum output peak power up to 0.52 kW was generated. The typical pump and output pulse train as well as extended pulse shape of

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single pulse was recorded by a Lecroy digital oscilloscope (Wave pro 7100, 10G samples/sec, 1 GHz bandwidth) and shown in Fig. 8. The output pulse with long tail follows in the characteristic of pump source. But the turn-on time of output pulse is slightly different between in-well and barrier pumping [19], where the former has a nearly 10-ns advance. The output peak power fluctuates within 10% variation and it mainly comes from the fluctuation of pump source. Experimental result shows that the output beam possesses an excellent beam quality. The half divergence angle of output beam was measured by using knife-edge method to be approximately 0.01 rad. Consequently, the M square value was estimated to be smaller than 1.3.

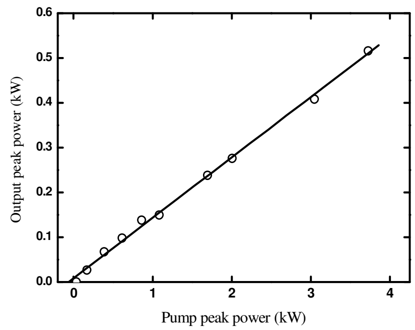

Fig. 7. The output peak power of double-chip AlGaInAs eye-safe laser at repetition rate of 20 kHz. At the pump peak power of 3.7 kW, the output peak power is up to 0.52 kW.

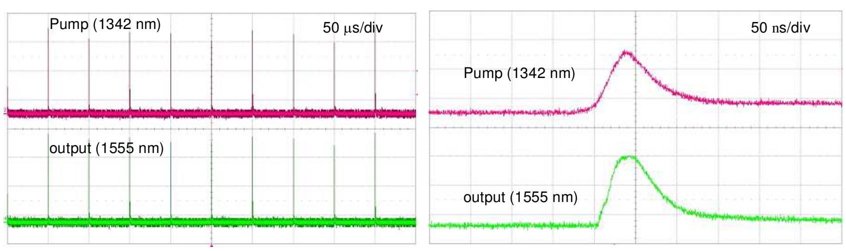

Fig. 8. The typical pump and output pulse train and the expanded pulse shape of a single pulse.

4. Conclusions

We have demonstrated an optically pumped high-peak-power AlGaInAs/InP eye-safe laser by using a pump method with lower quantum defect. The pump source is an actively Q-switched 1342-nm laser. With lower quantum defect, the thermal effect in gain medium decreases and results in improvement of optical conversion efficiency. The conversion efficiency is enhanced over three times compared with conventional pumping method. Double gain chips were used to increase the absorption efficiency of pump laser and a high peak output power of 0.52 kW was generated at a pulse repetition rate of 20 kHz and peak pump power of 3.7 kW.

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