Optimized Packaging Solutions for Multi-Emitter Laser Modules

Giulia Pippione*, Simone Codato *, Alberto Maina *, Alessandro Mirigaldi†, Martina Riva‡, Roberto Paoletti *
*Convergent Photonics Prima Electro S.p.A., Via Schiaparelli 12, Torino (TO), 10148, Italy
giulia.pippione@primaelectro.com
†Dept. of Electronics and Telecommunications, Politecnico di Torino, 10129 Torino, Italy
‡ ALITE SRL, Applied Lightwave Technologies, Via Schiaparelli 16, Torino (TO), 10148, Italy

Packaged high-power diode lasers have applications in many areas ranging from optoelectronic high density data storage, high power industrial laser for material processing, to medical (chirurgical/aesthetical) applications. The paper presents the development of families of laser modules which, using the same platform and assembly lines, can achieve a specific combination of power, brightness, compactness and cost effectiveness, depending on final application. Results for products emitting at *9XX nm* and at *450 nm* will be presented, describing the design, the realization and the production.

Keywords: High-power diode laser, spatial beam combining, polarisation beam combining.

I. INTRODUCTION

Low cost, manufacturable customized compact sources, enabling mass production of laser modules able to supply hundreds of watts of optical power at defined wavelengths, are of great interest in the diode laser source scenario. In the Torino facility of Convergent Photonics we developed a production line for the fabrication of multi-emitter laser source, with a flexible design enabling a set of product families (different wavelength, optical power, brightness), based on custom requirements and market demand.

The packaging architecture combines single emitter laser sources coupled into an optical fiber, as flexible solution for many possible applications. Core technology of the present realization is the single emitter source developed in Torino Diode Fab of Convergent Photonics, based on a semiconductor laser device mounted on a submount (Chip on Carrier, CoC) [1] [2]; CoC are then soldered on a platform (package) and electrically connected by aluminum wire bonding. In order to scale up the optical power, a combination of spatial multiplexing, polarization multiplexing and wavelength multiplexing (implementing a multi-emitter module) is fruitfully used, achieving the desired range of output power and/or wavelengths. Optical layout, including fast and slow axis collimators, reflecting mirrors, polarization beam combiner components, focusing lenses, has been designed starting from single emitter beam (Near Field and Far Field) and power specifications, and considering the output power, emitted wavelength and brightness required target. Final multi-emitter architecture has been eventually designed aiming an optimal integration with the Convergent Photonics production line.

II. DESIGN AND MODELING

A. Optical design and simulation

The laser module families exploit the power scaling with spatial and polarization multiplexing. The first multiplexing level is the spatial combination of single sources CoC. The beam coming from each diode should be collimated along the Fast Axes (FA) and Slow Axes (SA) separately, in order to correctly manage the different divergences of the beam along parallel and transverse axes. A certain number of CoC are electrically connected in series (bank), collimated and directed toward a fiber using a focusing lens (Fig. 1).

However, power scaling through spatial multiplexing is limited by the Beam Parameter Product (BPP) required at the delivery fiber. In order to further scale up power maintaining high brightness, second multiplexing level employs the polarization combining, providing almost a factor of two in term of final optical power. The module presents two banks and, since the single emitters are almost completely s-polarized, the collimated beams of the second bank pass through a half-wavelength plate to rotate their polarization plane, before being focused on the fiber throughout the focusing lens (Fig. 2).

In order to define the optical design, which includes the Fast Axis Collimator (FAC) and Slow Axis Collimator (SAC) to collimate each single emitter and the Fiber Lens (FL) to focus their combination into the fiber, two sets of optical simulations have been performed.

The first set of optical simulation is based on the easiest assumption of gaussian beam propagation through aberration-free thin lenses. The single emitter source is defined by means of the Fast Axis and Slow Axis waists dimension and their divergence. A Gaussian beam is then propagated in the limits of the paraxial approximation and thus analyzed through the Gaussian beam ray-equivalent model, exploiting five paraxial rays. In this model each laser beam is modeled by the geometrical propagation of five rays which propagates through the optical path according to the rule of the ray tracing [3] [4] [5]. Defining the spatial position of the FAC and SAC, the beam stacking on the plane of the FL is therefore computed.

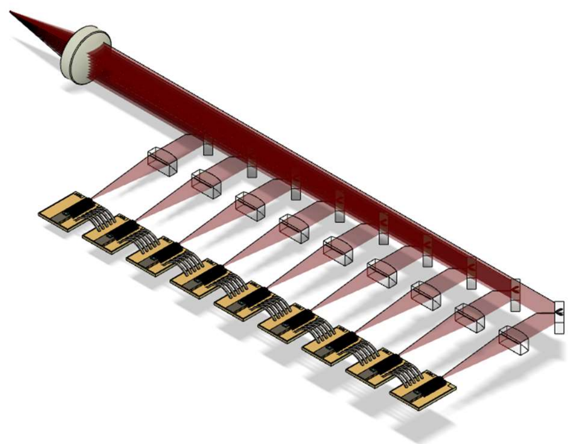

Fig 1. Scheme of the multi-emitter packaging s-serie with a spatial multiplexing. Beams from each single emitter are collimated with Fast and Slow axes collimator, then directed toward a focusing lens and launched in a fiber. System represents a "bank" of sources.

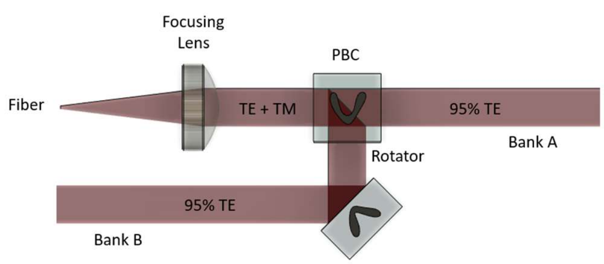

Fig 2. Scheme of a polarization multiplexing. Two s-polarized beams pass through a polarization Beam Combiner: one beam rotates its polarization plane by a half-wavelength plate, then its contribution is added to the other beam.

According to the FL focal lens, the coupling characteristics into the fiber core are eventually evaluated, in terms of magnification and Numerical Aperture (NA) of the coupled beams. Thanks to its extremely low computational cost, this model is useful to roughly determine the features of the optical elements to be used, according to the target NA and magnification.

A second set of optical simulations, based on the wave-optics framework [6], is performed to further optimize the optical design. In this model each laser beam is modeled as a complex electromagnetic field, whose propagation along the optical path and through optical elements such as lenses and mirrors is computed according to the Fourier Optics. Compared to the simpler five rays' model, this approach allows a much more detailed study of the beam's propagation through an arbitrary optical path with a significantly higher precision. Moreover, the model can take into account features, like for instance the optical filamentation in the diode laser output beams, not evaluated by the Gaussian approximation simple model; drawback is the required larger computational cost. The combination of the two models finally leads to the optimized optical design in terms of desired NA (usually required lower than 0.17 at 95 % peak power), and magnification, strictly related to the fiber core dimension (i.e. 50 µm, 105 µm or 200 µm). An example of this simulation output is shown in figure 3.

B. Mechanical design

Implementing only the spatial multiplexing level, the *S-series* package has a very compact foot print of 53 mm x 107.5 mm and has been designed in order to host a stack of a defined number of CoC.

CoCs are mounted by using a particular technology where a Sn-based soldering preform is locally melted by a laser pulsed beam. This technology delivers important advantages over standard soldering techniques, in terms of cycle time, precision and thermal dissipation. Each CoC is first passively aligned on the housing step, then positioned and soldered by using the preform properly activated by the laser beam. The process is performed at room temperature, without any heating cycles or chemical treatment.

After a visual inspection on diodes front facets, the CoCs are connected in series and to the package electrodes by aluminum heavy wire bonding.

Beam coming from each CoC is then individually collimated. A 90 ° reflection allows the beams to be stacked and focused together and launched in an optical fiber. The platform is a step layout in which the parameter are the step height and the number of steps. As the beam NA is mainly influenced by the number of emitters [7], in order to maximize the number of diodes the step height has been optimized, maximizing the stacked beam filling but avoiding at the same time the overlapping of two adjacent beams. According to the simulation described in the previous chapter, optics have been selected in order to have the right spot size on fiber core and NA, starting from the SA and FA Far Field divergence and ridge dimensions of the emitters.

Even if the physical characteristics of IR laser diode and visible are different, the soldering on a submount (Carrier) allows to use the same versatile assembly line.

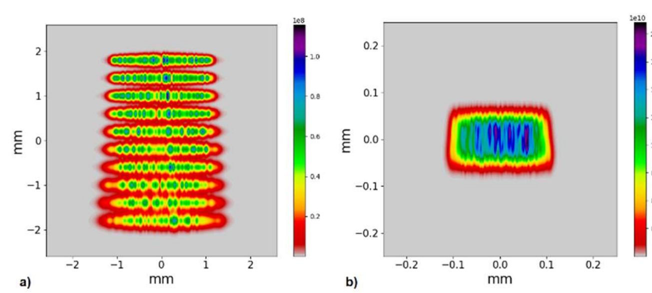

Fig. 3. Example of optical simulation based on wave-optics. On the left (a) beams stacking at fiber lens entrance, on the right (b) focalized beam into the fiber core.

The second *D-series* package (53 mm x 136 mm) can host a double number of diodes, implementing two stacks of beams; one of them pass through a half-wavelength plate, and is overlapped with the other stack by a Polarization Beam Combiner; the two stacks combined together are then routed, similarly to the *S-series* package, to the Fiber Lens.

III. Realization and production

Multi-emitter architectures have been designed aiming an optimal integration with the Convergent Photonics production line. Both for *S-series* and *D-series* package, the dimensions of the components are comparable among different laser modules. Thanks to this modular approach, the power scaling and/or different laser families can be produced minimizing the New Product Introduction (NPI) expensive tasks usually required by a more conventional design.

A. Manufacturing

A high yield automatic production machine for CoC soldering on package has been developed with an industrial partner to address the specific requirements of the previously described novel bonding technology adopted. This process can now be realized for the first time on an automatic die-bonder system at room temperatures, avoiding possible Sn reflow. Typical bonding accuracy achieved, mainly limited by package features mechanical definition, is 20 µm, more than sufficient for the optical components' assembly.

Wire bonding technology has been optimized to ensure high reliable electrical connections of the package, where a series of aluminum wires are bonded by a high throughput automatic industrial system. To ensure a low electric resistance up to six 250 µm thick wires are used to connect parts.

Robotic systems are also used in the production line to align the optical components, collimate the laser beam, perform a coupling loss assessment, and control the quality of high-power diode laser modules. Implementing a cost-effective trade off, some optics and components, such as PBC, Slow Axes Collimator and fiber, are passively aligned and soldered, optimizing time and cost in the production line. Other components, like FAC, mirrors and focusing lens, are actively aligned by precisely placing the lens in front of the emitter while controlling the beam shape, divergence, and center position as indicators of the quality of the beam collimation. Compared to passive alignment, where the lens is placed in a previously calculated position, active alignment improves the accuracy of the micro-optics placement, but the alignment time is often one order of magnitude higher.

Considering that some parts are still assembled manually, the automated process exceeds the 90% of the time spent for the production of one multi-emitter, effectively reducing the labor time and ultimately the production cost.

B. Family products

Near Infra-Red (NIR) high-power multi-emitter laser diode modules have been developed using the Convergent-Torino Diode Fab which produces a portfolio of GaAs-based semiconductor laser diodes. The *9XX nm family* product is suitable as pump source for low-cost multi-kW Yb-doped fiber laser modules. First generation multi-emitter was a laser module emitting 100 W at 920 nm, using the *S-series* spatially multiplexed package [8].

Second generation of multi-emitter modules has been designed based on CoC emitting at 976 nm [9], precisely tuned to the Yb absorption peak, therefore enabling higher conversion efficiency [10]. Respect to the previous 920 nm source, this new product is effectively contributing to a further cost reduction and therefore represents the most cost-effective laser pump source solution for Yb-doped fiber laser modules in industrial market.

With same *S-serie* package, a new multi-emitter emitting at 793 nm has been developed: it provides 70 W CW and up to 140 W QCW on 200 µm core fiber, with a NA of 0.17. The application for this product is as pump laser of Tm-doped QCW fiber lasers in surgery application, a promising rapidly growing new market.

The family product in visible range has been developed as a high performance and cost effective alternative in the market of material processing, especially of high reflective materials, such as copper, and other emerging applications (battery packs, additive manufacturing, etc.). The challenge is to improve brightness, reducing cost-per-watt of the products currently available in the market.

The Convergent's multi-emitters sources are based on GaN CoC emitting at 450 nm. Preliminary results [11] demonstrated very promising combination of power, brightness, compactness and cost, making use of the same platform and assembly lines of NIR modules.

Table 1 and table 2 resume the Convergent's results for the *S-series* and *D-series* layout respectively.

PN	Package s-serie				
	Wavelength (nm)	***Output power (W)***	***Fiber core/cladding (µm)***	***NA***	***Brightness (W/µm² ster)***
AL-100-D	920	100	135/155	0.19	0.05
BL-100-D	976	100	135/155	0.19	0.05
GL-100-E	793	80	200/220	0.16	0.03
DL-030-E	450	30	50/125	0.18	0.15
DL-040-G	450	40	105/125	0.15	0.07

Tab.1 Product' specifications for the product assembled in a *S-series* package (first multiplexing level).

PN	Package d-serie				
	Wavelength (nm)	***Output power (W)***	***Fiber core/cladding (µm)***	***NA***	***Brightness (W/µm² ster)***
AL-200-E	920	200	200/220	0.16	0.05
BL-250-E	976	250	200/220	0.16	0.10
DL-080-G	450	75	105/125	0.15	0.12

Tab.2 Product' specifications for the product assembled in a *D-series* package (second multiplexing level).

C. Second cycle and reclassify

An important aspect of the manufacturing process of the multi-emitter is the second cycle production and recycle for some parts of the product. A defined percentage of multi-emitters will fail quality criteria after being assembled, i.e., fiber damaged or contaminated, power drop of a diode, CoC soldering integrity. In the last year, dedicated tests have been implemented to detect anomalies, and a failure analysis' procedure has been introduced in line to identify the root cause. For some parts in the module, for example the ferrule, an optic, a diode, a focused strategy of rework has been studied. The damaged part is removed and a new one assembled, allowing functionality from the otherwise scrapped entire module. The rework procedure is considered a second cycle in the production line, and it is able to restore around 50% of the modules that failed quality criteria after the first cycle. Some parts are not mechanically reworkable, or the rework is only 40% effective: for example, some critical carriers are not removable after soldering. In this case, the diode fail is short circuited inside the module and its contribution in terms of power neglected. The multi-emitter is reclassified according different specs, therefore belonging to a "class b" product, useful for applications with reduced power specs.

The second cycle production and the reclassify of the product allowed a considerable increase of the efficiency and sustainability of the line. Precise cost model is being currently developed, able to evaluate if reclassifying, reworking or scrapping.

IV. FUTURE PLAN

The future generations of multi-emitter are requiring advanced electronics, not only sourcing the high-power supply for the laser bias, but also featuring a set of controls sensing the diodes and the package temperature, the optical power emitted from the diodes bank(s), implementing the necessary safety features and the control logic, storing device logs, etc. The new multi-emitter series currently under development will therefore integrates such advanced electronics in the package itself, leading to a generation of "*turn-on key*" stand alone compact sources with unmatched characteristics.

The increase of the brightness of a multi-emitter module in visible wavelength range is particularly attractive and, in some case, mandatory (e.g. for the additive manufacturing application with copper or aluminum). Power scaling through spatial multiplexing is limited by the BPP, and polarization multiplexing can only double the power. A further level of multiplexing consists in combining chips emitting at different wavelengths in the so-called "Wavelength Division Multiplexing" (WDM). This approach has been demonstrated [12] [13] by using Convergent proprietary technology, HPDL-DBR (High Power Diode Laser monolithically integrated with DBR) featuring a wavelength-stabilized narrow-linewidth emission, enabling therefore a dense wavelength multiplexing by using dichroic elements.

A process of optimization of the package structure is currently under development, aiming to a new high brightness multi-emitter future series.

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