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Baohua Wang, Weirong Guo, Zhijie Guo, Dan Xu, Jing Zhu, Qiang Zhang, Thomas Yang, Xiaohua Chen, "Spectral beam combining of multi-single emitters," Proc. SPIE 9733, High-Power Diode Laser Technology and Applications XIV, 97330F (4 March 2016); doi: 10.1117/12.2210834

Event: SPIE LASE, 2016, San Francisco, California, United States

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ABSTRACT

Spectral beam combination expands the output power while keeps the beam quality of the combined beam almost the same as that of a single emitter. Spectral beam combination has been successfully achieved for high power fiber lasers, diode laser arrays and diode laser stacks. We have recently achieved the spectral beam combination of multiple single emitter diode lasers. Spatial beam combination and beam transformation are employed before beams from 25 single emitter diode lasers can be spectrally combined. An average output power about 220W, a spectral bandwidth less than 9 nm (95% energy), a beam quality similar to that of a single emitter and electro-optical conversion efficiency over 46% are achieved.

In this paper, Rigorous Coupled Wave analysis is used to numerically evaluate the influence of emitter width, emitter pitch and focal length of transform lens on diffraction efficiency of the grating and spectral bandwidth.

To assess the chance of catastrophic optical mirror damage (COMD), the optical power in the internal cavity of a free running emitter and the optical power in the grating external cavity of a wavelength locked emitter are theoretically analyzed.

Advantages and disadvantages of spectral beam combination are concluded.

Keywords: Spectral beam combination, single emitter diode laser, rigorous coupled wave analysis, catastrophic optical mirror damage

1. INTRODUCTION

Diode lasers have advantages of high efficiency, compact structure, low cost, high reliability and long service life, etc. But the relative poor beam quality limits the direct application of diode lasers on material processing. Increasing the output power and improving the beam quality has always been a focus of research of diode lasers. Currently in the field of diode lasers, matured technologies to increasing output power are mostly incoherent beam combining technologies, including spatially beam combination, polarization beam combination and spectral beam combination. Spectral beam combination has rapid development in recent years. In 2011, Teradiode realized dense spectral beam combination of multiple conduction cooled diode laser bars and achieved 2030 W output power from a 50μm core diameter, 0.15 N.A. fiber [1]. In the same year, Christian Wirth and Oliver Schmidt, et al spectrally combined beams from 4 channel fiber amplifiers and achieved output power of 8.2 kW and M^2<5 [2]. Spectral beam combination of micro-channel cooled diode laser stacks is also reported [3].

BWT Beijing Ltd has done researched on spectral beam combination of single emitter diode lasers. After spatial beam combination and beam transformation, beams of multiple single emitter diode lasers are spectrally combined, and an output power of 222.4W is achieved with beam quality similar to that of a single emitter. The spectral bandwidth is also similar to that of free running single emitters. And the spectral bandwidth is kept stable at different output power level.

2. TECHNICAL APPROACH AND EXPERIMENTAL STUDY

2.1 Technical approach

Different from diode laser bars and diode laser stacks, beams from single emitter diode lasers need to be spatially combined firstly to expand power. Human induced error of beam directivity and error of beam spot uniformity in spatial beam combination may cause deterioration of beam quality. BWT Beijing Ltd has rich experience in spatial beam combination and know-how of accurate adjustment, providing a solid foundation for spectral beam combination after

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High-Power Diode Laser Technology and Applications XIV, edited by Mark S. Zediker, Proc. of SPIE Vol. 9733, 97330F · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2210834

spatial beam combination and beam transformation. As shown in Fig. 1, 25 single emitter diode lasers are spatially beam combined in a patented equal-light-path arrangement.

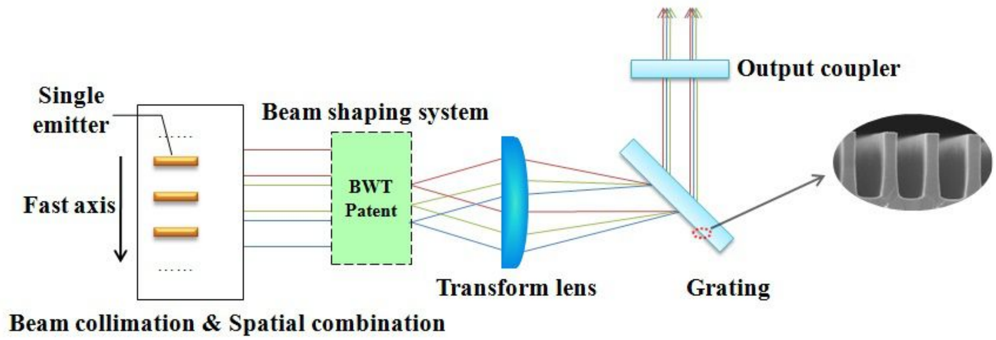

Figure 1. Multiple single emitter diode lasers are spatially beam combined before spectrally beam combination

A one dimension binary grating is used for spectral beam combination. The transmission grating is etched on a fused silica substrate. Compared with reflective gratings, the limitation of substrate material makes the diffraction efficiency of transmission grating more sensitive to degree of polarization of incident beam. For reflective gratings, multiple layers of coatings with various refractive indices on metal or glass substrates can achieve high diffraction efficiency insensitive to polarization and high damage threshold. However, compared with transmission gratings, the placement of refractive gratings is more likely to collide with other optics in the optical path. Hence, a transmission grating is used in the experiment. The influence of emitter pitch and focal length of transform lens on diffraction efficiency and spectral bandwidth of combined beam are numerically analyzed with Rigorous Coupled Wave theory [4], as shown in Fig. 2(a) without beam shaping system and (b) with it.

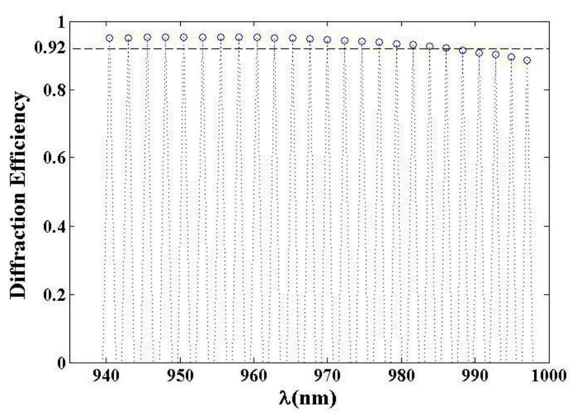

Figure 2. (a) Diffraction efficiency and spectral bandwidth without beam shaping system

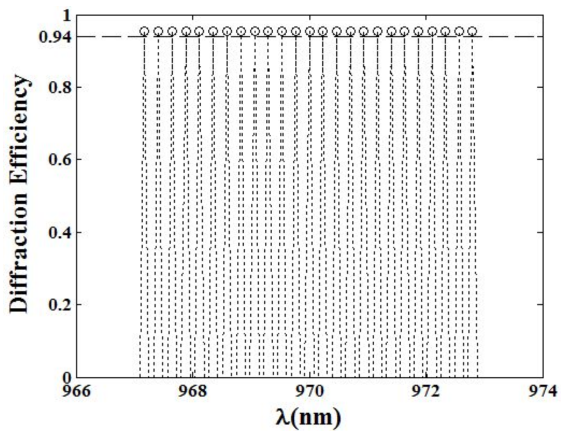

Figure 2. (b) Diffraction efficiency and spectral bandwidth with beam shaping system

After FAC and SAC, 25 single emitters are spectrally beam combined along the fast axis. Parameters used in the simulation of Fig. 2 are:

Diameter of beam waist in fast axis 0.4mm, emitter pitch 0.6mm, transform lens focal length 100mm, grating groove density 1600 l/mm, grating depth 4 μm, fill factor 50%, fused silica substrate, the center wavelength 970 nm.

It can be seen from comparison between Fig. 2 (a) and (b) that for diffraction efficiency > 90%. But the higher the spectral brightness is, the higher the diffraction efficiency is. The fact is that the incident angle bandwidth of grating and gain bandwidth of diode laser limits the spectral bandwidth. Therefore, number of spectral beam combined emitters, beam spot width and emitter pitch need to be considered synthetically to carefully control the spectral bandwidth of combined beam and ensure high electro-optical conversion efficiency.

As shown in Fig. 3 (a) and (b), optical power in the internal cavity of a free running emitter and optical power in the grating external cavity of a wavelength locked emitter are theoretically analyzed.

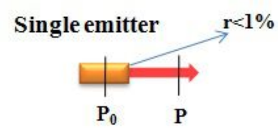

Figure 3. (a) optical power inside and out of the internal cavity of a free running emitter

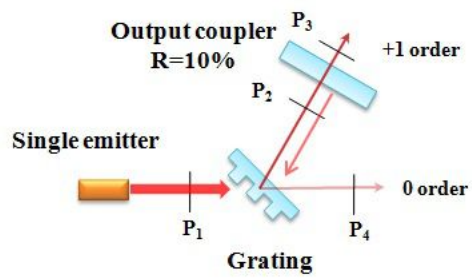

Figure 3. (b) optical power inside and out of the grating external cavity of a wavelength locked emitter

r is reflectivity of the front facet of the emitter, η_{diff} is the diffraction efficiency of +1 diffraction order (only 0 diffraction order and +1 diffraction order is considered), R is reflectivity of external cavity mirror. P_E is the electrical power injected in the diode laser, η_{EO} is electro-optical conversion efficiency of a free running emitter, η is electro-optical conversion efficiency of a wavelength locked emitter.

As Fig. 3 (a) shows, optical power in the internal cavity of a free running emitter is:

$$P_0 = \frac{(1+r)}{(1-r)} \cdot P = \frac{(1+r)}{(1-r)} \cdot \eta_{EO} \cdot P_E \tag{1}$$

As $\boldsymbol{r} < 1\%$, there is:

$$P_0 < 1.0202 \cdot \eta_{EO} \cdot P_E \tag{2}$$

As shown in Fig. 3 (b), while the external cavity works, optical power before the grating is P_1, transmitted optical power of the +1 diffraction order is P_2, optical power outputted from the external cavity is P_3, transmitted optical power of the 0th diffraction order is P_4. The powers at different positions have following relationships:

$$P_2 = \frac{(1+R)}{(1-R)} \cdot P_3 \tag{3}$$

$$P_2 = \eta_{diff} \cdot P_1 \tag{4}$$

$$P_3 = \eta \cdot P_E \tag{5}$$

$$P_4 = (1-\eta_{diff}) \cdot P_1 \tag{6}$$

$$P_3 + P_4 = \eta \cdot P_E \tag{7}$$

Combining (3)~(7) gives:

$$P_1 = \frac{1}{\left(\eta_{diff} \cdot \frac{(1-R)}{(1+R)} + (1-\eta_{diff})\right)} \cdot \eta \cdot P_E \tag{8}$$

As $\boldsymbol{R} = 10\%$, $\eta_{diff} > 94\%$, there is:

$$P_1 > 1.20614 \cdot \eta \cdot P_E \tag{9}$$

Comparison between (2) and (9) indicates that with external cavity optical-to-optical conversion efficiency>84.6%, at the same injecting electrical power, the optical power inside of an emitter with feedback of external cavity is slightly higher than that in a free running emitter. This agrees with the conclusion of literature [5] in that: with high electrical power injection, a diode laser with feedback of external cavity is more vulnerable to catastrophic optical mirror damage (COMD) than a free running diode laser. However, some optimizations such as facet passivation of semiconductor lasers, optimization of reflectivity of internal cavity and external cavity, can reduce the chance of COMD.

2.2 Experiment

200μm stripe width broad area emitters were used. The fast axis full divergence angle that contains over 95% energy is 70°, and slow axis full divergence angle is 8°, when the current is 12A. It can be seen that only fundamental transverse mode exists in fast axis, and multimode exists in slow axis. Front facet of emitters have antireflection coating with $r < 1\%$, and back facet have broadband high reflection coating with reflectance >99%. Cavity length is 4mm and central wavelength is 976nm. Emitters output TE polarized beams with degree of polarization >94%.

After fast axis collimation, slow axis collimation and beam shaping, beams from 25 single emitters are spatially combined along the fast axis. A transmission grating with fused silica substrate with groove density of 1600 l/mm and central wavelength of 970 nm is used. The diffraction efficiency in the range of 925~1025nm is shown in Fig. 4.

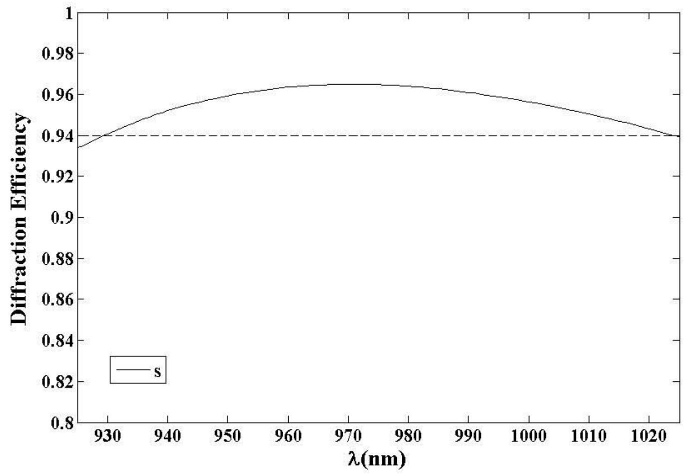

Figure 4. diffraction efficiency of the +1 diffraction order (provided by supplier)

Focal length of transform lens is 100 mm. The output coupler is a plane mirror. One side of the mirror has a reflectance R=10% over 900~1000nm, and the other side has broadband antireflection coating with low reflectance over 900~1000nm.

Fig.5 (a) and (b) show the output power and electro-optical conversion efficiency versus current, as well as spectrum.

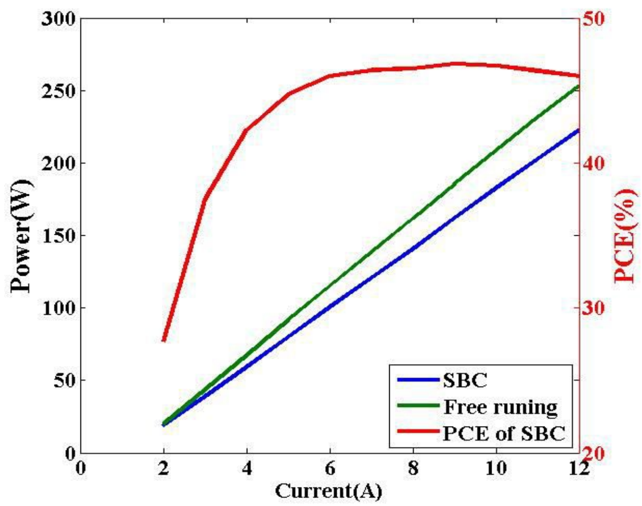

Figure 5. (a) Output power of free running and spectral beam combined emitters in the range of 2~12A

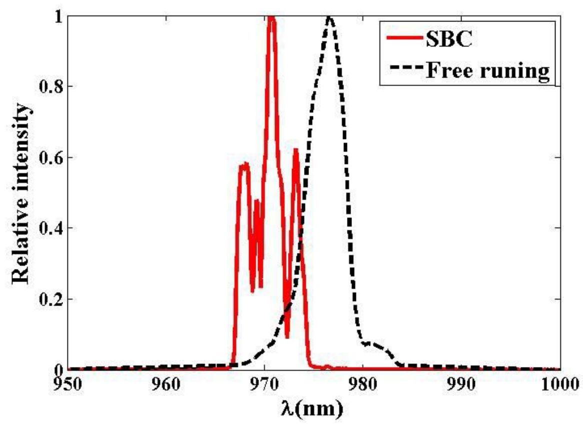

Figure 5. (b) Spectrum of free running and spectral beam combined emitters

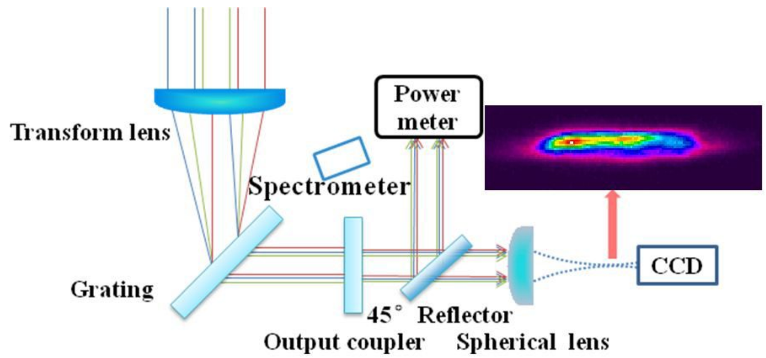

Figure 6. Principle of measurement after spectral beam combination

The principle of measurement as shown in Figure 6, the output power, spectrum, and energy distribution of the spot can be monitored at the same time. We collected a number of spots near the beam waist, and then solved beam parameter product (BPP) by numerical fitting. The BPP of spectral beam combined emitters with fast axis BPP 0.7mm*mrad and slow axis BPP 7.5mm*mrad at current 12A, which contains over 95% energy, is slightly bigger than that of a single emitter. This mainly caused by the difference of beam spot uniformity induced in collimation and error of beam directivity induced in spatial beam combination. It can be seen from spectrum that all emitters are spectrally beam combined by the external cavity. At current of 12A, free running output power is 253 W and wavelength locked output power is 222.4W. The optical-to-optical conversion efficiency of 87.9% is slightly higher than previously computed efficiency of 84.6%. This indicates that at higher current (>12A), chance of COMD may increase. As beam quality of an emitter deteriorates at higher current, the operation current can be set around 12A.

3. CONCLUSION

With spatial beam combination, beam transformation and spectral beam combination, beams from even more single emitter diode lasers can be combined while keeping the beam quality of the combined beam near to that of a single emitter. However, this is achieved with the cost of increased spectrum bandwidth.

Spectral beam combination is a kind of incoherent beam combining technology. The laser sources to be combined can be diode laser, fiber laser or solid-state-laser. Multiple laser modules can be passively beam combined through wavelength locking with dispersion component and external cavity, and modules with certain spectrum width can also be actively beam combined with dispersion component. However, the brightness of combined beam is limited by the damage threshold of the dispersion component. Moreover, level of irregularity caused by thermal stress or position error (such as the smile effect of a diode laser bar) that exists in the arrangement of laser modules, and dispersion caused by the spectrum width of a single laser module deteriorate the beam quality of combined beam [6].

Both passive wavelength locking with feedback of external cavity and active wavelength locking without external cavity bring forth many advantages: obvious improvement in beam quality, relative high efficiency of beam combination, relative high resistance to back reflection and good spectrum stability. All these features are quite beneficial for direct using of diode lasers on material processing.

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