Advances in power-delivery and loss-handling capabilities of small connectors for fiber-optic launching of high-power diode lasers

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OPTOSKAND ● DILAS DIODENLASER
ABSTRACT

Constant advancement in laser sources leads to commercial and industrial lasers with ever higher output powers and brilliance. The increasing capabilities of diode laser sources in particular produces extreme challenges for fiber launching. The difficulties arise due to the nature of the diode lasers, which are often designed with a numerical aperture (NA) exceeding the optical fiber’s NA and a spot size overfilling the fiber core so as to maintain the best possible brilliance. In addition to these properties, the spot imaged onto the fiber facet is typically rectangular. The combination of these properties result in an imperfect launch efficiency, forcing the connector built around the optical fiber to cope with the radiation which is “lost” from the core of the fiber.

Improvements in the Optoskand SMAQ connector are discussed, along with the presentation of results showing the increased power- and loss- handling capabilities when used with a variety of diode laser sources at 976 nm. The sources used in the tests are optimised for an optical fiber of core diameter (Ø) 200 µm and NA of 0.22. The sources range in maximum power from 150 W to 1000 W with a coupling efficiency of between 80 and 90%. Additional complimentary results are shown for a Ø=400 µm fiber guiding light of NA=0.12 where launch efficiency is 90 to 95%.

Keywords: Optical fiber, fiber launched diode laser, high-power diode, loss handling fiber.

1. INTRODUCTION

When considering launching and guiding light in an optical fiber we define “useful” light as the light which is guided in the core of the chosen fiber. For the sake of the optical fiber and the safety of the cable holding the fiber and any living or inanimate objects in the proximity of the cable, the light which is not useful should be removed in the connector before the fiber enters into the cable. Removing this light with a mode stripper results in an inefficiency between the raw power the laser produces and the useful power contained within the core of the fiber, which in this paper will be called “losses”. There are two loss mechanisms when coupling a laser beam into the fiber. The first is overfilling the core, focusing the laser beam down to a spot size which is larger than the fiber core. The second is overfilling the numerical aperture (NA) of the fiber, entering the fiber at an angle larger than that which is accepted by the fiber.

When launching industrial lasers such as fiber- or disc- lasers into an optical fiber, choosing a focusing lens and fiber core diameter to achieve near-zero losses while not significantly reducing beam quality is not a process which involves significant compromise. Conversely, when launching industrial diode lasers into an optical fiber, the nature of the beam and the spot (both quadratic), their differences to the fiber and disc lasers result in a compromise choice between launch efficiency, losses and brilliance, which will be discussed in subsequent sections.

Fiber-launched high-power diode lasers are routinely used for myriad applications, significantly as pump sources for fiber lasers and for materials processing. To find new applications and to enable cost reductions in these applications, the diodes are continually being manufactured with increased power. Losses are inherent when launching diode lasers into optical fibers, so to increase the power transported by an optical fiber coupled to a diode laser is not a straightforward process. The optics and mechanics connectorising the optical fiber must be able to withstand the increased optical and thermal loads inevitable with the rise in lost power associated with an increase in useful power.

This report will describe the performance of the Optoskand SMAQ connector regarding overfilling the fiber with a variety of different diode laser sources at 976 nm in order to demonstrate the connector’s capability in dealing with the demands of increasingly powerful sources.
2. FIBER INCOUPLING

2.1 Ideal incoupling
To achieve ideal efficiency when coupling a laser beam into a fiber, the launch angle of the beam should be within the numerical aperture of the fiber and the focal spot imaged onto the fiber facet should be smaller than the fiber core.

![Diagram of ideal launch conditions](Image)

\[ \alpha > \beta \text{ and } d_{co} > d_s. \]

If the spot-to-core ratio is too large, there will be power losses as light will be launched into the cladding. The angle of the laser beam entering the fiber should be within the acceptance angle for the fiber. When designing the optical system for fiber coupling, the angle of the beam should not be larger than the smallest possible acceptance angle or there will be power losses from the high-angle light leaking from the core.

2.2 Losses by overfilling the fiber core
Launching a laser beam into the fiber when the spot diameter is larger than the core diameter will result in light inside the cladding material. The light will remain the in the cladding material and has the potential to leak out into the jacket along the fiber length.

![Diagram of overfilling the core](Image)

\[ \alpha = \text{Acceptance angle} \quad d_{co} = \text{Core diameter} \quad d_{cl} = \text{Cladding diameter} \]
\[ d_s = \text{Spot diameter} \quad \beta = \text{Launch angle} \]

If the jacket is manufactured with a guiding material, with refractive index lower than that of the cladding, the cladding light will be confined along the length of the fiber, but damage or delamination of the jacket will likely result in a damage point and destruction of the fiber optic. The point where the jacket begins (and ends) is also a weak point when there is power in the cladding, as the surface is typically uneven and partially delaminated.

To avoid the potentially damaging leakages along the fiber length, a mode stripper could be used to remove the light in the input fiber connector. A mode stripper is typically applied to the first few centimeters of fiber after the entrance facet. The light exiting the fiber will then be confined to the core and well defined at the output end.
2.3 Losses by overfilling acceptance angle of the fiber

Launching a laser beam into a fiber core where the angle exceeds the acceptance angle of the fiber means that the fiber will leak power into the cladding. This will result in power losses in the fiber and it is difficult to specify the power distribution leaking from the core.

![Figure 3. Overfilling the fiber NA. $\beta > \alpha$.](image)

It is possible to guide the laser beam in the cladding to avoid power leaking from the fiber, provided there is a coating outside the cladding that allows the laser beam to be guided. To guide the power inside the cladding is not preferable as this puts demands on the coating material since as in section 2.2, damage or delamination of the jacket will likely result in a destructive damage point on the fiber optic. The point where the jacket begins to surround the cladding is also a weak point when there is power in the cladding, as the surface is typically uneven and partially delaminated. Additionally it is difficult practically to deal with high NA light when it leaves the fiber on the output side.

Using a mode stripper to remove high NA light inside the cladding is not easy when working with larger angles than the acceptance angle. The mode stripper needs to be very long to be certain to remove all the light in the cladding.

3. SMAQ CONNECTOR DESIGN

The Optoskand SMAQ connector is based around the SMA905 interface (IEC 61754-22) but differs from the standard in that the Optoskand connector’s fiber end plane (FEP) does not lie at the end of the ferrule, but is moved forward 25 mm by a capillary extending from the ferrule. The protruding fiber is mode stripped to remove light from the cladding.

![Figure 4. Optoskand SMAQ connector.](image)

The front of the capillary and the fiber are both welded to a fused silica cylinder (a “quartz block”) and all three components consist only of low-OH (<1 ppm) fused silica material. This “All-in-quartz” design [Ref 1] is utilised so the components of the connector do not absorb any significant level of the mode stripped laser radiation and therefore do not experience a temperature rise due to the losses.

![Figure 5. Cut-away drawing of the end of the SMAQ connector.](image)
The Optoskand quartz block design results in a more robust solution in systems with high power density on the fiber end surface. For example, a beam of NA=0.20 launched into a 200 µm diameter core sees a reduction of a factor 50 in the intensity present at the air-to-glass interface when a quartz block is used on the SMAQ. The anti-reflection (AR) coating on the quartz block eliminates Fresnel reflections providing nearly 8% extra light transmitted through the double-ended fiber cable. Due to this design, when the light enters the fiber cabling, almost no radiation exists in the fiber cladding assuming the NA is not overfilled. Since all light is well defined within the core, no light can leak from the cladding and heat up the surrounding cable material.

The connector does not have integrated cooling, but it is necessary to mount the fiber in a holder, which can be cooled. The Optoskand holder has openings in the side to allow mode stripped light to escape the holder. The light escaping the holder will meet the cooler, allowing absorption of the light on the cooler surface for optimal energy removal. The necessary cooling level depends upon the losses expected associated with in-coupling, for higher losses the water cooler should be used. For lower losses the air cooler can be used.

![Figure 6. (a) SMAQ connector, holder and water cooler. (b) SMAQ connector, holder and air cooler.](image)

4. FIBER COUPLING OF DIODE LASER MODULES

High power (>200 W) diode laser modules typically exceed both the diameter of the fiber and the NA. Two examples are shown in the sections below.

4.1 Diode laser loss mechanisms: Spot loss

Collimated beams are focused to a quadratic - typically rectangular - spot on the circular core of the fiber. The corners of the rectangle lie outside the core and so create loss, as shown by the shaded area in the figure below.

![Figure 7. A perfectly aligned rectangular spot (185x130 µm) overfills the circular core (Ø=200 µm) of a fiber even though the fast and slow axes are both smaller than the core diameter.](image)
In this example, the shaded region accounts for 785 µm² of the total beam area of 24050 µm² or 3.3% of the beam area falling outside the fiber core. If for example, the spot size was changed to 185x150 µm, then the shaded region accounts for 1633 µm² of the total beam area of 27750 µm² or 5.9% of the beam area falling outside the fiber core. In reality, the quadratic spots are not sharp 90° corners, the intensity is not necessarily uniform across the spot and alignment not perfect, so this method is not able to determine exactly the loss expected in a system, but to demonstrate that losses are inherent in the design.

4.2 Diode laser loss mechanisms: NA loss

Square beams also raise difficulties in defining the NA of a diode laser before fiber launch, as even if both X and Y axes lie within the NA, for example a 12x12 mm beam focused with a lens of effective focal length 30 mm gives an NA=0.20.

![Figure 8. A square-form collimated beam in X and Y planes within the NA of a fiber.](image)

The same beam sectioned at 45° between the X and Y axes results in a much larger effective NA since the diagonal “diameter” of the beam is of course larger than the two edges. In our example with a 12x12 mm beam and a focal lens of EFL=30 mm the NA of the corners of the beam will be 0.273.

![Figure 9. The same beam from the previous figure but viewed in the 45° plane between X and Y planes sees far higher NA.](image)

4.3 Diode laser launch compromises

4.3.1 Spot losses vs. NA losses

Increasing the focal length of the focusing lens will result in a reduction of NA and an increase of spot size. The compromise here is not technically challenging, the choice facing the optical engineer is where the losses will come from, spot size or NA?

4.3.1 Brilliance vs. spot losses

Unlike the circular spots discussed in Section 2, the square spots of the diode lasers dictate that finding a solution to eliminate spot losses will result in a significant reduction in brilliance of the radiation exiting the fiber compared to the spot. Following the 185x130 µm and Ø=200 µm example from above, the area of the beam overlapping the core is
23265 µm², but the area of the core is 31416 µm², immediately reducing brilliance by 27%. Increasing the spot size (or decreasing the core diameter) will result in a better overlap of spot area to core area and therefore better preservation of brilliance, but will increase losses.

A compromise between brilliance and overall (electrical to useful optical) efficiency of the system is made. The loss handling ability of the fiber connector must be included in this balance as arbitrarily increasing loss to increase brilliance could result in damage to the connector. Similarly, choosing the incorrect balance of spot losses to NA losses could also result in damage to the connector, depending upon connector design.

5. EXPERIMENTAL METHOD

The focusing objective of the modules was adjusted in X, Y and Z to allow optimal coupling of the spot into the fiber core. The output from the fiber was allowed to diverge onto the absorption plate of the power meter. The power meter(s) were calibrated.

During the experiments, temperature measurements were made on the connectors, which had the black plastic bend protection removed for the duration. The temperature was measured at two points on the input side (IS) and one point on the output side (OS) as shown in the picture below.

![Figure 10. Positions of temperature sensors during experiments.](image)

The temperature sensors were positioned at the points where the connector would have the highest temperature due to a significant quantity of mode stripped light (T1) and where the connectors would have highest temperature due to high-NA light (T2 and T3) that is not mode stripped. These positions had been confirmed with a thermal-camera during previous tests (see figure 11 (a) & (b) below) where high spot and NA losses were induced in the connector. The temperature data was continuously logged.

![Figure 11. (a) IR thermal-camera picture of a connector with high spot-loss induced. (b) Visible picture of the same connector.](image)
6. RESULTS

The results sections are split into four sections categorised by the four sources tested, then into the two fiber configurations tested, first the Ø=200 µm, NA=0.22 raw fiber. The fiber tolerances were Ø=202 ±2 µm and NA=0.215 ±0.005 resulting in a maximum BPP of 22.4 mm·mrad. Second, the Ø=400 µm NA=0.22 fiber. This fiber had tolerances of Ø=400 ±9 µm, NA=0.22 ±0.02 resulting in a maximum BPP of 49.1 mm·mrad.

The laser units are based on a modular laser concept with a single baseplate as basic building block [Ref 2]. The beam quality of the baseplate is shown in Fig. 12.

6.1 Single-plate IS21

The IS21, which is a laser unit with one baseplate, emitted a collimated beam which was focused to a spot size of about 180x75 µm on the fiber facet. Therefore there should be no loss from spot size since the maximum diameter is 195 µm. The corresponding numerical aperture was 0.18 in each direction and therefore the unit exhibited a maximum possible NA of 0.255 so NA-losses are expected. When converted to the 400 µm version, the spot size was doubled and the NA was halved by appropriate focusing optics, meaning neither spot-loss nor NA-loss is expected. The raw power was about 260 W at a drive current of 40 A. This laser had an internal holder for the connector, which was conduction cooled by the laser chassis as shown in figure 13.

Figure 12. Measurement of the beam caustic for the baseplate with resulting beam quality of 16.4 mm·mrad (M²=53) in slow-axis direction and 6.6 mm·mrad (M²=21) in fast-axis direction, respectively.

Figure 13. Single plate IS21 module with internal holder and SMAQ connector.
6.1.1 Single-plate IS21 - Ø=200µm
Several hundred cables were tested with the 200µm version, transmission was measured to be typically 230 W, implying a coupling efficiency of 88.5% and an overall electro-to-optical efficiency of 52.3%. The loss in the connector was 29 W, resulting in temperatures of T1=23°C, T2=23°C, T3=23°C, which was identical to room temperature.

6.1.2 Single-plate IS21 – Ø=400 µm
Nine cables were tested with the 400 µm version, transmission was measured to be 243 W, giving a coupling efficiency of 93.5% and an overall efficiency of 55.2%. The loss in the connector was 17 W.

6.2 Dual-plate IS43
The IS43 unit was realised by combining two baseplates to one common laser unit. The collimated beam was focused to a spot size of about 180x150 µm on the fiber facet. In this case the spot losses are expected to be significant since the diagonal of the spot is 234 µm. The corresponding numerical aperture was 0.18 and 0.09 respectively, meaning NA losses are not expected since the maximum NA is 0.201. For the IS43 the water-cooled holder was used for testing the connectors. The raw power was about 500 W at a current of 40 A.

6.2.1 Dual-plate IS43 - Ø=200 µm
Two cables with an SMAQ connector on the input side and uncoated pigtail end at the output side were tested with the 200 µm version up to a current of 32 A. Transmission was measured to be 335 W at a current of 32 A corresponding to a coupling efficiency of about 88% and an overall efficiency of 48%. The loss in the connector was 53 W. This resulted in a temperature of T1=30-35°C

6.3 Quad-plate: IS45
The IS45 unit was built by combining four baseplates to one common laser unit. For the 200 µm version the collimated beam was focused to a spot size of about 180x150 µm on the fiber facet. As with the two-plate version, in this case spot losses were expected since the diagonal of the spot is 234 µm. The corresponding numerical aperture was 0.18 in each direction, so as with the single-plate version NA losses were expected as the maximum NA=0.255. The raw power was about 970 W. A different IS45 unit was used for the 400 µm version. Compared to the 200 µm version the spot size was doubled to 360x300 µm and the NA was halved to 0.09 in each direction by appropriate focusing optics. With the change in optics the NA loss was eliminated, but the spot-loss still existed due to a maximum diameter of 469 µm. The raw power was about 818 W. As these sources had been tested to have raw power of up to a kiloWatt, losses of several hundred Watts are likely so the water-cooled holder was used to test the connectors.
6.3.1 Quad-plate: IS45 - Ø=200 µm
Three cables were tested with the 200 µm version, transmission was measured to be around 723 W, giving a coupling efficiency of 74.5% and an overall efficiency of 40.5%. The loss was around 246 W, resulting in temperatures of T1=75-80°C, T2=55-60°C, T3=30-35°C. The power was ramped up in steps of 5 A drive current per minute, then after roughly three minutes of operation at full power (40 A) the temperature of the connector had stabilised.

![Figure 15 Temperature stabilisation of SMAQ #8342 operated at 721 W transmission (from 480 sec) with 248 W loss.](image)

6.3.2 Quad-plate: IS45 - Ø=400 µm
Nine cables were tested with the 400 µm version, transmission was measured to be about 770 W, giving a coupling efficiency of about 94% and an overall efficiency of 54%. The loss was up to 50 W. In this case T1 = 30-35°C.

6.4 Special unit IS46
This unit was a special design, not based upon the plate modularity of the first three modules. The design was governed by a tough specification upon the weight and size of the module, so neither the module nor the connector was well cooled and it was because of this characteristic that the unit was included in this study.

The IS46 unit emitted a collimated beam, focused to produce a spot of 205x120 µm on the fiber facet. The corresponding numerical aperture was 0.20 and 0.12, respectively. This produced a numerical aperture maximum of 0.231 and a maximum spot diameter of 238 µm. Therefore spot-loss and NA-losses were expected. The raw power was 370 W. As with the single-plate laser, the holder was integrated into the laser chassis and therefore cooled by conduction, however the laser house operated close to 60°C around the holder so cooling was not as efficient as with the single plate module.

6.4.1 Special unit IS46 - Ø=200 µm
More than fifty cables have been tested with the 200 µm version, transmission was typically measured to be around 310 W, giving a coupling efficiency of typically 84%. The loss was 60 W, resulting in temperatures of T1=75-80°C, T2=55-60°C, T3=30-35°C. The compact design of the module resulted in a high operating temperature of all components despite the fact that the losses were not of the highest absolute values.
7. SUMMARY & CONCLUSIONS

7.1 Summary
The four sources tested with the 200 µm fiber demonstrated that the SMAQ connector handled mode stripping up to 250 W power loss, while delivering up to 700 W of diode laser power.

<table>
<thead>
<tr>
<th>200µm</th>
<th>Baseplates</th>
<th>Slow Ø (µm)</th>
<th>Fast Ø (µm)</th>
<th>Diag Ø (µm)</th>
<th>Slow NA</th>
<th>Fast NA</th>
<th>Max NA</th>
<th>Power (W)</th>
<th>Transmission (W)</th>
<th>Loss (W)</th>
<th>Max Temp (°C)</th>
</tr>
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<tbody>
<tr>
<td>IS21</td>
<td>1</td>
<td>180</td>
<td>75</td>
<td>195</td>
<td>0.18</td>
<td>0.18</td>
<td>0.255</td>
<td>260</td>
<td>230</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>IS43</td>
<td>2</td>
<td>180</td>
<td>150</td>
<td>234</td>
<td>0.18</td>
<td>0.09</td>
<td>0.201</td>
<td>388</td>
<td>335</td>
<td>53</td>
<td>35</td>
</tr>
<tr>
<td>IS45</td>
<td>4</td>
<td>180</td>
<td>150</td>
<td>234</td>
<td>0.18</td>
<td>0.18</td>
<td>0.255</td>
<td>970</td>
<td>730</td>
<td>240</td>
<td>80</td>
</tr>
<tr>
<td>IS46</td>
<td>n/a</td>
<td>205</td>
<td>120</td>
<td>238</td>
<td>0.20</td>
<td>0.12</td>
<td>0.231</td>
<td>370</td>
<td>310</td>
<td>60</td>
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</table>

The two sources tested with the 400 µm fiber demonstrated that the SMAQ connector can handle mode stripping up to 50 W from the cladding while delivering up to 780 W of diode laser power.

<table>
<thead>
<tr>
<th>200µm</th>
<th>Baseplates</th>
<th>Slow Ø (µm)</th>
<th>Fast Ø (µm)</th>
<th>Diag Ø (µm)</th>
<th>Slow NA</th>
<th>Fast NA</th>
<th>Max NA</th>
<th>Power (W)</th>
<th>Transmission (W)</th>
<th>Loss (W)</th>
<th>Max Temp (°C)</th>
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<tbody>
<tr>
<td>IS21</td>
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<td>360</td>
<td>150</td>
<td>390</td>
<td>0.09</td>
<td>0.09</td>
<td>0.127</td>
<td>260</td>
<td>243</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>IS45</td>
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<td>300</td>
<td>469</td>
<td>0.09</td>
<td>0.09</td>
<td>0.127</td>
<td>818</td>
<td>774</td>
<td>44</td>
<td>35</td>
</tr>
</tbody>
</table>

To confirm that the durability of the connectors matches the capability demonstrated in this paper, long-term tests have been made with the IS21 module and the 200 µm fiber. These tests have currently passed 2000 h without degradation or damage, showing no temperature rise above the ambient temperature (25-30°C) despite having some 30 W mode stripped from the fiber.

The connector has additionally begun long-term testing with the IS46 module and 200 µm fiber without degradation or damage after more than 900 h of testing. The connectors are coping with 60 W of loss while operating at a temperature of ~70°C when used with conduction cooling to the laser house.

7.2 Conclusions
A loss of 246 W from the IS45 produces a stable temperature of ~75°C on the connector when it is water cooled, near identical to the operating temperature of connectors under long term tests with the IS46 and so suggests that a long term test with the IS45 would be unlikely to damage the connector. Improving the design of the cooler will further reduce the temperature so the connector is safe to handle at all specified powers and improve the chances of a successful long term test.

The SMAQ connector is proven with the current diode power levels of 200-300 W (with 30-60 W loss) and the results in this study show it to be capable of dealing with significantly higher power levels. The increasing output power of diode lasers and the increased spot- and NA-loss that this trend demands will continue to be tested together with the SMAQ connector.

8. REFERENCES
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