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MICRO-JOULE CAVITY-DUMPED WAVELENGTH-TUNABLE SEMICONDUCTOR DISK LASER

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We report on cavity-dumping of a semiconductor disk laser as a method to generate energetic wavelength-tunable nanosecond pulses with repetition rates ranging from 0.1 to 4MHz. Experimentally, emission of 24ns pulses with peak output power of 41W in a single beam output (and of 30ns with peak power of 57W in a combined beam output) with wavelength tuning from 1045–1080nm was obtained.

Introduction

In the past decade, semiconductor disk lasers (SDLs), also known as vertical external-cavity surface-emitting lasers (VECSELs), have proven to be attractive sources for the generation of high-brightness laser radiation [1–4].

The combination of a surface-emitting semiconductor gain element and a bulk external optical cavity has enabled SDLs to produce (multi)-Watt-level single-transverse-mode operation with fundamental emission wavelength ranging from the red to 2.8μm [1–3, 5–6]. Furthermore, efficient intracavity nonlinear-frequency-conversion in these lasers has permitted output from the ultraviolet [1, 7–8] to the mid-infrared [9]. So far, these sources have primarily been operated in continuous-wave [1–3, 10] or quasi-continuous, high-repetition-rate mode-locked regimes [4], capitalizing on the nanosecond upper state lifetime characteristic of the III–V semiconductor gain section. However, recently, there has been increased interest in investigating their potential as sources of energetic nanosecond pulses. To-date, this regime of operation has been approached by gain-switching [1, 11 – 14] with either pulsed semiconductor or solid-state laser pumps. Here, we introduce and demonstrate an alternative method, cavity-dumping, which exploits a CW-pumped gain section and an intracavity acousto-optic deflector to generate wavelength-tunable nanosecond pulses from an SDL. This approach benefits from ready access to the high-power intracavity fields inherently associated with SDLs to facilitate high-energy pulsed emission and is, in principle, applicable to SDLs at any wavelength. Furthermore, it capitalizes on a simple implementation of the modulation to generate pulses of controlled repetition rate as high as tens of mega-Hertz in contrast to direct pump modulation. Finally, it readily offers the ability to generate electrical trigger signals for applications requiring electrical/optical synchronization.

Laser description

The SDL cavity arrangement used in this initial demonstration around 1060nm is similar to that proposed in early papers on cavity-dumped solid-state lasers [15–17]. A four-mirror cavity was formed by an InGaAs/GaAs SDL gain/mirror structure [18] placed at the focus of a 150mm radius of curvature (ROC) mirror M1, and two curved mirrors with ROC of 205mm (Figure 1).

The semiconductor structure includes 10 strain-compensated quantum wells (QWs), distributed over 10 anti-nodes of the optical field, and a 35.5-pair $Al_{0.2}Ga_{0.8}As/AlAs$ distributed Bragg reflector. An acousto-optic modulator (AOM) was placed at the waist of the laser mode (mode radius 52m) between mirrors M2 and M3 (see Figure 1) with the output beam extraction being carried out as described in [17].

The modulator had plane-plane parallel surfaces with anti-reflection (AR) coatings centered at 1060nm. A 2-mm-thick birefringent filter (BRF) was placed in a long cavity arm between mirrors M1 and M2, and provided laser wavelength tuning. The gain medium was pumped by a fiber-coupled laser diode array emitting at 808nm and delivering power of up to 25W. The pump spot diameter on the gain element was ~100μm. The laser gain element was thermally managed using a 250-μm-thick type-IIa natural diamond heatspreader.

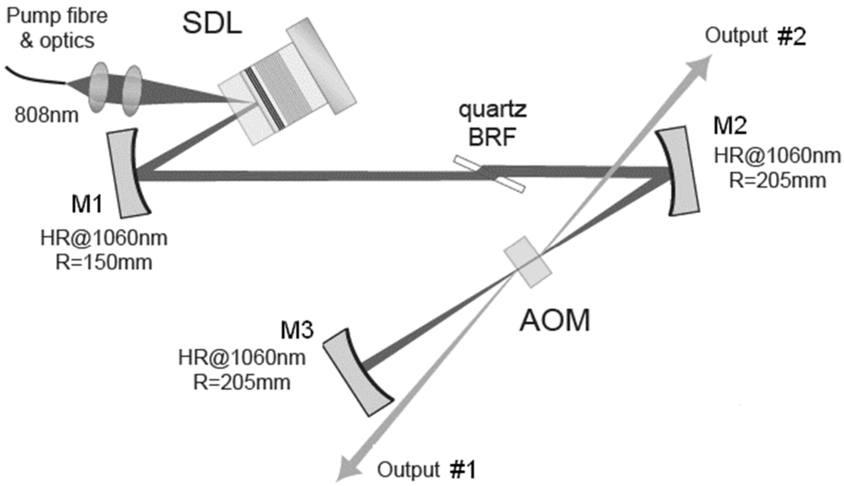

Figure 1 – Schematic of the cavity-dumped SDL

This was bonded to the epilayer surface using liquid capillarity and the ensemble was mounted in a brass holder cooled to 6ºC via chilled water circulation.

The crystal quartz AOM provided 60 % single-pass diffraction efficiency of the linearly polarized beam (with its polarization plane perpendicular to the acoustic propagation direction) at 1060nm. The acoustic frequency of 210MHz inside the AOM was excited by a driver with an average RF power of 20W.

The desired laser pulse repetition rate was controlled by the external frequency generator which triggered the driver. The frequency generator delivered square pulses with a 31 to 60ns on-time pulse duration (rise/fall time of 18ns) within the frequency range from 100kHz up to 4MHz. The difference in applied pulse duration for the various repetition rates is explained below.

Both diffracted beams were measured to have the same output power and pulse duration. The experimental results below will first be presented for only one of the extracted beams (Output #1 (see Figure 1)).

It was possible to combine both outputs into a single beam by reflecting "Output #2" back into the resonator by the mirror M2. The results of such combined output are also presented at the end of the experimental section.

Experimental results

The dependence of the average output power of the diffracted beam on the incident pump power (on the diamond/semiconductor structure) is plotted in Figure 2 (a).

The characteristic rollover in this power transfer curve is observed at ~20W of pump power. Such behavior is typical for SDLs [18] and is attributed to induced thermal effects in the gain material at high pump powers. In the remainder of this work, the pump power was kept constant at 20W to ensure the highest output power from the laser.

The frequency response of this cavity dumping scheme was studied using a 60ns-duration RF pulse within the 100-500kHz range and monotonically decreasing the pulse duration (down to 31ns) going from 500kHz up to 4MHz. As shown in Figure 2 (b), the energy of the extracted laser pulse at the incident pump power of 20W decreased from 1 down to 0.17 J as the AOM signal frequency increased from 100kHz up to 4MHz with a cut-off frequency (defined as the frequency for which the energy is halved) of ~1.2MHz. As expected, the pulses occurred at repetition rate corresponding to the RF driver signal. They were measured to be of duration 24±3ns full width at half maximum (Figure 2 (b), inset), independent of the pulse repetition rate, a fact which will be explained below. The corresponding peak power of the pulse therefore had the same dependence upon the RF signal frequency and reached its maximum value of ~41W at ~200kHz and below (see Figure 2 (b), right-hand vertical scale). The similarity between the frequency responses obtained for pump powers of 11 and 20W (Figure 2 (b)) suggests that the cavity build-up time is only weakly dependent on pump power.

Figure 3 (a) shows the evolution of the intracavity field (measured with a fast silicon detector placed behind the mirror M1) over a 500ns time window around the pulse emission time for AOM modulation frequencies of 200kHz (RF pulse duration 60ns) and 1.2MHz (RF pulse duration 44ns), respectively.

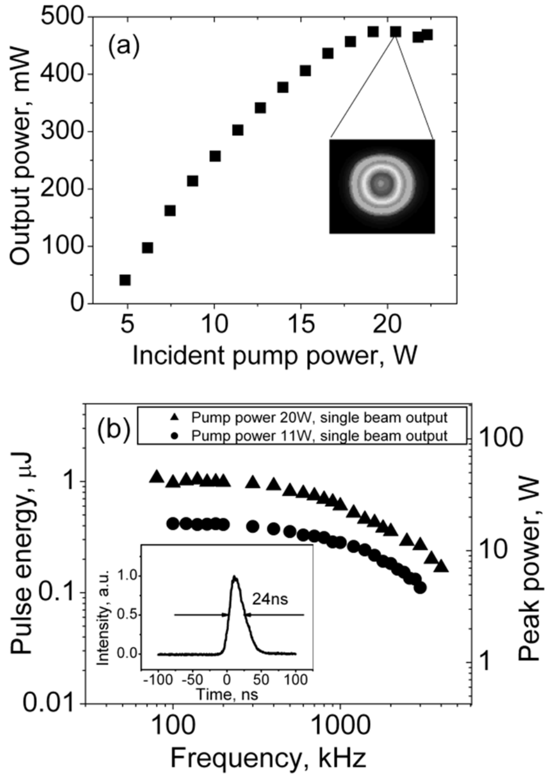

Figure 2 – (a) Dependence of the average diffracted single beam output power on incident pump power at a dumping frequency of 600 kHz. Inset: Profile of the diffracted single beam at the incident pump power of 20W. (b) Pulse energy and corresponding peak power of the 24-ns-long pulses extracted from the SDL cavity as a function of the AOM frequency at two different incident pump powers of 20W (triangles) and 11W (circles). Inset: cavity dumped pulse with duration of 24ns

It can be observed that, at high repetition rates, the intracavity field is neither restored to its maximum value nor fully depleted, explaining the drop in pulse energy. We also note that the field initial build up phase is apparently faster at high repetition rates, most probably as a consequence of the higher value of the intracavity field remaining after laser pulse extraction.

The dependence of the diffracted pulse energy at high frequencies (namely, 1.2MHz) on the RF pulse duration is shown in Figure 3 (b). As illustrated, the improved peak power performance associated with shorter RF pulses results from a better management of the intracavity field temporal evolution. Indeed, the reduced cavity opening time promotes an incomplete depletion of the intracavity field by the end of the pulse which subsequently leads to higher field intensities being reached at the end of the period.

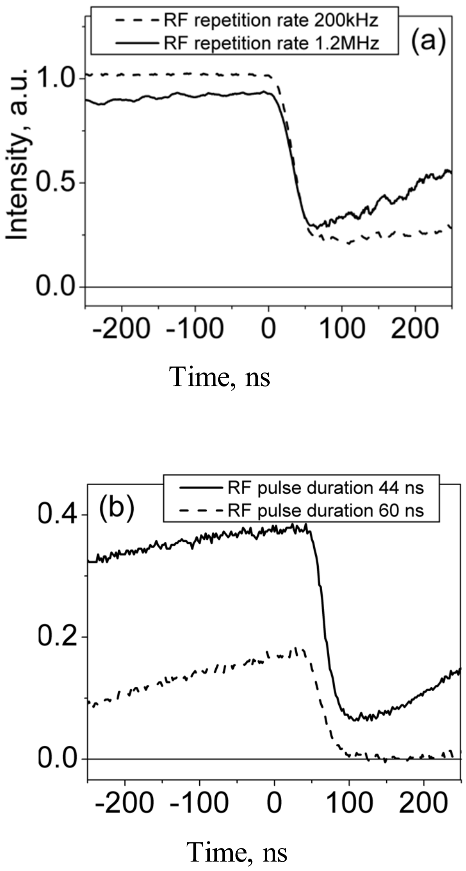

Figure 3 – (a) Dynamics of the SDL intracavity field intensity for cavity dumping frequencies of 200 kHz, RF pulse duration of 60ns (dashed line) and 1.2 MHz, RF pulse duration of 44ns (solid line) respectively. (b) Dynamics of the SDL intracavity field intensity for cavity dumping frequency of 1.2MHz for RF pulse duration of 60ns (dashed line) and 44ns (solid line)

We note that, in practice, the combination of a reduced RF pulse duration and the finite (18ns) switching times of the AOM driver also decreases the effective AOM diffraction efficiency (from 60 % down to 52 %) which, in turn, further enhances the above-described effects. This optimization of the output energy was the prime determinant of the selected laser driving conditions.

Wavelength tunability of the cavity-dumped emission was recorded to range from ~1045 up to ~1080 nm (see Figure 4 (a), circles) and, in comparison with the tunability of the laser without AOM (Figure 4, squares), was limited only by the characteristics of the AR coatings of the AOM.

This demonstrates that the all-important tuning characteristic is retained in this form of operation of an SDL, offering tunable nanosecond output around any central wavelength at which SDLs can be demonstrated to operate.

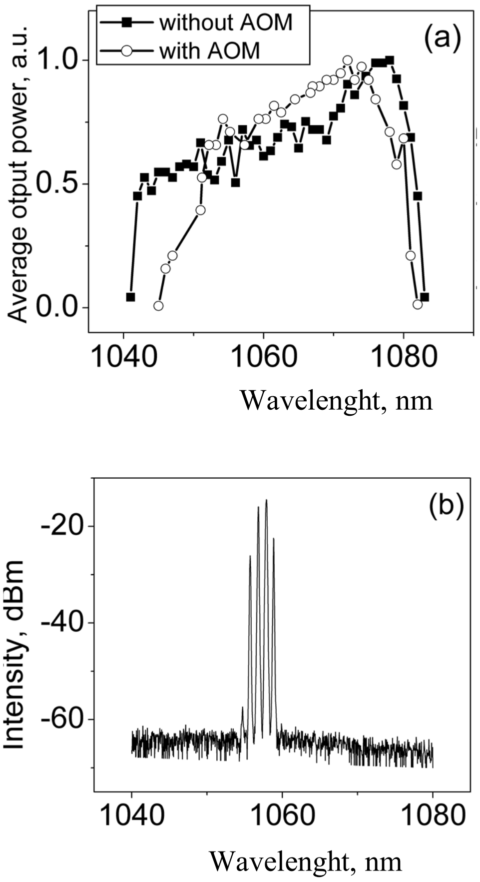

Figure 4 – (a) Wavelength tuning of the SDL using the intracavity BRF: with the cavity dumping (circles) and without it (squares). (b) A typical spectrum of the output pulses

The fine structure in the output pulse spectrum (Figure 4 (b)) is typical for the SDL with the heatspreader on top of the gain material and is associated with the etalon-modes of the diamond heatspreader mentioned above.

Beam profile (see Figure 2 (a), inset) assessment performed using the knife-edge scanning technique revealed an M^2 factor of ~1.7×1.4 at the incident pump power of 20W and of 1.5×1.4 at the incident pump power of 11W (which corresponds to a pulse energy of 0.4J, see Figure 2 (b)). This could be further improved by adjusting the cavity length in order to achieve a ratio between the intracavity mode and the pump spot at the semiconductor chip slightly larger than unity.

This should not come at the expense of a significant energy penalty if the trend follows the behavior observed during continuous-wave operation [18].

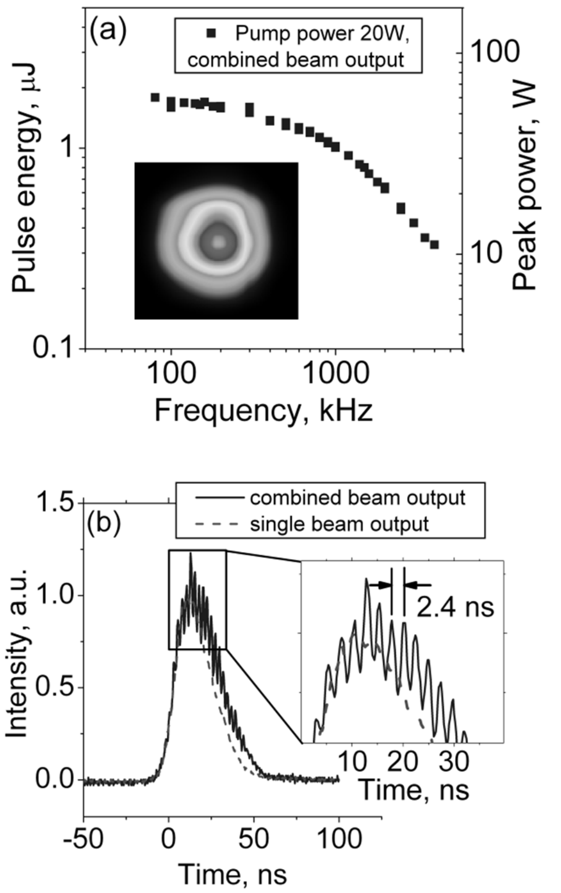

Figure 5 – Frequency response (a) (inset – output beam profile) and (b) pulse characteristics of the cavity-dumped SDL with combined output (solid line) and single output (dashed line, for comparison)

The performance of the laser when the two output beams (Outputs #1 and #2) are combined is shown in Figure 5. The pulse energy rises to ~1.7 J (Figure 5 (a)) whilst the FWHM pulse duration increases to 30 ns (Figure 5 (b), solid line).

The resulting maximum peak power is therefore ~57W (Figure 5 (a), right-hand vertical scale). Both the tunability range and M^2 factor of the laser with the combined beam output remain the same as for the single beam output. Contrary to single output beam operation, the combined output pulse shape exhibits oscillations that are mainly noticeable at on the pulse falling edge.

The oscillation frequency was measured to be ~420MHz which corresponds to twice the frequency of the acoustic wave generated in the AOM. This is consistent with the fact that a fraction of the reflected beam is fed back into the cavity and this fraction undergoes two frequency shifts when being reflected in and out of the cavity [15].

Conclusions

In conclusion, we report what we believe to be the first demonstration of a cavity-dumped SDL for the generation of wavelength-tunable, micro-Joule, nanosecond pulses. This form of operation takes full advantage of the high intracavity powers and broad wavelength tunability available in SDLs and the rapid and stable recovery of the intracavity field due to the short carrier lifetime gain medium. Furthermore, it is in principle applicable at any fundamental emission wavelength at which SDLs have been demonstrated, currently 650nm – 2.8μm. Stable pulse trains with repetition rates varying from 100kHz to 4MHz and a pulse peak power of 57W and beam M^2 factor of 1.7×1.4 were obtained at 1075nm. Wavelength tunable pulsed operation was also achieved from 1045 to 1080nm.

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Полупроводниковый дисковый лазер с перестраиваемой длиной волны излучения, генерирующий методом разгрузки резонатора импульсы с энергией несколько микроджоулей.

Представлены результаты использования метода разгрузки резонатора для получения в полупроводниковом лазере с дисковой структурой импульсов излучения высокой энергии, наносекундной длительности с частотой следования, варьируемой в диапазоне от 0,1 до 4 МГц и перестраиваемой длиной волны. В указанном лазере экспериментально получены импульсы излучения на длине волны, перестраиваемой в диапазоне 1045 – 1080 нм, и длительностью 24 нс с пиковой мощностью 41 Вт в режиме генерации одного выходного пучка и, соответственно, 30 нс и 57 Вт в комбинированном режиме.

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