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Published in:
Optics Express

Link to article, DOI:
10.1364/OE.19.001228

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Müller, A., Vijayakumar, D., Jensen, O. B., Hasler, K-H., Sumpf, B., Erbert, G., Andersen, P. E., & Petersen, P. M. (2011). 16 W output power by high-efficient spectral beam combining of DBR-tapered diode lasers. *Optics Express*, *19*(2), 1228-1235. https://doi.org/10.1364/OE.19.001228

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16 W output power by high-efficient spectral beam combining of DBR-tapered diode lasers

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Abstract: Up to 16 W output power has been obtained using spectral beam combining of two 1063 nm DBR-tapered diode lasers. Using a reflecting volume Bragg grating, a combining efficiency as high as 93.7% is achieved, resulting in a single beam with high spatial coherence. The result represents the highest output power achieved by spectral beam combining of two single element tapered diode lasers. Since spectral beam combining does not affect beam propagation parameters, M^2-values of 1.8 (fast axis) and 3.3 (slow axis) match the M^2- values of the laser with lowest spatial coherence. The principle of spectral beam combining used in our experiments can be expanded to combine more than two tapered diode lasers and hence it is expected that the output power may be increased even further in the future.

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OCIS codes: (140.2020) Diode lasers; (140.3298) Laser beam combining.

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1. Introduction

Since their development, it has always been a goal to increase the output power of diode lasers. Although a lot of efforts have been put into diode laser technology, there are still some fundamental issues that limit the output power. One major problem, especially for CW lasers, is the heat generated [1]. The output power is mostly limited by heat effects causing degradation and optical damage. One way of increasing the output power while maintaining the beam quality, is to use beam combining [2]. This principle basically describes the combination of two or more moderately operated lasers by an external optical element without affecting the beam quality. This allows for high-power laser systems with increased brightness.

There are two techniques, coherent and incoherent beam combining [2,3]. In both cases the beams are combined using different optical elements. Power scaling is simply done by increasing the number and/or the output power of the individual lasers. In coherent beam combining a precise control of wavelengths and relative phases of the gain elements are required. Only if single frequency operation and phase stabilization are achieved, the individual fields will add constructively in the near and far-field. This of course becomes more challenging the more elements that have to be combined. However, several hundreds of watts have been reported by several groups based on coherent beam combining of fiber laser arrays [4,5]. Beam combining efficiencies, representing the ratio of the combined power to the sum of power emitted from the individual gain elements, of more than 90% can be reached using this technique [6,7]. When looking for an alternative to sophisticated fiber lasers, diode lasers offer lower optical output powers but very high optical conversion efficiencies [8,9]. Moreover, due to their reduced dimensions such lasers allow for compact combining systems with increased cost-effectiveness. In this regard 12.8 W of output power was achieved when coherently adding a 47 emitter array [10].

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When coherence is not the important issue, incoherent beam combining can be used [3]. The biggest advantages here are the reduced tolerance requirements allowing for much simpler setups. One example is polarization coupling [11]. With this method, two orthogonally polarized laser beams are combined using components like a thin film polarizer, polarizing beam splitters and others. The resulting beam is a single unpolarized beam with the added power of the individual lasers. But due to the requirements of orthogonal polarizations, power scaling just by increasing the number of comparable lasers is not possible.

An example suitable for power scaling is spectral beam combining (SBC) [2,3]. Here, two or multiple lasers at slightly different wavelengths are combined. The spectrum then consists of multiple peaks corresponding to the individual laser emissions. As for coherent beam combining the highest output powers are achieved using fiber lasers. In this respect 522 W of average output power with a combining efficiency of 93% was reported when using a surface grating [12]. With a reduced combining efficiency of 61% even 2 kW of power was shown [13]. Reaching these high output powers makes the combination of fiber lasers very attractive for certain applications. However, when focusing on applications requiring only several tens of Watts, e.g. welding of polymers and metal foils [14], bending of glass and ceramics [15], soldering of electric circuit boards [16], marking of plastics [16] or sintering of metal powders [16,17], using high power fiber lasers would not fully exploit their potentials. In this regard diode lasers represent a suitable alternative. Besides their advantages mentioned above, diode lasers also offer a wider range of wavelengths due to their material compositions [18]. This might provide additional advantages for certain applications and even enable new applications not accessible using laser emissions based on atomic transitions. Furthermore, these applications may benefit from the possibility of power scaling using diode lasers.

When spectrally combining comparable diode lasers it is recommended to reduce the wavelength separation. In both cases mentioned above [12,13], lasers emitting around 1060 nm and spectrally spaced 2.5 nm to 5 nm were used. Using comparable diode lasers this could cause a serious reduction of performance due to heat effects when tuning their wavelengths by changing the laser temperatures. Unfortunately, realizing small spectral separation using surface gratings requires large source-to-grating distances in order to spatially separate the individual emitters. One solution to this problem could be using diode laser arrays. Here the wavelength spread is given by the focal length of the lens used within the setup, the pitch between the emitters and the dispersion of the grating depending on the grating period and the angle of incidence for the center array element [19]. In this context combining of a 100 emitter array reaching 35 W in pulsed mode at 915 nm with a beam quality of 1.4 was reported [20]. Vijayakumar et al. demonstrated the first ever combining of a tapered diode laser bar reaching 9.3 W with a combining efficiency of 63% [21]. However, diode laser arrays have the disadvantage of mounting induced smiles, leading to a degradation of the beam quality even when the array consists of individual near diffraction limited emitters [20]. Furthermore, setups for spectral beam combining of diode laser arrays are limited by the gain bandwidth of the semiconductor material and large focal length lenses are required to obtain small wavelength separation between individual emitters. Another possible drawback comes into play once emitters fail, with an exchange of single emitters being clearly impossible.

When combining single lasers instead, the resulting beam quality matches the value of the individual lasers. This immediately increases the chance of achieving a combined near diffraction limited beam just by choosing the proper lasers. Regarding SBC of individual lasers with smaller wavelength separations, volume Bragg gratings (VBG) have been shown to be a suitable alternative [22,23]. In these experiments five diode lasers as well as five fiber lasers emitting at around 1060 nm and spectrally spaced 0.5 nm were successfully combined. Written in photo-thermo-refractive (PTR) glass such gratings offer excellent thermo-mechanical properties, high transmittance in the visible and near-infrared, polarization insensitivity and diffraction efficiencies exceeding 99% [24]. These characteristics make volume Bragg gratings (VBG) suitable for compact and robust high power, high brightness, beam combining systems. In this respect a maximum of 770 W was achieved coupling 5 fiber lasers with a combining efficiency of 91.7% [24]. Comparable combining efficiencies of 92% - 94% were achieved coupling 5 low power fiber-pigtailed diode lasers [22]. This also proofs the reliability of such gratings within a large power range. The increase in combining efficiency compared to the combining of diode laser arrays [21] might result from an increased flexibility in terms of optical alignments and adjustments of laser parameters.

In this paper, we present spectral beam combining of high-power 1060 nm DBR-tapered diode lasers using a volume Bragg grating. Previously, such lasers have been demonstrated to emit 12 W of output power with nearly diffraction limited beam qualities measured up to 10 W [25]. By combining two lasers, spectrally separated by 0.5 nm, we achieve a single beam with 16 W of output power and a beam quality of 1.8 (fast axis) and 3.3 (slow axis). To the best of our knowledge this represents the highest output power in spectral beam combining of single emitter diode lasers. The corresponding combining efficiency of 93.7% is comparable to the values reported above and even slightly increased to 95.4% at low powers.

These results clearly indicate the feasibility of simple, high-efficient, compact diode laser based light sources. By combining multiple high-power DBR-tapered diode lasers, future systems could then offer several tens of Watts with single, near diffraction limited output beams. As a consequence, this would make these light sources interesting for applications within materials processing as mentioned above.

2. Experimental setup

The configuration of the setup for spectral beam combining is shown in Fig. 1. A detailed description of the structure and layout of the 1060 nm DBR-tapered diode lasers can be found in [25,26]. Each of the 6 mm long lasers is mounted p-side up on a CuW heat spreader, which itself is mounted on a 25 x 25 mm^2 conduction cooled package (CCP) mount allowing for efficient cooling. The current to the ridge and the tapered section of both lasers are controlled individually. Each laser is collimated in both axes using AR-coated lenses to avoid optical feedback. Collimating the fast axes is done by aspheric lenses with a focal length of 3.1 mm and a numerical aperture of 0.68. The slow axes are collimated by cylindrical lenses with a 15 mm focal length. This generates a nearly circular beam around 2 mm in diameter and compensates for astigmatism, originating from the tapered diode laser. Since the astigmatism of these lasers changes with current, the setup allows for correcting the position of the cylindrical lenses when changing the injection currents.

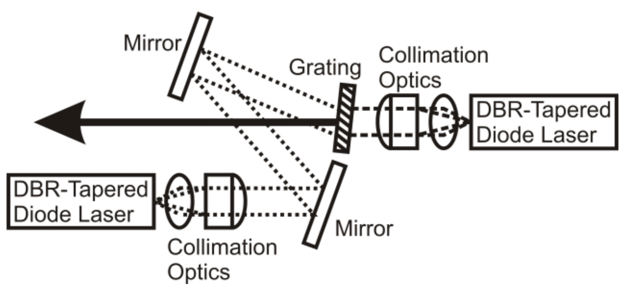

Fig. 1. Sketch of the spectral beam combining setup based on two DBR-tapered diode lasers and a reflecting volume Bragg grating. The beam transmitting the grating is indicated by dashes, the diffracted beam by dots. The arrow signifies the propagation of the combined beam.

The grating (*OptiGrate*) is a reflecting VBG, meaning the planes of constant refractive index are parallel to the surface of the PTR glass [22]. Therefore the transmitting beam (dashes) passes through and the diffracted beam (dots) reflects back to the same side of the grating as the incoming beam. Due to the unique performance of such Bragg gratings, having diffraction efficiencies close to unity when the Bragg condition is fulfilled and close to zero at multiple points offset from this condition, optimum SBC is achieved by adjusting the angles of incidence and wavelengths properly. The spectral spacing between maximum diffraction and zero diffraction depends on the spatial frequency of the grating [28]. According to the

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specification sheet the VBG used in this setup (L x W x H = (3.4 x 10 x 10) mm^3) has an average diffraction efficiency of 99.2% at 1062 nm and a spectral selectivity of 0.3 nm (FWHM).

3. Individual laser characterization

As discussed above, the injection currents for the ridge and the tapered section of both lasers are controlled individually. For all experiments, the DBR ridge sections are operated constantly at 300 mA. Therefore the term injection current in the following text and figures refers to the tapered sections only. Additionally, the laser whose beam is transmitted by the grating hereinafter is referred to as transmitted laser, the laser whose beam is diffracted as diffracted laser. Figure 2a shows the power-current characteristics of both lasers at laser temperatures of 20 °C. At 14 A, the diffracted laser emits 8.46 W of output power and the transmitted laser 8.92 W. The slope efficiencies are 0.71 W/A and 0.74 W/A, respectively. Within the measured current range both lasers show no signs of thermal roll over.

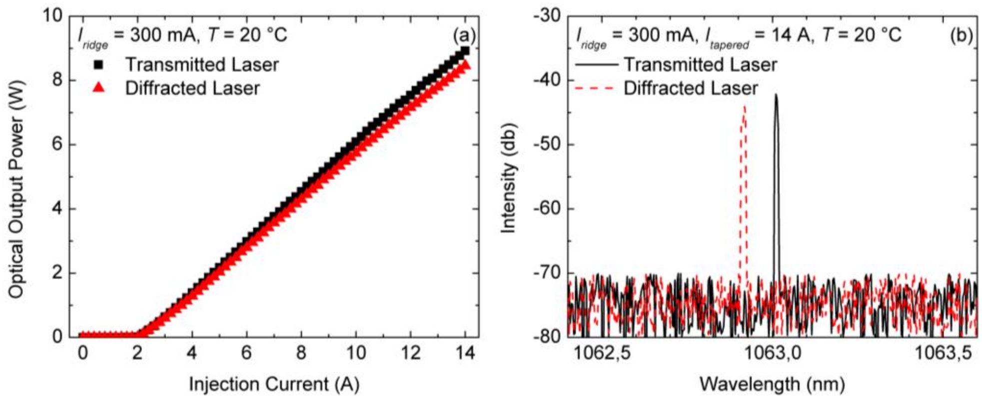

Fig. 2. (a) Power current characteristics of DBR-tapered diode lasers at 300 mA to the ridge section and operating temperatures of 20 °C. (b) Optical spectra of the lasers at 14 A to the tapered section.

At maximum current the centre wavelengths are 1062.92 nm for the diffracted laser and 1063.01 nm for the transmitted laser (Fig. 2b). All spectra are measured with an *Advantest Q8347* optical spectrum analyzer. Due to the intrinsic wavelength stabilization DBR-tapered diode lasers emit light in single longitudinal modes, resulting in spectral widths below 10 pm (FWHM). In both cases side mode suppression above 25 dB is achieved limited by the dynamic range of the optical spectrum analyzer.

The optimum SBC requires a proper adjustment of wavelengths. There are different ways of tuning the emission wavelengths of diode lasers. One of them is by changing the injection current (Fig. 3a). Assuming a linear dependence at higher currents a shift towards longer wavelengths of 0.02 nm/A is measured. Another and more effective way is by changing the laser temperature (Fig. 3b). At maximum current a shift of 0.09 nm/K is observed. With the given spectral characteristics and the wavelengths being tunable, both lasers are suited for spectral beam combining with the specified grating.

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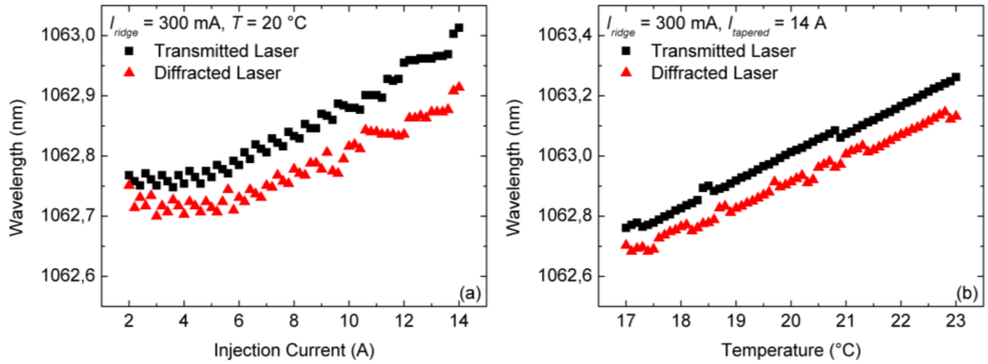

Fig. 3. (a) Wavelength versus injection current of DBR-tapered diode lasers at 300 mA to the ridge section and operating temperatures of 20 °C. (b) Wavelength versus temperature of the lasers at 14 A to the tapered section.

Additionally, the beam propagation parameters (M^2_{1/e^2}) are calculated by measuring the beam widths along the beam waists of the focused beams. This is done using an additional spherical lens with a focal length of 120 mm and a *Photon, Inc.* beam scanner. The measured widths are then fitted to a hyperbolic equation. At maximum current, the values for the diffracted laser are 1.4 (fast axis) and 3.2 (slow axis). The transmitted laser shows 1.5 (fast axis) and 2.1 (slow axis). In comparison, the decrease in beam quality for the diffracted laser could be explained by side lobes in the beam profile, therefore increasing the measured beam widths using the $1/e^2$ criteria.

A more thorough characterization of comparable lasers including the beam profiles, astigmatism and power current characteristics at different current settings can be found in [25].

4. Spectral beam combining of two tapered diode lasers

The optimum SBC is obtained only by the proper adjustment of the angles of incidence and the emission wavelengths. Figure 4a shows the measured output power achieved with spectral beam combining at various injection currents.

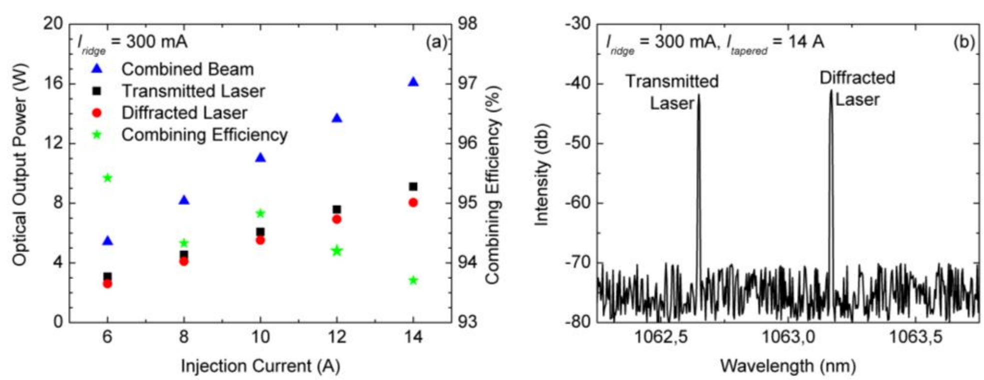

Fig. 4. (a) Output power of the individual lasers and the combined beam at 300 mA to the ridge section and different injection currents to the tapered section. The angles of incidence and the laser temperatures are adjusted for maximum diffraction and transmission at each current value. Star symbols indicate the corresponding combining efficiency achieved at each current. (b) Optical spectrum of the combined output beam at 14 A to the tapered section.

At each current value, the angles of incidence and wavelengths are adjusted for maximum transmission and diffraction. The highest combined output power at maximum current is 16.08 W corresponding to an electro-optical efficiency of about 25%. At this current, the transmitted laser is operated at 15.47 °C, emitting 9.11 W at 1062.65 nm and the diffracted

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laser is operated at 23.0 °C, emitting 8.05 W at 1063.17 nm, resulting in a combining efficiency of 93.7%. A slight increase in combining efficiency is measured at lower currents. Observations with lower efficiencies in high-power regimes are usually associated with a slight degradation of laser parameters rather than deteriorating grating parameters [27]. Losses in general can be linked to finite divergences [28] and grating vector non-uniformities across the large aperture. However, the results ranging between 93% and 96% are comparable to the values achieved by others [22–24]. The temperature tuning of both lasers for optimum performance results in a wavelength separation of 0.5 nm (Fig. 4b).

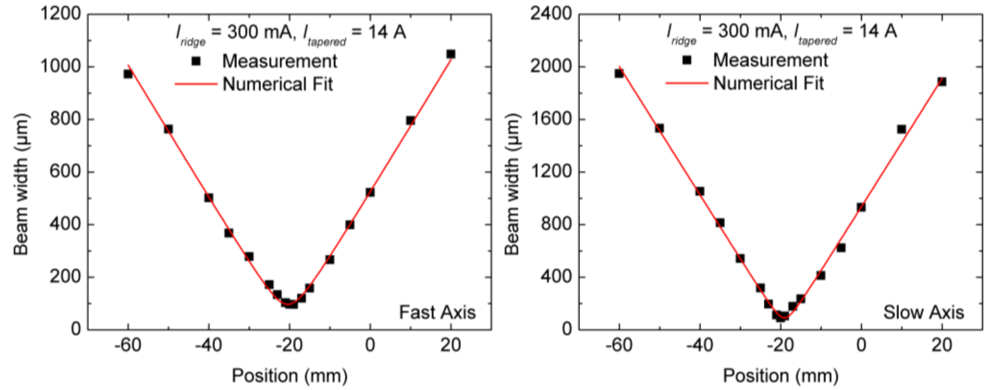

Fig. 5. Beam caustics of the combined beam at 300 mA to the ridge section and 14 A to the tapered section.

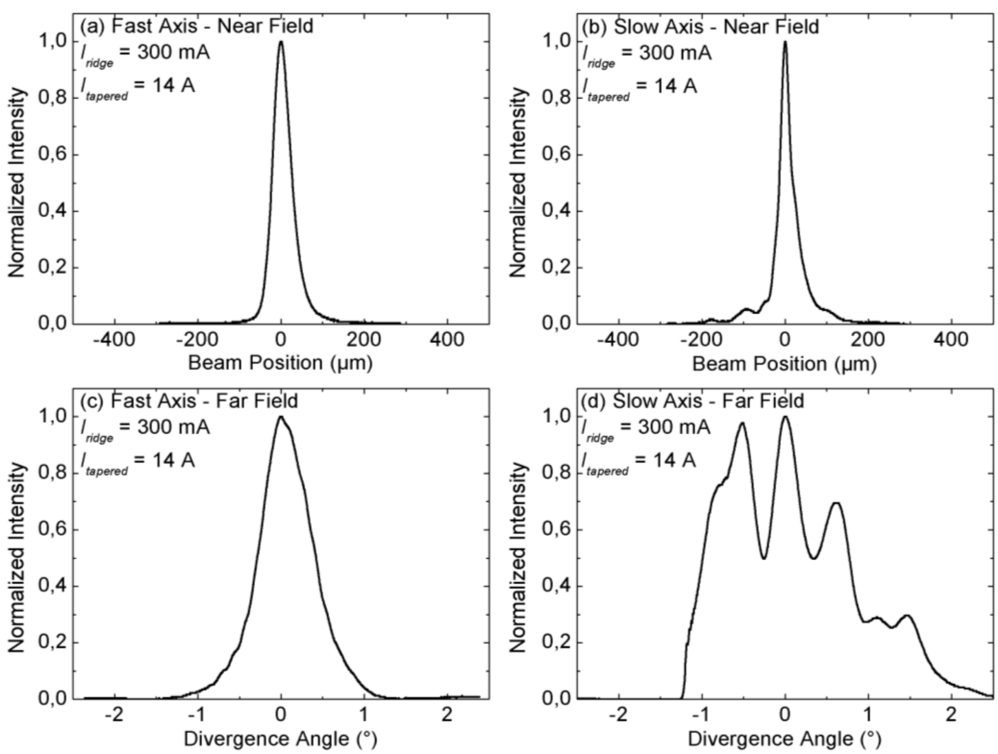

Fig. 6. Beam profiles of the combined beam at 300 mA to the ridge section and 14 A to the tapered section. (a) Near field profile in the fast axis. (b) Near field profile in the slow axis. (c) Far field profile in the fast axis (d) Far field profile in the slow axis.

The beam propagation parameters (M^2_{1/e^2}) of the combined beam at maximum current are 1.8 (fast axis) and 3.3 (slow axis). The corresponding beam caustics for both axes of the combined beam are shown in Fig. 5. The resulting values are comparable to the laser with lowest beam quality. A similar behavior is observed at low currents. While measuring the beam widths along the beam waist of the focused beam, the beam profiles of the combined beam are recorded simultaneously. Figure 6 shows the corresponding near field and far field profiles measured at injection currents of 14 A. In the near field the combined beam shows beam widths of 97.0 µm (fast axis) and 88.7 µm (slow axis). The divergence angles are measured to be 1.4° (fast axis) and 2.9° (slow axis). At 6 A the beam widths of the near field are more or less comparable. The divergence angles are reduced, improving the beam propagation parameters to 1.6 (fast axis) and 2.4 (slow axis) at that current value.

5. Conclusion

Spectral beam combining of two DBR-tapered diode lasers is demonstrated with a combined output power of 16 W. Both DBR-tapered diode lasers emit around 1063 nm and are spectrally separated by 0.5 nm. Using a reflecting volume Bragg grating we obtain combining efficiencies of 93% - 96%. As expected, the beam propagation parameters are not affected by this technique. Therefore the values of 1.8 (fast axis) and 3.3 (slow axis) match the tapered diode laser with lowest beam quality.

Power scaling using multiple high-power DBR-tapered diode lasers should be possible in the future. This could lead to efficient, cost-effective and compact systems offering single, near diffraction limited output beams with multiple tens of Watts.

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