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High-power multi-emitter modules with fiber Bragg grating stabilization

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ABSTRACT

The paper reports on the wavelength stabilization of high-power laser diode multi-emitter modules using as the external reflectors fiber Bragg gratings that are directly inscribed into the large mode area module delivery fiber using a femtosecond laser. Experiments have been carried out in a 200 µm fiber at 976 nm, but the approach can be extended at other fiber diameters and wavelengths. The results have demonstrated an effective stabilization over a broad driving current range, with power penalties in line or slightly lower than those of more traditional architectures that make use of discrete components, such as volume Bragg gratings, but with the advantage of not requiring the alignment of additional elements.

Keywords: Multi-emitter diode laser modules, Laser diode stabilization, Fiber Bragg gratings, Femtosecond written fiber Bragg gratings, High-power laser diodes.

1. INTRODUCTION

The remarkable success of laser materials processing is pushing the quest for higher power and higher efficiency lasers, in particular of Fiber Lasers (FLs), which are the current dominant technology on the market; in turn, this calls for the development of increasingly powerful and higher-brightness laser diodes for pumping. The achievements on High-Power Laser Diode (HPLD) modules in the last years are so relevant that, besides for being used in pump units, they are enabling the development of Direct Diode Lasers (DDLs), which are becoming a particularly interesting alternative to FLs for their higher overall efficiency given the absence of additional pump-to-signal conversion efficiency loss.[1,2]

State-of-the-art in HPLD single diodes is constituted by broad-area chips emitting about 20 W for continuous operation, which represents a hard to break upper limit (although in test conditions an almost double power can be obtained), especially considering how high becomes the power density on the chip facet.[3] Indeed, given the stringent reliability constraints and considering the limitations imposed by thermo-optic effects that cause distortion in the laser beam, it is very difficult that current performance can be significantly improved in the near future. Therefore, modules emitting hundreds of watts are made by combining a plurality of laser chips either in bars or in multi-emitter configurations, the latter being the preferred choice of recent products for its higher reliability. The most common arrangements utilize a two-level scheme in which spatial multiplexing (also known as "beam stacking") is applied first, followed by polarization multiplexing.[4–6]

In spatial multiplexing individual laser beams are simply set side-by-side in a one- or two-dimensional array, thus increasing the output power although at the expenses of the beam size, which leads to a degradation of the beam quality and thus poses a strong limitation on the number of chips that can be combined. On the other hand, polarization multiplexing does not degrade the beam quality (at least in principle), but it is limited to a factor of roughly two.

A so far not fully exploited alternative, is the Wavelength Beam Combining (WBC) or Spectral Multiplexing (SMUX), in which a dispersive optical element, such as a diffraction grating or a dichroic mirror, is used to spatially overlap beams of different wavelengths.[5] Again, the output power increases, but keeping an almost constant beam size and thus an almost constant beam quality. The WBC approach has been already successfully applied to both diode and fiber lasers, using as the spectral combining elements dielectric filters, dichroic mirrors

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and planar diffraction gratings. Since efficient multiplexing requires lasers with very narrow spectral width and very stable peak wavelength emission with temperature, these requirements rule out most of the high power laser diodes, which for power density constraints are based on a multimode Fabry-Perot (FP) cavity. However, the problem can be solved by spectrally stabilizing these diodes using an external reflector that dominates over the laser intrinsic cavity.

Spectral stabilization of laser using external cavities has been known for several decades and widely exploited in the realization of low power, narrow-band, single mode diode lasers for telecom applications. In these cases, Fiber Bragg Gratings (FBGs) inscribed in the single-mode delivery fiber have been typically used to provide the external feedback. As for high-power diodes, the stabilization is way less common and it has been obtained through external discrete components, such as Volume Bragg Gratings (VBGs), or by developing special high-power DFB chips.[7] The use of VBGs requires the positioning of additional components in the multi-emitter, with all the related alignment errors and corresponding mitigation techniques already analyzed for other discrete components, such as the collimating lenses.[8–10] Besides, it requires additional assembly time, with consequent reduction of the process throughput. On the positive side, it allows the stabilization of common FP chips, without having to modify the output facet coating, although at the expenses of a slight decrease in the power efficiency. Instead, the use of FBGs inscribed on the delivery fiber would have all the advantages of VBGs without requiring additional components and thus alignments.

The critical point in the case of FBGs is the realization of effective reflectors in large diameter fibers. Indeed, while the realization of FBGs in single-mode fibers is a well mastered technology with applications both in telecom and in sensing,[11,12] the use of multi-mode fibers becomes practically impossible with the traditional FBG fabrication approach that relies on the exposure to an intense UV laser beam through a phase mask. However, in recent years the diffusion of femtosecond lasers has introduced more degrees of freedom in the fabrication of FBGs, enabling for example the modification of the refractive index in a large area cross section by partially overlapping spots focusing the beam at different heights. The remaining of the paper reports on the stabilization of laser diodes using as external reflectors FBGs that are directly inscribed into the large mode area delivery fiber using a femtosecond laser.

2. BACKGROUND

As well known, lasing conditions can be reached only in a small wavelength region and this, together with the cavity design, explains the quite narrow emission spectrum of lasers. Nevertheless, compared to single mode laser diodes, HPLDs exhibit a much wider spectrum because of the combination of longer cavities, poorer wavelength selectivity of the mirrors, and, more important, non linear thermo-optical effects.[13,14] Moreover, HPLDs exhibit a strong dependence of their spectral characteristics on driving current and the temperature because they are dominated by the modal gain behavior given the poor wavelength selectivity of the FP cavities. As the current or temperature increase, the gain peak shifts toward longer wavelengths and, consequently, the laser peak wavelength shifts in the same direction too. Besides, the current induced temperature increase causes also a broadening of the spectral width. Typically, the peak wavelength shift is about $0.3\,\mathrm{nm\,K^{-1}}$ for a common FP laser diode. This must be compared with the temperature induced shift of a fiber Bragg grating that could be used as the external reflector for stabilization, which is well known to be of about $0.01\,\mathrm{nm\,K^{-1}}$, one order of magnitude smaller than the bare laser spectral shift.

Depending on the relation between the reflectivity of the front facet and that of the external reflector, it is possible to identify three different working regimes. If the front facet reflectivity is much higher than that of the external reflector, the contribution of the latter will be negligible and the dominant effect will be that given by the modal gain. In this case the laser will substantially behave just like a spectrally un-stabilized chip. If both values of reflectivity are of the same order of magnitude, the HPLD is "semi-stabilized" since there is a temperature interval in which the external cavity dominates over the internal cavity; however, as the temperature increase, the laser passes from a condition where the external cavity dominates over the intrinsic one, to a condition where the intrinsic cavity dominates and the laser behavior becomes again equal to that of the un-stabilized version. This transition is marked by the appearance of two wavelengths sharing the same net gain, which makes possible the simultaneous presence of two peaks in the laser spectrum. Finally, if the reflectivity of the output facet is much smaller than that of the external reflector, the HPLD is spectrally stabilized over a very large temperature interval. From a quantitative point of view this condition happens when the reflectivity of the external reflector is about one order of magnitude larger than the reflectivity of the front facet.

3. FBG INSCRIPTION

The goal is to write an FBG with high enough reflectivity to overcome the chip output facet reflectivity to stabilize the emission, in a large, multimode, as typically are the fibers used for high power laser delivery. This represents a critical task because in order not to couple light from the core to the cladding, the refractive index modifications forming the FBG should be as homogeneous as possible, covering the whole area of the fiber core which, in the case of the delivery fiber for HPLDs, is typically in the order of 200 µm. FBGs can be fabricated either by exposure to a UV laser through a phase mask or by direct writing using a femtosecond laser. In general, the phase mask based method allows for the inscription of an extremely precise refractive index modulation, but with a transverse spatial extension of few tens of micrometers at most; hence it is not well suited for the inscription in very large core area fibers. On the contrary, the femtosecond laser direct writing might be less accurate, especially for what concerns the refractive index variation homogeneity, but it allows modifying the refractive index at any position in the core by changing where the beam is focused. Usually femtosecond laser writing of FBGs is carried out by modifying the refractive index in a sequence of points at predefined positions along the fiber core axis, with an approach known as the point-by-point method. However, the possibility to focus the writing beam in different positions inside the core for each section can be exploited to partially overlap the ellipsoids in which the refractive index is modified at each laser pulse to produce lines or even planes. This leads to the so called line-by-line and plane-by-plane writing methods.[15] For the considered application a variant of the line-by-line method has been selected and implemented using a laser micro-machining workstation based on a frequency doubled femtosecond laser at 532 nm. Following a detailed study of the laser parameters, some gratings a 200 µm core fiber have been fabricated, as shown in Fig. 1. Unfortunately, the dimensions of the fiber made the characterization of the grating in reflection quite difficult because of the high insertion loss when connected to an optical spectrum analyzer through a coupler. Therefore, the fabrication process has been monitored by evaluating in real-time the effects of the writing on the spectrum of laser diode. This way, it has been experimentally found that the best results were obtained for a 30 mm long grating.

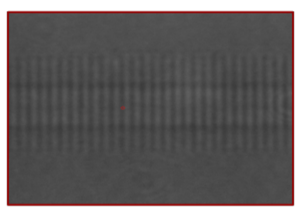

Figure 1. Example of a line-by-line written FBG.

4. PRELIMINARY STABILIZATION RESULTS

The gratings fabricated as detailed in the previous section have been used to stabilize a multi-emitter laser diode module nominally emitting at 976 nm with an output power of 200 W on a 200 µm core fiber at 16 A. In particular, in this paper are reported the results obtained with a 30 mm long FBG with a pitch that produced a main peak reflectivity closer to 977 nm.

Figure 2 reports the spectra of the module for different driving current values before the stabilization. As it can be seen, the spectra are quite broad due also to the slightly different emission wavelengths among the various chips composing the multi-emitter. Moreover, the spectra shown a remarkable shift with the current. Figure 3 reports the spectra for the same current values after having written the FBG in the delivery fiber: it is evident the narrowing of the spectra for all the current values, demonstrating the almost identical wavelength locking condition for all the chips, and the much lower wavelength shift as the current changes.

The effectivity of the grating in stabilizing the emission wavelength as the current changes can be better appreciated from Fig. 4 in which the peak emission wavelength is plotted against the driving current for both the unstabilized and the FBG stabilized modules. The wavelength variation in the module with the grating is

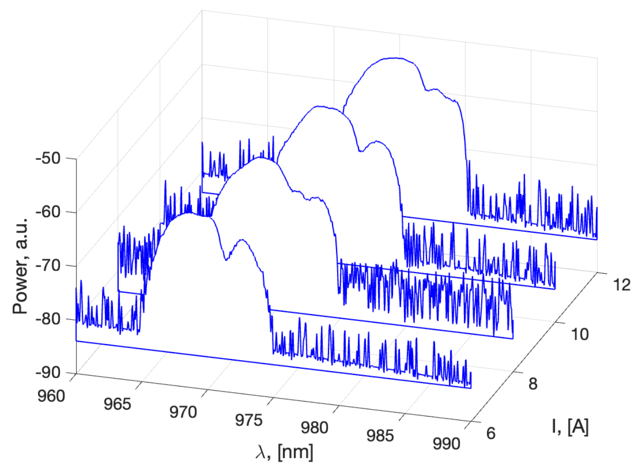

Figure 2. Spectra of the unstabilized module for different driving current values.

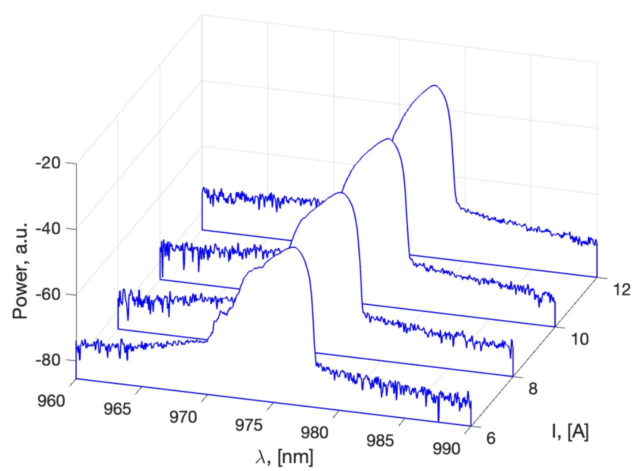

Figure 3. Spectra of the module with the stabilization FBG for different driving current values.

drastically reduced in a broad current range extending from 6 A to 14 A, demonstrating that at least in this range the FBG reflectivity dominates over the intrinsic reflectivity of the various chips.

Fig. 5 reports the power-versus-current characteristics for the two configurations: considering the presence of two splices (one before and one after the grating), the losses induced by the presence of grating can be estimated to be between 20% and 22 %. This is comparable with previous experiments carried out with VBGs that provided similar stabilization characteristics, hence presumably having the same reflectivity.

5. CONCLUSIONS

The feasibility of the stabilization of an entire multi-emitter laser diode module using an external FBG inscribed into the large core module delivery fiber has been experimentally demonstrated. The proposed approach extends to the high-power laser diodes a method already well known for low-power laser diode used for telecommunication applications. The obtained results showed that an effective stabilization can be obtained over a broad driving current range and that the performance in terms of power-versus-current and of additional loss are similar to that previously obtained with discrete components, such as VBGs, but without the need of further components requiring specific alignment procedures.

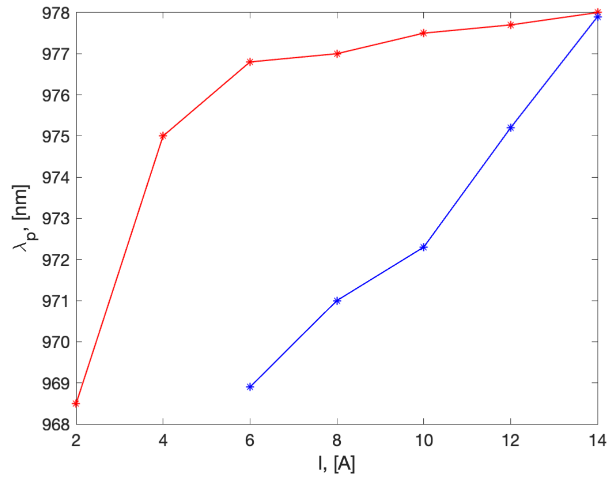

Figure 4. Peak emission wavelength versus the driving current for the unstabilized module (blue points) and the FBG stabilized module (red points).

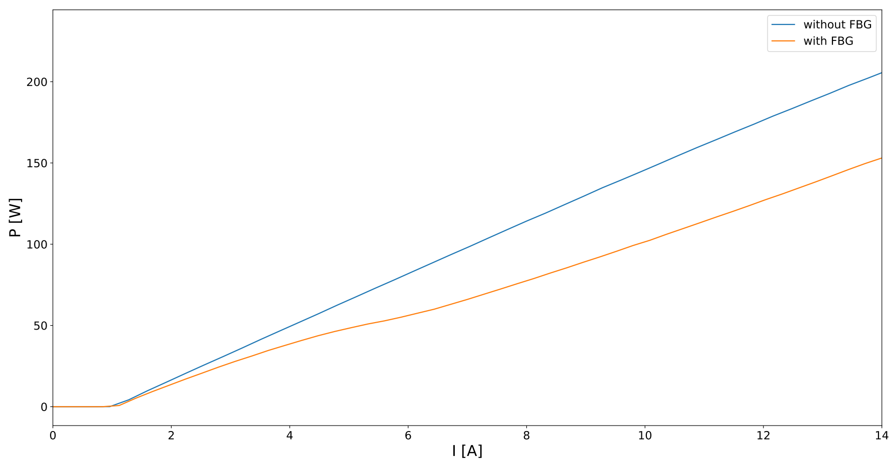

Figure 5. Fiber coupled power versus the driving current for the unstabilized module (blue curve) and the FBG stabilized module (red curve).

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