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Power scaling of laser diode modules using high-power DBR chips

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ABSTRACT

A family of laser diode modules emitting hundreds of watt and based on intrinsically wavelength stabilized narrow linewidth high-power Distributed Bragg Reflector (DBR) chips has been manufactured and fully characterized. The module layout exploits a proprietary architecture to combine through spatial and wavelength multiplexing several highly manufacturable chips that integrate a grating and therefore do not require additional external stabilization devices to allow dense wavelength multiplexing. Power levels going from 200 W to 400 W in a 135 micron core fiber have been achieved using two to four wavelengths. The narrow spectral emission of each chip makes the modules suitable not only for direct-diode material processing, but also for laser pumping.

Keywords: High-power DBR diodes, Multi-emitter diode module, High-brightness laser diodes, High power laser diodes

1. INTRODUCTION

Although recent progresses in High Power Laser Diodes (HPLDs) have led to broad area Fabry-Perot (FP) chips capable of almost 20 W of emitted power, still applications require fiber coupled modules with total power one order of magnitude higher; and this is typically achieved by combining a plurality of such emitters mainly exploiting spatial and polarization multiplexing.[1–3] However, power scaling through spatial multiplexing is limited by the Beam Parameter Product (BPP) required at the delivery fiber, while polarization multiplexing can only provide a factor of two (clearly, provided that the polarization purity of the chips is adequately maintained in the assembly process). In particular, given the limited variability range for the Numerical Aperture (NA) values of standard fibers, increasing the number of stacked emitters in spatial multiplexing means enlarging the core of the delivery fibers, which goes from the about 100 µm of the previous generation of HPLD modules capable of emitting 100-150W, to the about 200 µm of the current generation of HPLD modules capable of emitting 200-300W. Therefore, it is evident that further power scaling without using larger fibers can be obtained only through an additional level of multiplexing, the so-called "Wavelength Division Multiplexing" (WDM), which consists in combining chips emitting at different wavelengths.[4]

WDM approaches are easy to implement if the considered wavelengths are quite far apart, but this choice limits the applications since some of the wavelengths can be outside the absorption peak of the material with which the laser light interacts: for example, this is the case of modules used for pumping rare-earth doped lasers.[5] On the other hand, closely spaced WDM ("dense", D-WDM) requires not only high performance dichroic mirrors or gratings to combine the beams, but also wavelength stabilized chips to ensure a very small drift of the emission wavelength peak due to changes in the operating current and temperature. In practice, this approach is typically implemented by locking the emission of high-power FP chips with an external wavelength selective feedback, usually given by a Volume Holographic Grating (VHG).

The paper discusses an alternative approach to power scaling, based on intrinsically stabilized high-power chips that integrate a grating in a DBR configuration. In more details, the paper presents the design and prototyping of a new family of multi-emitter modules that exploit D-WDM implemented using narrow linewidth and intrinsically wavelength-stabilized Distributed Bragg Reflector (DBR) HPLDs.[6,7] Since these new chips

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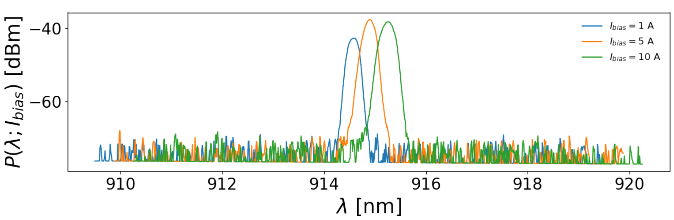
integrate a wavelength stabilization grating, they do not require external feedback devices, therefore greatly simplifying the assembly process and reducing the overall costs. Moreover, they are highly manufacturable since they can be realized without significant modification of current FP chip manufacturing flow; further, they enable a great freedom in choosing the wavelengths, even in the same wafer, simply by changing the period of the grating through photolithographic techniques. Compared to their FP counterparts, however, these DBR have a slightly lower efficiency, resulting in a 10% lower emitted power for the same driving current, but exhibit a spectral drift of only 2 nm going from 2 to 14 A of driving current, instead of 10 nm of broad area FP diodes.[7]

The mentioned design flexibility in selecting the emission wavelength make possible to increase the module efficiency by reducing as much as possible the spacing among different wavelength. For example, using a stochastic model of real DBR–HPLD it is possible to fit up to seven 6.5 nm spaced wavelengths into the 905–945 nanom ytterbium pump band. This leads to a family of high power modules that can be used both for pumping ytterbium-doped fiber lasers and for direct-diode material processing. Here we report on the design and manufacturing of two modules with output power of 140 W and of 400 W coupled in a 135 µm/0.15 NA delivery fiber.

2. MODULE DESIGN

The module design is based on the use of the highly manufacturable Convergent's HPLD–DBR presented in another paper at the same Conference.[8] These chips emit about 10 W when fed by a current of 10 A, with very similar slope efficiency as that of the "standard" high-power broad area FP chips. However, thanks to the DBR structure, they offer a peak wavelength shift with respect to injection current about one order of magnitude smaller, a thermal drift smaller or equal than 0.1 nm/K, and a much narrower spectrum for which about 90% of the total power is within a 0.5 nm width, as it is shown in Fig. 1 and in Fig. 2. These features make these chips ideal for WDM approaches, which requires high wavelength stability and narrow spectrum.



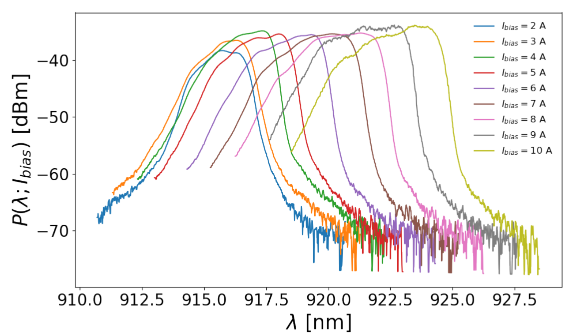


Figure 1. DBR–HPLD (left) and FP–HPLD (right) power spectra for different injected current values.

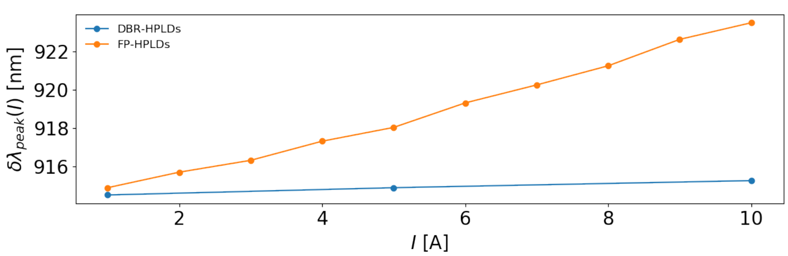


Figure 2. Comparison between the high power FP (FP-HPLD) and DBR (DBR-HPLD) peak wavelength shift as function of the injection current.

A stochastic model to simulate the module in realistic condition has been implemented to maximize the number of wavelengths that can be effectively multiplexed, and therefore choose the optimal wavelength spacing and the optimal design for the dichroic mirror (Fig. 3). This model takes into account the chip peak wavelength and spectrum distribution to compute the total average power transmitted through the dichroic mirror as function of the temperature (considered range for the module after having been mounted on a proper cold-plate from 15 °C to 35 °C) and its standard deviation and the dichroic mirror transition wavelength $\Delta\lambda_t$ and the laser diode wavelength spacing $\Delta\lambda_L$. Clearly, ideally $\Delta\lambda_t$ should be as small as possible and $\Delta\lambda_L$ should be at least 1 nm larger than $\Delta\lambda_t$ to take into account possible laser diode wavelength variations. However, considering the operating polarization of the chips, current state of the art in the manufacturing of the dichroic mirrors imposes at least 6 nm for the transition wavelength, therefore setting the laser diode wavelength spacing lower bound to 6.5 nm.

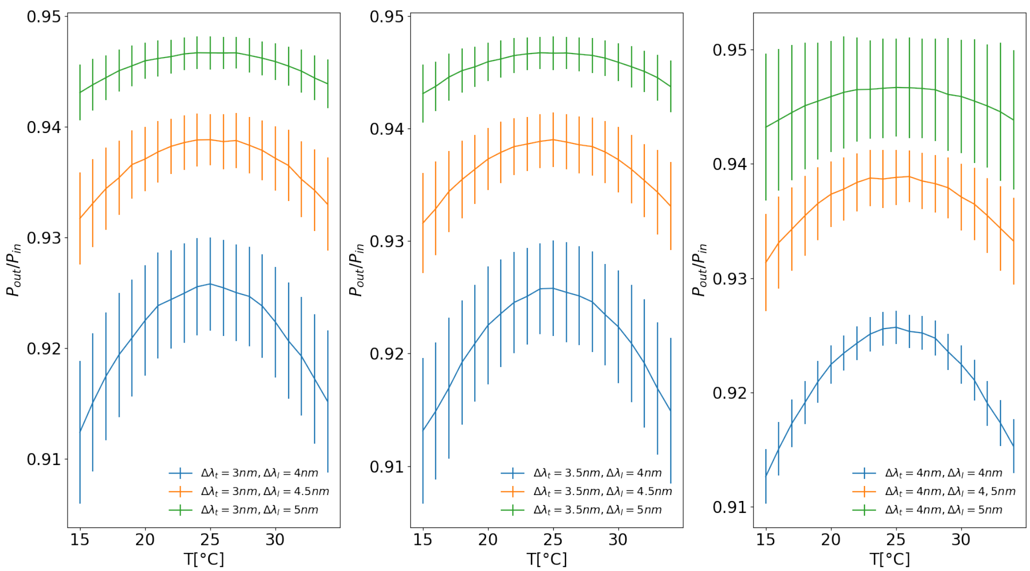


Figure 3. Dichroic efficiency as function of the temperature and of the design parameters.

The choice of the remaining optical elements has been carried out using an ad-hoc optical model, already extensively validated.[9,10] Considering the beam parameters of the chips and the core size and numerical aperture of delivery fiber, up to 10 emitters can be spatially combined. Therefore, result of the design is a family of modules that with two wavelengths only can theoretically deliver up to 400 W, as shown in Fig. 4; in particular:

- Spatial combination of 10 emitters per wavelength and multiplexing of 2 wavelengths, for a delivered power up to 200 W. This solution has the big advantage of not requiring any change in the "standard" design of 200 W modules, which are typically based on beam stacking and polarization multiplexing, since the dichroic mirror can directly replace the polarization combiner.
- Spatial combination of 10 emitters per wavelength followed by a two-wavelength multiplexing and then the polarization multiplexing for a delivered power up to 400 W.

3. EXPERIMENTAL RESULTS

In this paper only the 200 W configuration is considered because more attractive since it can constitute a direct replacement for the currently available modules, without requiring any modification in the package. The assembly of the prototype module has been made by using an ad-hoc automatic assembly line that exploits artificial intelligence approaches to optimize the positioning and alignment of the optics while minimizing the required time.[11,12]

For limitations in the prototypal assembly station, so far only a demonstrator module composed of two sets of 9 DBR-HPLD (generation 1) each (instead of 10) has been realized, for a theoretical maximum power of 180 W.

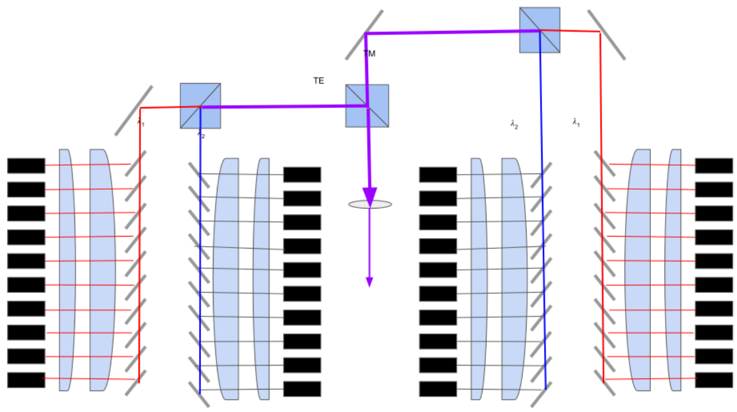


Figure 4. Generic scheme of a module that exploits a combination of beam stacking, WDM, and polarization multiplexing.

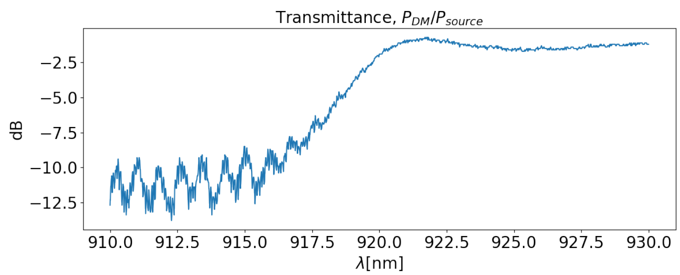


Figure 5. Dichroic mirror measured transmission spectrum.

The module uses two wavelengths quite far apart, 913 nm and 923 nm, combined through a custom designed dichroic filter with a 9 nm 5%-95% transition bandwidth, whose characterization is shown in Fig. 5.

Fig. 6 reports the measured spectrum of the assembled module, with the two peaks corresponding to the two wavelengths.

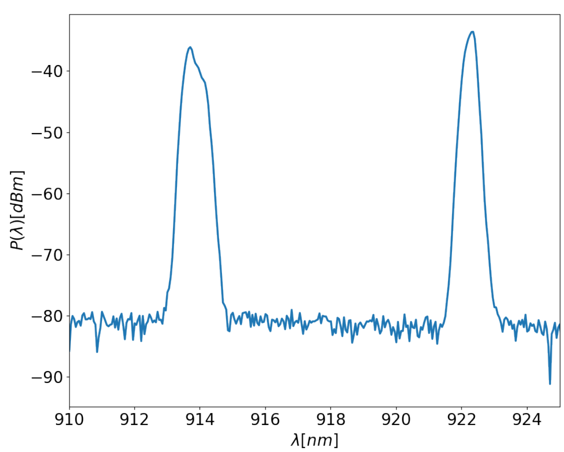


Figure 6. Measured spectrum of the assembled module (the vertical axis scale is after an attenuator).

The measured power is about 120 W at 10 A and 150 W at 12.5 A, as can be seen in Fig. 7. The difference between the predicted output power and the measured one is mostly due to DBR-HPLDs used in this module. Indeed, compared to the latest DBR-HPLDs available (the “generation 2”), which deliver an average output power of 9 W at 10 A, the DBR-HPLDs used in this work belongs to the generation 1, which are less performant and capable of delivering only about 8 W at 10 A, limiting the module maximum average output power to about 140 W at 10 A. Then, the remaining dissipated power is due to the dichroic mirror power dissipation, as predicted by the aforementioned stochastic model, and the optical coupling between the laser diodes and the rest of the optical elements involved. Considering these limitations, the overall efficiency is 83%, which is a similar value as that obtained in “standard” modules that exploit polarization multiplexing. In other words, the loss introduced by the dichroic mirror coupling is similar to that due to the polarization beam combiner, demonstrating that WDM with the new DBR-HPLDs can effectively substitute (or complement for further power scaling) polarization combining to increase the brightness of the multi-emitter high power modules.

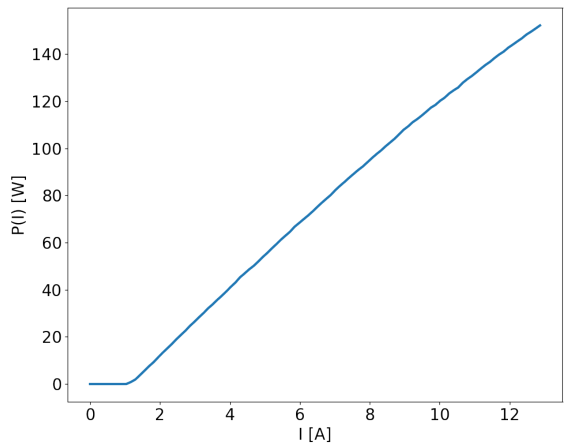


Figure 7. Coupled power against the driving current for the assembled module.

4. CONCLUSIONS

The feasibility of a high-power, high-brightness diode module based on new DBR-HPLDs and exploiting beam stacking, WDM and polarization multiplexing has been analyzed. It has been shown that, taking advantage of the design flexibility intrinsic in the new DBR-HPLD and upon proper optimization, it is possible to realize high-power device suitable both for fiber laser pumping and direct diode applications. A two wavelength configuration without polarization multiplexing has been assembled using the same package footprint of the more conventional device that exploits polarization multiplexing instead of wavelength multiplexing to achieve about the same level of emitted power. Preliminary results obtained with generation 1 of the DBR-HPLD have not permitted so far achieving the expected theoretical full power value due to limitations in the maximum power emitted by each chip; however, an efficiency comparable to “standard” devices has been demonstrated. An emitted power closer to the expected values is therefore expected with generation 2 of the DBR-HPLDs.

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