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Compact high-brightness and highly manufacturable blue laser modules

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ABSTRACT

Blue laser diode sources have already proved to be an effective alternative for material processing, especially of high reflective materials, such as copper; now the challenge is to increase their power while improving brightness and reducing the cost-per-watt. The paper presents the development of a family of blue laser modules that, making use of the same platform and assembly lines of similar 9xx nm modules, can achieve an unprecedented combination of power, brightness, compactness and cost reduction. These modules rely on a proprietary architecture to combine a plurality of chips through spatial and polarization multiplexing, obtaining up to 100 W of output power in a 100 µm fiber. Preliminary experimental results for module making use of spatial multiplexing report 35 W output power in a 50 µm fiber.

Keywords: Blue lasers, Laser material processing, Spatial beam combining, Copper laser welding

1. INTRODUCTION

Laser processing of copper is attracting a growing interest thanks to the many emerging applications, such as electrode welding of battery packs for electrical vehicles and energy storage, and additive manufacturing of complex parts from metal powders. However, the wider deployment of laser tools for the manufacturing of copper components demands further improvements in the processing speed and in the quality of the outcomes. Targeting more specifically the welding application, these requirements mainly mean increasing the effectively usable laser power combined with the absence of sputters and porosity defects.[1] Unfortunately, copper, like other Highly Reflective and conductive Materials (HRMs), cannot be properly processed by today typical industrial laser sources, which are based on kilowatt fiber lasers emitting in the Near Infra-Red (NIR) range, roughly from 1030 nm to about 1100 nm, because of the poor absorption at these wavelengths (Fig. 1).

The curve in Fig. 1 is for copper at room temperature, as the absorption in the NIR increases with rising temperature and it abruptly jumps up when the melting temperature is reached, leading to blow-outs and spattering and ultimately to porosities, deformations of the substrate and thus a poor quality of the weld. This makes the control of the power quite complex when using NIR lasers because, at first, it should be very high to counteract the strong reflectivity, but, as the proper temperature is reached, it should be immediately reduced to avoid overheating. Therefore, while power could not be such an issue, the really limiting factor is the strong variability in the absorption.

These problems can be overcome working at shorter wavelengths, such as in the green (~ 530 nm) or in the blue (~ 440 nm), where the absorption is much higher, as it can be seen again in Fig. 2.[2] Green emission is obtained by frequency doubling of a NIR beam through a nonlinear crystal, such as Lithium Triborate (LBO) or Potassium Titanyl Phosphate (KTP); blue emission, on the other hand, can be directly obtained by Gallium Nitride (GaN) based diodes. Despite green emitting lasers have been available on the market for a longer time than high power blue lasers, they are not practically used for welding applications because of the reliability concerns and energy efficiency of wavelength conversion that results in a high cost-per-watt. Moreover, these lasers typically work in pulsed regime, while for most welding applications a continuous wave operation is preferable. Overall, for

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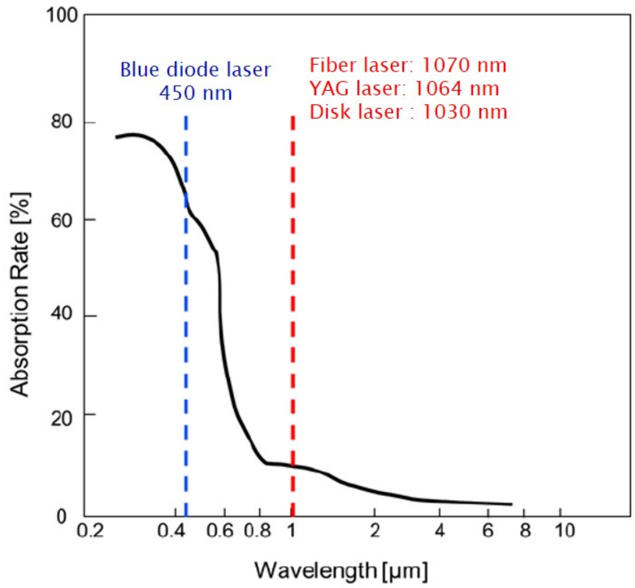

Figure 1. Absorption rate in copper for different wavelengths.

industrial applications it is more attractive working at the blue wavelengths, where copper presents an absorption close to 70% and for which diode-based high-power sources are starting to be available.[3–6]

Current state of the art in single blue semiconductor emitters is chips capable of delivering around 5 W. Therefore, to obtain the power needed for copper processing (at least some tens of watts) quite a large number of such diodes must be combined and it is challenging to obtain a high enough output power while preserving the beam quality. Until very recently, these single blue emitters were available in TO9 packages only and in a recent paper an architecture that allows achieving a very high brilliance using such commercially available diodes is presented.[7] However, the use of in-package emitters, while may have some advantages in terms of reliability, poses many limitations to the compactness of the module and, most important, on the brightness of the combined beam due to the physical separation requirements between two consecutive spatially combined diodes. For instance, the high power in the small diameter fiber reported in the cited paper[7] was obtained only resorting to wavelength division multiplexing in addition to the spatial and polarization multiplexing, which are the most common power scaling methods in commercial high-power multi-emitter modules at 9xx nm. Moreover, the use of in-package diodes is not compatible with the assembly lines employed for 9xx nm modules, which make use of Chip-on-Carried (CoC) devices, and, since these modules represent the largest production volume for high-power laser diodes, this lack of synergy is one the causes that contribute to the currently very high cost-per-watt of high-power blue modules.

The paper reports on the first demonstration of a compact multi-emitter blue module that can be assembled using the same lines of multi-emitter laser diode modules in the NIR.[8–10] This is possible thanks to the use of recently introduced CoC devices emitting in the blue, which maintain electro-optical characteristics similar to those of the TO9 diodes, but with a footprint similar to that of the corresponding NIR devices.

The developed architecture allows the realization of an entire family of devices, with power ranging from 35 W delivered in a 50 µm/0.22 Numerical Aperture (NA) fiber using only spatial multiplexing to almost 70 W in the same fiber adding the polarization multiplexing, up to about 140 W in a 150 µm fiber by combining spatial and polarization multiplexing, always in modules that have sizes similar to those of the equivalent NIR devices.

2. MODULE DESIGN AND SIMULATION

The developed module family exploits for the power scaling the spatial and polarization multiplexing techniques, which represent the de-facto standard combination approaches in 9xx nm multi-emitter modules, although implemented in a proprietary architecture. For this preliminary series no wavelength multiplexing is considered, so no specific wavelength stabilization is necessary.

The first multiplexing level is the spatial combination of a plurality of single emitter diodes, as sketched in Fig. 2: the beam coming from each diode is first collimated along the Fast Axis (FA) and the Slow Axis (SA), then is directed towards the collecting fiber using a focusing lens. Since the single emitters are almost fully s-polarized, two of such rows can be further multiplexed by having one of the spatially combined beams pass through a half-waveplate to rotate its polarization plane and then using a polarization combining cube.

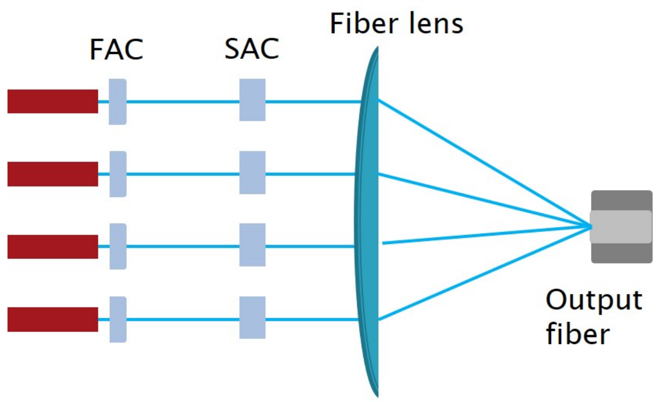

Figure 2. Scheme of a multi-emitter module.

The opto-mechanical layout has been designed with an ad-hoc simulation tool, which exploits Gaussian beam propagation and ray tracing techniques to propagate the field distribution from each chip through the various lenses and compute the coupled power into the collecting fiber.[11,12] As an example of the results, Fig. 3 shows the simulated impact of the focal length of the collecting lens on the coupling losses and on the NA of the output beam.

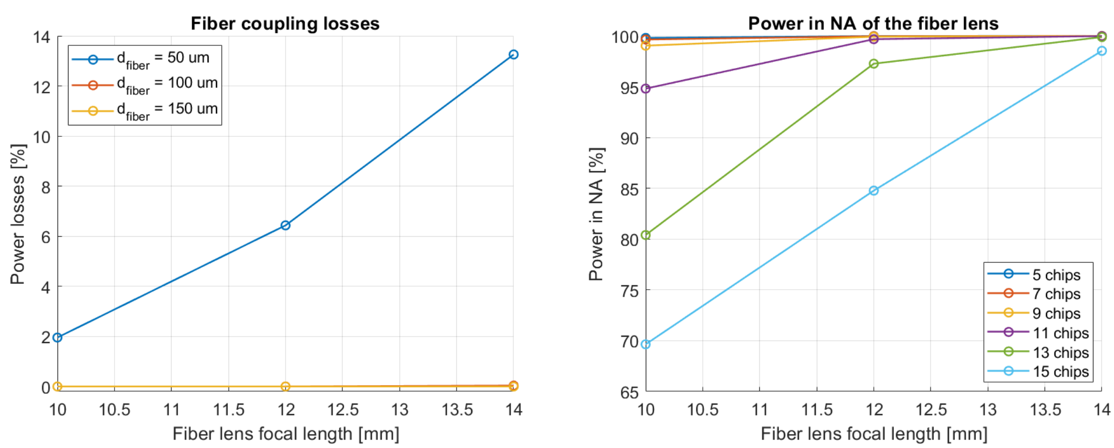

Figure 3. Effects on focal length of the collecting lens on the NA of the output beam and on fiber coupling losses.

Considering the results of the simulations and the constrains imposed by the use of the automatic production line, three prototypes have been designed, whose maximum output power and delivery fiber are reported in Tab. 1.

The first experimental implementation reported in this paper is based on the first design, as described in the following section.

Table 1. Designed prototypes.

Fiber core	Power (spatial comb.)	Power (spatial+pol. comb.)
50 µm	35 W	65 W
100 µm	55 W	95 W
150 µm	75 W	140 W

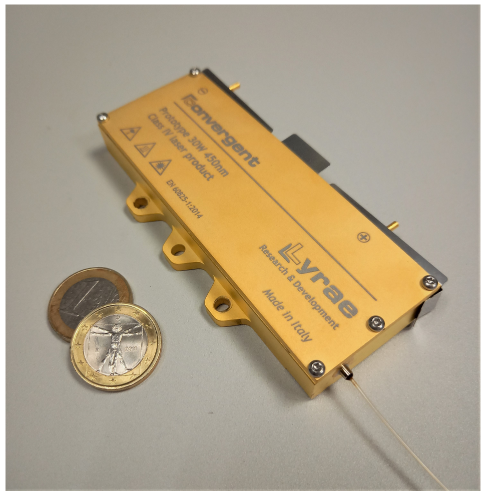

Figure 4. The first 35 W multi-emitter blue laser diode module.

3. EXPERIMENTAL REALIZATION

Aiming to demonstrate the proposed technology and its compatibility with the standard production line tools of Convergent Photonics in Torino, the preliminary prototype series has been assembled using the packages employed in the NIR module production and therefore with dimensions not properly optimized for the blue laser chips (Fig. 4). Nevertheless the characterization results are encouraging and well in line with the simulations as it can be seen from Fig. 5, which reports the power versus current curve as measured from the delivery fiber. The simulation prediction of 35 W of maximum power has been obtained at 4 A, still in the linear region, without signs of kinks or power saturation.

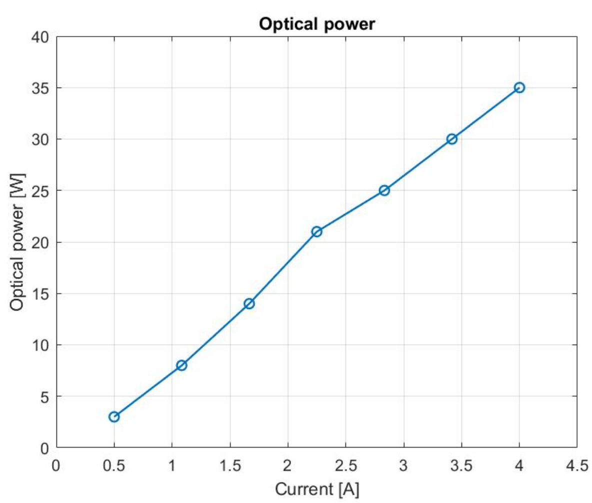

Figure 5. Fiber coupled output power against current for the first assembled module, which relies on spatial beam combining only.

An important parameter both for device operation and reliability is the percentage of the total delivered power within the fiber NA. As reported in the far field analysis shown in Fig. 6, 95% of the beam is contained in a numerical aperture between 0.18 and 0.184, equivalent to an half divergence angle between 20.8° and 21.2°. Since the NA of the delivery fiber is 0.22, the power delivered in the fiber can be considered cladding mode free. Moreover, again as evident from Fig. 6, the effect of the driving current on the divergence angle is negligible.

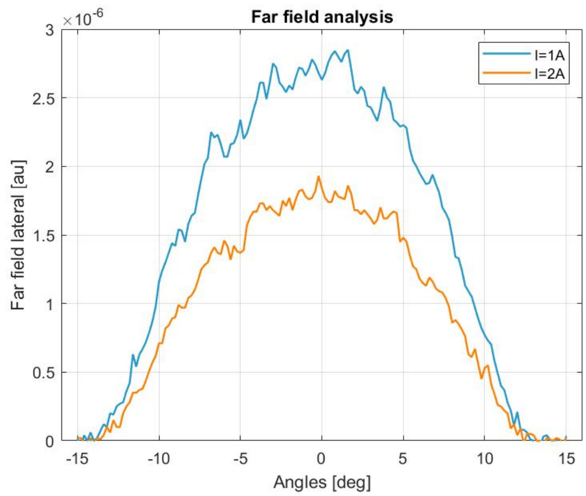

Figure 6. Far field characterization of the first assembled module for two driving current values.

4. CONCLUSIONS

A family of new multi-emitter compact blue laser modules has been designed and simulated using an ad-hoc tool. The first type, a device that relies on the spatial multiplexing only, has also been assembled using the automatic production line for the NIR laser modules and fully characterized. The final results are in-line with expectations, although further studies to optimize the device and to further scale the power by adding the polarization multiplexing are currently ongoing.

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