Low-temperature study of lasing characteristics for 1.3-μm AlGaInAs quantum-well laser pumped by an actively Q-switched Nd:YAG laser

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ABSTRACT

We report a low-temperature 1.3 μm AlGaInAs quantum-well laser pumped by a 1.06μm active Q-switched laser quenched by a low-temperature vacuum system. An average power of 330mW is achieved at temperature as low as 233K compared to the average power of 50mW obtained at room-temperature without cooling device both at pumping repetition rate of 30 kHz. And the average rate of gain peak shift was found to be 0.47 nm/K between 293-133 K.

Keywords: VECSEL ; AlGaInAs ; quantum well

1. INTRODUCTION

High-peak-power all-solid-state laser sources in the 1.3-1.6μm spectral region are of particular interest in remote sensing, eye-safe optical ranging, fiber sensing, and communication [1-4]. To achieved this, diode pumped solid state lasers (DPSSLs) has vantage points 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]. Unfortunately, the spectral range of DPSSLs is limited by the properties of doped ion in crystals and glasses. Vertical-external-cavity Surface-emitting semiconductor lasers (VECSELs) which combines both advantages of DPSSLs and semiconductor lasers allows for flexible choice of emission wavelength via bandgap engineering have successfully conquered this situation. Typically this structure

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consists of a highly reflecting distributed reflector (DBR) grown on a lattice-matched substrate with resonant-periodic-gain structure that comprises a series of barriers to provide the pump absorption, quantum wells to provide gain, and cap layers to prevent surface recombination and oxidation.

The long wavelength (1.3-1.55μm) semiconductor laser occurred at spectral range covered by lasers based on GaAs and InP substrates. For InGaAs/GaAs system, at an operation over 1 μm there would be too much scattering loss to have good efficiency due to compressed strain. But the introduction of strain-compensating GaAsP layers as buffer layer could improve the high power operation [6]. On the other hand, laser gain structure based on InP substrate like InGaAsP solid solution system [7,8] suffers from poor temperature characteristic due to their small conduction band offset. To conquer this, an alternative of using AlGaInAs material system with deeper conduction band offset has brought up . But there still have difficulties forming DBRs like low refractive index contrast, low thermal conductivity or high complexity of growth [9-11]. Another way to achieve long wavelength range is using GaInNAs/GaAs system with high contrast GaAs/AlGaAs DBRs and larger conduction band offset [12]. Adding a few of nitrogen will result in the redshift of absorption wavelength and a reduction of lattice mismatch to GaAs [13]. So we can adjust the ratio of indium and nitrogen content to reach the wavelength we want. Because nitrogen is too small in this quaternary alloys, there is a drawback that too many nitrogen content will introduce large number of nonradiative defects. As a result it is difficult to fabricate this compound for long wavelength range. In this work, we use AlGaInAs/InP MQWs as our gain region of optically pumped VECSEL and with cooling temperature at 283K we obtained 140mW output power at the repetition rate of 10kHz and 1.2W input power [14]. Raising input power will decrease the lasing efficiency and a roll-over effect came into existence. However, the temperature dependent laser performance and physics have not been realized. But we believed that it mainly caused by the diffusion of carrier from the gain region due to the heat produced by the high absorbed power. To study the optical characteristics under low temperature, we made a simple cavity put in a vacuum system cooled by liquid nitrogen and heated by Lake Shore 331 Temperature Controller and the temperature is controlled at the suitable degree.

In this article we present a low-temperature 1.3μm AlGaInAs quantum-well laser pumped by a 1.06μm Nd:YAG active Q-switch laser quenched by liquid nitrogen. An average power of 330mW is achieved at temperature as low as 233K compared to the average power of 50mW obtained at room-temperature without cooling device both at pumping repetition rate of 30 kHz. And the average rate of gain peak shift was found to be 0.47 nm/K between 293-133 K.

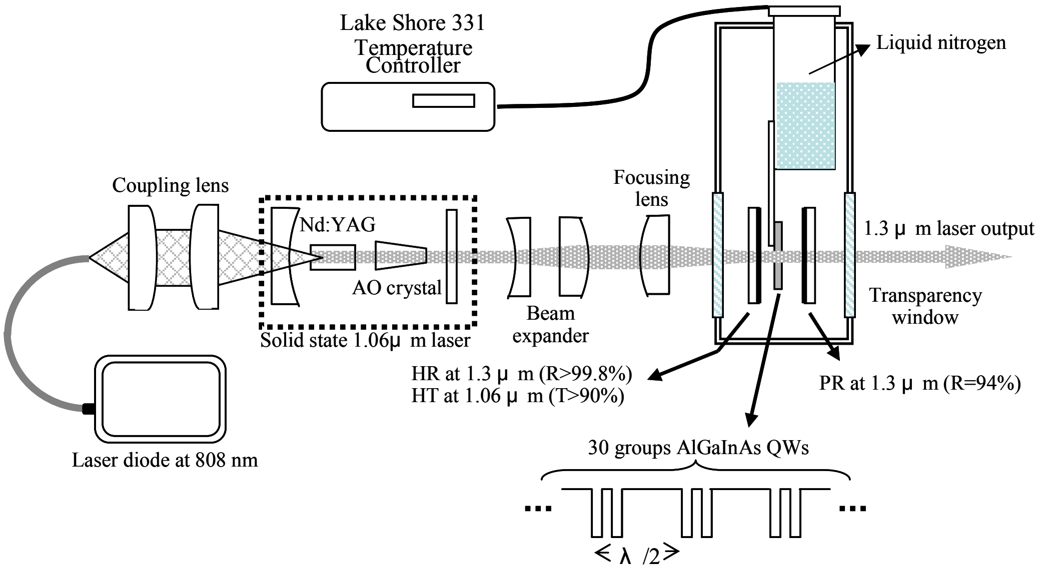

Fig. 1 Experimental setup of low temperature AlGaInAs/InP semiconductor disk laser at 1.3μm pumped by a 1.06μm A-O Q-switched laser and quenched by a low-temperature vacuum cooling system

2. EXPERIMENTAL SETUP

Fig. 1 shows the experimental configuration of the low-temperature 1.3μm AlGaInAs quantum-well laser pumped by a 1.06μm Nd:YAG active Q-switched laser. The pumping source provides 20-60 ns pulses at repetition rate between 20 and 60 kHz. We controlled pump spot diameter to be about 420μm to have efficient spatial overlap with lasing mode. The gain region consist of 30 groups of two QWs spaced at half-wavelength intervals by AlGaInAs barrier layers with the bandgap around 1070 nm. This is a RPG structure that barrier layers are used not only to absorb pumping light but also to locate the quantum well region at the anti-node of the lasing field standing wave and it can enhance the wavelength selection [15-17], and we obtained the peak luminescence wavelength around 1365 nm.

The laser resonator is a plano-plano cavity with front mirror which has anti-reflection 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(T>90%) on the other face. The reflectivity of the output coupler is 94% at 1365 nm and the overall cavity length is about 5mm. This flat-flat cavity is stabilized by the thermal induced lens in the gain medium [18,19]. It is an attractive design because it reduces complexity and makes the system compact and rugged. The gain medium is cooled down by liquid nitrogen and the temperature is controlled by Lake Shore 331 Temperature Controller. The whole structure of laser cavity is inside the Janis VPF-100 cryogenic vacuum equipment to avoid the fog of stream on the window. And the two transparency windows have high transmittance for spectral range of both lasing and pumping wavelength.

The gain medium was composed of an AlGaInAs QW/barrier structure grown on a Fe-doped InP transparent substrate by metalorganic chemical-vapor deposition. Compared to the conventional S-doped InP which has strong absorption in the 1.0-2.0 spectral region, Fe-doped InP has better transparency at lasing wavelength . It is worth mention that In-P based systems suffer from the lack of good DBR and has been challenging to transfer from edge-emitting lasers to surface-emitting lasers. By the use of Fe-doped InP, we could replace DBRs in the VECSEL by an external mirror. An InP window layer was deposited on the gain structure to avoid surface recombination and oxidation. The back side of the substrate was mechanically polished after growth. Both sides of the gain chip were anti-reflection coated at lasing and pumping wavelengths to reduce backreflections and coupled-cavity effects. And the total residual reflectivity of the AR-coated sample is approximately 5%.

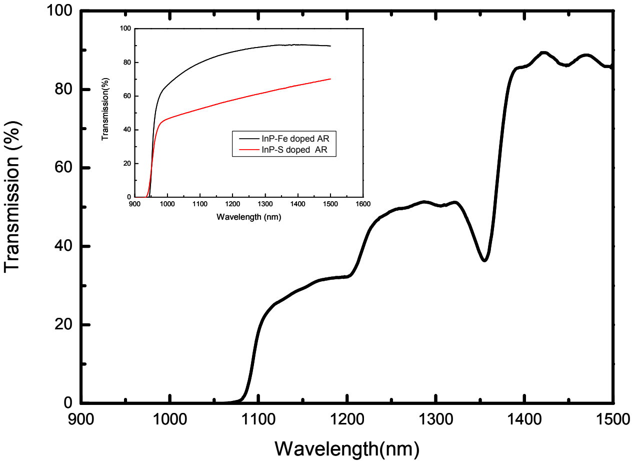

Fig. 2 Transmittance spectrum of AR-coated AlGaInAs/InP MQWs gain chip at room temperature. Inset, room temperature transmittance spectrum of S-doped and Fe-doped InP chip with anti-reflection coating.

Figure 2 shows the transmittance for the AR-coated AlGaInAs/InP gain chip at room temperature. It can be seen that the strong absorption of the barrier layers leads to low transmittance near 1070nm. The total absorption efficiency of the barrier layers at 1064 nm was found to be approximately 95% for the pulse pumping. On the other hand, an abrupt change in transmittance near 1365nm comes from the absorption of the AlGaInAs QWs. The inset of Figure 2 shows the transmittance of Fe-doped and S-doped InP with anti-reflection coating. We could observe that the transmittance is about 90% for Fe-doped InP and 60% for S-doped InP near 1365nm.

3. RESULT AND DISCUSSION

Fig. 3 shows the performance of the optically-pumped 1.3 μm AlGaInAs MQWs laser operated with different cooling temperature ranged from 293 K to 233 K at repetition rate of 15 kHz at low power and 30 kHz at high power. The pulse width at repetition rate of 15 kHz and 30 kHz are ranged from 50 ns to 30 ns and 120 ns to 52 ns respectively. The transverse mode was measured to be the fundamental mode over the complete output power range. The beam quality factor was determined by the Gaussian fit to the laser beam waist and the divergence angle which was found to be less than 1.5. We can see that the slope efficiency is increasing with decreasing temperature, and the maximum output power of 293 K and 233 K are 50 mW and 330 mW respectively. From the past work of our group [14,20,21], we know that the roll-over of output power at low repetition rate is resulted from the gain saturation or the transparency induced by the pumping beam. Although the pumping energy density is larger than the lasing energy density, the gain-saturation effect is more conspicuous than the nonlinear transparency of the barrier due to it's long absorption length. So we could still observe the roll-over of output power at 1.8W pumping power even at temperature as low as 293 K.

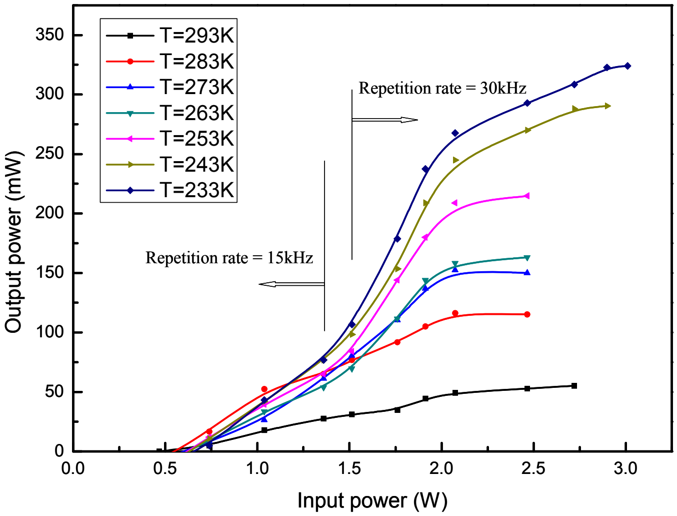

Fig. 3 Experimental results of AlGaInAs 1.3μm MQWs laser pumped by an 1.06μm active Q-switched Nd:YAG laser at different cooling temperature. It shows the output power of 15 kHz repetition rate at low input power and 30kHz at high input power.

Fig 4 is the photoluminescence of AlGaInAs MQWs wafer excited by a 1.06 μm active Q-switched laser with 1.2 W pumping power and 800 μm pumping spot size at 30 kHz and cooled from 293 K to 133 K. There are two peaks at about 1350 nm and 1245 nm due to the n =1 and n=2 transition at 293 K respectively. The n=1 peak wavelength shifts from 1350 nm to 1275 nm with the slope of 0.47 nm/K and the n=2 peak disappears gradually. The line-width of n=1 peak became narrower with decreasing temperature due to the reduction of collision broadening.

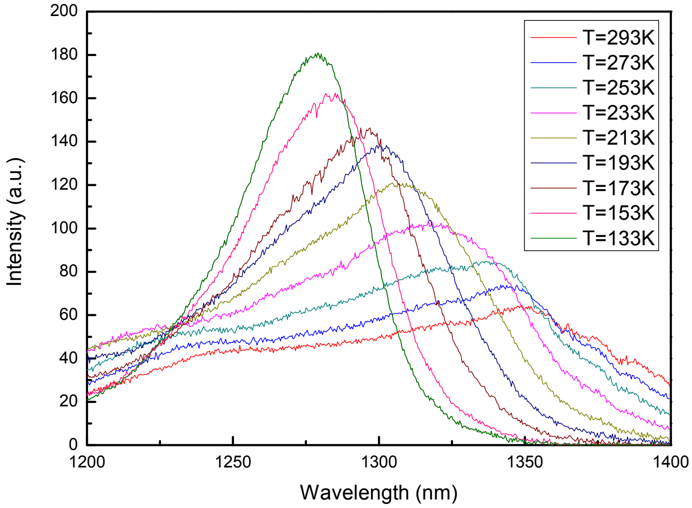

Fig. 4 Experimental results of photoluminescence pumped at input power of 1.2W and repetition rate of 30kHz at different cooling temperature.

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