Chapter 4

Optical-pumped

Vertical External Cavity Surface Emitting Laser

The booming laser techniques named VECSEL combine the flexibility of semiconductor band structure and advantages of solid-state laser such as beam quality, intracavity techniques… etc. In general, the wafer must be under low temperature with surface contact cooling through heat spreader of diamond to reach high output power [17,18]. But it is more practical if laser can be operated under room temperature. So we chiefly demonstrate a room-temperature high-peak-power nanosecond AlGaInAs 1.36-μm TEM_{00} laser pumped by a diode-pumped actively Q-witched Nd:YAG 1.06-μm laser.

4.1 Vertical External Cavity Surface Emitting Laser

We can simply categorize laser diodes into edge-emitting laser and surface-emitting laser. The Vertical Cavity Surface Emitting Laser (VCSEL) has higher beam quality than edge-emitting lasers, but generates low average output power of only milliwatt level. Typically, a VCSEL device with a monolithic laser cavity consists of a highly reflecting and a partially reflecting DBR, a periodic gain structure, and layers to confine emitting aperture, conduct current, and prevent oxidation. It is a semiconductor lasers where the emitted light leaves the device in a direction perpendicular to all layers showed in Fig 4.1 (up).

In a traditional V**E**CSEL, the partially reflecting DBR is replaced by a mirror separated from the device showed in Fig 4.1 (down). The laser mode size in the semiconductor chip is basically defined by the external cavity setup and pumping sopt size. VECSELs can have high output power which benefit from much larger beam areas than VCSELs. The laser cavity can contain aditional optoelectronics elements and can be folded with additional mirrors for intracavity nonlinear conversion. Further more, all DBR can be replaced by external mirrors. Ideally, VECSELs have advantages of typical solid-state laser, but without restrict of wavelength decided by energy level of doped ion.

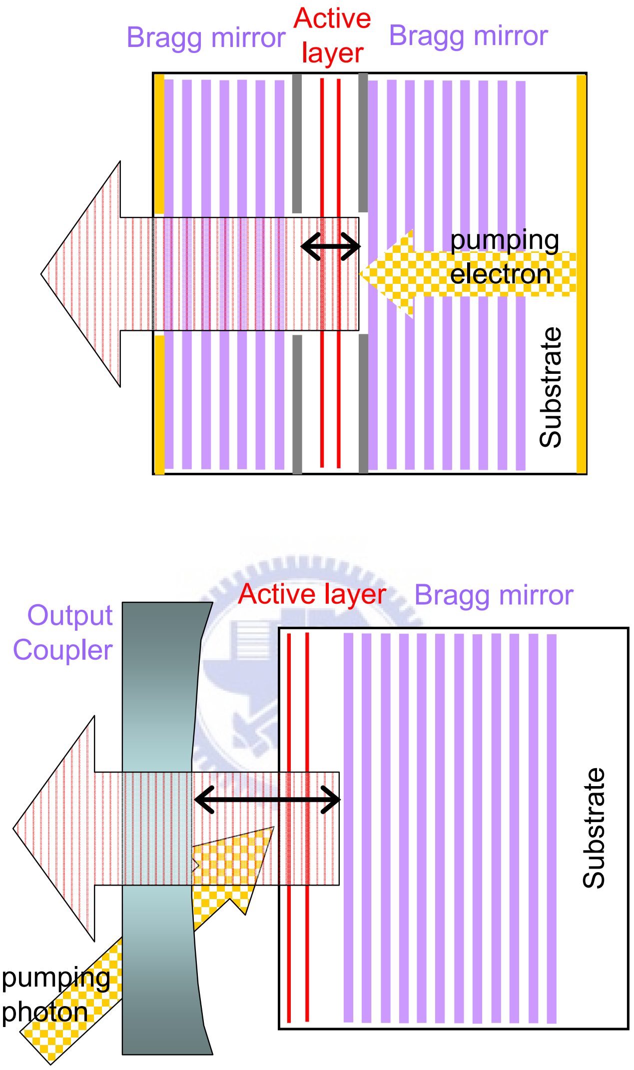

Fig. 4.1. Typical structure of electrical pumped VCSEL (up) and optical pumped VECSEL (down).

4.2 AlGaInAs QW 1.3-um Laser Pumped by a AQS DPSSL in Room Temperature

We report on a room-temperature high-peak-power nanosecond AlGaInAs 1.36-µm TEM_{00} laser pumped by a diode-pumped actively Q-witched Nd:YAG 1.06-µm laser. With an average pump power of 1.0 W, an average output power of

140 mW was obtained at a pulse repetition rate of 10 kHz. With a peak pump power of 8.3 kW, the highest peak output power was up to 1.5 kW at a pulse repetition rate of 5 kHz.

High-peak-power all-solid-state laser sources in the 1.3-1.6 μm spectral region are of particular interest in remote sensing, eye-safe optical ranging, fiber sensing, and communication [1-4]. Diode pumped solid-state lasers (DPSSLs) that have the advantages of relatively compact size, high power, excellent beam quality, long lifetime, and low heat production have been widely used for various applications including industry, pure science, medical diagnostics, and entertainment [5]. Nevertheless, the spectral range of DPSSL systems is limited by the properties of existing doped crystals and glasses. Recently, the optically pumped vertical-external-cavity surface-emitting semiconductor lasers (VECSELs) have been proposed to be a novel class of all-solid-state lasers with potential spectral coverage from the near ultraviolet to the midinfrared [6,7].

Typically, a VECSEL device consists of a highly reflecting distributed Bragg reflector (DBR) and a resonant periodic gain structure that comprises a series of barriers to provide the pump absorption, quantum wells (QWs) to provide gain, and layers to prevent oxidation. Although the InP-based material could offer a gain region with a smaller lattice mismatch for 1.3-μm wavelengths, the small contrast of refractive indices hinders the performance of the DBRs. As a consequence, until now the InP-based material has never been used as a VECSEL device at 1.3 μm. To reach a wavelength near 1.3 μm, GaInNAs/GaAs quantum wells have been developed as a gain medium [8] and a 0.6-W cw output power has been demonstrated [9]. Even so, there has been no experimental demonstration of room-temperature high-peak-power 1.3 μm laser sources with semiconductor QWs as gain media in an external cavity.

In this section we report, for the first time to our knowledge, a room-temperature high-peak-power nanosecond semiconductor QWs laser at 1.36 μm, using a diode-pumped actively Q-witched Nd:YAG 1.06-μm laser as a pump source. The gain medium was composed of an AlGaInAs QW/barrier structure grown on a Fe-doped InP transparent substrate. Note that the conventional S-doped InP substrate has a significant absorption in the 1.0-2.0 μm spectral region. Since the Fe-doped InP substrate is transparent in the lasing wavelength, the function of the DBRs on the VECSEL device can be replaced by an external mirror. With an average pump power of 1.0 W, an average output power of 140 mW at a pulse repetition rate of 10 kHz was obtained. The peak output power was up to 1.5 kW at a pulse repetition rate of 5 kHz.

4.2.1 The QW wafers can be gain medium in VECSEL or SESA in PQS DPSSL

The gain medium is an AlGaInAs QW/barrier structure grown on a Fe-doped InP substrate by metalorganic chemical-vapor deposition. The AlGaInAs material system own a larger conduction band offset compared to the most widely used InGaAsP system [10-13]. This larger conduction band offset has been confirmed to yield better electron confinement in the conduction band and higher temperature stability. The AlGaInAs material has been used to be a surface-emitting optical amplifier pumped by a laser diode [14]. However, until now there has been no experimental realization involving the VECSEL with the AlGaInAs material.

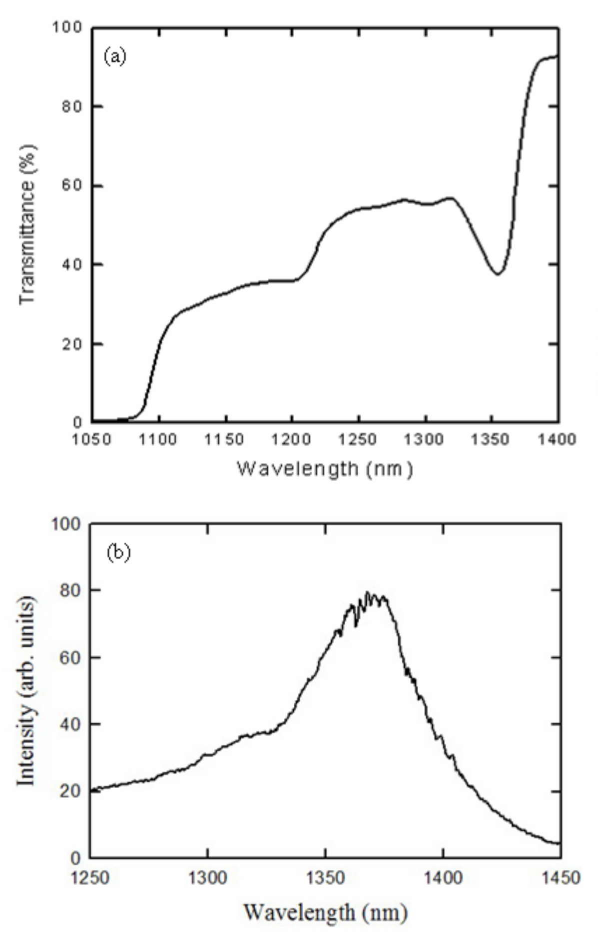

Fig. 4.2. (a) transmittance spectrum at room temperature for the AR-coated AlGaInAs/InP gain chip. (b) room-temperature spontaneous emission spectrum, obtained by pulse excitation at 1064 nm.

The present gain region consists of 30 groups of two QWs with the luminescence wavelength around 1365 nm, spaced at half-wavelength intervals by AlGaInAs barrier layers with the band-gap wavelength around 1070 nm. The barrier layers are used not only to absorb the pump light but also to locate the QW groups in the antinodes of the optical field standing wave. An InP window layer was deposited on the gain structure to avoid surface recombination and oxidation. The backside of the substrate was mechanically polished after growth. The both sides of the gain chip were antireflection (AR) coated to reduce back reflections and the couple-cavity effects. The total residual reflectivity of the AR-coated sample is approximately 5%.

Figure 4.2(a) shows the transmittance spectrum at room temperature for the AR-coated AlGaInAs/InP gain chip. It can be seen that the strong absorption of the barrier layers leads to a low transmittance near 1070 nm. The total absorption efficiency of the barrier layers at 1064 nm was found to be approximately 95%. On the other hand, an abrupt change in the transmittance near 1365 nm comes from the absorption of the AlGaInAs QWs. The room-temperature spontaneous emission spectrum, obtained by pulse excitation at 1064 nm, is shown in Fig. 4.2(b). As expected, the emission is quite broad with peak around 1365 nm and has a long tail extending to shorter wavelength.

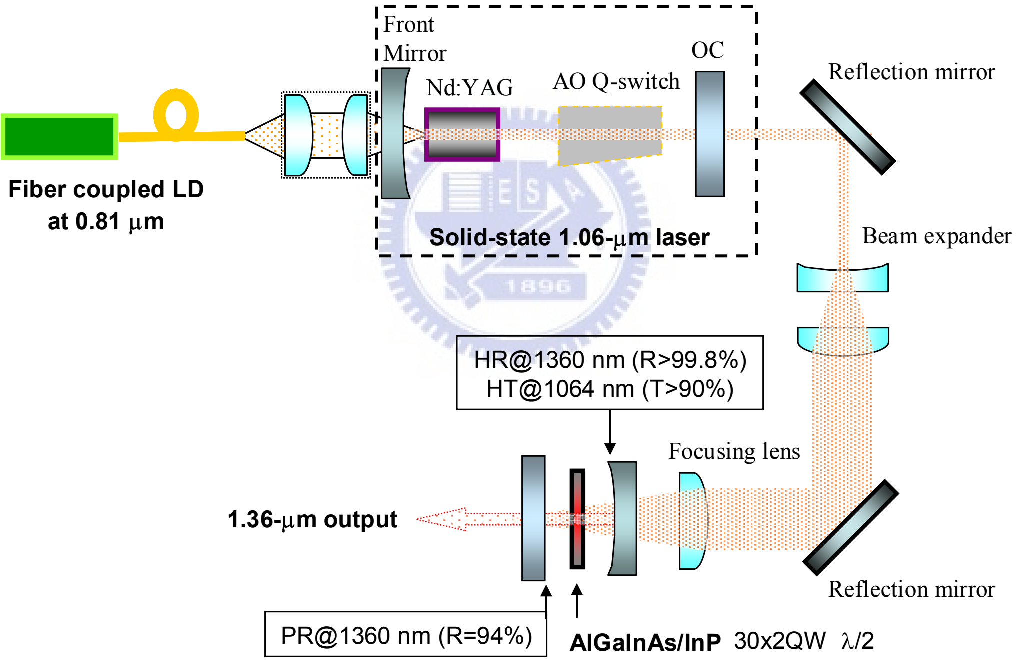

Fig. 4.3. Experimental configuration of the room-temperature optically pumped AlGaInAs laser at 1365 nm.

4.2.2 Setup and Experiment Result

Figure 4.3 shows the experimental configuration of the room-temperature high-peak-power AlGaInAs QWs laser at 1365 nm. The pump source is a diode-pumped acousto-optically Q-switched Nd:YAG 1064 nm laser to provide 15~50 ns pulses at repetition rates between 5 kHz and 50 kHz. The pump spot diameter is controlled to be 380±20 μm for the efficient spatial overlap with the fundamental transverse mode. The gain chip was mounted on a copper heat sink, but no active cooling was applied. The laser resonator is a concave-plano cavity. The input mirror was a 500 mm radius-of-curvature concave mirror with antireflection coating on the entrance face at 1064 nm (R<0.2%), high-reflection coating at 1365 nm (R>99.8%) and high-transmission coating at 1064 nm on the other surface (T>90%). The reflectivity of the flat output coupler is 94% at 1365 nm. The overall laser cavity length is approximately 10 mm.

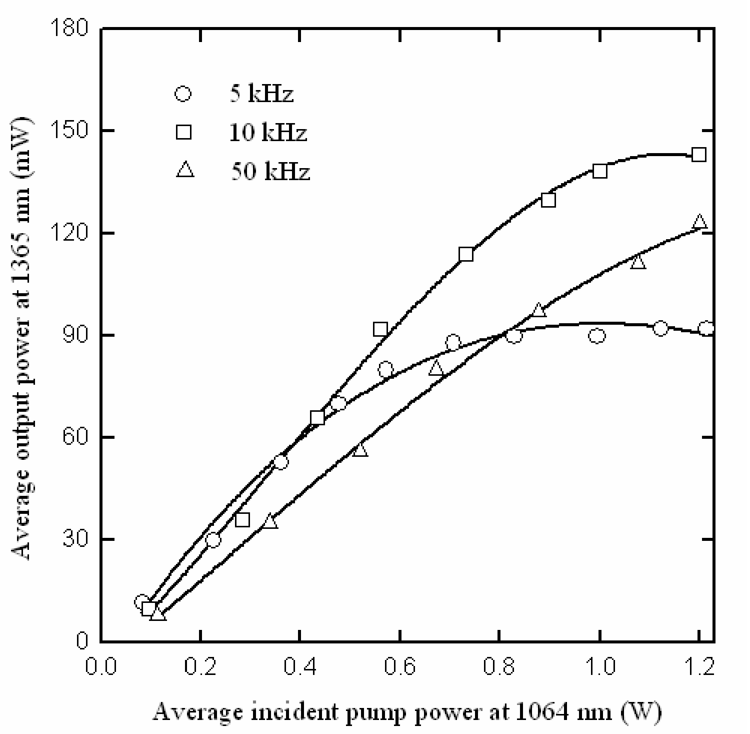

Fig. 4.4. Experimental results for the optically pumped AlGaInAs laser at pump repetition rates of 5, 10, and 50 kHz.

Figure 4.4 shows the performance of the optically pumped AlGaInAs laser at pump repetition rates of 5, 10, and 50 kHz. The transverse mode of the output beam was found to be the fundamental mode over the complete output power range. The beam quality factor was estimated to be less than 1.5. At a repetition of 10 kHz, the average output power could be up to 140 mW; the output power saturation beyond the average pump power of 1.0 W was due to the thermally induced gain degradation.

At a repetition of 5 kHz, the absorption efficiency of the gain chip for the pump power higher than 0.7 W was found to be significantly reduced because of pump-saturation effects of barrier layers. As a consequence, maximum average output power at a repetition rate of 5 kHz was nearly saturated to 90 mW. With the experimental data, the pump saturation intensity was estimated to be 8.2 MW/cm^2. This value was two-to-three orders of magnitude higher compared to conventional solid-state laser crystals because of its shorter fluorescence decay time [15]. On the other hand, the lower conversion efficiency at the 50 kHz repetition rate might be due to longer pump pulse duration that enhanced the local heating effect. Nevertheless, further investigation is needed to explore the cause for the lower conversion efficiency at the longer pulse duration.

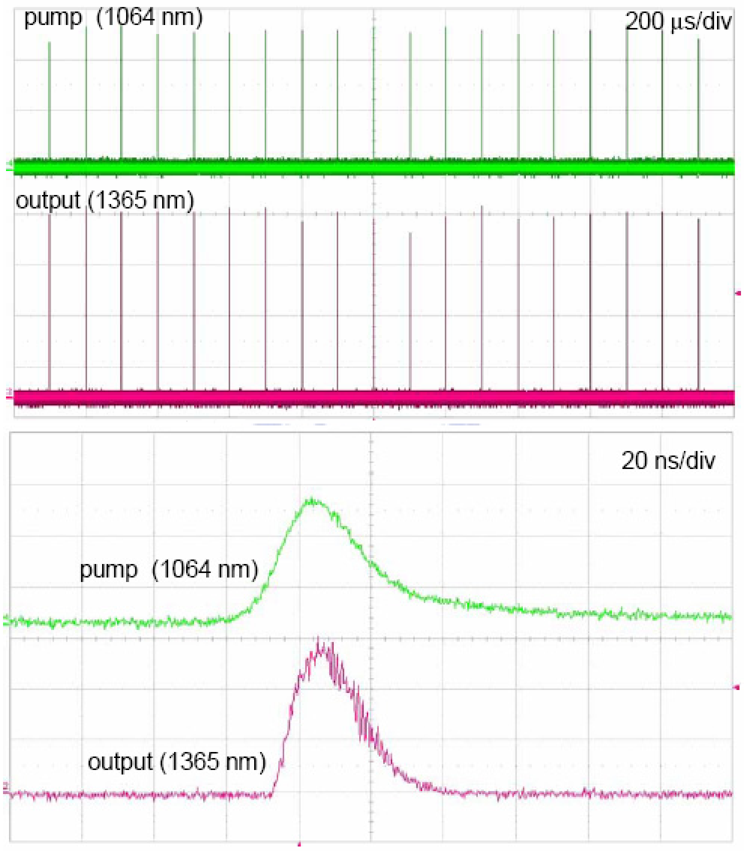

Fig. 4.5. (a) typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 G-samples/sec, 1 GHz bandwidth) with a fast p-i-n photodiode. A typical oscilloscope trace of a train of output pulses and an expanded shape of a single pulse are shown in Fig. 4.5. Under the optimum alignment condition, the pulse-to-pulse amplitude fluctuation was found to be within ±10%, which is mainly attributed to the instability of the pump beam. With the experimental pulse widths, the peak output powers were calculated. Figure 4.6 shows the peak output power as a function of peak pump power. The peak output power was up to 1.5 kW at a peak pump power of 8.3 kW, and the slope efficiency was approximately 18%. To our best knowledge, this is the highest peak power yet achieved for optically pumped AlGaInAs lasers.

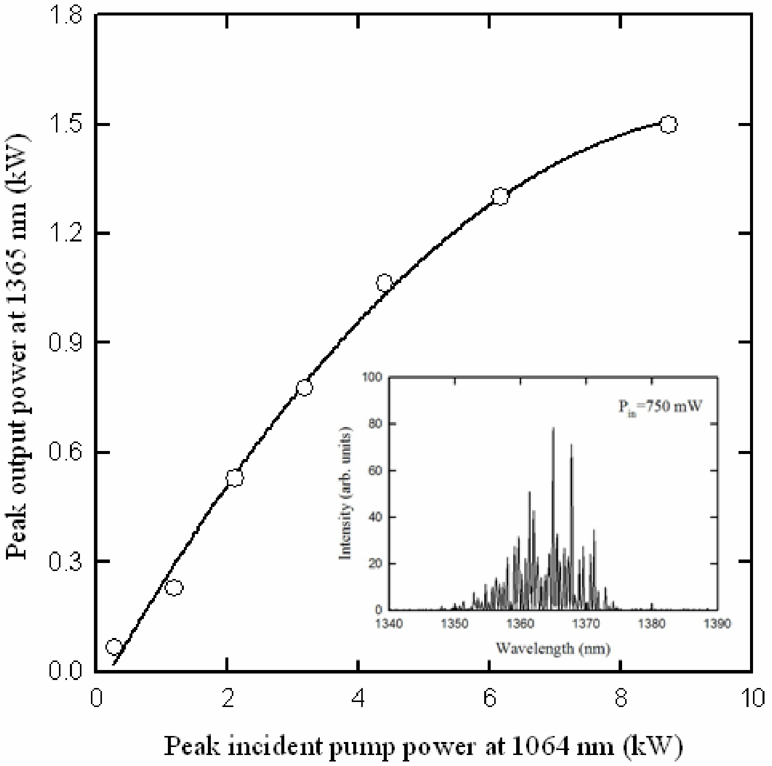

Fig. 4.6. Experimental results for the peak output power as a function of peak pump power. Inset, typical lasing spectrum obtained with 500 mW of average pump power at a repetition rate of 10 kHz.

Spectral information on the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer with a diffraction monochromator can be used for high-speed measurement of pulse light with a resolution of 0.1 nm. It was found that the qualitative nature of the lasing spectrum changed with pump power and its peak generally occurred between 1358 nm and 1368 nm. The typical lasing spectrum shown in the inset of Fig. 4.6 was obtained with 500 mW of average pump power at a repetition rate of 10 kHz. The lasing spectrum was composed of dense longitudinal modes, and its bandwidth was up to 20 nm for the average pump power greater than 200 mW. The wide spectral range indicates the potential for achieving ultra-short pulses in the mode-locked operation.

4.3 VECSEL in Low-temperature System Cooled by Liquid Nitrogen

According to the trend of semiconductor that higher optical efficiency comes with lower temperature, we cooled the VECSEL in low-temperature vacuum system without tunable setup and fine cavity. Then we got rudimentary 5 times of average output power below the temperature of 220 K. The low-temperature system is controlled by LakeShore 331 Temperature Controller in Janis liquid nitrogen pourfill system (VPF). The modification of mechanics is under way. Although to build up VECSEL in low-temperature vacuum system might not be practical, it could help us understanding and improving the physics and device.

4.4 Conclusion

Conclusion and Future Work

In summary, an AlGaInAs QW/barrier structure grown on a Fe-doped InP transparent substrate was developed to be a gain medium in a room-temperature high-peak-power nanosecond laser at 1365 nm. Using an actively Q-witched 1064 nm laser to pump the gain chip, an average output power of 140 mW was obtained at a pulse repetition rate of 10 kHz and an average pump power of 1.0 W. At a pulse repetition rate of 5 kHz, the peak output power was found to be up to 1.5 kW at a peak pump power of 8.3 kW.

After a little modification of heat sink, the average output power has been scaled up recently. This means the correct and better technology of heat spreader is still important for VECSEL, and the average output power could be several times the 140 mW in the room temperature. Nowadays, output powers of even about 10 W at 1060 nm may be achieved with optically pumped continuous-wave VECSEL using a diamond heat spreader with output coupling mirrors with reflectivities of 99%, claimed by K. S. Kim et al. [16].

The modification of mechanics in low-temperature system for VECSEL is under way. Then in the section 4.2.1 we point out that these AlGaInAs QW wafers can be used as SESA in diode-pumped PQS solid-state laser, too. This work will be finished soon.

Difficulties in Processing Design of SESAM and VECSEL

To estimate, decide, and control the thickness of each semiconductor structure layer is difficulty. Lasing properties can bring information to help correcting parameters, but it is hard to lasing without right structure. Further more, the optimization of these parameters seems very critical for high output power.