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Kilowatt Wavelength-Stabilized CW and QCW Diode Laser

Dan Xu, Di Ma, Zhenkun Yu, Lei Xu*, Xiaohua Chen
BWT Beijing Ltd., No.4A Hangfeng Rd., Fengtai High-Tech Park, Beijing 100070, P.R. China

ABSTRACT

High power wavelength-stabilized 976nm diode lasers attract more attention recently with the development of higher power, higher efficiency and higher brightness fiber lasers. The wide spectrum of a high-power diode laser without wavelength stabilization (about 5 nm), together with thermal shift at about 0.3 nm/℃, strongly limits the conversion efficiency benefits at 976 pumping. In this paper, we will report the development of kilowatt wavelength-stabilized CW and QCW diode lasers at BWT.

Keywords: Volume Bragg grating (VBG), diode laser

1. INTRODUCTION

In recent years, a fast-growing market for fiber lasers was established for cutting, welding and brazing applications. Fiber-coupled direct diode lasers and fiber lasers with high system efficiencies allow for energy savings, lower operating costs and simple cooling system, and are widely used in today's manufacturing facilities. New exciting QCW applications further increase the demand for high power and high brightness lasers.

Most lasers for materials processing operate at a wavelength about 1um. This wavelength can be provided by direct laser systems using 9xxnm semiconductor diode lasers or fiber lasers with active fibers doped with Yb pumped by diode lasers. Recently, fiber laser pumped by diode lasers at ~976nm has attracted much attention because of its higher conversion efficiency and ability to achieve higher power in single mode. However, the wide spectrum of a high-power diode laser without wavelength stabilization (about 5 nm), together with thermal shift at about 0.3 nm/℃, strongly limits the conversion efficiency benefits at 976 pumping. Thus, many companies and institutes have developed wavelength-stabilized high-power diode laser pumps for high brightness fiber lasers.

BWT Beijing Ltd is supplying a family of wavelength-locked pump lasers from a few Watts to a few hundreds of Watts in the market for years. In this paper, we will discuss our recent progress on kilowatt wavelength-stabilized CW and QCW diode lasers out of 200um/0.22NA fiber. Studies on locking mechanism will be also discussed.

2. WAVELENGTH LOCKING WITH VBG

2.1 Background

The principle of laser wavelength stabilization by the use of external feedback typically comprises a wavelength-selective device positioned in the optical path of the laser beam that feeds a narrow portion of the laser emission spectrum back into the laser cavity[1]. Volume Bragg Gratings (VBG) are widely used as wavelength-selective devices in pump lasers to stabilize wavelengths against changes in operating current and temperature.

A VBG is a diffraction grating in which there is a periodic modulation of the refractive index through a photosensitive material. When an incoming collimated light is diffracted by a VBG, only a small fraction of the spectrum is affected, and light at other wavelengths pass through the filter without diffraction. For a simple uniform grating, its characteristics are completely determined by the thickness of the volume element, the index modulation depth, the grating spacing, and the slant angle relative to the surface.

The common technique for stabilizing the spectrum of a diode laser is to use collimation lenses and a VBG that provides feedback around a certain wavelength by effectively forming an extended cavity laser, as illustrated schematically in Fig 2.1.

*ray.xu@bwt-bj.com; phone 86 010 8368 1053; www.bwt-bj.com

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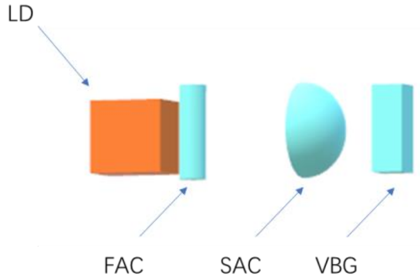

Fig.2.1 schematic of wavelength stabilization for a semiconductor laser diode. A set of fast axis collimator (FAC) and slow axis collimator (SAC) lenses are used to collimate laser beam from the laser diode (LD). VBG is positioned after SAC to provide feedback.

Catastrophic optical mirror damage (COMD) is an important failure mode for semiconductor laser diode (LD). Study [3] have shown that at the same injecting electrical power, the peak optical power near the front facet of an emitter with feedback of external cavity could be higher than that in a free running emitter. At high power, such external feedback makes the diode more vulnerable to COMD. As a result, we usually limit the operation current to be 10% lower than the rated operation current of a free-running laser chip.

2.2 Wavelength locking with a single emitter

It is well known that locking range is determined by the reflectivity of the VBG, if all other factors (such as chip AR coating, coupling process, chip wavelengths, etc) are fixed. Higher reflectivity will lead to wider locking range (for both current and temperature), but also reduce output power and efficiency of the laser. In order to choose the right VBG reflectivity for our product, we need to measure locking-range of the emitters to be used. The emitters should be randomly selected from the batch of chips to be used in modules. The goal is to use VBG with low reflectivity but still meet locking specifications. On the other hand, this kind of tests also give us guidance on selecting chips with the right center wavelength for wavelength-stabilized products.

As one example of such tests, we studied a 976nm chip with about 100um aperture width, and spectra were collected under different driving currents and different operation modes (CW or QCW) to evaluate the wavelength locking range.

Its free running spectra is shown in fig 2.2 with a center wavelength around 974nm at 10A, and “cold” wavelength around 964nm (“cold” means tested at junction temperature around ambient temperature, e.g., at very low duty cycles in pulse mode). The emitter beam is collimated by a set of FAC and SAC, and then aligned with 975.5nm VBGs of reflectivity of 6.9%, 10.9% and 15%.

In CW mode, its spectra with VBG of different reflectivity were collected from 1A to 10A at 20 ℃ cooling temperature. The results are summarized in fig 2.3. As we can see clearly, the locking ranges are from 6A to 10A with 6.9% reflectivity, from 3A to 10A with 10.9% reflectivity, and from 1A to 10A (fully locked) with 15% reflectivity. As expected, higher reflectivity of VBG to wider wavelength-locking range.

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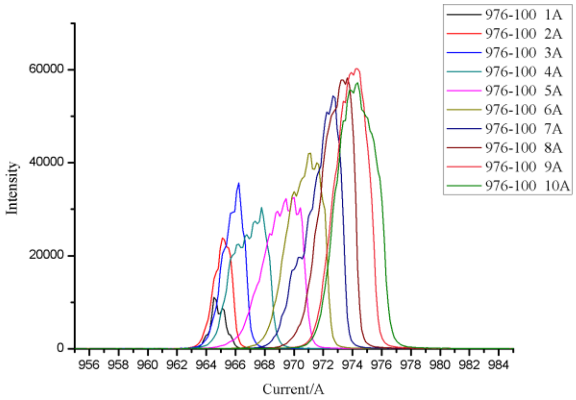

Fig 2.2 Spectra of a 976nm single emitter in free-running CW mode at different current

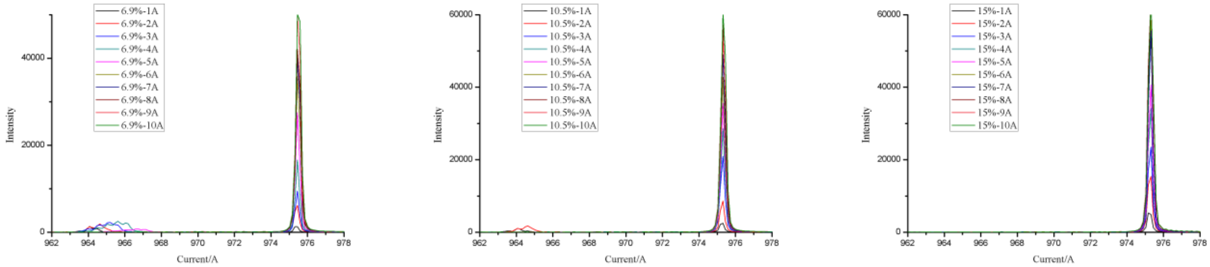

Fig 2.3 Spectra of the same single emitter (as in fig 2.2) in CW mode with different reflectivity of VBG (a) left: 6.9%;(b) middle: 10.5%;(c) right: 15%

We also studied its locking performance in QCW mode. Fig 2.4 shows spectra of the same chip studied in CW mode above measured at different QCW mode and duty cycles. A VBG of 15% reflectivity is used in the experiment. We can see that locking range are changing with the duty cycles. We believe it is mainly caused by the blue shift of wavelength due to junction temperature decreasing with lower duty cycles. At 36% duty cycle, wavelength locking range is till from 1A to 10A (same as CW mode). When duty cycle becomes smaller than 36%, the side mode around 964nm becomes visible.

From fig 2.4, one can observe that energy above 967nm are all “pulled” into the locking band (around 975.5nm) under all test conditions. Even though the competition mechanism among internal and external cavity modes is still unclear, we can draw a conclusion that the pulling range of a 15% VBG is about 8-9nm from short wavelength side with this chip. The pulling rang from the long wavelength side need to use chips of the same design with a longer wavelength, which is not discussed here. To build a clean correlation between reflectivity and locking range is still a big challenge even for the same kind of chips due to variation among wafers, die attach processes, optical alignment, thermal cooling, etc. These results are used as general guidance for chip and VBG selection in manufacturing.

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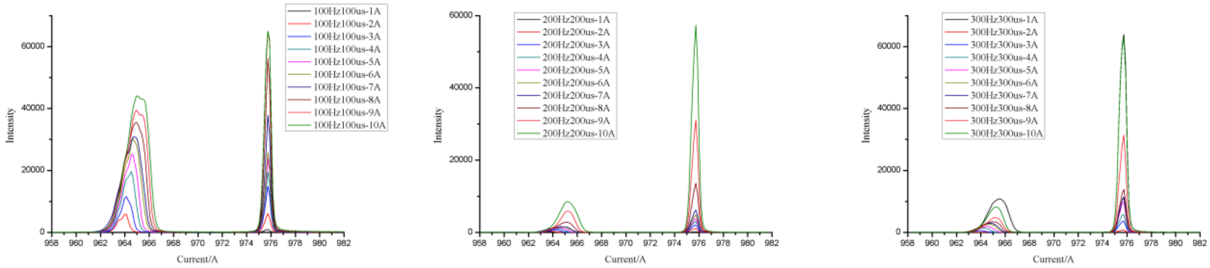
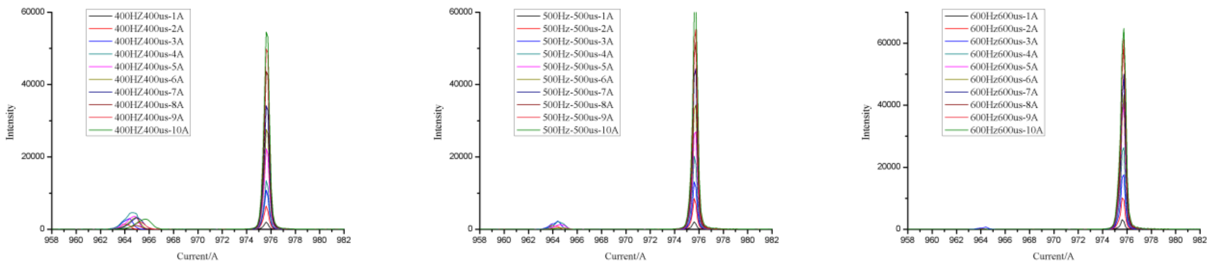


(a)100Hz-100us (1% duty cycle) (b) 200Hz-200us(4% duty cycle) (c)300Hz-300us(9% duty cycle)



(d)400Hz-400us(16% duty cycle) (e) 500Hz-500us(25% duty cycle) (f)600Hz-600us(36% duty cycle)

Fig 2.4 Spectra of a single emitter in QCW mode with different duty cycles at 20℃.

3. KILOWATT CW DIODE LASER

In our previous work, we have demonstrated a Kilowatt diode laser module achieved by combining power from more than one hundred single emitters [4]. To minimize the size of the module, we introduced a three-dimensional optical train design. Along this path, in the wavelength-locked laser module, we built single emitters on both sides of multiple heatsinks with water cooler channels (the beam combination scheme is shown in Fig 3.1). Beams from emitters are collimated by FACs and SACs and then stacked up in both directions of fast axis and slow axis. After polarization combining with a PBC (polarization beam combiner), beams from 156 single emitters are coupled into 200um/0.22NA fiber with an aspherical aberration-reduced lens.

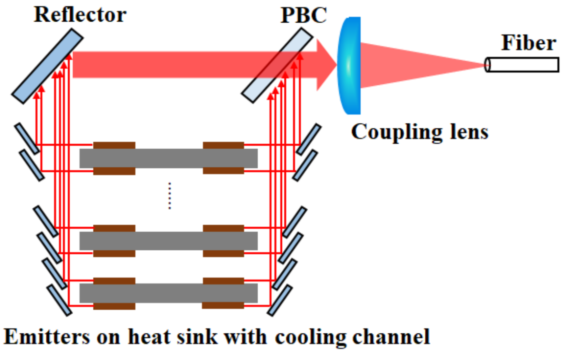


Fig 3.1 The beam combination scheme.

As shown in the power vs current curve (fig 3.2 (a)), the module output power reaches 1037W at 10A. Spectrum at 10A shows a clean locking within +/-1nm around 975.5nm (fig 3.2 (b)). Beam profile before coupling lens are as expected by

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design (see fig 3.3), and beams size at the coupling end of the fiber are a little larger than fiber core diameter. As locking of many emitters at the same time is always a challenge to multi-emitter lasers partly due to the consistency of feedback from VBG to each emitter, we chose a 15% VBG in this design to reach a locking range from 1A to 10A, and E-O efficiency is around 43%.

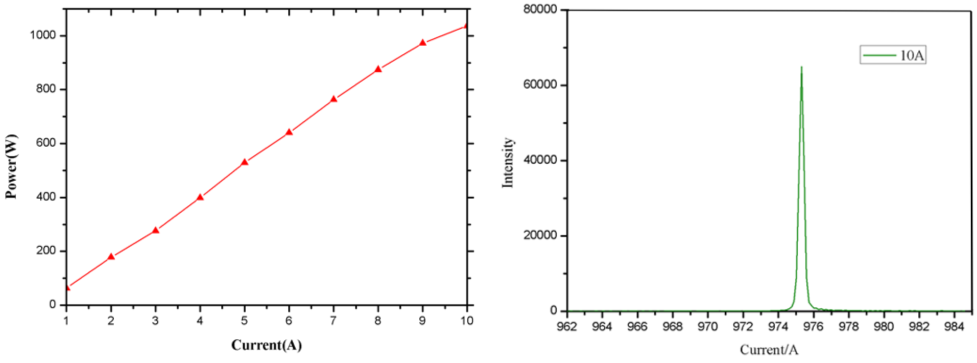

Fig 3.2 (a) left: P-I curve (b) right: spectrum at 10A. Cooling water temperature is around 20°C.

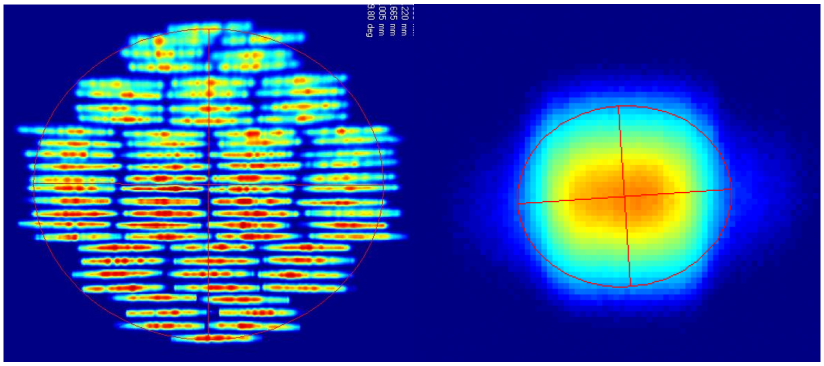

Fig 3.3 (a) left: beam profile right before the coupling lens, and the red circle illustrates 0.22NA; (b) right: beam profile at the coupling end of the fiber, and the red circle illustrates 200um fiber diameter

4. KILOWATT QCW DIODE LASER

With less heat load in QCW mode, we can further reduce the size of the laser module by using mini bars to achieve kilowatt QCW output power. In our prototype, 32 mini bars on Silicon nitride submounts are placed on cooling plates with water channels underneath to minimize thermal resistance and lower the junction temperature. Polarization combining technique is also used by combining 2 groups of beams from 16 bars with a PBC to match the fiber BPP. Fig 4.1 shows the schematics of the optical design, and beam profiles after alignment are shown in fig 4.2.

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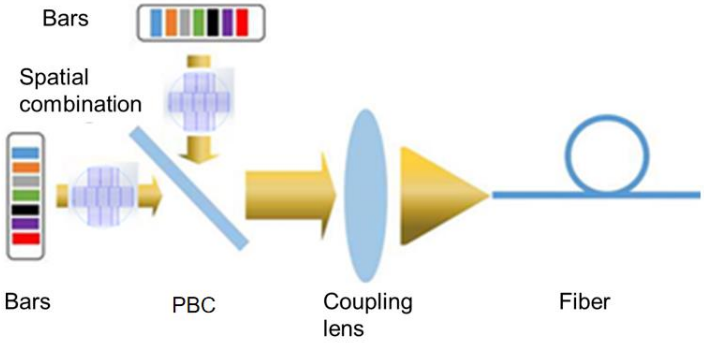

Fig 4.1 The schematics of optical train design for the QCW koliwatt laser

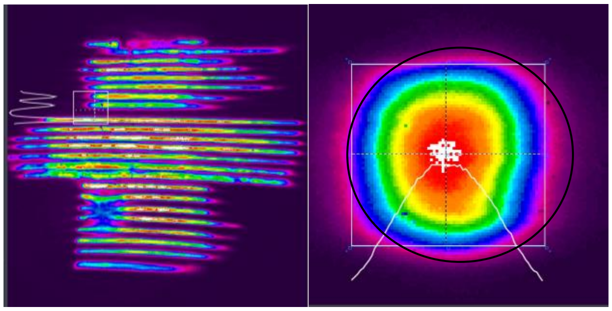

Fig 4.2 (a) left: beam profile at the coupling lens (b) right: beams profile at the coupling end of the fiber

As already discussed in section 2, locking range increases with higher feedback while efficiency drops. Spacing between the cold wavelength of the bars and the center wavelength of the VBG is also critical to the QCW locking performance. Changes in duty cycle of QCW mode also lead to junction temperature change at the same drive current, which impact both output power and center wavelength of chips. In our study, we used bars with cold wavelength around 969nm with 6% VBGs to evaluate the performance of our design.

At 200Hz, 5% duty cycle, the prototype achieved 1000W peak power out of 200um/0.22NA fiber with 20°C water cooling temperature (fig 4.3 (a)) at 65A. However, laser is not fully locked at the VBG center wavelength, 975.5nm (fig 4.3 (b)). Roll over at high current can be seen clearly mainly due to blooming of beam divergence. When we increase the duty cycle, the locking gets better with the red shift of free-running wavelengths of the laser chips; in the meantime, power also reduces with the junction temperature rising due to higher thermal load. The laser is fully locked in CW mode.

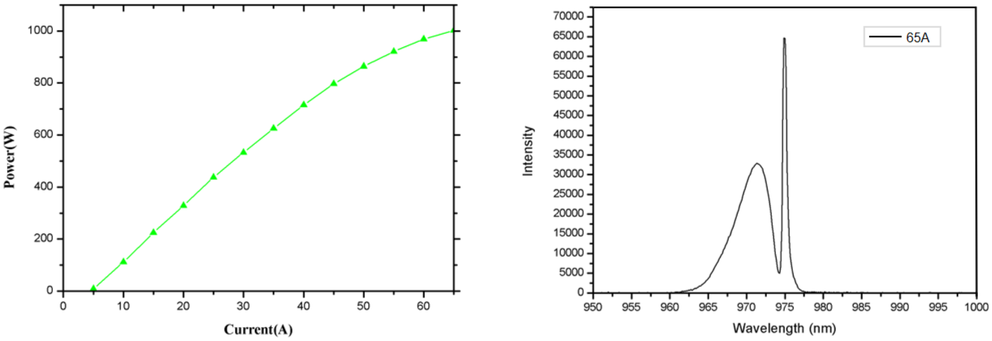

Fig 4.3 (a) left: P-I curve (b) right: spectrum at 65A. Cooling water temperature is around 20°C, 200Hz, 5% duty cycle

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Further improvement is still underway to increase the coupling efficiency by improving the mounting and alignment process, and to use VBG with higher reflectivity.

5. SUMMARY

In this paper, we reported our progress on kilowatt wavelength-stabilized CW and QCW diode lasers at BWT, and discussed key parameters affecting the wavelength-locking performance. To achieve wider wavelength-locking range, VBG wavelength should "match" the chip's free running wavelength considering operation conditions. Higher VBG reflectivity can always improve wavelength-locking range. However, the reduction in output power and risk of COMD need to be considered as well.

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