Specialty flat-top beam delivery fibers with controlled beam parameter product

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ABSTRACT

Beam delivery fibers have been used widely for transporting the optical beams from the laser to the subject of irradiation in a variety of markets including industrial, medical and defense applications. Standard beam delivery fibers range from 50 to 1500 μm core diameter and are used to guide CW or pulsed laser light, generated by solid state, fiber or diode lasers. Here, we introduce a novel fiber technology capable of simultaneously controlling the beam profile and the angular divergence of single-mode (SM) and multi-mode (MM) beams using a single-optical fiber. Results of beam transformation from a SM to a MM beam with flat-top intensity profile are presented in the case of a controlled BPP at 3.8 mm*mrad. The scaling capabilities of this flat-top fiber design to achieve a range of BPP values while ensuring a flat-top beam profile are discussed. In addition, we demonstrate, for the first time to the best of our knowledge, the homogenizer capabilities of this novel technology, able to transform random MM beams into uniform flat-top beam profiles with very limited impact on the beam brightness. This study is concluded with a discussion on the scalability of this fiber technology to fit from 50 up to 1500 μm core fibers and its potential for a broader range of applications.

Keywords: Specialty fiber, Beam shaping, Beam homogenizer, Mode mixing, Flat-top beam, CW and pulsed laser, Multimode diode laser, Material processing.

1. INTRODUCTION

Controlling the properties of a light beam is a common requirement to a large number of light-based applications and a broad variety of techniques have already been demonstrated [1]. Beam control can refer to beam shaping, for example by transforming its intensity profile or converting its angular divergence or controlling polarization. Free space beam control techniques can be applied to any sort of beam, propagating either in free space or in optical waveguide structures. Such techniques are generally limited to low beam conversion/transformation efficiency, high maintenance and difficult integration. With the development of fiber-based and fiber-coupled light sources, techniques to achieve beam control in optical fibers offered unmatched benefits. Several fiber-related beam control techniques have also been reported such as shaped-core fibers [2, 3], long period gratings [4] and MM interference devices [5]. Even though these techniques offer benefits associated with fiber technologies (low loss, small footprint, low maintenance, enhanced compatibility), most of them remain impractical, difficult to integrate in existing optical systems and performance limited. Therefore, there is a need for high performance, and scalable, all-fiber techniques to control optical beams.

To our knowledge no fiber waveguide designs for achieving flat top intensity profiles and furthermore achieving application specific BPP targets has been developed. These fibers are typically pure silica core, step index fibers with 0.22 NA. They have served well to deliver high power beams and preserve the input beam parameters. However, several applications demand specific beam parameter product (BPP) and intensity profile. Here, a novel fiber technology able to achieve beam control of both single-mode (SM) and multi-mode (MM) optical beams is introduced. To demonstrate its unique performances, this technology was applied to fibers used in laser-assisted material processing applications which have strict requirements for flat-top beam profile and specific beam parameter product (BPP). The uniqueness of this technology 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 of the standard beam delivery fibers. The fiber was designed using numerical tools and experimental fibers were fabricated and characterized. The novel flat top fiber introduced here employs standard beam delivery fiber geometry, 100 μm pure-silica core, 0.22 NA with 360 μm cladding, widely used for laser material processing. Experimental demonstration of beam control within a single-fiber which is compatible with existing optical systems is demonstrated in the case of (1) the transformation of a SM beam into a flat-top MM beam with controlled BPP and (2) homogenizing MM beams without brightness degradation.

2. TOOLS FOR BEAM CONTROL IN OPTICAL FIBERS

2.1 Context of the study

The goal of this study is to propose an all-fiber solution to achieve beam shaping and beam control while offering the advantages of monolithic fiber-based systems: low-loss, low-maintenance, small footprint and cost-effectiveness. Therefore, the scope of this work has been limited to single-fiber techniques able to efficiently shape, transform and control SM and MM beams. In other words, this “all-fiber approach” refers to a method able to achieve beam shaping and beam control by transformation of the light as it enters the core of an optical fiber and as it propagates down its length. The following concepts are not limited to fiber laser systems and can be applied to light beam from any rod, disk or diode laser source. In the case of fiber-based applications, preferred single-fiber solution for beam shaping and/or beam control are directly compatible with the fiber architecture of the system employing standard and simple splicing techniques. On the other hand, single-fiber methods for beam control can also be integrated in any sort of optical systems with the use of appropriate free-space optics coupling schemes.

In this context, Nufern introduces a novel fiber technology which has been developed based on a single specialty fiber carefully designed to control SM and MM beams. The beam control aspects addressed in this study are related to beam profile and beam parameter product (BPP), two widely employed industry standards to characterize optical beams [2]. This fiber technology offers a remarkable scalability, enabling a variety of beam profile and BPP combinations by fine tuning the fiber design. Therefore, the potential of this technology is anticipated to benefit a diversity of applications in industrial, defense and medical markets. In the following, the beam control performances of this novel fiber have been demonstrated using beam delivery fibers, typically employed in laser-assisted material processing, as an example. These applications have strict requirements in terms of beam profile and BPP which will be targeted. Additional beam control aspects such as beam shape and polarization are not elaborated in the present work.

2.2 General concepts for mode-mixing in optical fibers

The electromagnetic field of the beam emerging an optical fiber is the superposition of so-called transverse modes and can be defined as

$$E_{out} = \sum_{n} \rho_{0,n} \times e^{i\beta_n z} \tag{1}$$

where, $\rho_{0,n}$ is the fraction of power, also called mode power carried by the n^{th} mode, β_n is the propagation constant of this mode and z the length of the optical fiber. In order to control the output beam from an optical fiber, one must, first of all, control the mode content excited in this fiber. Fig. 1 represents the intensity profile of a few transverse modes available in a circular core step-index fiber and the number at the top left corner indicates the order of each mode.

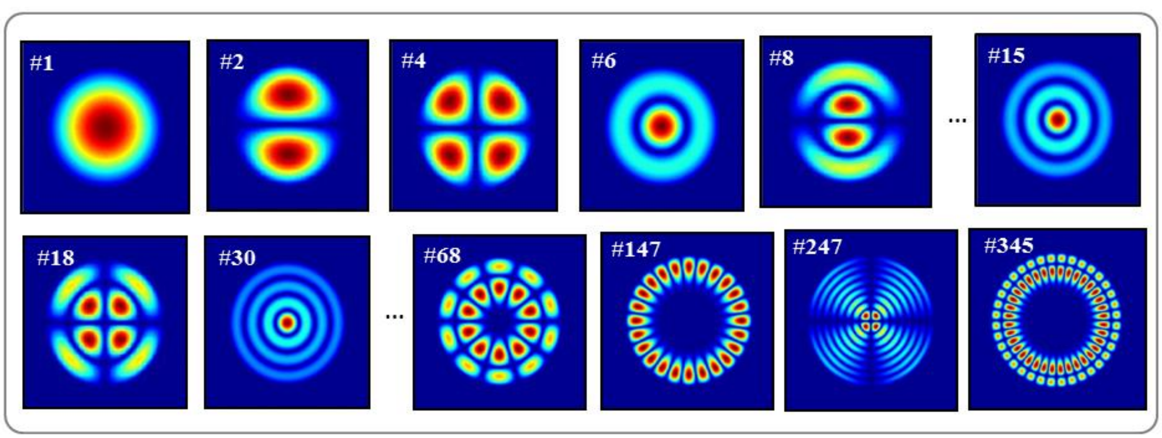


Fig. 1: Intensity profile of a few of the transverse modes available in the core of multimode step-index circular core fibers.

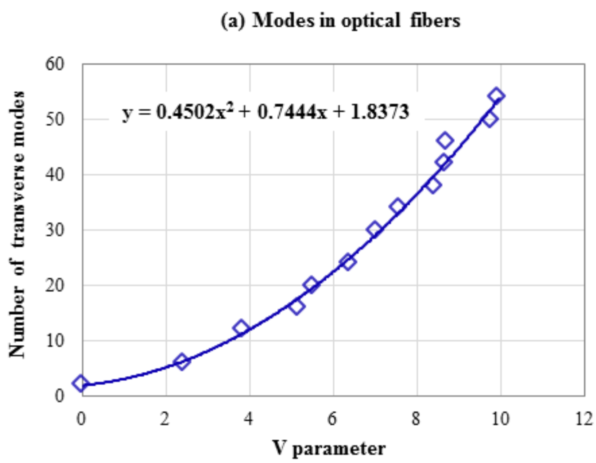
The type and number of modes available in an optical fiber are defined by the well-known V-parameter which can be calculated using the fiber core radius, r, the fiber core numerical aperture, NA, and the wavelength of light, λ, as

$$V = (2\pi r NA)/\lambda \,. \tag{2}$$

The number of modes available in an optical fiber depends on the value of the V-parameter and is indicated by the markers on the plot in Fig. 2(a). This dependence is commonly extrapolated using a polynomial fit which is used to predict the available number of modes in an optical fiber. However, the modes which are excited when light propagates in an optical fiber generally differ from the total number of modes available. This is governed by the so-called mode overlap integral which defines the mode power $\rho_{0,n}$ as a function of the input field, E_i, and of the field of each transverse mode in the fiber, E_f, as

$$\eta = \frac{\left|\int E_{i,n}{}^{*} E_{f,m} dA\right|^2}{\int \left|E_{i,n}\right|^2 dA \int \left|E_{f,m}\right|^2 dA} \tag{3}$$

Where, $E_{i,n}$ denotes the field of the n^{th} mode in the input fiber and $E_{,f,m}$ the field of the m^{th} mode in the optical fiber. Therefore, the number and type of modes excited in the fiber directly depends on the properties of the input beam such as size, shape, alignment, etc. Tuning the mode overlap integral at the fiber input facet determines the modes excited and propagating which define the profile of the output beam.



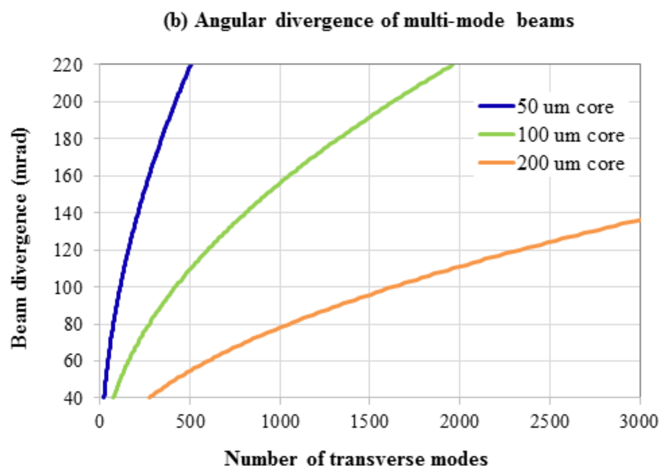


Fig. 2: (a) Number of modes available in a MM fiber as function of the V parameter. (b) Calculation of the beam divergence as function of the order of the HOM excited in the MM fibers. Results are shown for 50, 100 and 200 µm core diameter fiber with 0.22 NA.

In addition, the divergence of the beam is also determined by the excited mode content. Modes of higher order intrinsically propagate at larger divergence angles and, it is possible to predict the beam divergence as function of the mode number from the V-parameter definition Eq. (2). Calculations were performed for 50, 100 and 200 µm core fibers made with a pure fused silica core and a fixed NA of 0.22 and results are summarized in Fig. 2(b). According to the beam divergence requirements, it is possible to predict how many higher order modes must be excited in the optical fiber. For example, some beam delivery applications require divergence angles comprised between 80 and 100 mrad when using a 100 µm core fiber. According to Fig. 2(b), this target is achieved when ~ 400 modes are excited in this fiber. Similar concept applies to tailoring of the BPP, which is defined as the beam divergence in mrad multiplied by the beam size in mm. As a result, all-fiber methods to control the beam profile, the beam divergence and the BPP require a precise control of the mode content excited in the optical fiber.

3. NEW FIBER DESIGN FOR IN-FIBER BEAM PROFILE AND BPP CONTROL

3.1 Fiber approach for beam control

This section illustrates the concepts of tailored mode mixing to control the properties of the output beam using numerical simulations and experimental results. The emphasis is placed on controlling the beam profile and angular divergence via a few different scenarios involving optical fiber techniques. The particular case of beam transformation from a SM beam to a MM beam with flat-top intensity profile, commonly required in material processing applications, was selected. We consider a typical kW class fiber laser delivering a single mode beam through a LMA-GDF-20/400 fiber with 20 μm core, 400 μm cladding and 0.06 NA core. Material processing applications employing such lasers also require flat-top beam profiles with a specific BPP of 3 to 4 mm*mrad, and preferable 3.5 to 4 mm*mrad, in the case of a 100 μm core process fiber. For the purpose of the demonstration, we therefore use the example of a step-index, pure silica core fiber with 100 μm core diameter and 0.22 NA core.

According to Eq. (2), the V-parameter of the process fiber is 65.2 in the 1 μm wavelength range which corresponds to a total of ~ 1,960 modes. In the case where all the modes are excited, the angular divergence of ~ 220 mrad leads to a BPP of ~ 11 mm*mrad which is out of the 3 to 4 mm*mrad range specified by the application. In practice, the laser from the LMA-GDF-20/400 fiber is coupled to the 100 μm core fiber using a conventional splice as is illustrated in Fig. 3(a). In this case, the mode overlap integral was calculated and the results are presented in Fig. 3(b) where the normalized fraction of power guided in each mode is plotted as a function of the mode number. To ensure the clarity of the plot, only the first 400 modes are presented on the x-axis and the mode power is plotted in log scale on the y-axis. The mode overlap integral calculation results suggest that only a very limited set of modes are excited in the MM fiber under these launching conditions. The poor mode mixing is expected to lead to non-uniform beam and low angular divergence. This configuration was reproduced in the lab and the beam emerging the MM fiber was recorded. Results are presented in Fig. 3(c) showing a non-uniform beam profile with a BPP around 2.6 mm*mrad which does not meet the flat-top beam or BPP requirements. Such results emphasize the needs for a single-fiber solution to convert and control the laser beam.

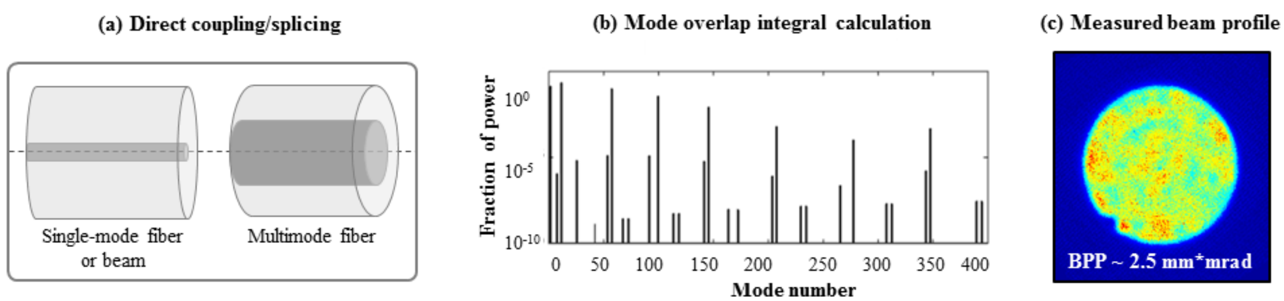


Fig. 3: (a) Schematic of the direct coupling between the SM and the MM fibers. (b) Calculation results of the mode overlap integral. (c) Profile of the beam measured at the MM fiber output (100 μm core, 0.22 NA) when the SM fiber is directly spliced.

A possible alternative to increase the mode mixing is to perturb the mode overlap integral at the coupling facet of the MM fiber. This can be done by introducing an offset coupling or splice as illustrated in Fig. 4(a). The mode overlap integral calculation results, shown in Fig. 4(b), confirm that a larger number of modes are being populated when introducing an offset. The measured beam profile (Fig. 4(c)) also shows an overall improvement in the intensity uniformity. Even though introducing an offset splice does increase the mode mixing, this approach does not provide enough beam control to achieve an efficient beam profile and BPP conversion. In addition, this method is limited by severe practical limitations such as poor reproducibility, limited range and increased coupling losses.

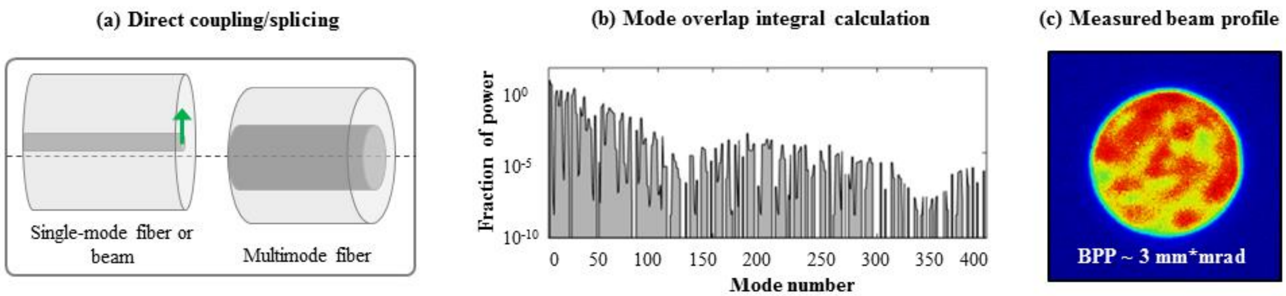


Fig. 4: (a) Schematic of the offset coupling between the SM and the MM fibers. (b) Calculation results of the mode overlap integral. (c) Profile of the beam measured at the MM fiber output (100 μm core, 0.22 NA) when the SM fiber is offset spliced.

Another approach to control the beam properties is to design shaped-core MM fibers. This has been demonstrated to work well to transform MM circular beams into MM square beams [2]. In the case of SM to MM flat-top beam conversion, it has been demonstrated that using shaped core fibers remains a challenging approach [3]. The mode overlap calculation for the configuration represented in Fig. 5(a) shows a relatively poor mode mixing (Fig. 5(b)). The corresponding beam profile emphasizes the lack of uniformity and fails to achieve the required beam control leading to a MM flat-top beam with BPP comprised between 3.5 and 4 mm*mrad.

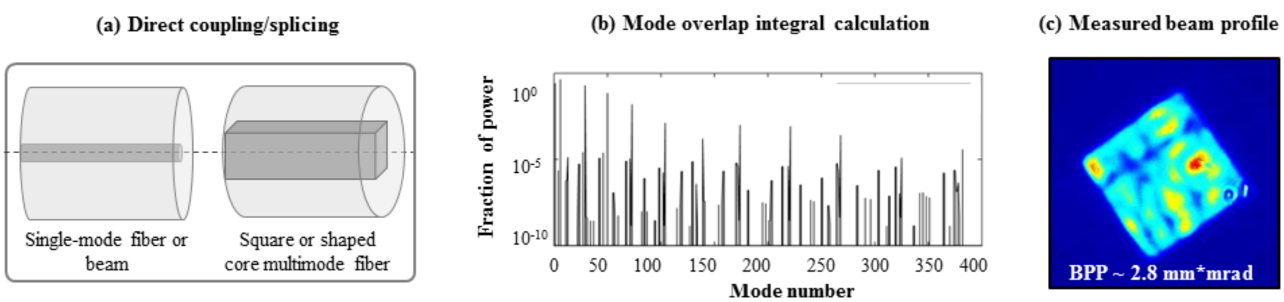


Fig. 5: (a) Schematic of the direct coupling between the SM and the MM shaped-core fibers. (b) Calculation results of the mode overlap integral. (c) Profile of the beam measured at the MM square-core fiber output (100 μm core, 0.22 NA) when the SM fiber is directly spliced.

These results emphasize the difficulty to tailor the mode mixing in MM fibers when SM inputs are used and justify the needs for efficient in-fiber beam control techniques.

3.2 Novel fiber design for beam control

Here, we introduce a novel fiber design which can be tailored to achieve beam profile and BPP requirements of a wide range of applications. To demonstrate this concept, we continue with the case of material processing applications using SM lasers with kW-power levels coupled in large core step-index process fibers. It is important to note that the following design is not restricted to 100 μm core fibers but can be scaled to any MM fiber to tailor beam profile and BPP. Fig. 6 shows a schematic representation of a typical process fiber on the left. The corresponding refractive index profile is also provided. On the right of Fig. 6, the specialty MM fiber is represented, made with identical geometry as the process fiber with the addition of one or multiple mode mixing elements in the core. The shape, size and location of the mode mixing element(s) affect the mode overlap integral and tailor the mode content excited in the fiber to allow a fine control of the output beam.

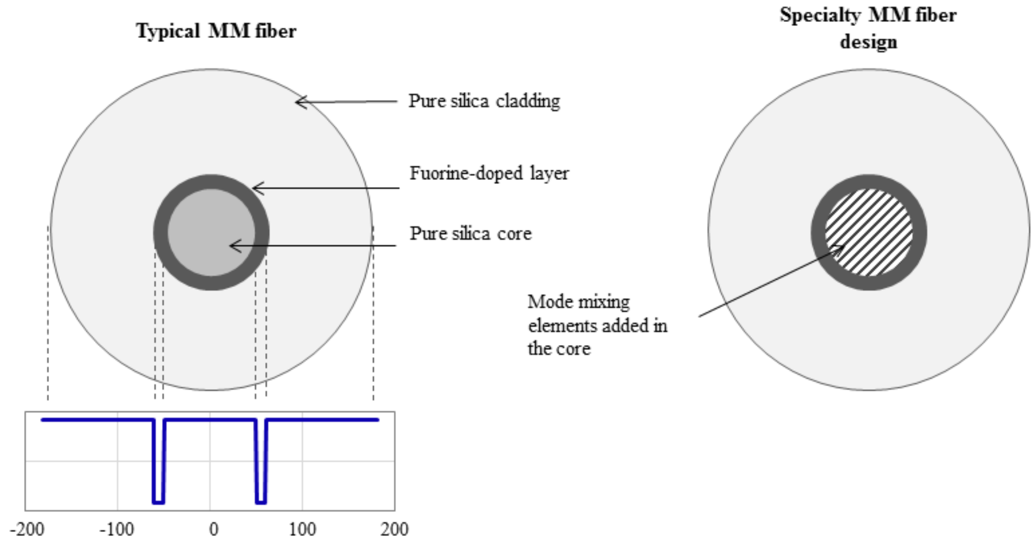


Fig. 6: Schematic of typical MM process fiber with 100 μm core and 0.22 NA (left) and of the specialty MM fiber for beam control (right).

Mode overlap calculations were performed using a SM beam launched in to the specialty MM fiber and the design of the mode mixing elements was tuned in order to increase the mode mixing and to homogenize the power distribution among the modes. Calculation results are depicted in Fig. 7 where the fraction of power among the modes is plotted for the first 400 modes in the standard MM fiber and an optimized design of the specialty MM fiber in black and green, respectively. These results predict a significant increase of the mode mixing and of the power distribution among the modes in the MM fiber with mode mixing elements, which seems to be a good candidate for SM to MM flat-top beam conversion.

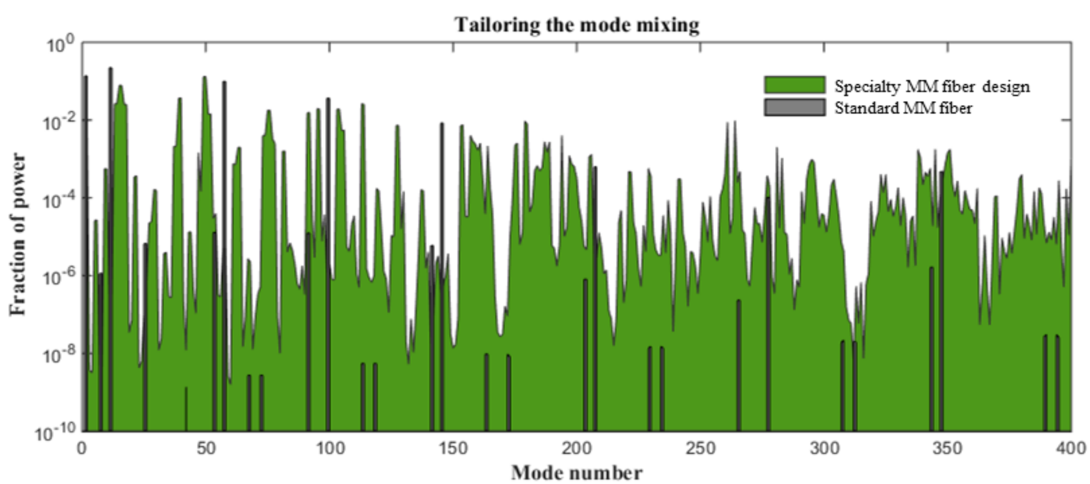


Fig. 7: Mode overlap calculations showing the mode mixing in a standard MM fiber (black) and in the specialty fiber design (green) in the case of an incident SM beam.

4. DEMONSTRATION OF SM TO FLAT-TOP MM BEAM CONTROL

The specialty fiber design has been fabricated using conventional optical fiber fabrication techniques and its performances have been tested for core attenuation, geometry and beam properties. Results are discussed in this Section.

4.1 Specialty fiber attenuation

A fiber preform was assembled using a pure-silica core and with the mode mixing element(s) according to the numerical predictions. For this demonstration, the fiber dimensions were matched to the 100 μm core, 0.22 NA process fiber dimensions with a 120 μm fluorine-doped layer and a 360 μm pure-silica cladding. The core attenuation was measured from 750 nm to 1350 nm using a broadband light source and an optical spectrum analyzer (OSA). The results are summarized in Fig. 8 along with the core attenuation measured in the standard MM fiber of identical geometry but without mode mixing element(s) (dashed line).

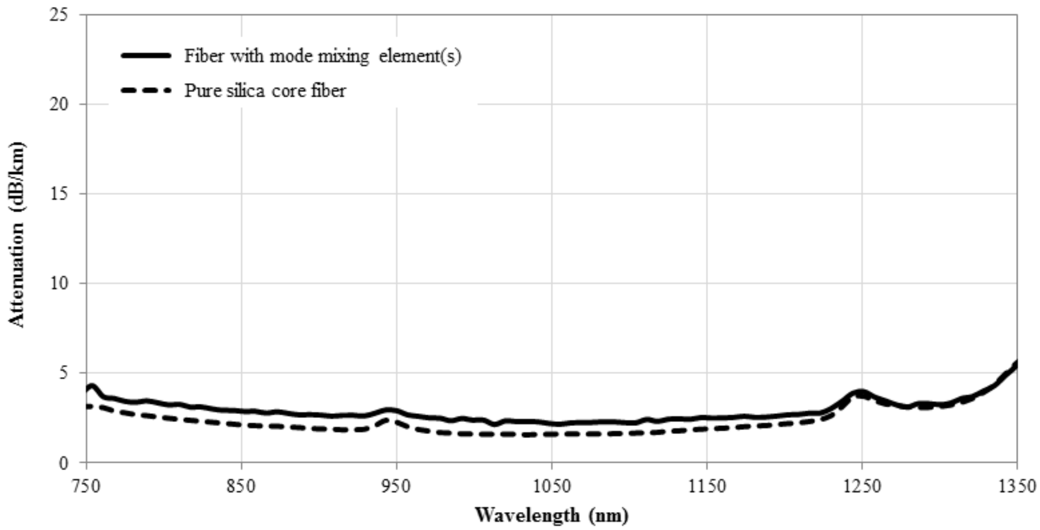


Fig. 8: Measured core attenuation compared between a standard MM fiber and the same fiber with mode mixing elements in the core. Both fiber core diameters are 100 μm.

Results show that, the attenuation of the flat-top transformation fiber is not significantly different than that of standard step index fibers with pure silica cores and is within expected lot-to-lot variation. These results indicate that the introduction of mode mixing elements in the core, along with the fiber process, did not have negative impact on the light propagation. Such fibers are well suited to be used within a broad wavelength range, in applications using hundreds of meters of fiber as well as for process fiber, able to handle multi-kW power lasers for material processing applications.

4.2 Experimental demonstration of SM to MM beam transformation

The new specialty fiber has been tested using a laser operating at a wavelength around 1.07 μm coupled in the LMA-GDF-20/400 fiber and delivering a SM beam. In the rest of this study, the specialty fiber will be referred to as the flat-top fiber. The MM process fiber and the flat-top fiber were respectively fusion spliced to the SM fiber using a conventional splicing program, without introducing any off-set. A fiber length of 20 meters long was loosely coiled on the optical bench in order to mimic the deployment condition of material processing applications. The output facet was cleaved at a flat angle and the beam profile was imaged in the near-field and far-field as well as the beam angular divergence. From these measurements, it is possible to evaluate some beam properties such as the beam profile as well as the BPP. Measured results are summarized in Fig. 9. The top row represents the SM beam coupling in to the standard MM fiber and the beam emerging from the fiber. The lower row shows the beam emerging the flat-top specialty fiber design when the same beam is launched in the fiber under identical conditions. The results highlight the controlled mode mixing achieved in the specialty fiber design leading to the conversion of a SM beam into a uniform flat-top beam profile. In addition, the BPP was evaluated from the beam divergence measurements leading to 2.6 mm*mrad in the standard MM fiber compared to 3.8 mm*mrad obtained in the flat-top specialty fiber. These measurement results are in good agreement with the numerical predictions which confirm the effectiveness of the introduction of well designed mode mixing element(s) in the core of the fiber. This technology offers a unique approach to achieve beam control, including beam transformation and BPP conversion in a single fiber which is entirely compatible and can be easily integrated in existing optical systems.

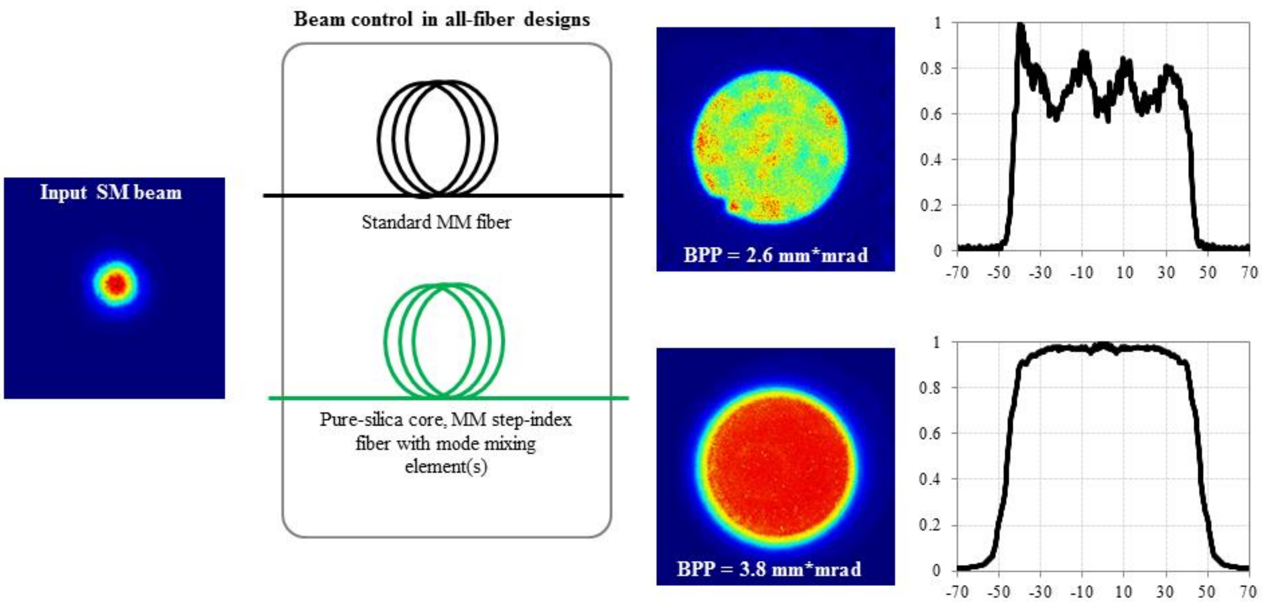


Fig. 9: Measurement of the beam properties, including 2D and 1D beam profiles and angular beam divergence emerging from standard MM fiber (top) and from the specialty flat-top MM fiber (bottom) when a SM beam is launched using conventional splicing or coupling techniques.

Furthermore, the MM flat-top fiber design has been investigated in order to evaluate its scalability potential. In other words, the beam profile and BPP were recorded for various specialty fiber designs while maintaining the same measurement conditions as described above. It is important to note that, due to the proprietary patent pending character of the fiber design, no additional detail can be shared at this time. Several specialty fibers were fabricated while tuning only one design parameter of the mode mixing element(s) and the results of the beam characterization are provided in Fig. 10. The measured BPP is plotted for different scaling values showing that, by adjusting the fiber design, the mode content can be tailored, leading to beams with increasing BPP while the output beam profile remains a uniform flat-top. In addition, the BPP results seem to follow a linear trend as function of the design parameter. As the fiber design progress, such results can be used to draw a map of expected beam properties and performances which can facilitate the development steps. This demonstration is, to the best of our knowledge, the first single-fiber solution for beam control technique able to transform a SM into a MM flat-top beam while achieving various BPP values, which can fit a large diversity of applications.

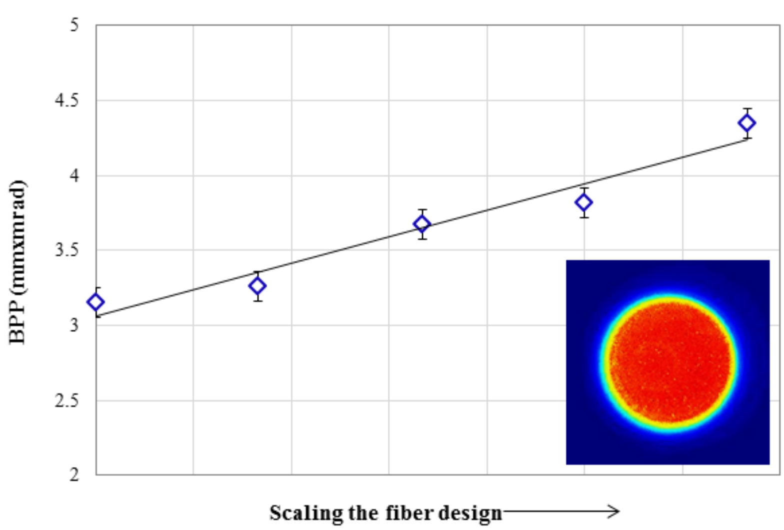


Fig. 10: Measured BPP emerging the specialty flat-top fiber as one design parameter of the mode mixing element(s) is tuned. As the BPP increases linearly, the beam profile maintains a uniform flat-top shape.

5. DEMONSTRATION OF ALL-FIBER MM BEAM HOMOGENIZER

In this last Section, the flat-top specialty fiber was further designed to be used with MM launch beams. Compared to SM input beams, MM beams significantly vary in size, shape and BPP from one application to the other. However, most applications using MM beams have one common goal: to eliminate the MM beam hot spots and other imperfections and obtain homogenized MM beams. The flat-top MM fiber was designed in order to tailor the mode mixing, leading to the generation of MM beams with uniform intensity distributions. This is beneficial for direct diode fiber delivery [7], speckle-free lasers and imaging [8].

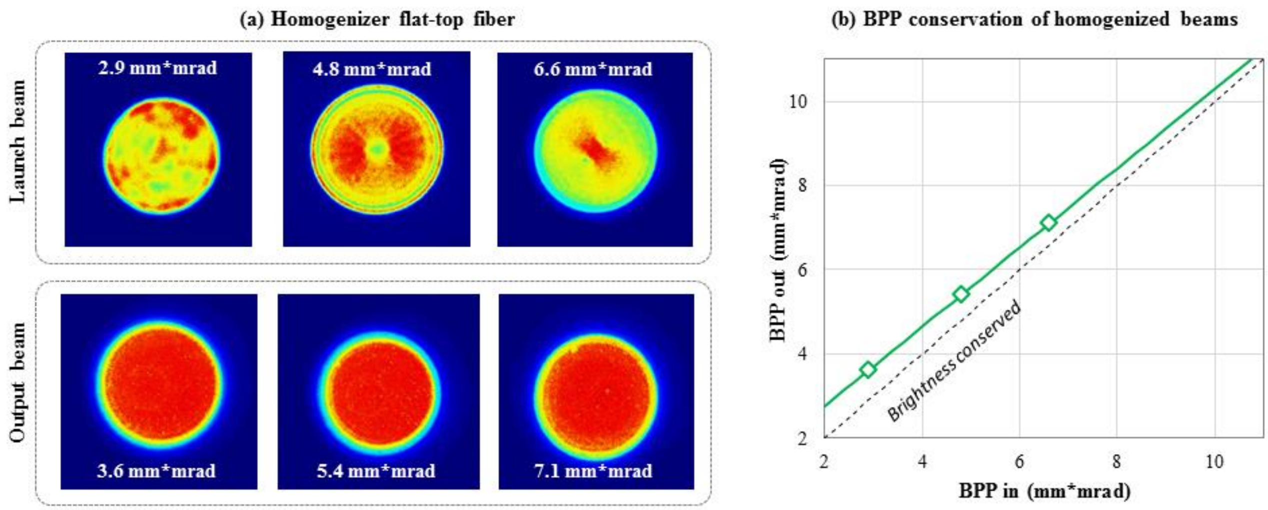


Fig. 11: (a) Experimental demonstration of the homogenizer capabilities of the flat-top fiber design for a variety of MM input beams. (b) Plot of the BPP measured at the output of the specialty flat-top fiber as function of the BPP of the launched beam. Measurements shown with the green markers are compared against the ideal case of BPP conservation (dashed line), i.e. brightness conservation. Both launch fiber and flat-top fiber cores were 100 μm in diameter.

Measurements were recorded, launching various MM beams in a flat-top specialty fiber design. The deployment conditions used for these experiments are identical to the SM beam control experiments. Results are summarized in Fig. 11(a) where three MM beams showing various profiles have been coupled in the specialty flat-top fiber. For each incident beam, the corresponding output beam was measured and results are shown in the row underneath. For every MM beam used, regardless of its profile, the specialty fiber acted as a homogenizer medium and transformed the beam into a perfectly uniform top-hat beam profile.

Furthermore, the BPP values of the homogenized beams have been measured for various input beams and plotted as function of the input BPP. Results are depicted in Fig. 11(b) and where the dashed line indicates the limit where BPP and brightness are conserved. Brightness conservation is an important criteria for numerous applications. These measurements show that homogenized beams suffer a small BPP increase of less than 8% of the BPP of the input beam. Additional cut-back experiments were conducted in order to evaluate the BPP and beam profile change as function of fiber length. Results proved that the homogenizer properties were conserved for a fiber length varying between a couple of meters up to several ten's of meters. Within this range, the BPP remained stable within the +/- 0.2 mm*mrad measurement error.

6. SUMMARY AND PERSPECTIVES

In summary, we introduce a novel approach to all-fiber beam control which involves a single specialty fiber, designed with mode mixing element(s) to finely tune the mode mixing, and therefore, the properties of the output beams in terms of beam profile and beam angular divergence, or BPP. First SM to MM flat-top beam transformation was numerically and experimentally demonstrated using the example of a LMA-GDF-20/400 fiber with 0.06 core NA, directly coupled to a 100 μm core, 0.22 NA fiber via standard splicing techniques or cable connectors. The SM beam was effectively transformed in a MM flat-top beam profile. In addition, it was shown that the BPP of the flat-top beam could be tuned by adjusting the fiber design. The result is an all-fiber solution able to transform a SM beam into a MM flat-top beam with controlled BPP in order to suit the beam requirements of a wide range of applications. Then, it was experimentally demonstrated that the specialty flat-top fiber design offers unmatched performances as a homogenizer for MM beams. In this case, the brightness of the beam suffers a small penalty. However, as the fiber development continues, one of the focus areas will be to provide effective beam homogenization with minimal impact on brightness.

This novel fiber technology can not only be scaled to different core sizes but can also be used for tailoring the design to achieve BPP values anywhere from near single-mode to the maximum BPP defined by the fiber core size and NA. Based on these performances, this all-fiber solution for beam control can be implemented to meet the beam requirements of an extremely broad range of applications, including both pulsed and CW fiber lasers, diode lasers and other solid state lasers for both industrial and medical lasers. The technology can also be used for a wide range of operating wavelengths ranging from UV-Vis to mid-IR.

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