Efficient, high-brightness wavelength-beam-combined commercial off-the-shelf diode stacks achieved by use of a wavelength-chirped volume Bragg grating

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We report a method of scaling the spatial brightness from commercial off-the-shelf diode laser stacks through wavelength beam combining, by use of a linearly wavelength-chirped volume Bragg grating (VBG). Using a three-bar commercial stack of broad-area lasers and a VBG, we demonstrate 89.5 W cw of beam-combined output with a beam-combining efficiency of 75%. The output beam has a propagation factor $M^2 \sim 26$ on the slow axis and $M^2 \sim 21$ on the fast axis. This corresponds to a brightness of $\sim 20\,\mathrm{MW/cm^2\,sr}$. To our knowledge, this is the highest brightness broad-area diode laser system. We achieve 81% coupling efficiency into a 100 μm, 0.22 N.A. fiber. © 2006 Optical Society of America

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Increasing the spatial brightness of diode laser arrays with high efficiency is a long-standing goal in laser technology.[1,2] Most known techniques for improving or reformatting the beam quality of diode array bars and stacks, such as diffractive optics, two-mirror beam shapers, microstepped mirrors, and micro-optical beam transformation systems, do not increase the brightness relative to a single diode element.[3–5] High-brightness diode bars and stacks are currently of great interest for many applications, including for pumping multikilowatt rare-earth-doped fiber lasers. The output power of the fiber laser is limited mainly by the available pump brightness.[6–8] Recently, significant progress has been made by a technique originally demonstrated by Fan, Sanchez-Rubio, and coworkers called wavelength (or spectral) beam combining.[1,9,10] In this Letter we report a variation of the wavelength-beam-combining (WBC) cavity. The cavity is easy to implement, efficient, and highly robust. It has the potential to increase the brightness of the commercial diode bars and stacks by up to 2 orders of magnitude. One of the key components in this cavity is a linearly wavelength-chirped volume Bragg grating[11] (VBG).

Figure 1 shows a schematic diagram of the basic WBC implementation. The WBC system consists of a linearly wavelength-chirped VBG, a transform lens, and a diffraction grating. On the horizontal axis each emitter is controlled by the wavelength-chirped VBG to lase at a wavelength that varies linearly across the array. The cavity of each laser diode emitter is formed between the back facet of the laser and the VBG.[11] Each emitter in a bar is fed back a unique and controlled wavelength by the wavelength-chirped VBG. In the vertical (or stacking) dimension, each emitter locks to the same wavelength. The emission from all emitters within a given bar is spatially overlapped at the grating by means of the cylindrical transform lens. The grating is adjusted to provide the proper dispersion such that the diffracted beams from each bar propagate collinearly in both the near and the far fields. WBC is accomplished for each bar of the array such that the beam quality of the combined beam in the horizontal axis is approximately that of a single broad-area emitter. The beam quality in the stacking dimension remains unaffected.

We achieve near-ideal WBC of a commerical off-the-shelf three-bar diode stack by using this implementation. The three-bar stack has 19 emitters in each bar. Each emitter is 150 μm wide, and the emitter pitch is 500 μm. Without the VBG, the lasing threshold is ~ 9 A, with the free-running wavelength at 910 nm within a bandwidth of 4 nm, full width half-maximum (FWHM). Each bar has a low-reflectivity ($<1\%$) antireflection- (AR) coated front facet and is collimated on the fast axis by a cylindrical microlens. The beam-combining cavity consists of a 15 nm/cm wavelength-chirped VBG, an $f = 150$ mm cylindrical transform lens, and a gold-coated 2000 g/mm holographic grating on a Zerodur substrate. The efficiency of the grating is approximately 90%. The peak reflectivity of the VBG was about

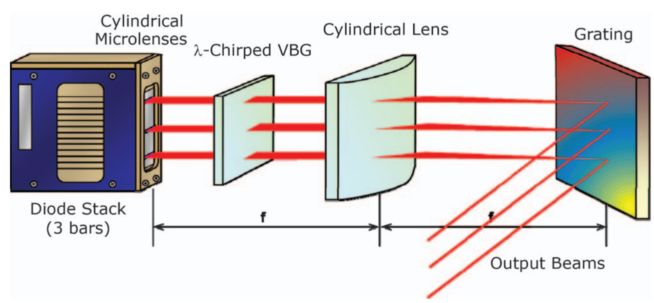

Fig. 1. Basic architecture for WBC of a diode stack (three-bar stack) by using a wavelength-chirped VBG.

15%. The VBG has a 3 mm thickness and a 0.1 nm FWHM reflectivity bandwidth. The VBG was positioned ~0.5 mm from the cylindrical microlens.

A typical wavelength versus position (current I = 35 A) for a single bar is shown in Fig. 2. In this figure the wavelength is plotted along the ordinate, while the position along the laser bar is plotted along the abscissa. Each point or image corresponds to a broad-area laser element. Each laser lases at its unique wavelength assigned by the VBG. The spread in wavelength for each bar is 14 nm, as shown in Fig. 3 (I=35 A). Figure 4 shows the output power (left axis) and beam propagation quality M^2 (right axis) of the three-bar stack as a function of the applied current. At 50 A, the wavelength-beam-combined output power was 89.5 W. This corresponds to a WBC efficiency of 75%. The WBC efficiency is defined here as the ratio of the measured wavelength-beam-combined output power to the measured free-running output power without the VBG. For this particular stack the free-running output power at the nominal operating current is nearly the same when compared with the specification of a similar stack with a coating optimized for output power. The beam propagation factor M^2 measurement was performed with the ModeMaster beam-propagation instrument from Coherent, Inc. Near threshold ($I \sim 3.5$ A), M^2 on the slow axis for a single bar is close to diffraction limited. This is not unexpected, as this was demonstrated previously in broad-area diodes wavelength-stabilized by the use of VBGs.[11–13] The beam propagation factor on the slow axis increases with current up to 35 A, after which it remains relatively constant. At the highest applied current of 50 A, the beam-combined output from a single bar has $M^2 \sim 23$ on the slow axis and $M^2 \sim 1.5$ on the fast axis. With three bars operating, the output beam has $M^2 \sim 26$ on the slow axis and $M^2 \sim 21$ on the fast axis. As expected, when three bars are operated in this cavity the beam propagation on the slow axis remains roughly the same as that of a single bar, while the beam propagation factor on the fast axis increases roughly as $M^2 y N \eta/\mathrm{FF}$, where $M^2 y$ is the beam-propagation factor of each bar on the fast axis, N is the number of bars, η is the degradation due to "smile" (packaging-induced bowing of the array) and pointing error, and FF ~ 0.3 is the fill factor. Two of the three bars have less than 1 μm of smile. The third bar has a measured smile of about 2–3 μm.

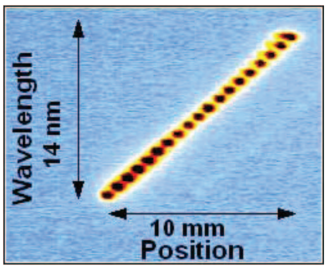

Fig. 2. Near-field-image spectrum versus position for one bar at 35 A.

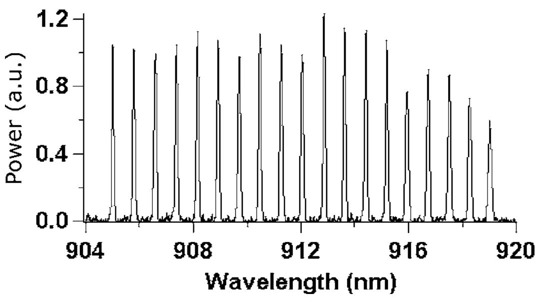

Fig. 3. WBC spectrum of one bar at 35 A.

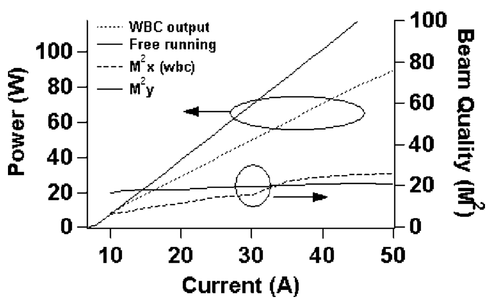

Fig. 4. Left axis, WBC and free-running output power versus current for a three-bar stack. Right axis, beam-combining efficiency and beam quality versus current for a three-bar stack.

We have coupled the wavelength-combined output beam of the three bars into both 200 and 100 μm diameter, 0.22 N.A. uncoated fibers. We used a single 25 mm diameter, 30 mm focal length doublet lens for both fibers. We measured 76 W out of the 200 μm fiber, or about 85% coupling efficiency. With the 100 μm fiber we measured 62 W of output power with 76 W of input power, or about 81% coupling efficiency, when running the stack quasi-cw at 1% duty cycle. When operating cw we measured 52.7 W of output power with 68 W of input power, or 77% coupling efficiency, from the 100 μm fiber. To our knowledge this is the highest-brightness diode laser system based on broad-area emitters. In the cw 100 μm fiber-coupling experiment the WBC output power and fiber-coupling efficiency decrease is likely due to damage of the grating.

The performance and efficiency of the system can be improved with a lower AR coating reflectivity of the front facet of the stack, lower smile (<1 μm) and pointing error, lower VBG reflectivity ($<10\%$), lower distortion grating, and with AR coating of the fiber ends. The optimum VBG reflectivity for these commercial stacks having a front-facet reflectivity of $<1\%$ is experimentally determined to be about 10% and is comparable with the front-facet reflectivity without an AR coating. Scaling the system to higher power would involve increasing the number of bars in the stack. Stacks that are rated at 120 W/bar (without collimation) with 65% wall-plug efficiency are now commercially available.[14] The beam-propagation factor for each broad-area laser in the stack is 11 by 1.5 times diffraction limited. Assuming near ideal WBC and negligible packaging-induced smile or pointing error, up to 2 side-by-side units of 7-bar stacks (assuming a near-unity side-by-side fill factor, $M^2 x \sim 22$ and $M^2 y \sim 35$), for a total of 14 wavelength-beam-combined bars, could be coupled into a 100 μm, 0.22 N.A. fiber. With polarization multiplexing, as many as 28 bars, in principle, can be efficiently coupled into a 100 μm, 0.22 N.A. fiber. Under these conditions we project that nearly 3 kW (assuming optical efficiencies of 90% for WBC and 90% fiber coupling) could be coupled into a 100 μm, 0.22 N.A. fiber. At these power levels a dielectric-coated diffraction grating or fused-silica transmission grating is needed to reduce the risk of grating damage. The wall-plug efficiency of such a fiber-coupled system could be as high as 52%. The current state-of-the-art commercial off-the-shelf fiber-coupled diode laser system available on the market has an output power of 35 W from a 100 μm, 0.22 N.A. fiber with about 17% wall-plug efficiency. Higher wall-plug-efficiency ($\sim$35%) fiber-coupled diode laser systems are available, but only with larger-diameter fibers. With the currently used VGBs, the bandwidth of the above envisioned system would be $\sim$14 nm. In applications where a narrower spectral bandwidth is required, VBGs with a smaller wavelength chirp can be used.

In summary, we demonstrate a robust method of scaling power and spatial brightness from diode array stacks by WBC by using a linearly wavelength-chirped VBG. Using a 915-nm, three-bar commercial stack of broad-area lasers operating cw, we measured 89.5 W of average power with an overall wavelength-combining efficiency of 75%. The beam-propagation factor on the slow axis is $M^2 \sim 26$, and $M^2 \sim 21$ on the fast axis. This corresponds to a brightness of $\sim 20\ \mathrm{MW/cm^2\,sr}$. To our knowledge, this is the highest-brightness broad-area diode-laser system. We achieve 81% coupling efficiency into a 100 μm, 0.22 N.A. uncoated fiber. This sets the stage for multikilowatt stacks that can be efficiently coupled into a 100 μm, 0.2 N.A. fiber.

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