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Tunable dual wavelength emission and bandwidth narrowing of a laser diode array with a simple external cavity

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ABSTRACT We report on the performance of a commercial, non-AR-coated diode laser bar of 20 W output power, consisting of 20 emitters, which uses an external cavity to achieve tunable, dual-wavelength emission. The separation between the wavelength peaks can be continuously tuned from 0 nm to 5 nm. An output power of 2.9 W is achieved at 3.7 nm peak-to-peak separation and higher powers are achieved for less separation. This is the highest dual wavelength output power reported so far using a standard diode laser array.

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1 Introduction

For numerous scientific and industrial applications, it is of interest to have tunable, dual wavelength laser emission. Such applications include wavelength-division-multiplexing in optical communications systems, optical sensing of single or multiple species [1] and optical pumping of mm-wave lasers. For these diverse applications, several types of broad emission bandwidth lasers have been employed such as Ti:Sapphire [2] and dye lasers [3]. Because of its high power output, low cost and small dimensions, the high-power diode laser array (HPDL) has become nowadays a common broadband laser source. Several injection locking schemes based on external cavities have been developed that permit tuning of one or more wavelengths [4]. These schemes can be divided into master-injection lasers and self-seeded lasers [5]. The complex master-injection schemes [6] use external lasers whereas the simpler, self-seeded diode lasers use an external cavity to generate a selective feedback of the HPDL's emission [5, 7].

Nevertheless, the small photometric[1] and spectral brightness[2] of diode lasers hampers their use in most applications. Pumping of solid state lasers, production of hyperpolarized noble gas, LIDAR and terahertz generation, all these applications benefit to some extent if either type of brightness is increased. For example, in order to achieve efficient solid-state laser pumping in longitudinal pumping schemes, it is necessary to achieve mode matching of pump and intracavity beams that can only be achieved for high brightness pump beams. Also, the emission bandwidth should be small enough to be efficiently absorbed by the absorption peak of the active media. Using a diffraction grating in an external cavity is an effective technique to narrow the emission spectra of commercial diode arrays [7]. An array consists of a large number of emitters, typically twenty to sixty, arranged in a line. Emission from these emitters is highly astigmatic showing typically divergence angles of 40° and 10° perpendicular and parallel to the line, respectively. The light from each individual emitter needs to be collimated and imaged upon the diffraction grating from which it is reflected back at an appropriate angle into the emitter. Intensity injected back into the diode is what matters and the higher the diode current the higher the re-injected intensity should be in order to force the diode's oscillation at the desired frequency. Therefore, the imaging system has to re-inject the light with high efficiency. This task is further complicated by a small curvature of the emitter line, called diode "smile", produced during the manufacturing process [8]. Usually, the smile is in between 3 μm and 10 μm at the center of the curvature [7]. If the diode smile is present, an additional contribution to the emission linewidth of about 0.9 nm/μm is added. It is also essential to compensate for this smile because narrowing can only be achieved if the emissions of the individual emitters overlap [9]. For this reason a telescope of magnification M can be used in the re-imaging system, which creates a magnified image of the emitters on the grating. This reduces the angular spread on the grating resulting from smile and from the emitters by a factor of $1/M$, which in turn increases the light intensity re-imaged onto the emitters and also increases the frequency selectivity of the grating, generating further frequency narrowing of the diode's emission [7] at less re-injected power. Self-injection bandwidth narrowing is proportional to the number of emitters and it has been shown that a linewidth of 0.07 nm can be achieved with three emitters and 0.26 nm with a specially selected diode array that has 46 emitters and only a 1 μm smile [10, 11]. The diode smile can be decreased by introducing an inclined, cylindrical, plano-convex lens in front of the

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[1] Photometric brightness or radiance (L): the radiated power per unit solid angle per unit area normal to the direction defined by the solid angle Ω. $L = P/(\Omega A \cos\Theta)$

[2] Spectral brightness (L_f): the radiance per unit frequency interval: $L_\text{f} = L/\Delta f$. Some authors define the spectral brightness in W/THz.

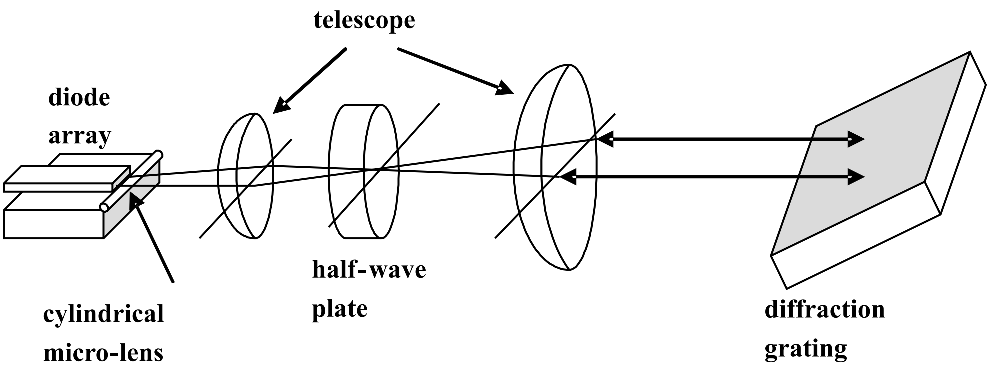

FIGURE 1 Diagram of the external-cavity diode-laser array

diode bar [8]. The inclination of the lens serves to lift the emitters at the center of the diode bar by

$$\Delta x \approx \alpha \frac{y^2}{3 f_\mathrm{b}}\,, \tag{1}$$

where f_b is the back focal length of the lens with index of refraction 1.5, α is the inclination angle and y is the half-width of the beam at the lens position. It follows from the above formula that this method works best for lenses with short focal length and diodes with parabolic curvature, whose center of curvature is exactly at the middle of the array. It has been shown [8] that smile can be reduced by approximately a factor 3 with a diode array that nearly fulfills above criteria.

Most of the dual-wavelength injection schemes are either low power [12] or not tunable [5]. Some of the simpler dual wavelength self injection schemes are composed of a grating and a dual wavelength selective device such as a highly reflective mirror and a couple of slits [13], an intra-cavity etalon with an appropriate FSR [5] or two external cavities [14, 15]. In this letter we investigate an even simpler external cavity which permits high power, dual-mode output with tuning of the mode separation and wavelength. This laser will be used to pump YLF crystals, co-doped with thulium and neodymium at the absorption peaks centered at 792 nm and 796.5 nm, respectively, in order to investigate the thulium blue emission [16]. For this investigation, different ratios of 792 nm to 797 nm pump power are used. For effective absorption the linewidth of the emissions should be below 1.3 nm and their separation of the order of 4 nm to 5 nm. Fine tuning of the set of emission wavelengths can be achieved by temperature tuning of the diode (0.3 nm/°C). This work demonstrates, to our knowledge, the highest dual mode spectral output power so far reported.

2 Experimental setup

We used a commercial, TE polarized diode array, without special AR coating on its facets, emitting nominally at 792 nm and consisting of 20 emitters (OPC A020) with a maximum of 20 W output power. The factory mounted, fast-axis collimating fiber lens had a diameter of 440 μm and a focal length of 240 μm. A telescope (4× magnification), consisting of two spherical lenses with 2.5 cm and 10 cm focal length, was used to focus the diode radiation onto the diffraction grating (2362 grooves per mm). The grooves of the grating were parallel to the polarization of the laser. The first order grating reflectivity was 85% and 14% for light polarized perpendicular and parallel to the grooves, respectively. A half wave plate was inserted at the location of the focus inside the telescope in order to control the power of the grating's first order reflection that is injected back into the diode Fig. 1. Laser output is taken from the zeroth-order reflection of the grating. The resolution of the spectrometer used to analyze the diode spectra was 0.22 nm (Ocean Optics HR2000 Spectrometer with 5 μm slit). In order to correct for the diode smile, we changed the spherical lens closest to the diode to a cylindrical lens of the same focal length, which was slightly inclined at an angle (10°) such that the array image on the grating appeared closer to a straight line (Fig. 2).

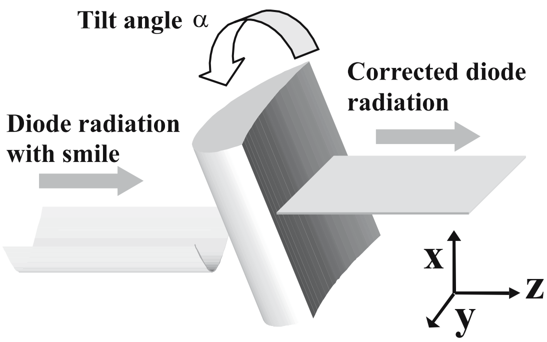

FIGURE 2 Schematic of the working principle of the inclined cylindrical lens. The rotation is about the *y*-axis

3 Experimental results and discussion

In free running operation we measured a bandwidth of 3.5 ± 0.11 nm at 20 W of diode output power. With

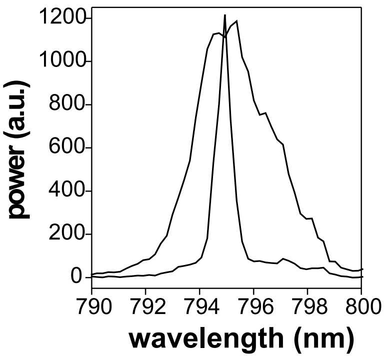

FIGURE 3 Original power spectra of the diode and high power (14 W), bandwidth-narrowed output

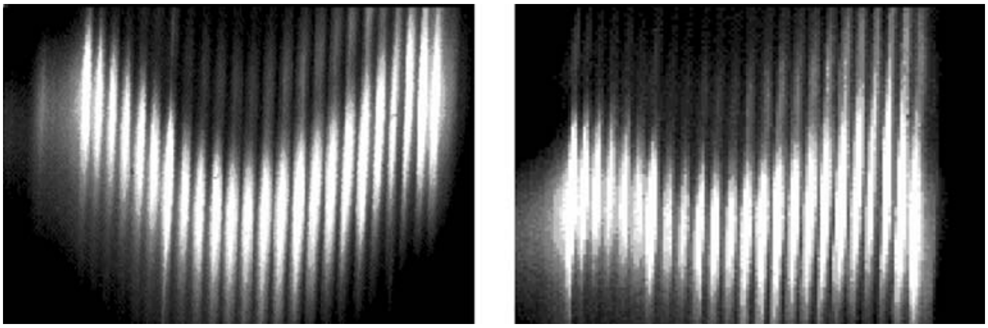

FIGURE 4 Diode smile as registered with a CCD before (*left*) and after (*right*) inclination of the inclined cylindrical lens [8]

the half wave plate adjusted to 29% reflection, the bandwidth was narrowed down to 0.65 ± 0.11 nm using the spherical lens in front of the diode (Fig. 3). Output power was 14 W. This corresponds to a spectral brightness increase of approximately a factor 3.7 resulting in 45 W/THz. When using the cylindrical lens we achieved slightly less frequency narrowing (0.75 ± 0.11 nm) at a smaller output power (10.5 W). The difference in bandwidth narrowing is probably due to the fact that the spherical telescope reduces the bandwidth by a factor four, as explained earlier, whereas the inclined cylindrical lens decreases the curvature by approximately a factor three, owing to residual deviation of the image from a straight line (Fig. 4). This indicates that with a diode that shows less smile it should be possible to achieve a smaller bandwidth using the inclined cylindrical lens instead of the spherical telescope.

In a second step, the grating was detuned from the diode's emission peak at 792 nm by 3.7 ± 0.11 nm. This generates a second emission peak at 795.7 nm. We then increased the diode's current gradually, maintaining the same amplitude of both emission peaks (792 nm and 796 nm) by adjusting the grating feedback with the half wave plate, until, even at the highest feedback (85%), the detuned peak (796 nm) became equal to the other one that is at the diode's gain center. At this condition a total of 2.9 W of output power was obtained from both peaks (Fig. 5) for 32 A of diode current. The width of the peak at 792 nm was 1.3 ± 0.11 nm and for the other peak we measured 0.75 ± 0.11 nm. No diode degradation was observed during the experiment. We also monitored the total output power of the dual wavelength emission as a function of the frequency separation between the peaks (Fig. 5). This was done at a fixed diode current of 16 A and 11 A. For each wavelength separation, the half-wave plate was adjusted in order to achieve two peaks of equal height. For comparison, the output powers of the single and dual wavelength peaks at 32 A drive current are plotted, too, in Fig. 5 (the dotted line serves only as a guide to the eye). Output power decreases linearly with the wavelength separation of both peaks. This is due to the fact that the diode's gain decreases strongly for emissions that are off gain-center. The larger the wavelength separation between the peaks the higher is the necessary retro-injected power to generate an off-gain-center peak of equal amplitude as the on-gain-center peak.

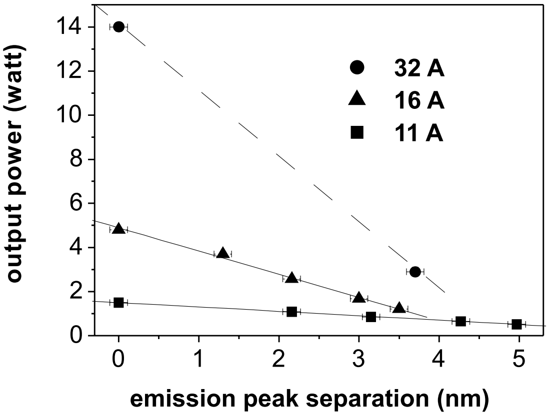

FIGURE 6 Total output power of the dual wavelength emission as a function of their frequency separation at fixed diode current. In all cases both wavelength have equal peak output power

Although the efficiency achieved for 3.7 nm of wavelength separation is low, the experimental set-up has a series of advantages when compared to other results of the literature. The wavelength separation is continuously tunable up to 3.7 nm at high diode current and more than 5 nm at low diode current. The set-up is simple, using only a few standard optical components. Recently, high efficiency has been achieved with a broad-stripe surface-emitting diode using an integrated dual-grating reflector [17, 18]. This highly sophisticated prototype generated 1.2 W of non-tunable cw output with 3.8 nm wavelength separation.

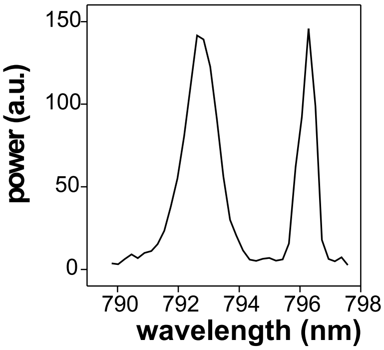

FIGURE 5 Dual wavelength output of 2.9 W

4 Conclusions

We have demonstrated spectral narrowing of a commercial diode laser array consisting of 20 emitters, with 8 μm of smile and 3.5 nm bandwidth, down to 0.65 nm and obtained a total output power of 14 W using a single grating external cavity. We also achieved continuously tunable dual wavelength output generating 2.9 W at 3.7 nm wavelength separation.

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