1450-nm high-brightness wavelength-beam combined diode laser array

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Abstract: We have demonstrated wavelength beam combining of a 1450-nm diode laser array with a novel smile compensation method. We have achieved 20-W cw from a 25-element single bar with an M^2 of 1.9 (fast axis) x 10 (wavelength-beam-combined dimension).

OCIS codes: (140.2010) Diode laser arrays; (140.3290) Laser arrays; (140.3300) Laser beam shaping; (140.3410) Laser resonators

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1. Introduction

The 1.5-μm eyesafe spectral region allows systems to operate in free space with significantly larger energies than at 1 micron, as limited by eyesafety concerns. A variety of applications require high-brightness eyesafe sources including lidar [1] and pumping of fiber and solid-state lasers [2,3]. Current eyesafe sources include erbium-doped fiber amplifiers [4], optical parametric oscillators [5], and Raman gas cell lasers [1,6]. However, these systems suffer from inefficiency and are limited in power scaling by nonlinearities and thermal management. In contrast, wavelength beam combining (WBC) is a simple and compact alternative, enabling increased brightness from diode laser arrays with high efficiency. Wavelength beam combining is similar to wavelength-division multiplexing in optical fiber communications. Each element of a laser array is locked to a different color and combined spatially with a lens and a dispersive element. The powers of each element add, and the brightness, power per unit area-solid angle, scales as the number of emitters. In contrast, arrays that are incoherently combined by placing elements side by side, are limited in brightness to that of a single emitter. Wavelength beam combining requires that elements have no spectral overlap, but does not require that the elements have the same polarization, amplitude or phase [7].

There have been several demonstrations of WBC at 9xx-nm wavelength with both broad-area and single-mode laser arrays. Chann et al. combined a 3-bar commercial stack at 915 nm, yielding 89.5 W cw with 75% beam-combining efficiency (ratio of WBC output to free running output). The M^2 was 26 (slow axis) x 21 (fast axis) and 81% coupling efficiency into a 100-μm, 0.22-NA fiber was achieved [8]. In another demonstration, a 5-bar stack at 900-nm wavelength was beam combined to yield 195 W cw from a 100-μm, 0.22-NA fiber with 83% fiber-coupling efficiency [9]. Wavelength beam combining has also been extended to an array of single-mode emitters. A 100-element, 100-micron pitch array of slab-coupled optical waveguide lasers at 970 nm was combined to yield 50 W of peak power with an M^2 of 1.2 in both directions [10]. Commercial realization of high power, high brightness diode laser systems is limited by stringent requirements on diode array smile (packaging-induced distortion of the elements in a bar). Effective smile compensation can be performed by fabricating a custom refractive plate [11] or custom lenslet arrays [12]. However, we have demonstrated a novel smile-compensation technique with the addition of commercially available lenses to a WBC cavity. In this paper, we report on results extending wavelength beam combining to eyesafe wavelengths, achieving record brightness from a diode laser array at 1450 nm and including such a smile compensation technique. A 1450-nm laser bar with a smile of 5 μm, containing 25 laser elements, has been combined to yield an output power of 20 W with an M^2 of 1.9 (fast axis) x 10 (wavelength-beam-combined dimension).

2. Wavelength-beam-combining experimental setup

For a WBC system, there are a number of key attributes desired from a diode-based source. It is important to have high power per element, good beam quality, low smile, and a low anti-reflection coating on the front facet. A broad-area commercial laser array was used for the experiments [13], with 25 elements per bar spaced at a 400-micron pitch. Each element was 100-microns wide, with an $M^2 < 19$ in the slow axis, and diffraction-limited beam quality in the fast axis. The laser bar was anti-reflection coated on the front facet, with a residual reflectivity of <0.5%. The laser elements are collimated in the fast and slow axis with crossed cylindrical microlenses. For comparison, we also studied a reference laser bar, fabricated from the same wafer, with an 18% reflectivity front-facet coating. Without an external cavity, the reference bar produced 30 W at 75 A (with a threshold at 10 A), and the AR-coated bar, 25 W at 80 A (with a threshold of 20 A). The AR-coated bar had a smile (peak-to-valley) of 5 microns, which is quite significant if left uncompensated. Additionally, due to an artifact of the specific microlens implementation, only approximately half of the power emited by each laser element was captured by the corresponding microlens into an axial

collimated beam element and the rest of the emited power spilled to the adjacent microlenses. As a result, the microlensed laser bar had +/- 9 degrees far-field sidelobes in the slow axis. The sidelobes, containing 50% of the power are blocked and do not contribute to the WBC cavity output, but degrade the measured system efficiency.

Figure 1 shows the beam combining setup [14, 15]. The cavity consists of the AR-coated laser bar, a cylindrical slow axis transform lens, a grating, a cylindrical telescope in the slow axis, a single cylindrical lens in the fast axis, and an output coupler. The cavity was designed for a wavelength spread of 18 nm, which determined the focal length of the transform lens and grating dispersion A 250-mm cylindrical transform lens (WBC dimension or slow axis) is placed a focal length away from the laser.   A 1200-l/mm holographic diffraction grating, with a first-order diffraction efficiency of 90% at 1450 nm, is placed one focal length away from the transform lens.   The transform lens makes all the beams overlap on the diffraction grating. After the grating, a 700-mm focal length cylindrical lens (vertical or fast axis) forms a telescope with the fast-axis collimating microlens and compensates the smile of the laser bar. The 700-mm lens is placed one focal length away from the output coupler; the facet of each laser element is, in this way, reimaged onto itself even in the presence of smile. The lens is followed by a 6:1 cylindrical telescope (300 mm/50 mm focal lengths) in the slow axis in order to reduce the beam size at the output coupler. The cavity is completed with a 7% reflectivity output coupler. After the cavity, the output is sent to a variety of diagnostics including a power meter, optical spectrum analyzer, camera, and beam-quality measurement system.

Smile results in vertical displacement of the emitters. Once the beams pass through the fast-axis collimating microlens, this vertical displacement is transformed to an angular displacement. The net effect in the conventional WBC cavity would be to reduce (or totally prevent) feedback to individual emitters. In the smile-compensated cavity, the 700-mm cylindrical lens prevents feedback losses due to smile-induced angular displacement of the element beams. The 700-mm lens forms a telescope with the fast axis microlens, effectively imaging the output coupler directly at the laser facet. This eliminates the loss in feedback caused by smile and improves the system efficiency. It is important to note that the smile compensation method does not improve the system beam quality.
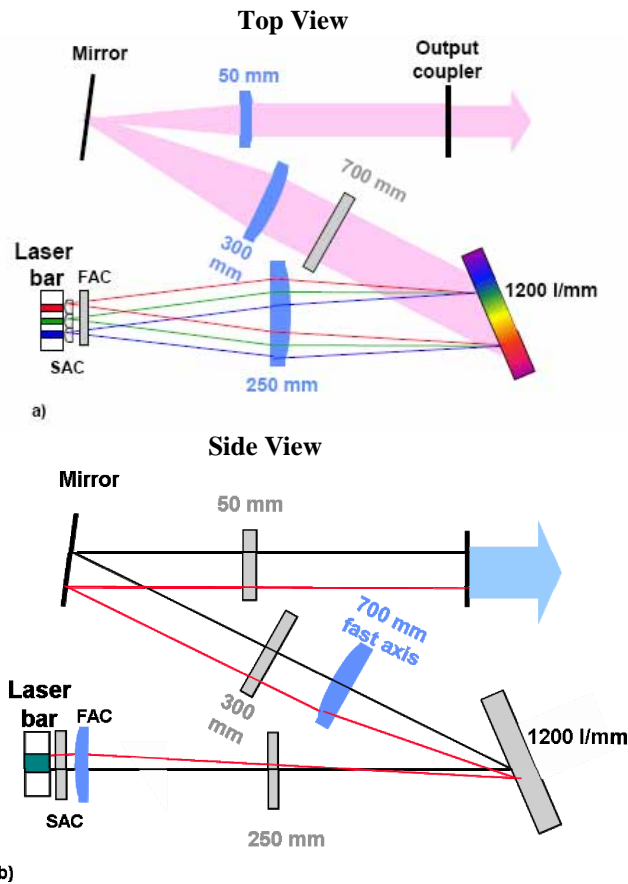
Top View

Side View

Fig. 1. (a) Top view of experimental setup. All lenses in the cavity are cylindrical. The 50 mm, 250 mm, and 300 mm lenses act in the WBC combined dimension, or slow axis. The 700 mm lens acts in the vertical or fast dimension. SAC; slow axis collimating lens. FAC; fast axis collimating lens. (b) Side view of experimental setup. The red line represents a single laser element with smile; the black, a single laser element without smile.

3. Wavelength-beam-combining results and discussion

Figure 2(a) shows a typical spectrum versus position for the laser bar at a current of 50 A. The wavelength of each element is plotted versus horizontal position in the laser array. Each element is clearly stabilized to a unique wavelength. Without the smile compensation lens, the bar would have some non-stabilized elements (lasers that are not receiving enough feedback from the WBC cavity). Figure 2(b) shows the optical spectrum of the output beam, taken at the same current. The output spectral spread agrees with the designed spectral output of 18 nm. By rotating the grating of the WBC cavity, it is possible to tune the output wavelength. The WBC cavity has a tuning range from 1404 to 1470 nm.
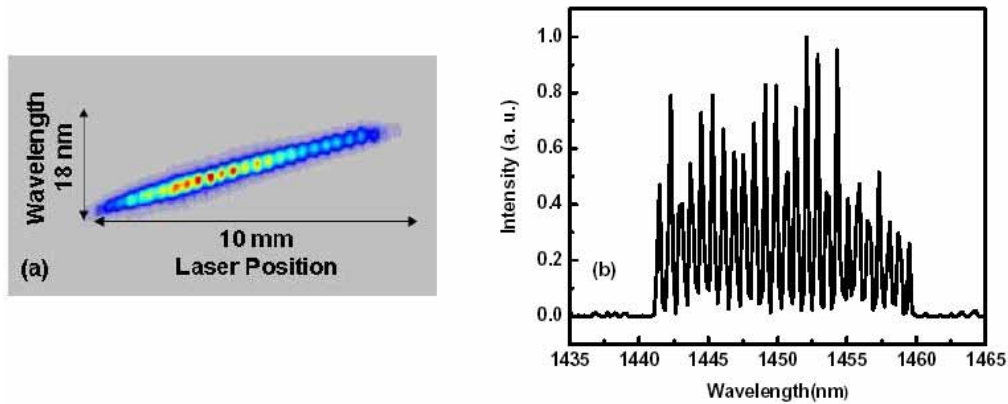
Fig. 2. (a) Wavelength versus near-field image of laser bar at 50 A. (b) Corresponding high resolution optical spectrum.

Figure 3 shows both the power and the beam quality versus current. The beam quality was measured with a ModeMaster beam propagation instrument from Coherent Inc. We achieved a maximum output of 20 W from the beam-combined cavity with the 7% output coupler. In Figure 3, the power versus current is also compared to the reference laser bar, which produces 25 W at 75 A. The M^2 in the slow axis ranges between 8 and 10; and in the fast axis, between 1.9 and 2.4. We can calculate the brightness of the WBC output. Brightness, B, is defined as

$$B = \frac{2P_{av}}{\lambda^2 M_x^2 M_y^2}$$ [16] where P_{av} is the average power, λ is the wavelength, M_x^2 is the beam

quality in the slow (WBC) axis and M_y^2 is the beam quality in the fast axis. The measured brightness is 93 MW/cm^2-str, which represents record brightness from a 14xx-nm diode laser array. This is to be compared with the brightness, 4.8 MW/cm^2-str, of a lensed (both fast and slow axis) 25 W bar without the benefit of wavelength beam combining.
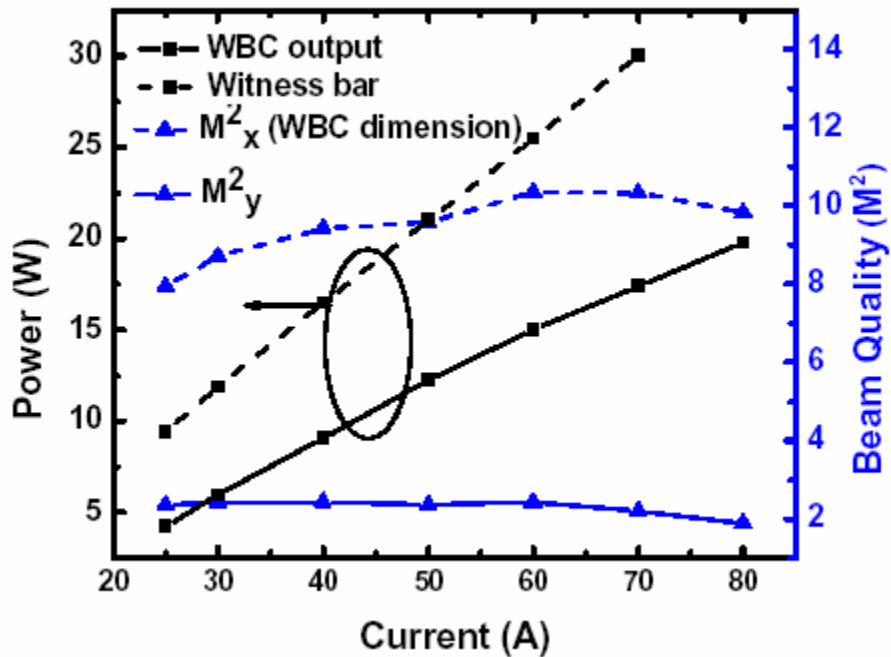
Fig. 3. Power and beam quality for a 25-element bar. Left axis: Output power versus current for the WBC output (solid line) and the reference laser bar with an 18% coating (dashed line). Right axis: Beam quality versus current for x-axis (WBC dimension, dashed) and y-axis (fast axis, solid).

4. Conclusion

We have demonstrated record brightness of 93 MW/cm²-str from a 1450-nm laser array in a WBC cavity using a smile compensation method relying on commercially available lenses. We have achieved 20 W beam combined with an M^2 of 1.9 (fast axis) by 10 (wavelength beam combined dimension). The use of stacks of laser bars should allow for higher powers at a similar brightness level.