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Wavelength beam combining of a 980 nm tapered diode laser bar in an external cavity

Deepak Vijayakumar, Ole Bjarlin Jensen, and Birgitte Thestrup
DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, P.O Box 49, DK-4000 Roskilde, Denmark

ABSTRACT

High power diode lasers are used in a large number of applications. A limiting factor for more widespread use of broad area lasers is the poor beam quality. Gain guided tapered diode lasers are ideal candidates for industrial applications that demands watt level output power with good beam quality. By adapting a bar geometry, the output power could be scaled even up to several tens of watts. Unfortunately, the high divergence which is a characteristic feature of the bar geometry could lead to a degradation of the overall beam quality of the laser bar. However, spectral beam combining is an effective solution for preserving the beam quality of the bar in the range of that of a single emitter and at the same time, enabling the power scaling. We report spectral beam combining applied to a 12 emitter tapered laser bar at 980 nm. The external cavity has been designed for a wavelength separation of 4.0 nm between the emitters. An output power of 9 W has been achieved at an operating current of 30 A. The combined beam had an M^2 value ($1/e^2$) of 5.3 along the slow axis which is comparable to that of a single tapered emitter on the laser bar. The overall beam combining efficiency was measured to be 63%. The output spectrum of the individual emitters was narrowed considerably. In the free running mode, the individual emitters displayed a broad spectrum of the order of 0.5-1.0 nm while the spectral width has been reduced to 30-100 pm in the spectral beam combining mode.

Keywords: Semiconductor lasers, tapered laser, spectral beam combining, external cavity.

1. INTRODUCTION

Tapered diode lasers are excellent light sources as far as output power and the beam quality is concerned. These devices fill the niche where a light source with watt level output power and a good beam quality is required [1]. They are quite useful in certain industrial applications such as cutting or marking of certain artificial materials. These devices are also power scalable when adapted into a bar geometry. A tapered laser bar is capable of delivering up to tens of watts [2]. But, a high divergence which is inherent to a bar geometry could lead to a reduction in the overall beam quality of the entire bar. Hence, if we could scale the output power of a tapered laser using a bar geometry and at the same time, maintain the beam quality of a single tapered laser, then these devices would be an excellent choice for an application that demands a light source which is of low cost, compact size and which could deliver high output powers with excellent beam qualities.

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

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., [6] has used an external cavity in an off-axis setup for improving the slow axis beam quality 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., [7] 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., [8] 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. This technique has the advantage that it could lead to beam qualities even better than that of a single emitter on

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the array. Regarding the external feedback to tapered bars, fewer works has been reported during the past years especially regarding spectral beam combining of tapered laser bars [9]. But, the recent achievements in this area are quite 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]. Here, 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. An output power level of 9.3 W has been achieved using this configuration. At 35 A of operating current, the output power increased up to 11 W. Here, the slow axis M^2 value degraded to 7.6.

2. EXPERIMENTAL SETUP FOR WAVELENGTH BEAM COMBINING

2.1 Tapered laser bar

The tapered laser bar consists of 12 identical tapered emitters. It is 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.

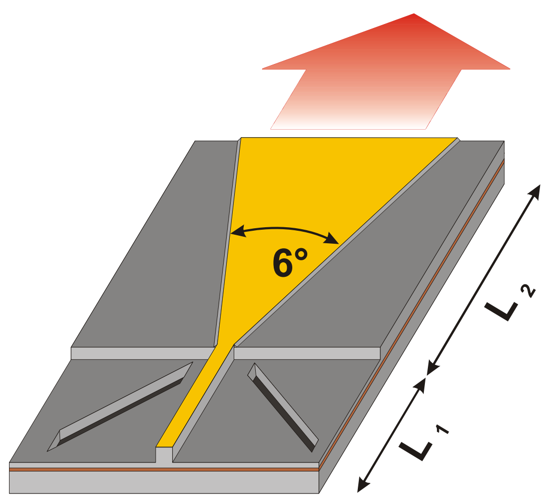

Figure. 1. Schematic view of a tapered diode laser with a ridge section length L_1 and a taper section length L_2.

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 figure 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 for the wavelength beam combining of the gain guided 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. 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. The zero order beam is imaged into the fiber of an optical spectrum analyzer using the lens L_3 which is a 300 mm spherical lens. The system has a magnification factor of 3.

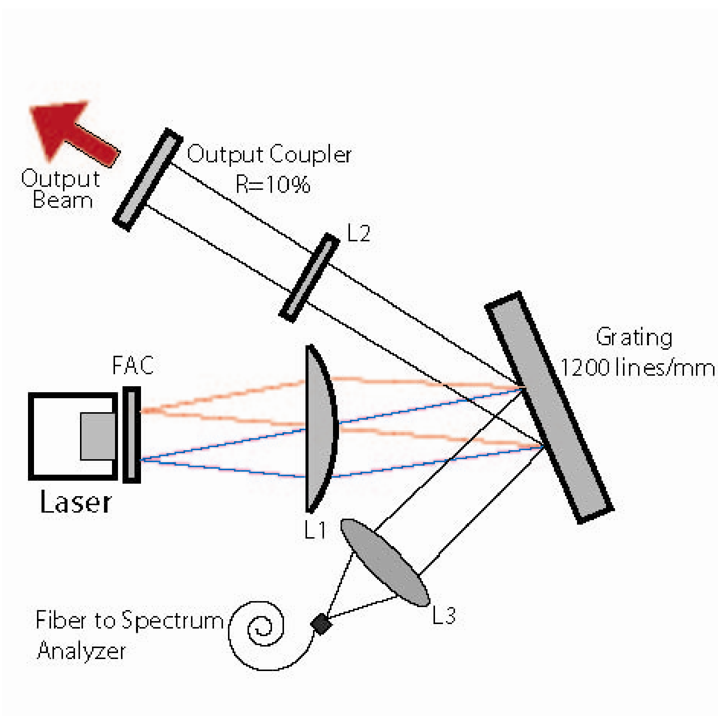

Fig. 2. Experimental setup of the spectral beam combining of the tapered diode laser bar. L_1 is a 100 mm focal length cylindrical slow axis collimation lens, L_2 is a 100 mm focal length cylindrical fast axis focusing lens and L_3 is a 300 mm cylindrical lens.

The collimated beam from all the 12 emitters are superimposed on the Fourier plane formed by L_1. The grating is placed in the Fourier plane and hence, the light from all emitters are superimposed on its surface and gets diffracted. The grating is aligned in such a way that the incident beam makes an angle of approximately 16 degrees with the grating normal. The first order beam is fed back into the laser using a plane output coupler. It ensures the parallel propagation of the light back into the laser. 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 spectrally resolved near field image of the laser. This gave a better insight to the spectral properties of individual emitters.

3. EXPERIMENTAL RESULTS

The combined laser beam has been analyzed regarding the output power characteristics, beam quality and the spectral behavior.

3.1 Light-current characteristics

At 30 A of operating current, the output from the beam combined laser was measured to be 9.3 W. At 35 A, the output increased to 11 W. The light current characteristics of both the free running and the beam combined laser are shown in figure 3.

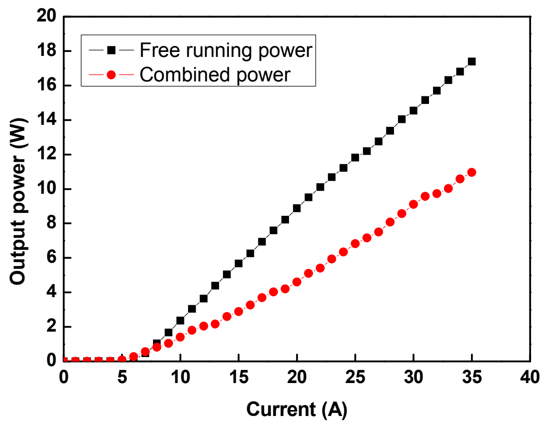

Fig. 3. Light current characteristics of the tapered diode laser bar in the free running mode (squares) and beam combined mode (dots).

The lasing threshold of the in the spectral beam combined mode was measured to be approximately 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 the free running laser bar. The efficiency is partly limited by the diffraction efficiency of the grating. The beam combining efficiency could be improved by using a grating with higher first order diffraction efficiency.

3.2 Beam quality

At 30 A of operating current, the output beam gave a slow axis M^2 value of 5.3. This value 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.

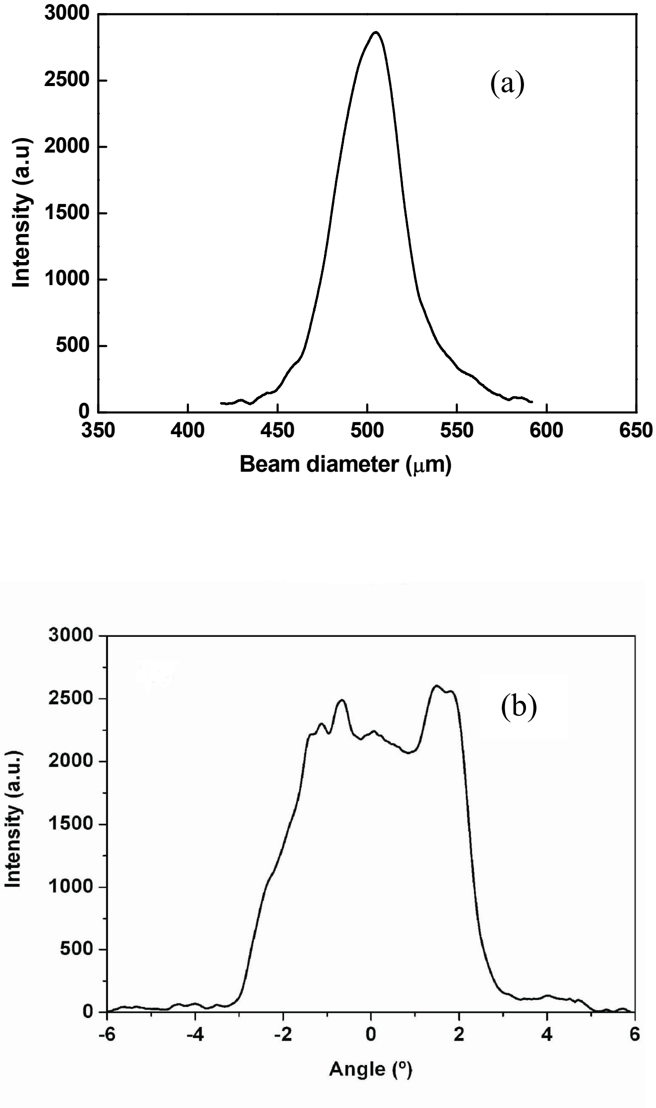

Fig. 4. (a) Profile of the output beam at the focus of a 100 mm achromatic lens (b) Far field profile of the output beam.

Figure 4(a) shows the profile of the combined beam at the focus of a 100 mm achromatic lens. Figure 4(b) shows the far-field profile of the output 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.)*. Figure 5 shows the caustic of the combined beam along the slow axis.

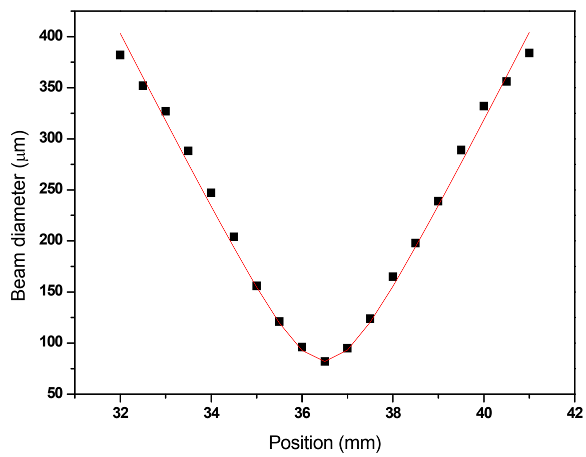

Fig. 5. The caustic of the combined beam along the slow axis. The solid line represents the numerical fit to the experimental data.

3.3 Spectral behavior

Figure 6 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 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 output 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. The difference in intensity from the different emitters observable in Fig. 6 is caused by a different amount of light from the different emitters coupled to the optical fiber used for the optical spectrum analyzer.

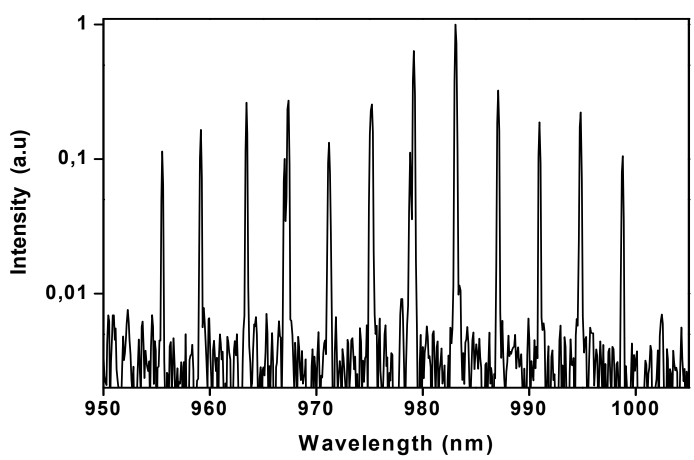

Fig. 6. Wavelength spectrum of the output beam

Inspection of the near field images formed from the zero order beam reflection by the grating 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. The output spectrum of the combined emitters are considerably narrower compared to the spectrum in the free-running mode. In the free-running mode, the emitters had a spectral width in the range of 0.5- 1.0 nm. This has been narrowed to the range of 30- 100 pm in the spectral beam combined mode. This could be attributed to the wavelength selectivity of the reflective grating. Figure 7 (a) shows the output spectrum of an emitter in the free-running mode and (b) shows the spectrum of the same emitter in the spectral beam combined mode.

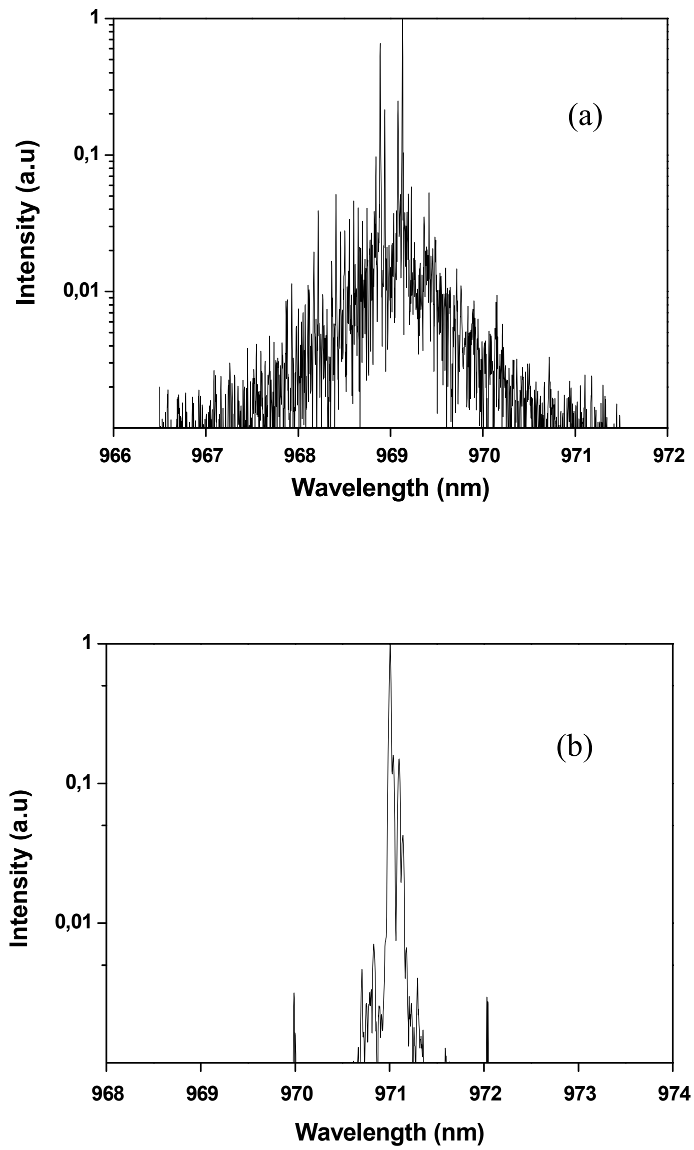

Fig. 7. (a) Spectrum of an emitter in the free-running mode. (b) Spectrum of an emitter in the spectral beam combined mode.

4. CONCLUSION

We have successfully demonstrated spectral beam combining of a 12 emitter 980 nm gain-guided tapered diode laser bar. The overall spectral beam combining efficiency was measured to be 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. The individual emitters displayed a considerable narrowing of the output spectrum in the spectral beam combined mode as compared to the free-running mode. This is the first time; spectral beam combining has been applied on a gain-guided tapered laser bar.

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