High-power (>1 W) dilute nitride semiconductor disk laser emitting at 1240 nm

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Abstract. We report on a high-power GaInNAs/GaAs optically pumped semiconductor disk laser operating at a wavelength of 1240 nm. The laser structure consisted of 12 dilute nitride (GaInNAs) quantum wells placed on top of a GaAs/AlAs distributed Bragg reflector, the whole structure being grown by molecular beam epitaxy. A diamond heat spreader was bonded onto the sample for improved heat dissipation. When cooled down to 8 °C, the laser produced continuous-wave output power up to 1.46 W in the TEM\textsubscript{00} mode, demonstrating the potential of dilute nitrides for high-power disk laser applications.

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1. Introduction

An optically pumped semiconductor disk laser (SDL), also known as a vertical external cavity surface emitting laser (VECSEL), combines many of the advantages of traditional solid-state lasers with the versatility that is offered by semiconducting gain materials. The external cavity configuration enables the use of intra-cavity filters to achieve a narrow linewidth [1] or a tunable wavelength [2]. Nonlinear elements can be included in the external cavity for ultra-short pulse generation [3] or for achieving efficient frequency conversion [4]. A compact, frequency-converted SDL is particularly important for accessing the visible spectrum. Such a laser producing high optical power and good beam quality is in demand for applications where replacement of expensive and large-size solid-state, dye, or gas lasers is desired [5]. One of the most impressive results was demonstrated with frequency-doubled SDLs where the fundamental wavelength of \( 940 < \lambda < 1040 \) nm was frequency-doubled to yield ultra-bright blue-green emission [4].

The rapid progress in the development of SDLs is due to the availability of high-power low-cost 808 nm pump diodes and the mature gallium arsenide technology which allows high-gain semiconductor structures and distributed Bragg reflectors (DBRs) to be prepared at \( 1000 < \lambda < 1100 \) nm. The development of frequency-converted red-light SDLs, however, has been slow because of a lack of good semiconductor heterostructures for the gain medium and the DBR in the interval \( 1200 < \lambda < 1300 \) nm. For such a DBR, one may prepare multiple pairs of GaAs/Al(Ga)As layers, which give a reasonable refractive index difference (\( \Delta n \)) between the adjacent layers of the mirror, but at the same time limit the choice of materials for the gain medium which is usually made of quantum wells (QWs). In fact, one is left with only two choices: GaAsSb/GaAs or GaInNAs/GaAs. The latter QW is preferred because it gives strong quantum confinement for electrons (though less so for the holes) [6, 7]. On the downside, incorporation of nitrogen into the InGaAs lattice generates non-radiative recombination centres which have detrimental effects on lasing features, ultimately leading to very weak optical transitions.

In this paper, we examine a GaInNAs/GaAs SDL launching the fundamental wavelength of \( \lambda \approx 1240 \) nm at very high continuous-wave (cw) power. This SDL, we believe, is an ideal light source for frequency conversion. It shows that GaInNAs, prepared by molecular beam epitaxy (MBE), meets the stringent quality requirements of monolithic SDLs in the spectral band which is the most difficult one for GaAs technology and is entirely dominated by indium phosphide (InP) technology.

2. Laser design

The laser chip was grown on an \( n \)-type GaAs (100) substrate by MBE, equipped with a radio frequency (rf) nitrogen plasma source. The monolithic structure of the chip consisted of a 30-pair GaAs/AlAs DBR (\( R_{\text{max}} = 99.9\% \)) and a gain region of 12 GaInNAs QWs, each 7 nm in thickness, the energy states of which were in resonance with the Fabry–Pérot standing wave modes in the 4.5-\( \lambda \) long cavity (figure 1). Compressive lattice strain of the QWs was alleviated by adding tensile-strained GaNAs layers in each QW. In addition to reduced total compressive strain, the GaNAs strain-compensating layers also provided some degree of spectral redshift by reduced barrier potential, allowing lower nitrogen concentration in the QWs for reduced N-related defects [8, 9]. This made the active region quite complex, but left the whole structure misfit-dislocation-free. An additional \( 1 - \lambda \) thick Al\(_{0.37}\)Ga\(_{0.63}\)As window layer and a GaAs cap
was grown on top of the gain section to ensure good confinement of photo-carriers generated in the GaAs barrier by optical pumping and to avoid non-radiative recombination of carriers near the surface of the chip. The Al$_{0.37}$Ga$_{0.63}$As window was protected against oxidation by depositing a thin GaAs layer onto the device.

Photoluminescence (PL) from the QWs could not be studied straightforwardly in a reliable way, because emission was affected by the DBR and the cavity. Therefore, a PL sample was prepared separately. A part of the gain structure was scribed off the wafer and bonded on a glass plate. Then the substrate was mechanically thinned down to about 100 µm; the rest of it was removed by wet etching. The DBR was also removed from this PL sample by reactive ion etching. Finally, we only had the gain section and the window layer left on the glass plate. Figure 2 shows the PL spectrum at room temperature obtained for this sample. It also shows PL from an as-grown sample as well as the stop-band pattern of the DBR superimposed in this diagram to emphasize the difference between the two PL spectra and to reveal the closeness of PL to the stop-band location.
The laser chip was cut from the wafer and capillary-bonded with water to a $\sim 300 \, \mu m$ thick type II-a natural diamond heat spreader to ensure efficient heat removal from the gain section. The bonded chip was fixed between two copper plates. A small opening in the top copper plate allowed free passage of pump light and the $1240\,nm$ signal. An antireflective 2-layer $\text{TiO}_2/\text{SiO}_2$ coating was deposited onto the diamond surface through the hole to reduce signal and pump reflection. The mounted sample was attached to a water-cooled copper heat sink.

The laser cavity, shown in figure 3, had a V-shape configuration. It consisted of the mounted chip, sometimes called a gain mirror, a high-reflectivity curved mirror with a radius of curvature (RoC) of 150 mm placed 90 mm away from the gain chip, and a plane 1% output coupler placed 200 mm away from the curved mirror, forming a 290 mm long laser cavity. A fibre-coupled 808 nm diode laser was used for pumping the gain structure. The pump beam was focused to a spot of about $180 \, \mu m$ in diameter at an angle of $35^\circ$ relative to the surface normal.

3. Results and discussions

The cavity was designed to match the lasing mode size with the pumped area of the gain mirror. Free-running laser emission was temperature-tunable within $1230 < \lambda < 1245\,nm$ by varying the mount temperature from 8 to $35^\circ\text{C}$. The optical spectrum of the laser, shown in figure 4, was measured using fibre coupling and an optical spectrum analyser. The comb-like shape of the spectrum with multiple spikes is a result from resonant wavelengths of the etalon formed by the intracavity diamond heat spreader. The etalon effect could not be removed with the two layer antireflective coating on the diamond surface.

The output power in excess of 1 W was obtained up to $35^\circ\text{C}$ by using a 1% output coupler. The maximum cw TEM$_{00}$ mode output was 1.46 W achieved at $8^\circ\text{C}$ with the pumping power of 20 W (figure 5). Measured pump reflection was 6.5%, which has not been taken into account in the light output characteristics. Interestingly, the laser threshold decreased as the chip temperature was increased (inset in figure 5). This phenomenon can be readily interpreted as due to a shift of the gain spectrum towards the centre of the DBR stop-band. In order to determine the temperature-dependent shift of PL we prepared a PL sample with QWs that were nearly identical to the ones used in the SDL. Dependence of the PL shift on the temperature is shown in figure 6 and its value was estimated to be $0.44\,nm\,^\circ\text{C}^{-1}$. This corresponds to about 12 nm shift from 8 to $35^\circ\text{C}$.
Figure 4. Spectrum of the SDL at maximum output power at chip temperature of 8 °C (solid line) and 35 °C (dash dot line).

Figure 5. Light output characteristics of the GaInNAs/GaAs SDL plotted against chip temperature for a 1% output coupler. Inset: dependence of the threshold pump power on chip temperature.

which is in good agreement with the spectral data shown in figures 4 and 5. The spatial beam profile of the laser was recorded with a CCD camera and is shown in figure 7.

Further improvement of the laser performance could be expected if the PL was in exact coincidence with the centre of DBR stop-band where reflection has its maximum value. Another critical issue is the location of the QWs at the standing wave anti-nodes, which may be addressed by slightly varying the positions of the QWs in the chip cavity and finding the optimal location.
4. Conclusions

We have demonstrated a GaInNAs/GaAs disk laser operating at $\lambda \approx 1240$ nm with cw emission exceeding 1.4 W. The overall performance of the laser provides evidence that high-quality multiple-QWs of dilute nitrides can be grown by MBE for optically pumped SDL applications in the technologically important spectral range from 1.2 to 1.3 $\mu$m. By further optimizing the layer structure, the cavity, and the pumping scheme, it is likely that greatly improved lasing performance can be achieved. We are planning to exploit this SDL to generate efficient red (620 nm) emission by frequency-doubling the fundamental energy.
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