Novel beam delivery fibers for delivering flat-top beams with controlled BPP for high power CW and pulsed laser applications

C. Jollivet*[a], K. Farley[a], M. Conroy[a], J. Abramczyk[a], S. Belke[b], F. Becker[b] and K. Tankala[a]
[a] Nufern Inc., 7 Airport Park Road, East Granby, CT 06026, USA
[b] Rofin Sinar Laser GmbH, Berzeliusstraße 87, 22113 Hamburg, Germany
*cjollivet@nufern.com

ABSTRACT

Single-mode (SM) kW-class fiber lasers are the tools of choice for material processing applications such as sheet metal cutting and welding. However, application requirements include a flat-top intensity profile and specific beam parameter product (BPP). Here, Nufern introduces a novel specialty fiber technology capable of converting a SM laser beam into a flat-top beam suited for these applications. The performances are demonstrated using a specialty fiber with 100 μm pure silica core, 0.22 NA surrounded by a 120 μm fluorine-doped layer and a 360 μm pure silica cladding, which was designed to match the conventional beam delivery fibers. A SM fiber laser operating at a wavelength of 1.07 μm and terminated with a large-mode area (LMA) fiber with 20 μm core and 0.06 NA was directly coupled in the core of the flat-top specialty fiber using conventional splicing technique. The output beam profile and BPP were characterized first with a low-power source and confirmed using a 2 kW laser and we report a beam transformation from a SM beam into a flat-top intensity profile beam with a 3.8 mm*mrad BPP. This is, to the best of our knowledge, the first successful beam transformation from SM to MM flat-top with controlled BPP in a single fiber integrated in a multi-kW all-fiber system architecture.

Keywords: Specialty Fiber, Beam delivery cable, Flat-Top beam, Mode scrambling, Beam control, High-power fiber laser, Material processing

1. INTRODUCTION

Multi-kW fiber lasers are commercially available and used in a wide variety of applications including material processing applications such as welding and cutting, sintering, marking, scribing, drilling, heat treating, etc. The kW-class laser beam generated either in single-mode (SM) or multi-mode (MM) fiber lasers is generally coupled into a so-called process fiber or beam delivery (BD) cable fiber. Fibers used in BD cables are highly MM and typically made of pure fused silica large step-index core geometries which can handle multi-kW power levels to guide the laser light from the fiber laser to the work piece, a few meters to tens of meters away. Standard BD fibers are protected from the external environment by cabling material and are terminated with special connectors able to facilitate handling, to improve coupling efficiency and to provide thermal management. SM fiber lasers are often preferred for their stable output performance and their diffraction limited beam profile. However, several applications such as cutting and welding have strict and well-established beam property requirements which drastically differ from the SM laser output beam characteristics. One requirement is beams with flat-top intensity profile in order to deliver uniform power density to the work piece. In addition, the beam must satisfy a specific requirement for beam parameter product (BPP), defined as the product between the beam radius (in millimeter) and the beam divergence (in mrad). For example, the BD cable standards for sheet metal cutting applications are either 50 μm core diameter beam delivery fiber with a BPP comprised between 1.5 and 2 mm*mrad (preferably 1.7 and 2 mm*mrad), or 100 μm core beam delivery fiber with 3 to 4 mm*mrad (preferably 3.5 to 4 mm*mrad) BPP. Larger core fibers, for example 200 μm, are also employed in thick sheet metal cutting and welding applications with BPP in the range of 6 to 8 mm*mrad. When directly coupling a SM beam into standard BD fibers, only a limited set of transverse modes are excited and the resulting beam does not meet the flat-top intensity profile and BPP requirements. To date, several methods for beam transformation have been demonstrated including shaped-core fibers [1,2], free space optics [3], long period gratings [4] and MM interference devices [5]. However, an all-fiber method to efficiently convert a SM beam into a flat-top beam while simultaneously controlling the BPP still remains a challenge.

Here, we introduce a novel fiber technology able to address the beam requirements set by material processing applications with the use of a single fiber. In the first section, typical system architecture and related technical challenges are discussed. The approach followed to develop an all-fiber solution to convert a SM beam into a flat-top with controlled BPP is detailed using numerical tools and mode overlap integral calculations. In Section 3, the novel flat-top fiber design is introduced and its potential to transform a SM beam into a flat-top beam with target BPP is numerically evaluated. Finally, the fiber was fabricated and characterized. Experimental results including core attenuation, beam profile and BPP, tested both with low power and with a 2-kW SM laser source are discussed and compared with standard BD fiber cables. This is, to the best of our knowledge, the first demonstration of simultaneous beam profile and BPP conversion occurring in a single fiber which can be integrated in an all-fiber system using conventional splicing techniques.

2. SINGLE-MODE TO FLAT-TOP BEAM: CHALLENGES AND APPROACH

2.1 Context of the study

The beam transformation performances of this novel flat-top fiber are suited for a wide range of applications from imaging and medical to industrial and defense markets. To demonstrate the fiber performances, we focused on laser-assisted material processing applications which face immediate needs for SM to flat-top beam with specific BPP transformation. The context of this study is illustrated in Fig. 1 showing a schematic representation of fiber laser-assisted material processing systems. A fiber laser terminated with a large-mode area (LMA) fiber (yellow) delivers a diffraction-limited, kW-class beam which is coupled to a BD fiber cable (blue). Typically, the LMA fiber and the BD fiber are fusion spliced together or, when used in conjunction with beam switches, the fibers may be connectorized and light is free space coupled from the SM fiber to the BD fiber. The length of the BD fiber cable varies from a few meters up to a few tens of meters long and guides the light to the workpiece. It is terminated with specially designed connectors, such as QBH connectors, which provide the required beam collimation and cooling capabilities. For this analysis we consider a kW-class fiber laser made with LMA-YDF-20/400 fiber spliced to a 20 μm core, 0.06 NA, LMA-GDF-20/400 passive fiber for delivering a Gaussian-shaped SM beam with a divergence of less than 40 mrad. In the following, the focus will be on standard BD fiber cable made with a 100 μm step-index pure-silica core, with 0.22 NA, surrounded by a 120 μm fluorine-doped layer and a 360 μm pure-silica cladding.

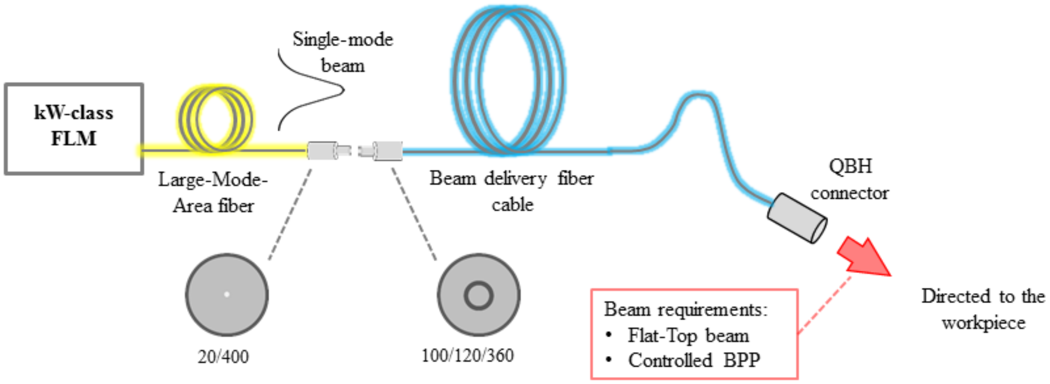


Fig. 1: Typical architecture of material processing systems using kW-class diffraction limited laser beams.

2.2 Technical challenges

In theory, a step-index, 100 μm core fiber with 0.22 NA can carry up to 1,700 transverse modes and can deliver a highly MM beam with a maximum BPP of 11 mm*mrad. In order to meet the application requirements of simultaneously delivering a flat-top beam profile with a BPP between 3 and 4 mm*mrad, the challenges are three-fold.

i. On one hand, the BPP must be controlled to achieve the tight specification window. In a MM waveguide, the higher-order modes (HOM) propagate with higher divergence angles and are responsible for the divergence of the output beam. Therefore, achieving the BPP relies on the control of the angular divergence which is done by carefully tailoring the HOM content propagating in the fiber.

ii. On the other hand, the beam shape is defined as the sum of the amplitude and phase of all the modes propagating in the fiber, weighted by the fraction of power carried by each mode. As a result, controlling the beam profile also requires tailoring the mode content excited in the BD fiber.
iii. Finally, material processing applications follow strict industry standards and well-established system designs. As a result, the successful method must preserve the current system configuration, satisfy the industry standard and provide the desired beam characteristics. Therefore, the present study was focused on achieving the beam profile and BPP transformation in the format of a single-fiber, designed with the same core shape, size and NA as the current BD cables. The novel flat-top fiber can be used in place of the standard BD cables without further processing, additional splicing and/or free-space coupling sections.

2.3 Tailoring the mode mixing

The mode content excited in an optical fiber is defined by the well-known spatial mode overlap integral between the modes available in the fiber and the incident mode content. To illustrate this concept, the intensity profiles of the SM input beam and of a few of the hundreds of modes available in the standard BD fiber cable are represented in Fig. 2(a) and (b), respectively (the order of each mode is indicated on the top left corner).

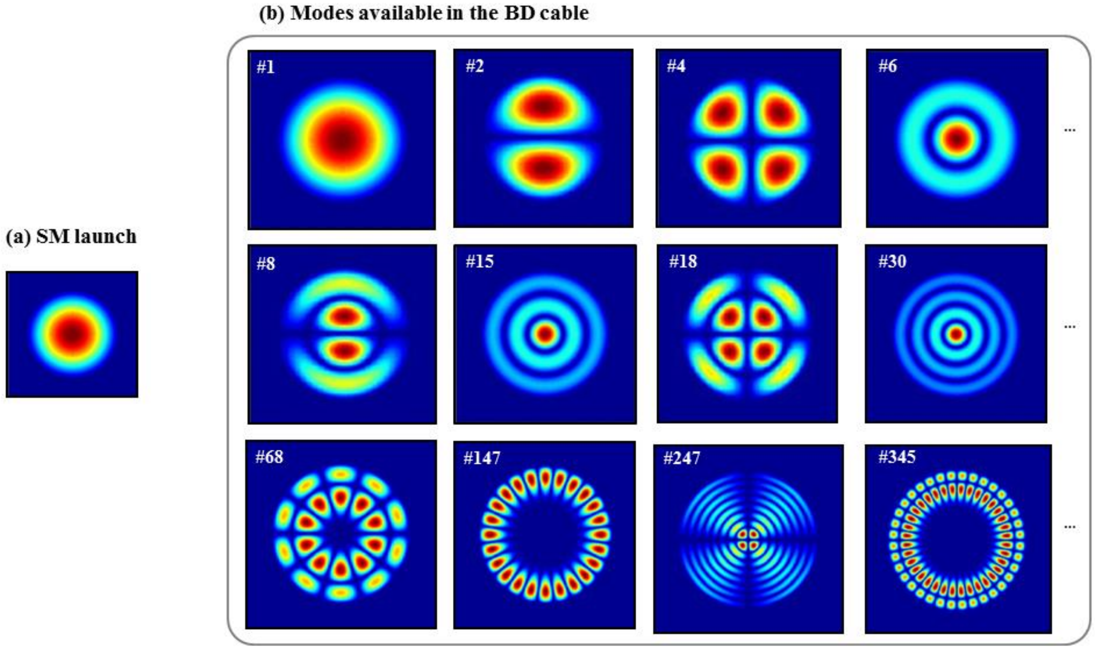


Fig. 2: Intensity profile of the input SM laser beam compared a few of the transverse modes available in the standard BD fiber cable with 100 μm core and 0.22 NA.

In this common case, there is a significant core size and NA mismatch between the LMA-GDF-20/400 laser output and the standard BD fiber. The size and Gaussian shape of the input beam dictates the mode overlap integral which results in very poor mode mixing in the BD fiber where only the modes with a non-zero intensity at their center will be excited, i.e. modes # 1, 6, 15, 30, etc. The profile of the beam resulting from this mixture of modes will most likely show a distorted and speckled shape and a low BPP in the range of 2 to 2.5 mm*mrad which does satisfy the application requirements.

The mode content excited in the BD fiber cable can be accurately predicted numerically using spatial mode overlap integral calculations. Calculation results are presented in Fig. 3 where the normalized fraction of power carried in each mode is plotted as a function of the mode number. Only the first 400 modes are shown to preserve the clarity of the plot. Fig. 3(a) shows the mode overlap integral results in the case of direct coupling/splicing between the LMA-GDF-20/400 fiber laser output and the 100 μm, 0.22 NA standard BD fiber cable described above. As expected, only a few modes are excited and propagate (Bessel-like modes # 1, 6, 15, 30 in Fig. 2 (a)) resulting in a poor mode mixing. The corresponding beam shown on the right hand side exhibits an uneven intensity profile which is not suited for material processing applications. In order to tailor the mode mixing, an offset can be introduced at the coupling section between the two fibers. In practice, this can be done by an offset launch or an offset splice. Mode overlap integral calculations were performed to illustrate the impact of an offset launch on the mode content excited in the BD fiber and results are depicted in Fig. 3(b) and (c) in the case of a 10 µm and 20 µm lateral offset coupling respectively. As the lateral offset increases, additional HOM are populated in the BD fiber, affecting the shape and BPP of the beam. Black arrows indicate a few of the newly excited modes #68, 147, 247 and 345 and their intensity profile is shown in Fig. 2(a). As the HOM content increases, the uniformity of the beam profile improves as can be seen from the beam profile images shown in Fig. 3.

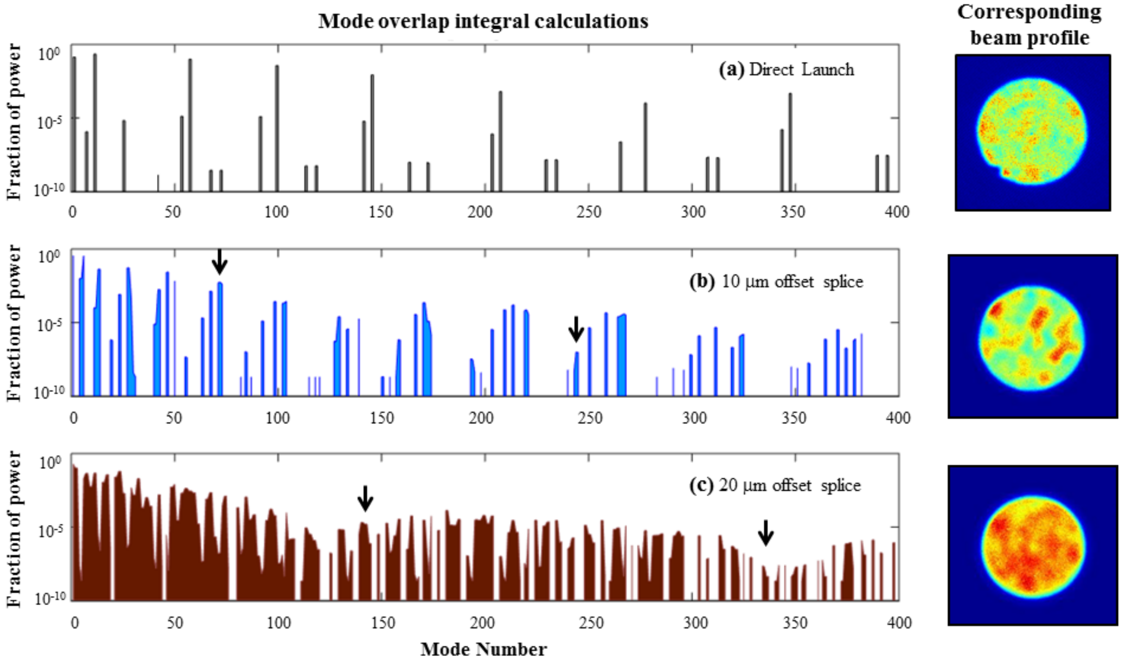


Fig. 3: Numerical calculation of mode overlap integral between the FLM's LMA fiber output and the 100 µm core BD fiber cable when both fibers are (a) aligned, (b) offset by 10 µm and (c) offset by 20 µm. The corresponding beam profile is shown for each case.

The use of an offset coupling of offset splice to increase and tailor the mode mixing in MM fibers has severe practical limitations such as limited tunability and challenging implementation. First, splicing two fibers with an offset is practically difficult, time consuming and lacks reproducibility. It also heavily relies on the precision of the splicing equipment and on the operator skills. Therefore, it remains challenging to obtain the same beam profile and BPP from one system to the other. In addition, the uniformity of the output beam and the range of BPP achievable with an offset splice remain limited by the size of the input Gaussian beam. Most importantly, offset splices may result in additional coupling losses which expose the system to catastrophic failure when operating at multi-kW power levels. Therefore, there is a need for a single-fiber solution to replace the standard BD cables able to tailor the mode mixing to generate a beam with a flat-top intensity profile at a controlled BPP.

3. FLAT-TOP BEAM DELIVERY FIBER: DESIGN AND FABRICATION

A novel specialty flat-top fiber has been developed to satisfy the beam requirements while being entirely compatible with existing system architecture and process. The main design parameters of the novel flat-top beam delivery fiber are summarized in Table 1 along with the main design elements of the fiber laser output fiber and the standard BD fiber. The flat-top fiber was designed with a 100 µm core, 0.22 NA, 120 µm fluorine-doped layer and a 360 µm cladding to match the dimensions of the industry standard BD fiber cable. The uniqueness of this design is the introduction of mode mixing element(s) in the fiber to tailor the mode content and therefore control the beam properties while maintaining all other geometrical and optical attributes identical to standard BD fibers. Using mode overlap calculations, the design of the mode mixing element(s) has been finely tuned to tailor mode up-conversion in order to transform the SM beam from the fiber laser to a flat-top beam with BPP comprised between 3.5 and 4 mm*mrad. This flat-top fiber offers a simple, low-maintenance all-fiber solution which can be used in place of the standard BD fiber to achieve the beam requirements set by material processing applications.

Table.1: Dimensions of the flat-top fiber deign compared to fibers typically used in material processing applications

Specification	**Single-mode launch**	**Standard BD cable**	**Flat-top fiber design**
Core diameter (μm)	~ 10 to ~50	100	100
Inner clad diameter (μm)	N/A	120	120
Outer clad diameter (μm)	400	360	360
Core NA	0.01 to 0.08	0.22	0.22
Number of modes	1	~ 1700	~ 1700
Length (m)	N/A	5 to > 30	5 to > 30
Mode mixing element	N/A	NO	YES

Mode overlap calculations were performed using the optimized flat-top fiber design and results are presented in Fig. 4 where the mode content excited in the new 100 μm core flat-top fiber (in green) is compared to the standard 100 μm core BD fiber cable (in black). To ensure the clarity of the plot, only the first 400 transverse modes are represented. As one can see, the mode mixing is significantly enhanced in the flat-top beam delivery fiber compared to standard BD cables when launching the SM laser beam with the LMA-GDF-20/400 fiber. All the populated modes now contribute to the output beam profile and BPP. Fine tuning of the fiber design allows tailoring the relative power between the modes to achieve the specific BPP requirements.

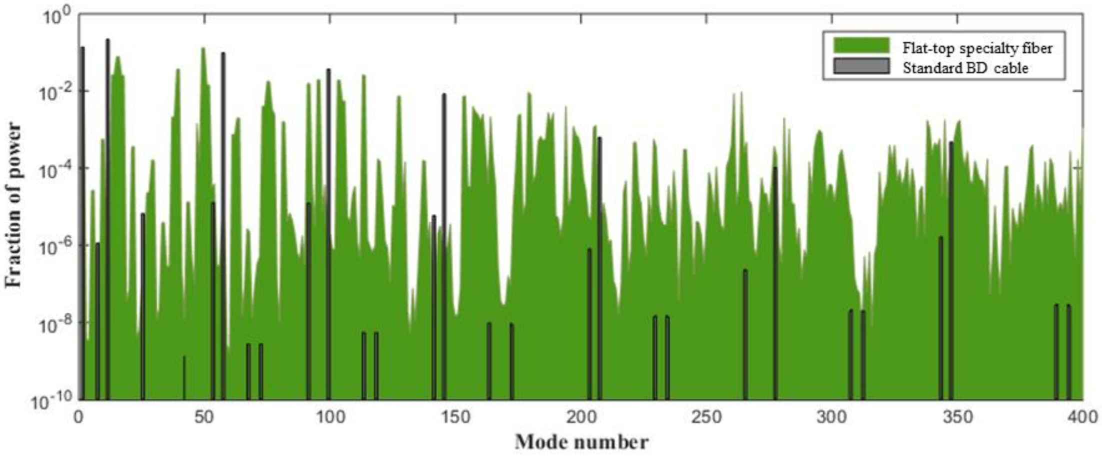


Fig. 4: Mode overlap integral calculations between the SM laser beam in the LMA-GDF-20/400 and the first 400 modes of the flat-top BD fiber (green) compared with the standard BD fiber (black).

The main difference between the standard BD cable and the flat-top beam delivery fiber is the introduction of mode mixing element(s) in the core allowing to tailor the mode content and to homogenize the power distribution among the excited modes to efficiently convert a SM into a uniform flat-top beam with a controlled BPP. In addition, it is important to note that this fiber design offers significant scaling capabilities since the BPP can be controlled by tuning the design of the mode mixing element(s) while maintaining a well homogenized flat-top beam profile. As a result, this novel fiber technology is suitable for material processing systems employing various sizes of BD fibers (i.e. with core diameters ranging from 50 to beyond 600 μm). It can furthermore be applied to a variety of applications beyond material processing which require homogeneous beams and target BPP.

4. EXPERIMENTAL DEMONSTRATION

The flat-top BD fiber has been fabricated using conventional optical fiber fabrication techniques. Several measurements have been recorded including attenuation, geometry and beam properties. Results are presented in details in the following section.

4.1 Measured core attenuation of the flat-top fiber

A fiber preform was assembled using a pure-silica core, a fluorine-doped layer with 0.22 NA and a pure-silica cladding. The novel beam delivery fiber is coated using Nufern's proprietary, highly reliable, low-index polymer material, NuCOAT_{FA}. Mode mixing element(s) were introduced in the core resulting in an all-glass final fiber structure. To verify if the introduction of mode mixing element(s) has any significant negative effect on the transmission losses of the fiber, core attenuation measurements were recorded using a 2500 Optical Fiber Analysis System from Photon Kinetics. The results are summarized in Fig. 5 where the core attenuation is compared between a standard BD fiber cable (black) and the flat-top fiber design (green)

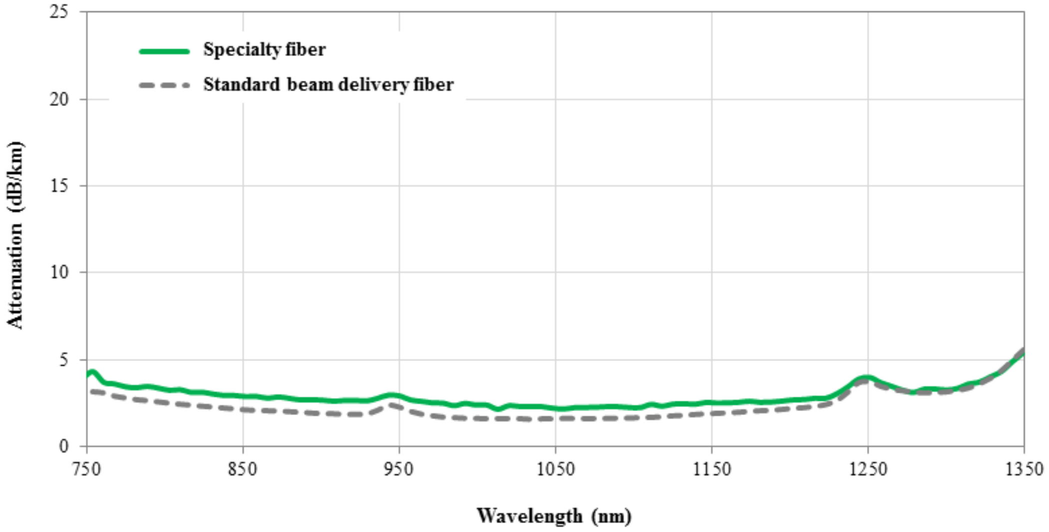


Fig. 5: Measured core attenuation of a standard BD cable fiber and the flat-top beam delivery fiber with mode mixing elements. Both fiber cores are 100 µm in diameter with 0.22 NA.

Results show that, the attenuation of the flat-top BD fiber is not significantly different than that of a standard BD fiber and is within expected lot-to-lot variation. These results indicate that the flat-top BD fiber design and fabrication are well suited for handling multi-kW power delivery without degradation of the laser power for the typical cable length of tens of meters.

4.2 Transformation of a SM beam into a MM flat-top beam with controlled BPP

The beam performances of the flat-top fiber design were tested using a low-power light source emitting light around 1.06 µm and coupled to a LMA-GDF-20/400 fiber with 20 µm core, 0.06 NA and 400 µm cladding. Both standard BD fiber cable and the flat-top fiber design have been tested using the same experimental procedure. The fiber under test was fusion spliced to the LMA fiber using conventional splicing techniques. To mimic the deployment conditions of beam delivery fiber cables for material processing applications, the fiber length was set to 25 meters and the fiber remained loosely coiled and placed on top of an optical bench. The output end of the fiber was flat cleaved and the beam profile and beam divergence were recorded. Results are summarized in Fig. 6(a) and (b) respectively. The beam emerging the standard BD fiber is not homogeneous and shows several randomly localized hot-spots. On the other hand, the beam emerging the flat-top fiber with mode mixing element(s) shows a top-hat profile with an almost fully-filled core and a homogeneous intensity profile.

The beam divergence was measured at the output of the standard fiber (black) and the flat-top fiber (green) and results are shown in Fig. 6(c). This plot shows the measured beam width while scanning the camera in the far-field by increments Δz of 2 mm. The divergence is extracted from the slope of the recorded data. Using the measured beam diameter, the BPP for the standard and flat top fibers can be estimated around 2.3 mm*mrad and 3.8 mm*mrad (+/- 0.2) respectively. Compared to the standard BD fibers, the flat-top fiber design is able to transform a single-mode beam into a uniform flat-top beam profile with a BPP comprised between 3 and 4 mm*mrad as required by the application. This novel generation of fiber design offers an all-fiber solution, fully compatible with existing systems with low maintenance and high performances.

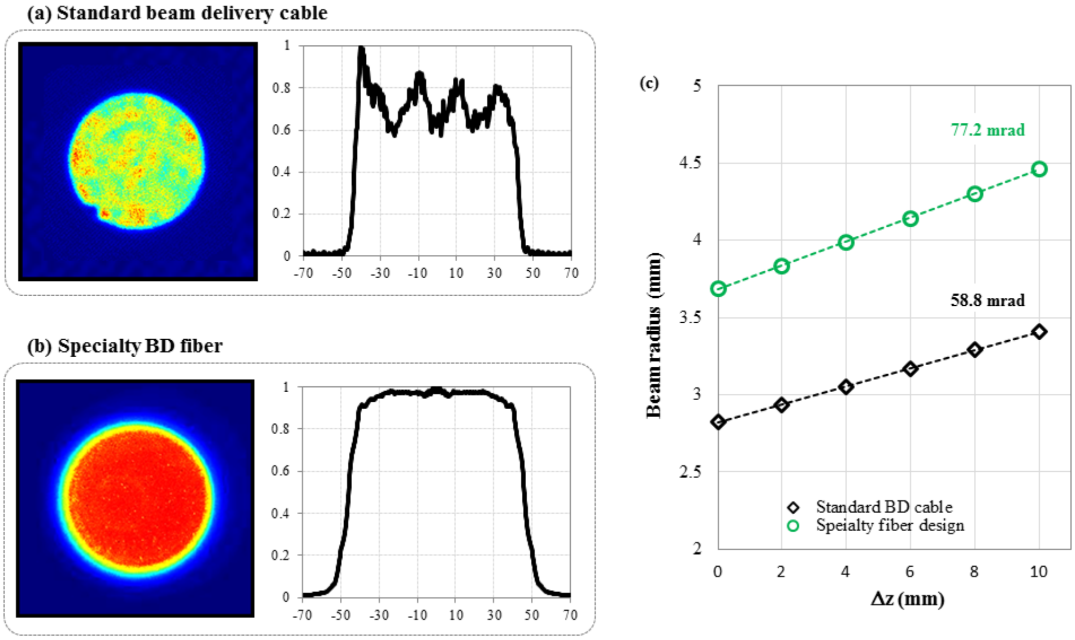
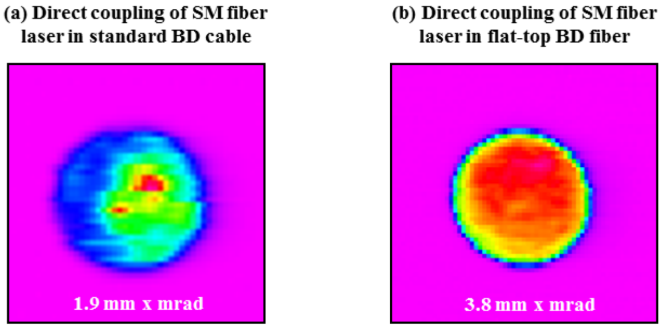


Fig. 6: Beam profile emerging the specialty designed fiber (b) compared to standard beam delivery cable (a). (c) The beam divergence was measured for each fiber by plotting the beam size while scanning the camera in the far-field by increments Δz of 2 mm. The corresponding BPP is calculated using measured beam radius and angular divergence.

4.3 Application to kW-class single-mode fiber laser

A fiber laser developed by Rofin and emitting 2 kW of power at 1.07 μm wavelength was used to test the novel flat-top fiber with 100 μm core. The beam properties, including intensity profile and BPP, were recorded using a Primes Focus Monitor FM-120. Two sets of measurements were compared, first when directly coupling the fiber laser LMA-GDF-20/400 to the standard BD fiber with 100 μm core diameter and then when using the novel flat-top fiber design. The experimental results, presented in Fig. 7(a) and (b) respectively, show a good agreement with the numerical predictions discussed in Section 2. When the fiber laser output is directly coupled to the standard BD fiber cable with no additional splice or coupling processing, the beam profile shows important distortions and the BPP remain low which is a confirmation of the poor mode mixing propagating in the BD fiber. Such beam does not satisfy the application requirements as it is. Tests were repeated using the novel flat-top fiber design with 100 μm core and show a significant improvement in beam uniformity (Fig. 7(b)) compared to standard BD fiber cable results (Fig. 7(a)). In addition, the measured output BPP of 3.8 mm*mrad is within the preferred specification window of 3.5 to 4 mm*mrad which confirms the control over the mode mixing and the spatial mode overlap achieved when employing the mode mixing element(s).


(a) Direct coupling of SM fiber laser in standard BD cable

(b) Direct coupling of SM fiber laser in flat-top BD fiber

Fig. 7: Measured beam profile and BPP of a 2-kW fiber laser beam (a) at the output of a standard BD fiber cable and (b) when using the novel flat-top BD fiber.

These results confirm that the specially designed flat-top BD fiber is capable of delivering multi-kW power levels with the desired BPP and a flat-top beam profile and is well-suited for laser-assisted material processing applications. In addition, since the geometry of this novel flat-top fiber is identical to the standard BD fibers commonly used in these applications, the flat-top fiber is a drop-in replacement which doesn't require any special redesign of cable or connectors. It is important to note that this study illustrates the effectiveness of the technology via the example of a 100 μm core fiber. Additional numerical simulations were performed and predicted that this concept can be scaled to fibers with various core sizes. On-going development is in progress to fabricate fibers with 50 and 200 μm core diameters and experimentally confirm the scalability of this technology.

5. SUMMARY AND PERSPECTIVES

In summary, a novel specialty fiber, designed to transform a SM beam into a flat-top intensity profile with controlled BPP has been demonstrated. The mode mixing in the MM BD fiber has been tailored to achieve specific BPP values, defined by the material processing industry standards for 100 μm core beam delivery cables. This novel flat-top fiber technology has attenuations comparable to standard BD fibers and has demonstrated the ability to handle and convert a 2-kW SM laser beam into a flat-top beam profile with 3.8 mm*mrad BPP. Furthermore, this flat-top fiber is an all-fiber solution which offers an efficient and low-maintenance drop in-replacement for standard beam delivery fibers where tight BPP control and stringent beam profile requirements need to be met. The novel design can not only be scaled to different core sizes but can also be used for tailoring the design to achieve BPP anywhere from near single-mode to the maximum BPP defined by the fiber core size and NA, opening its range of application beyond the material processing market. While this study focusses on demonstrating the new flat-top fiber technology for the special case of a SM fiber laser spliced to the beam delivery fiber, the authors foresee that this fiber technology can be used in a variety of beam delivery applications including both pulsed and CW fiber lasers, diode lasers and other solid state lasers for both industrial and medical applications. The technology can also be used for a wide range of operating wavelengths ranging from UV-Vis to mid-IR.

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