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Spectral beam combining of a 980 nm tapered diode laser bar

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Abstract: We demonstrate spectral beam combining of a 980 nm tapered diode laser bar. The combined beam from 12 tapered emitters on the bar yielded an output power of 9.3 W at 30 A of operating current. An M^2 value of 5.3 has been achieved along the slow axis. This value is close to that of a free running single tapered emitter on the bar at the same current level. The overall spectral beam combining efficiency was measured to be 63%.

OCIS codes: (140.2010) Diode laser arrays; (140.3298) Laser beam combining.

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1. Introduction

Tapered diode lasers are interesting devices that can deliver Watt level output power [1] with good beam quality. A tapered diode laser bar consisting of many such emitters could scale up the power levels even higher up to tens of Watts [2]. This could make them ideal candidates for industrial applications such as cutting or marking of certain artificial materials and metals. Still, most of these applications demand good beam quality and unfortunately, a high divergence is inherent to the bar geometry which in effect degrades the beam quality of the

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laser bar. However, if the divergence of the output beam could be limited to that of a single tapered emitter and at the same time, the advantage of power scalability of the bar geometry could be maintained, it could provide us with a compact and efficient laser system for high power applications.

Several research groups have made numerous different approaches to improve the beam quality of broad area diode bars. Spectral beam combining [3] is a well known technique used for improving the slow axis beam quality of broad area diode laser bars. Recently, Gopinath et al. [4], combined a 25 element broad area laser array using spectral beam combining. Spectral beam combining of a SCOWL arrays [5] can also provide high output power in a near diffraction limited beam.

Off-axis feedback is a well-known method for improving the beam quality of broad area lasers and stripe arrays [6]. Off-axis spectral beam combining is a relatively new technique which has also been used for improving the slow axis beam quality of broad area diode laser bars. Jechow et al. [7], has used an external cavity in an off-axis arrangement for spectral beam combining of a broad area laser bar and achieved a beam with $M^2 slow < 14$ and $M^2 fast < 3$ at an optical power in excess of 10 W. Moreover, Jensen et al. [8], has used off-axis spectral beam combining on a segmented broad area diode laser and achieved an improvement in the beam quality of a factor of 3.4 compared to that of a freely running single emitter on the array. Recently, Vijayakumar et al. [9], applied this technique on a 12 element broad area diode laser bar and achieved an improvement in beam quality of a factor of 5-6 to that of a free running emitter on the same bar.

Even though fewer works have been recorded on providing external feedback to tapered bars, the recent achievements in this area are promising. Recently, Paboeuf et al. [10], coherently combined an array of ten index guided tapered laser diodes in a Talbot cavity and achieved 1.7 W of output power. Additionally, experiments on off-axis feedback to an index guided tapered laser bar has shown promising results with single-lobe output [11]. In this article, we report on spectral beam combining applied to a 980 nm tapered diode laser bar. The experiments yielded an output beam with a beam quality which is almost similar to that of a free running single tapered emitter on the bar at the same current level. At 30 A, the slow axis M^2 value was measured to be 5.3. A power level of 9.3 W has been achieved using this configuration. This is the first time to our knowledge that spectral beam combining has been applied to a tapered laser bar.

2. Wavelength beam combining experimental setup

2.1 The tapered diode laser bar

The tapered laser bar is based on a (GaAlInAs) (GaAs) laser structure with a large optical cavity grown by molecular beam epitaxy (MBE). Reduction of internal losses was achieved by broadening the waveguide layers and careful optimization of the doping level in each layer. This reduces the overlap of the optical mode with the highly doped cladding layers. The active region of the laser structure consists of a single InGaAs-quantum well embedded in a 1060 nm thick AlGaAs core region with 20% Al content. The quantum well is 7 nm thick with a nominal In content of 19%. The optical waveguide is formed by 1 µm thick AlGaAs claddings with 40% Al. Si and Be have been used for n- and p-type doping, respectively. The doping concentrations start at a level of $5x10^{17}$ cm^{-3} near the core and increase to a level of $2x10^{18}$ cm^{-3} in the outer cladding regions. The GaAs cap layer is heavily p-doped ($6x10^{19}cm^{-3}$) in order to reduce the contact resistance. The layer design exhibits an overlap of the fundamental optical mode with the quantum well of 1.1%. The internal efficiency of the MBE-grown laser structure amounts to more than 98% with low internal losses of 1 cm^{-1} and a center wavelength of 977 nm.

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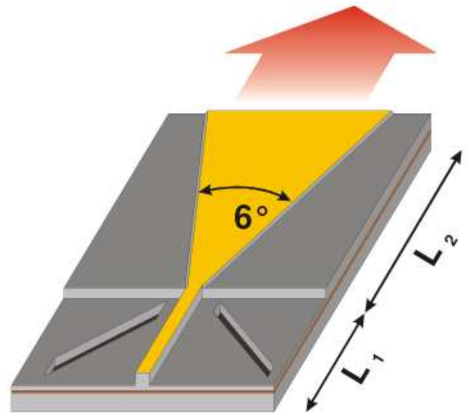

Fig. 1. Schematic view of a tapered diode laser with a ridge section length L_1 and a taper section length L_2.

Tapered laser oscillators were fabricated from the above described epitaxial layer structures. The lateral structure consists of a ridge wave section with a length of L_1 = 0.5 mm combined with a tapered section with a length of L_2 = 2 mm as shown in Fig. 1. The tapered angle amounts to 6°. Processing of the lateral tapered structures was done by inductively coupled plasma (ICP) etching followed by a lift-off metallization for p-contact formation. This results in more defined ridge-structures as compared to wet chemical etching. The ridge height was chosen appropriately for the propagating wave to fill the taper angle.

After processing the wafers were thinned and chipped into tapered laser arrays with a width of 6 mm. Since the 2.5 mm long emitters are separated by a pitch of 500 µm, a tapered laser bar consists of 12 single emitters. The ridge-sided facet was covered with a highly-reflecting mirror coating of residual reflectivity, $R > 97\%$, whereas the front facet was covered with an anti-reflection coating with a rest reflectivity of about 1%.

After facet coating the tapered laser bars were mounted directly p-side down on to copper mounts. Pumping of the laser medium is achieved by current injection via gold bond wires. The M^2 values of individual emitters along the slow axis on this tapered bar has been measured to be around 2.5-4.6 at 30 A of operating current. The output light has been collimated using a 910 µm focal length LIMO cylindrical micro lens attached to the heat sink. In the absence of the external cavity, the laser bar produced 14.5 W at 30 A of operating current.

2.2 Experimental setup

Figure 2 shows the experimental setup of wavelength beam combining of a 12 element tapered laser bar. The external cavity includes a fast axis collimation lens, a 100 mm Fourier transform cylindrical lens L_1, a gold plated reflective grating with 1200 lines/mm and a first order diffraction efficiency measured to be around 85% at 980 nm, a 100 mm fast axis focusing cylindrical lens L_2 and a plane output coupler with a reflectivity of 10% and an AR coated back side. Output couplers with 1 – 15% reflectivity have been tested with 10% reflectivity giving best performance. All lenses are broadband AR coated around the laser wavelength. The lens L_2 focuses the beam along the fast axis at the output coupler in order to increase the amount of feedback and improve the stability of the setup.

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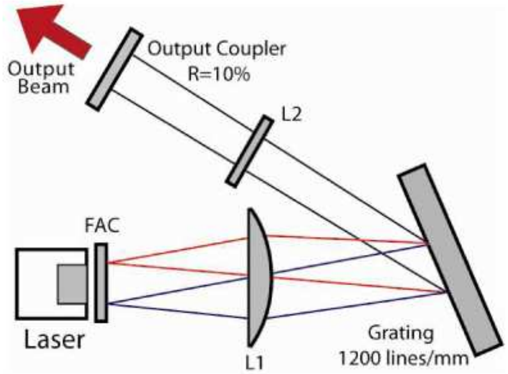

Fig. 2. Experimental setup of the spectral beam combining of the tapered diode laser bar. L_1 is a 100 mm focal length cylindrical slow axis collimation lens and L_2 is a 100 mm focal length cylindrical fast axis focusing lens.

The grating is placed at the Fourier plane formed by the 100 mm cylindrical lens so that the collimated beams from all the emitters are superimposed on its surface. The beam is incident on the grating with an angle of approximately 16°. The plane output coupler enforces the parallel propagation of the light beams from different emitters as the light is incident perpendicular to it. The incident angles of the light from different emitters on the grating are different. Hence, the external cavity selects a particular wavelength for each emitter. Thus the laser bar emits co-axial beams with different but controlled wavelengths for each array element. The zero order reflection from the grating was used to image the near-field of the emitters to record the wavelength versus near-field position of the individual emitters.

3. Spectral beam combining results and discussion

The analysis of the combined beam was done regarding the light-current characteristics, spectral behavior and the beam quality. Figure 3 shows the comparison of the light-current characteristics of the laser bar under free running and spectral beam combining mode. At 30 A of operating current, the spectral beam combined laser yielded 9.3 W of optical power and at 35 A, the output was measured to be 11 W. The laser threshold was measured to be 5 A. The light current characteristics of the combined beam gives a slope efficiency of 0.37 W/A. The system exhibits a spectral beam combining efficiency of 63% compared to a free running laser bar. The efficiency is partly limited by the diffraction efficiency of the grating.

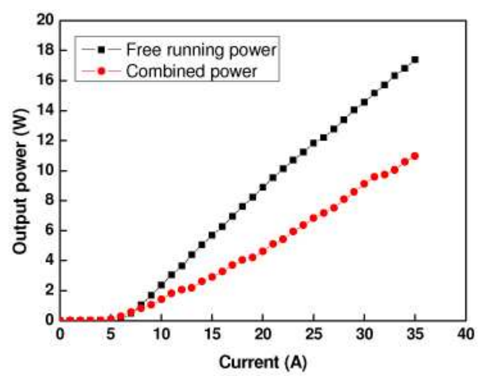

Fig. 3. Light current characteristics of the tapered diode laser bar in the free running mode (squares) and beam combined mode (dots).

Figure 4 shows the spectrum of the combined beam which consists of twelve distinct peaks, each corresponding to an individual tapered emitter on the laser bar. The external cavity has been designed for a wavelength spacing of 4.0 nm between the emitters [3]. The

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actual spacing between the emitters was measured to be 4 ± 0.005 nm which matches the calculated value. The total wavelength span is approximately 44 nm. The spectral tuning of the combined beam was limited to approximately 3-4 nm towards both directions due to the limited gain band-width of the laser. Beyond that, the feedback from the output coupler was not strong enough to force the emitters to operate at the wavelength determined by the external cavity. Inspection of the near field images of the laser facet, formed from the zero order beam reflection by the grating and imaging the near field using a 300 mm focal length spherical lens revealed that nine of the twelve emitters were perfectly locked while three emitters on one side showed single side peaks due to imperfect locking. This could be due to a slight smile observed on the laser bar. In particular, the three emitters showing side peaks in the spectrum were observed to be off-set in the fast axis direction compared to the remaining emitters. The difference in intensity from the different emitters observable in Fig. 4 is caused by a different amount of light from the different emitters coupled to the optical fiber used for the optical spectrum analyzer. The spectral width (FWHM) was below 0.2 nm for all emitters.

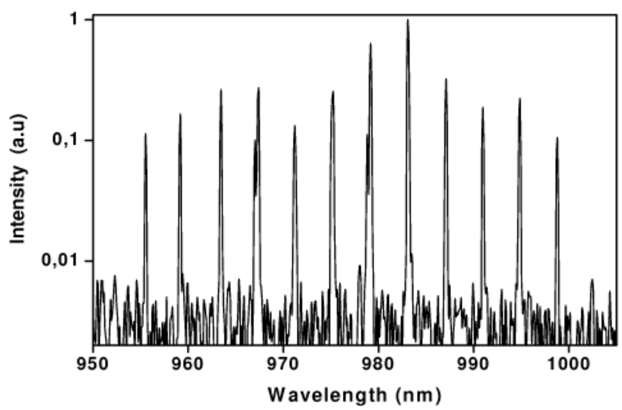

Fig. 4. Wavelength spectrum of the combined beam

At 30 A of operating current, the output beam gave a slow axis M^2 value of 5.3. This is comparable to the slow axis M^2 value of a single tapered emitter in the free running mode at the same current level. The slight mismatch is most likely because of the imperfect overlap of beams on the grating due to positioning errors. The M^2 value degraded to 7.6 at 35 A of operating current. Figure 5(a) shows the slow axis profile of the combined beam at the focus of a 100 mm focal length achromatic lens and the inset graph shows the caustic of the combined beam along the slow axis. Figure 5(b) shows the slow axis far-field profile of the combined beam at 30 A. The focus of the beam is near-Gaussian while the far-field is non-Gaussian. This is typical for the far-field of tapered diode lasers [12]. The $1/e^2$ values of the beam width have been measured throughout the experiment using a Nanoscan beam profiler (*Photon Inc.).*

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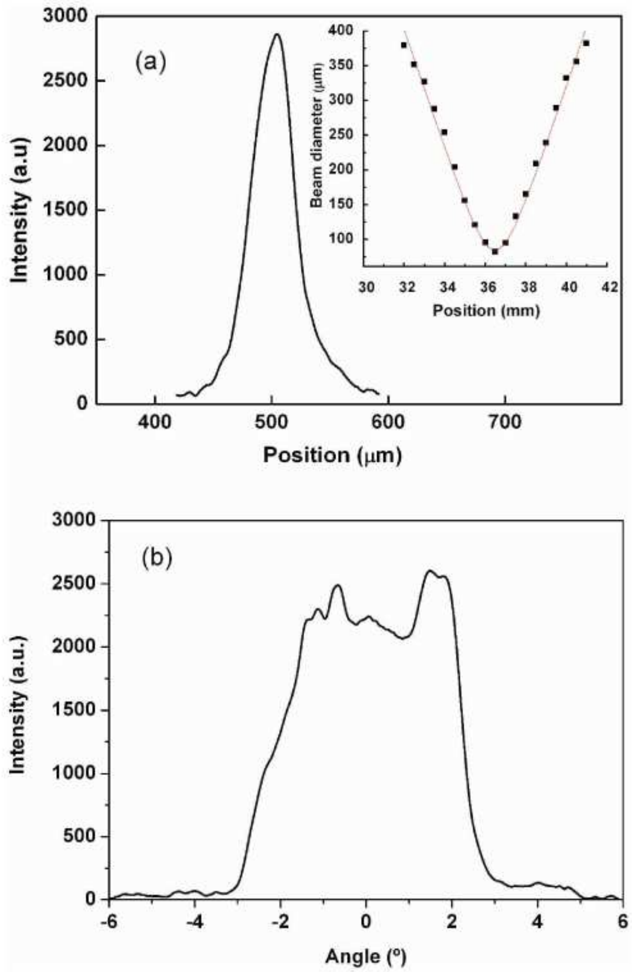

Fig. 5. (a) Profile of the combined beam in the slow axis direction at the focus of a 100 mm achromatic lens. The inset graph shows the caustic of the slow axis of the combined beam. The solid line represents the numerical fit to the experimental data. (b) Far field profile of the combined beam in the slow axis direction.

4. Conclusion

We have demonstrated spectral beam combining of a 12 emitter 980 nm tapered diode laser bar with an overall combining efficiency of 63%. The combined beam had a slow axis M^2 value of 5.3 which is comparable to that of a free running single tapered diode on the same bar at the same current level. The output power at 30 A was measured to be 9.3 W.

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