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# 980 nm high brightness external cavity broad area diode laser bar

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**Abstract:** We demonstrate off-axis spectral beam combining applied to a 980 nm high power broad area diode laser bar. The experiments yielded 9 W of optical power at 30 A of operating current and the measured  $M^2$  values of the combined beam from 12 emitters were 1.9 and 6.4 for the fast and the slow axis, respectively. The slow axis beam quality was 5-6 times better than the value obtained from a single emitter in free running mode. A high brightness of 79 MW/cm<sup>2</sup>-str was achieved using this configuration. To our knowledge, this is the highest brightness level ever achieved from a broad area diode laser bar.

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

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## 1. Introduction

High power broad area diode laser bars are interesting devices for a range of specific industrial applications such as, e.g., cutting/marking of certain artificial materials [1] or cladding pumping of fibre amplifiers [2]. The main advantages of these devices are that they are compact with sizes of the order of a few cubic millimetres; they can deliver relatively high output power levels above 100 W, and they have long life times up to 10,000s of hours. Furthermore, they have high wall-plug efficiencies up to 75% [3]. Hence they are promising candidates for applications that require a compact laser system that can deliver high output power levels. However, the main draw backs of these devices include poor beam quality and low spatial brightness that is a result of the high divergence along the slow axis caused by the broad emitter area.

Several research groups have used different approaches for improving the beam quality and spatial brightness of high power diode laser bar systems. One such approach applied on a broad area laser array is using an external cavity providing off-axis feedback to all the emitters in the array [4]. Another external coupling technique applied on a laser array is utilizing the Talbot cavity [5]. Spectral beam combining is another well-known technique which is used for improving the spatial brightness and beam quality of broad area diode laser bars and arrays [6]. Slab Coupled Optical Waveguide Lasers (SCOWL) provides very high output power levels with excellent beam quality [7]. Spectral beam combining of a SCOWL array [8] can provide high output power in a near diffraction limited beam. Recently, Gopinath et al., [9] combined a 25-element broad area diode laser bar using spectral beam combining. In general, the beam quality and brightness that can be achieved in the combined output from an array using this technique is limited by the spatial beam quality of the single emitters in the device. This particularly becomes an issue when using broad area laser bars, where the single emitter beam quality is far from diffraction limited.

Off-axis spectral beam combining is a recently developed technique, which has been used to improve the beam quality and spatial brightness of a segmented broad area laser diode. In 2006, Jensen et al., [10] applied off-axis spectral beam combining to a segmented broad area laser diode and achieved a beam quality improvement of a factor of 3.4 compared to a single free running segment. In 2006, Jechow et al., [11] 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.

In this paper, we report on off-axis spectral beam combining applied to a 980 nm high power diode laser bar. We applied off-axis feedback to 12 broad area emitters, which resulted in a 5-6 fold improvement in the beam quality along the slow axis of the output beam compared to a free running single emitter on the same laser bar. The spatial brightness of the output beam was compared with that of a free running standard laser bar. A 34 fold improvement was observed resulting in a brightness of 79 MW/cm<sup>2</sup>-str which to our knowledge is the highest obtained brightness for a broad area diode laser bar.

## 2. Off-axis spectral beam combining experimental setup

The 980 nm broad area laser bar used in the experiment consisted of 19 emitters, each 150  $\mu\text{m}$  wide and with a pitch spacing of 500  $\mu\text{m}$ . The epitaxial layers were grown by molecular beam epitaxy (MBE). The active region consists of a single InGaAs-quantum well embedded in a 1.06  $\mu\text{m}$  thick AlGaAs core region with 20% Aluminum content. The optical waveguide was formed by 1  $\mu\text{m}$  thick AlGaAs claddings with 40% Aluminium. After processing, the wafers were thinned and chipped into laser bars with a pitch of 500  $\mu\text{m}$ . The laser was coated with two pairs of a high-reflection Si/SiO<sub>2</sub> coating on the back facet with a reflectivity > 97% and a single layer anti-reflection (AR) SiN coating on the front facet with a residual reflectivity < 0.01%.

The  $M^2$  values of the individual emitters were measured to be approximately 30 - 35 along the slow axis and the beam along the fast axis was found to be nearly diffraction limited. The output light has been collimated along the fast axis by directly fixing a 910  $\mu\text{m}$  focal length

LIMO cylindrical micro lens to the laser heat sink. After fixing the micro lens only 12 of the 19 emitters were fully functional and, therefore, the subsequently reported results deal only with these emitters. In the absence of an external cavity, the laser produced 3 W of cw power at 30 A. Such a low output power is due to the efficient front facet antireflection coating. A similar laser bar with a standard anti-reflection coating, which has a residual reflectivity of approximately 5%, was used for comparison and it gave an optical output power of 22 W at 30 A of operating current.

Figure 1 shows a schematic of the experimental setup for off-axis spectral beam combining of the laser bar. The components in the external cavity setup were; the AR-coated laser bar, the fast axis collimation lens, the slow axis collimation lens with a focal length of 100 mm, a reflection grating with 1200 lines/mm with a first order diffraction efficiency measured to be around 95% at 980 nm, a D shaped sharp edged highly reflective mirror, a spatial filter, and a 10% reflective plane output coupler. The output beam from the external cavity was split into two using a plane glass plate (10% reflectivity) as a beam splitter. The low power part of the beam was focused on to a beam analyzer, using a 100 mm focal length achromatic lens, for measuring the beam quality. The high power part of the beam was focused on to a power meter, using a 100 mm biconvex lens. All lenses were antireflection coated.

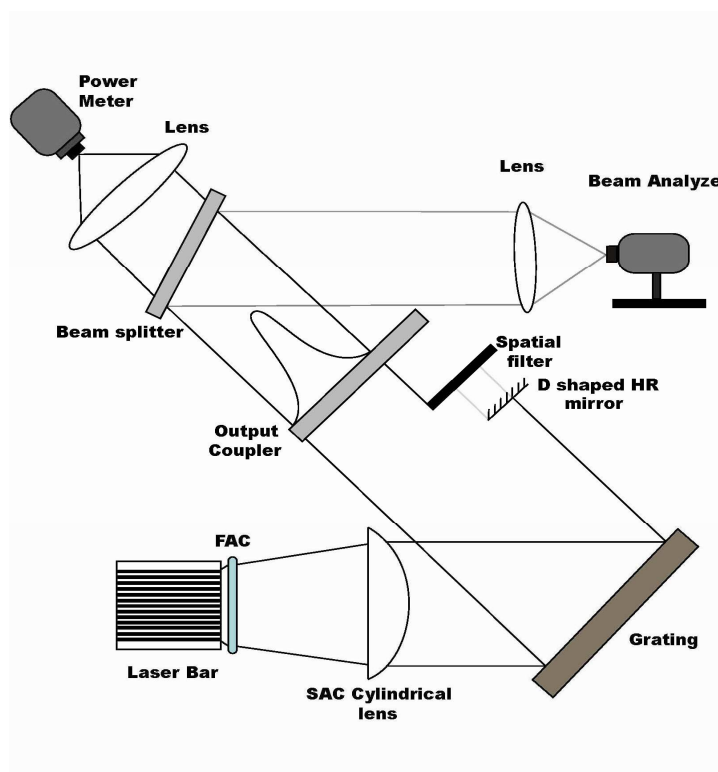


Fig. 1. A schematic of the top view of the off-axis spectral beam combining experimental setup.

The slow axis collimator (SAC), the grating and the output coupler were placed in a configuration similar to the standard spectral beam combining technique. The diffraction grating was placed in the slow axis Fourier plane formed by the 100 mm focal length cylindrical lens. The angle of incidence of the beam onto the grating was approximately 52 degrees. The first order diffracted beam was made to travel back in parallel into the emitters using a plane output coupler of 10% reflectivity placed 135 mm away from the grating. As the

light from each emitter was incident on the grating at a different angle, each emitter was forced by the external cavity to operate at a particular wavelength.

In addition to spectral beam combining, we applied off-axis feedback in our experiment using a similar method as described in ref. 10. Each broad area emitter exhibits the typical bi-lobed far field profile. By using a D shaped sharp edged highly reflective off-axis mirror in the first order diffracted beam, a few spatial modes in one of the two far field lobes were fed back to the emitters. In this way we were able to selectively amplify higher order spatial modes and suppress lower order spatial modes [12,13]. This yielded a narrow output beam with improved beam quality.

In principle, using standard spectral beam combining, the beam quality of the combined output of a laser bar can at most be as good as that of a single emitter. By using off-axis spectral beam combining, the beam quality of the combined beam can be improved even further, i.e., to a quality exceeding the beam quality of a single emitter.

### 3. Off-axis spectral beam combining results and discussion

The output from the external cavity laser was analyzed regarding power characteristics, spectral behaviour and beam quality. Figure 2 shows the light-current characteristics of the laser bar with off axis spectral beam combining and in free running mode. With off-axis spectral beam combining, the output power was measured to be 9 W at 30 A of input current. The laser threshold was measured to be 6 A, and the characteristics show a slope efficiency of 0.38 W/A.

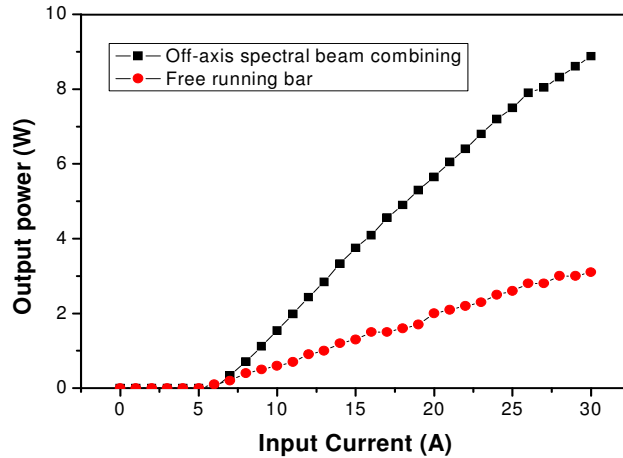


Fig. 2. Light-current characteristics of the laser bar with off-axis spectral beam combining (squares) and in free running mode (dots).

Figure 3 shows the optical spectrum of the output beam recorded at an operating current of 30 A with off axis spectral beam combining. 12 equally spaced main peaks over a spectral range of 30 nm are observed in the spectrum corresponding to that of 12 emitters combined. A few additional peaks were observed in the spectrum which may be due to a slight imperfection in the superimposition of the beams on the grating. A wavelength spacing of approximately 2.67 nm is observed between the main peaks. The wavelength spread  $\Delta\lambda$ , is related to the focal length,  $f$ , of the transform lens, the spatial extend,  $d$ , of the laser, and the grating dispersion,  $d\alpha/d\lambda$  by

$$d \approx f \frac{d\alpha}{d\lambda} \Delta\lambda \quad (1)$$

where the grating dispersion is given by

$$\frac{d\alpha}{d\lambda} = \frac{1}{\alpha \cos \alpha_0} \quad (2)$$

Here,  $\alpha$  is the grating period and  $\alpha_0$  is the angle of incidence relative to the grating normal for the centre emitter on the bar. The calculated wavelength separation for our experimental configuration was 2.56 nm, which is in good agreement with the experimentally obtained value of 2.67 nm. The output wavelengths were found to be in the range from 950 nm to 980 nm with a centre wavelength of approximately 965 nm.

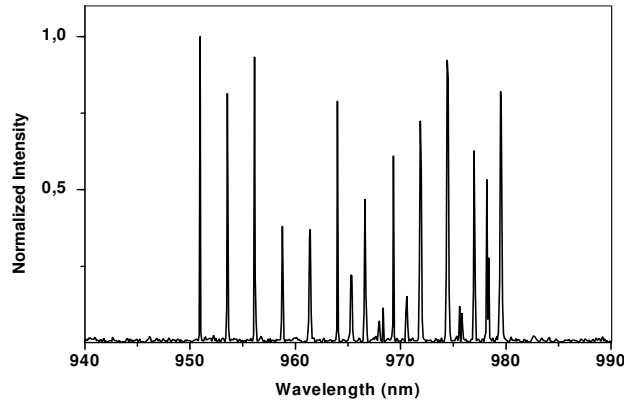


Fig. 3. Optical spectrum of the laser bar with off axis spectral beam combining.

The output beam was focused using an achromatic lens of 100 mm focal length and beam profiles along the beam caustic was recorded using a Nanoscan beam profiler (*Photon Inc.*). The  $1/e^2$  values of the beam width were measured throughout the experiment. Figures 4(a) and 4(b) shows the caustic of the output beam along the fast and the slow axis respectively. A slight astigmatism is present in the laser output as noted from Fig. 4.

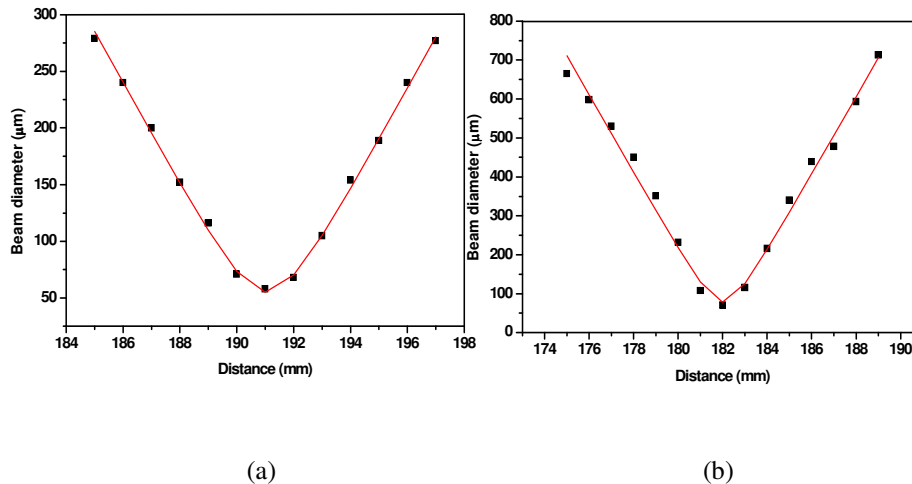


Fig. 4. (a). Caustic of the fast axis of the beam (b) Caustic of the slow axis of the beam. The solid lines represent numerical fits to the experimental data.

The  $M^2$  values of the output beam at 30 A of operating current were found to be 1.9 and 6.4 along the fast and slow axis, respectively. The  $M^2$  curve fitting shown in the figures is based on the well known formula for the propagation of a Gaussian beam,

$$W(z) = W_0 \left[ 1 + \left( \frac{z \lambda M^2}{\pi W_0^2} \right)^2 \right]^{\frac{1}{2}} \quad (3)$$

where  $W(z)$  is the spot size at a distance  $z$  from the beam waist,  $W_0$  is the spot size at the beam waist and  $\lambda$  is the wavelength.

The slow axis  $M^2$  value of 6.4 obtained from the off-axis spectrally beam combined laser is to be compared with the slow axis  $M^2$  value of approximately 30-35 which is measured for a single emitter on the free running laser bar. An improvement of a factor of 5-6 in the slow axis beam quality of the combined beam is achieved with off-axis spectral beam combining when compared with the single emitter free running laser beam. The slow axis  $M^2$  value of the whole bar in free running mode was found to be approximately 1580.

The beam profile along the fast and the slow axis at the beam waist are shown in Figs. 5(a) and 5(b), respectively. The beam could be focused to a spot of 60  $\mu\text{m}$  by 69  $\mu\text{m}$  diameter along the fast and the slow axis, respectively, by simple focusing of the beam with the  $f = 100$  mm achromatic lens.

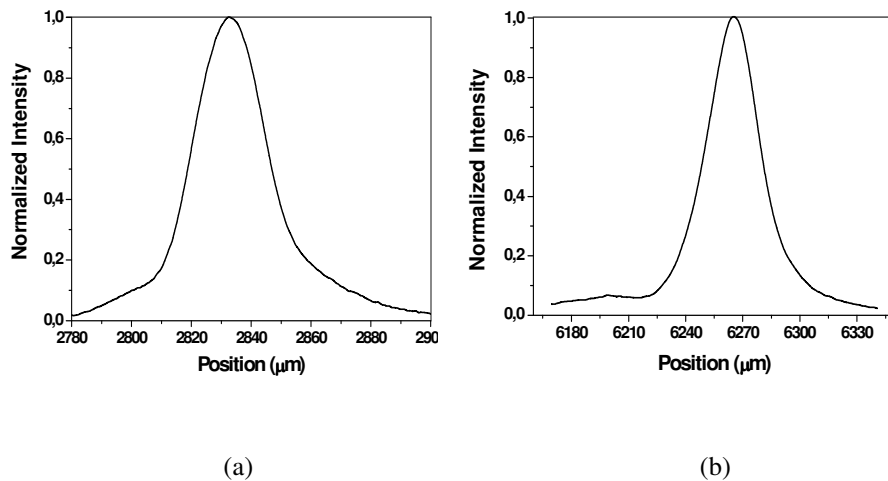


Fig. 5. (a). Fast axis beam profile at the focus of a 100 mm achromatic lens (b) Slow axis beam profile at the focus of a 100 mm achromatic lens.

We calculated the brightness of the output beam. The brightness,  $B$  is defined as [14],

$$B = \frac{P_{av}}{\lambda^2 M_x^2 M_y^2} \quad (4)$$

where  $P_{av}$  is the average power,  $M_x^2$  is the beam quality parameter along the slow axis and  $M_y^2$  is the beam quality parameter along the fast axis. The calculated brightness was 79  $\text{MW}/\text{cm}^2\text{-str}$ . To our knowledge, this is the highest brightness ever achieved from a broad area diode laser bar. We have measured the output power and the beam divergence of a standard anti-reflection coated laser bar with 19 emitters, same emitter width and same pitch spacing for comparison. In free running mode, the output power was 22 W and the beam divergence of

the laser bar was approximately 7 degrees giving a calculated brightness of around 2.3 MW/cm<sup>2</sup>-str.

#### **4. Conclusion**

We have demonstrated a 980 nm external cavity broad area diode laser bar system based on off-axis spectral beam combining. An output optical power of 9 W was achieved at an operating current of 30 A with an  $M^2$  value of 1.9 and 6.4 along the fast and the slow axis, respectively. We have obtained a high brightness of 79 MW/cm<sup>2</sup>-str from the broad area laser bar system.

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