# Design optimization of Tm-doped large-mode area fibers for power scaling of 2µm lasers and amplifiers

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## ABSTRACT

Large-mode area (LMA) thulium-doped fibers (TDF) are one of the key components when designing 2µm laser and amplifier systems aiming to further scale deliverable output powers. Current design limitations of LMA TDF's affecting optical-to-optical efficiency and output beam quality are well-understood. In the present work, design optimizations focused on the core and pedestal waveguides of the active fiber are proposed. Using experimental and numerical tools, the effect of splice-induced heat on the refractive index profile of the active fiber is investigated. We demonstrate that fibers designed with larger pedestal-to-core ratios suffer less index distortions during splicing allowing the end-user to achieve high coupling efficiencies and high beam qualities in a reliable fashion.

**Keywords:** Thulium-doped fibers, large-mode area fiber, specialty fiber, fiber design, 2µm amplifier, kW-class fiber amplifier

## 1. INTRODUCTION

The introduction of double-clad large-mode area (LMA) Thulium-doped fibers (TDF) has enabled the development of high power laser and amplifier sources emitting within the wavelengths range from 1950 to 2050nm. Applications such as pump sources, LIDAR, long range sensing and atmospheric propagation trigger increasing needs for further power scaling within this eye-safe range of the spectrum. Among the highest output power reported to date, kW-level was achieved in Tm-doped fiber amplifier [1] and recently > 500W in a Tm-doped fiber oscillator [2]. One of the key elements in order to accomplish power scaling is the ability of the optical fibers used in the system, especially the TDF, to offer high performances while operating at high power levels.

There are several criteria that the LMA TDF must fulfill in order to be suitable for further power scaling including high efficiencies and high beam quality. The active core must be designed with high Tm-doping concentration in order to favor the cross-relaxation process which enables achieving very high efficiencies, theoretically as high as 80% when pumping at 79Xnm [3]. Currently, up to 60% optical to optical efficiencies are being reported when using LMA TDF's [4]. In order to handle the power, LMA designs with typical core sizes around 25µm are being implemented. It has been demonstrated that the fundamental mode area overlap with the active region must be maximized in order to achieve highest efficiencies [5]. On the other hand, the high doping level in the core results in a high numerical aperture (NA) forming a multimode waveguide. In order to restrict the number of transverse modes guided in the core, a pedestal layer is added to effectively reduce the NA and therefore limit the mode content to only a few guided modes. Furthermore, the core design is tailored to allow for efficient higher-order modes suppression via coiling in order to achieve diffraction limited beam quality. As a result, the design of the core and pedestal are crucial in order to achieve high performances towards power scaling application.

## 2. CURRENT LIMITATIONS OF LMA TM-DOPED FIBER DESIGNS

In practice, operating LMA TDF's in laser and amplifier systems close to the theoretical limits of efficiency and beam quality still remains challenging. One of the reasons has been attributed to the presence of the pedestal layer surrounding the core. The pedestal is typically a step-index-like annular layer doped with Germanium in order to increase the index of pure silica. While the pedestal offers an effectively lower core NA, it also forms a larger waveguide surrounding the doped core. Therefore, any light missing the core due to coupling loss, splicing loss or mode-field mismatch is captured and guided by the pedestal. Due to the high NA of the pedestal waveguide, stripping out the pedestal light into the cladding of the fiber is particularly challenging and no effective technique has been demonstrated to date. Furthermore, coiling the TDF in order to suppress HOM's in the active core generates additional parasitic light in the pedestal with an increase likelihood for inter-modal coupling between the pedestal transverse modes and the fundamental core mode

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which directly affects the beam quality. Simakov et al. investigated the effect of the pedestal-to-core ratio (also called B/A) on parasitic inter-mode coupling [4]. In order to preserve single-mode propagation in the doped core, the overlap between the pedestal and the core modes must be as close to zero as possible. They claimed that implementing a pedestal diameter with B/A close to 3 would preserve high beam quality with minimal inter-mode coupling. Larger B/A values are at the limit of the manufacturability and lower B/A values are prone to beam degradations and instabilities due to core-pedestal inter-mode coupling.

Not only the pedestal design is key to achieve high performances, it also requires additional care when handling and integrating the optical fiber. The Germanium-doped glass used to form the pedestal layer is known to have a significantly lower melting temperature than the core and the cladding of the fiber. Recently, Walbaum et al. claimed that light coupling efficiency in the core of the TDF can be significantly improved by optimizing the splicing procedure [2]. It was demonstrated that using cooler splicing procedure helps to preserve the shape of the refractive index profile resulting in higher coupling efficiency between the fundamental mode of the TDF and the matched passive pigtail fiber. However in practice, developing optimized splicing recipes is time consuming and expensive. In addition, fibers which are highly sensitive to splicing optimization are difficult to process in a repetitive fashion.

In the following, an alternative study is proposed via an in-depth experimental and numerical analysis of the splice between TDF's and matching passive fibers. Details are provided regarding the effect of standard and optimized splicing recipes on fibers with different pedestal B/A value in order to reach high coupling efficiency and high beam quality.

## 3. INFLUENCE OF THE PEDESTAL DESIGN ON THE AMPLIFIER PERFORMANCES

### 3.1 Splice-induced index deformation

In order to investigate the effect of splicing on different pedestal fiber designs, two LMA TDF's were selected with 25 and 20µm diameter core, both with the same core NA = 0.11 and cladding diameter of 400µm. The noticeable difference between both fibers is the pedestal B/A value of 1.7 and 3 respectively. Each fiber was spliced to a matched passive fiber, 25/400 with 0.1 NA and 20/400 with 0.1 NA respectively. The fiber refractive index profiles were measured using an IFA100 and results are depicted in Fig. 1(a) and (b) for the TDF with 1.7 B/A and 3 respectively. The target index profile of TDF's is a step-index shape which is illustrated with a grey line in the background of Fig. 1. While the pedestal layer exhibits a consistent flatness, one can notice a center spike in some TDF cores. The spike is a process-related effect and it is closely monitored during glass fabrication to ensure a minimal magnitude. For example, in the case of Fig. 1(a), the center spike is only a cosmetic concern since it does not affect the key performances of the TDF, i.e. core NA, number of modes in the core, efficiency. The main practical outcome of such spike is a mode-field diameter on the short end of the specifications.

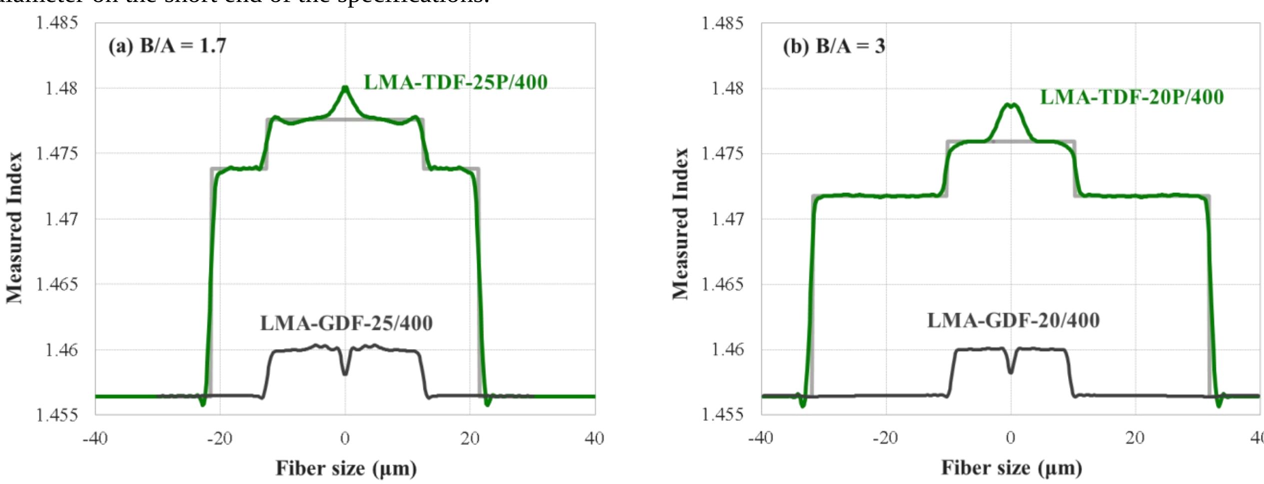


Fig. 1: (a) Measured fiber index profile of the LMA TDF with B/A = 1.7 overlapped with the matching passive fiber. (b) Measured index profile of the LMA TDF with B/A = 3 overlapped with the matching passive fiber.

Each pair of active and matched passive fiber has been spliced following two procedures. First a standard splicing program for 400µm clad fibers such as the one provided by commercially available splicers has been used. Then a second splice was made using an optimized splicing program with reduced heat duration and reduced heat power. The refractive index of the fibers at various positions along the splice has been recorded using a fiber profilometer (IFA-100).

Fig. 2 illustrates the splice characterization measurement with a schematic of the passive and active fiber with pedestal and a screenshot of the measurement screen at the center. The interference fringes are typical of the IFA-100 measurement device. On Fig. 2, one can see the splice interface between the passive and the active fiber. The dashed green lines illustrate the typical measurement window chosen to be 40µm in the present experiment. The refractive index is measured at the splice and away from the splice by translating the fiber chain by 40µm steps.

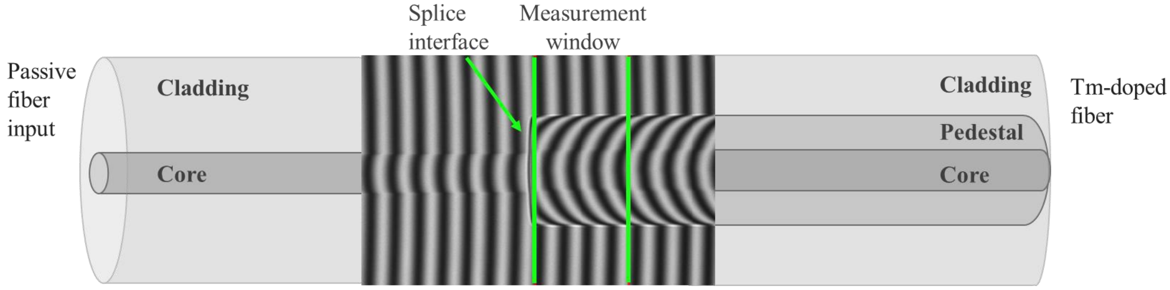


Fig. 2: Schematic of the refractive index measurement across a splice using the IFA-100 profilometer. The green arrows point at the splice interface which is clearly visible in this case. The green dots highlight the 40 µm wide measurement window.

For visibility purposes, only selected refractive index profiles (RIP) are plotted in Fig. 3. The fiber RIP's (black line) were recorded in a pristine fiber. The measurement displayed for a standard (dashed red line) and an optimized (light blue line) splice program correspond to the active fiber RIP measured at the closest location to the splice point. Fig. 3(a) represents measurements for the pedestal B/A of 1.7 and one can see significant RIP distortions in the vicinity of the splicing point. The index deformation is particularly severe in the pedestal layer area as it results from chemical elements diffusion when heat is applied. Index measured further away from the splice exhibit less deformation until it reaches the same index as the pristine fiber, 1 mm away from the splice in the case of the standard splice. Similar results are depicted in Fig. 3(b) for the TDF with pedestal B/A = 3.

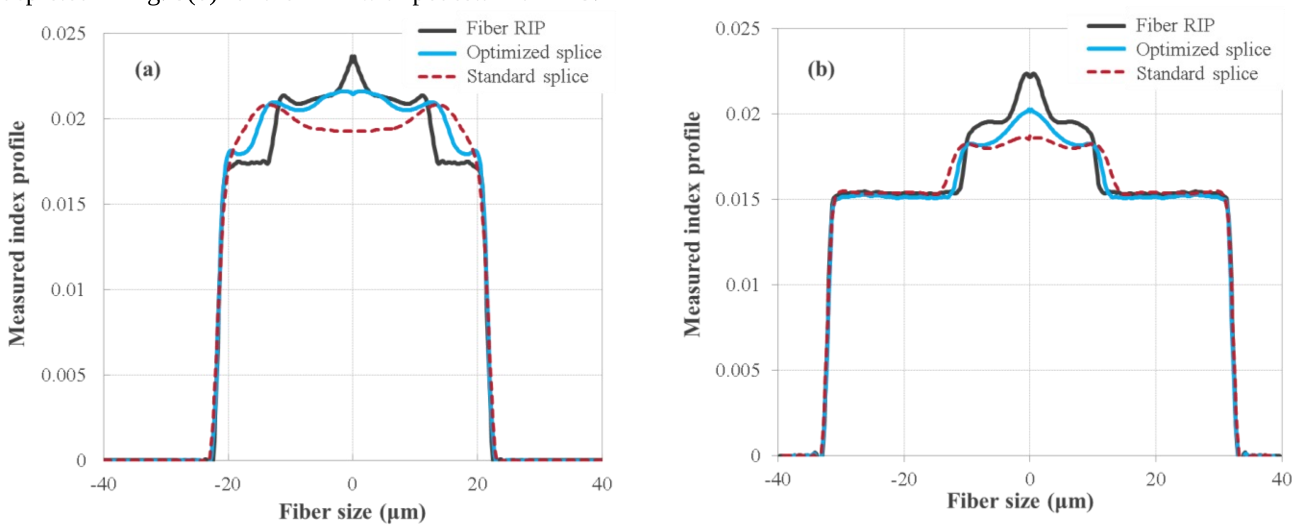


Fig. 3: (a) Results for B/A = 1.7 of the measure index of the pristine fiber (black), of the fiber location closest to the splice when using the optimized splicing recipe (light blue) and the standard splicing recipe (dash red). (b) The index measurement were repeated using the B/A = 3 TDF.

In the case of the pedestal B/A = 1.7, the index measurement indicates that the pedestal diffusion decreases from 7 µm down to 4µm when using an optimized splicing recipe compared to a standard approach. On the other end, the diffusion decreases only from 3µm to 1µm in the case of the B/A = 3 pedestal. In both cases, we verified that using an optimized splicing recipe allows to minimize index profile distortions. Most importantly, results on Fig. 3 indicate that larger pedestal-to-core ratios are also beneficial to minimize the pedestal diffusion. This concept is not yet fully understood but it suggests that fiber with larger B/A are less sensitive on splice temperature.

### 3.2 Coupling efficiency analysis and comparison

The measured index profiles were imported in a commercial modeling package (PhotonDesign) and used to solve light propagation equations through the splice including mode overlap integral and fractional power coupled in each core/pedestal mode. The wavelength for the calculation was set at 2µm. Using measured index profiles guarantees realistic calculation results. On the other end, importing measurements recorded every 40µm along the fiber splice ensures adiabatic calculations with minimal artifacts. Results of the mode overlap integral calculations are summarized in Table 1 for the two fibers with different B/A values. For these calculations, we assumed 100% of the incident light incoming from the matched passive fiber (which was also measured for index profile) and being launched in the TDF's using either the standard or the optimized splice program. The direct coupling case is an idealistic result based on measured fiber RIP and results with > 99% of light in the fundamental mode confirm that the passive and active fibers are matched by design. Similarly, both fibers perform well when using an optimized splicing program. In this case, the index deformation is minimal and the efficient coupling is preserved. In the case of the standard splice however, only 42% of the incident light is coupled in the fundamental mode of the TDF with 1.7 B/A while close to 90% is in $LP_{01}$ in the TDF with pedestal B/A = 3.

Table 1: Fraction of the incident power coupled in the $LP_{01}$ mode of the TDF through a standard splice and an optimized splice. Calculation performed at 2µm

| | Pedestal B/A | Direct coupling | Standard splice | Optimized splice |
|---|---|---|---|---|
| LMA-TDF-25P/400-HE | 1.7 | 99.7% | 42.1% | 97.6% |
| LMA-TDF-20P/400 | 3 | 99% | 89.9% | 99% |

The calculation results confirm that the active fiber with the larger pedestal-to-core ratio enables to reach higher coupling efficiencies independently of the splicing program or under minimal adjustments which is explained by the minimal index deformation in the vicinity of the splice.

## 4. IMPROVED LMA TM-DOPED FIBER DESIGN

According to these preliminary experimental results and based on the recently published studies investigating the impact of the pedestal design on the performances of the system, a new LMA TDF with improved design was manufactured. Test results are detailed in the following two sections.

### 4.1 Fiber design parameters

A fiber with an improved pedestal design was manufactured (LMA-TDF-25P/400-M) in order to simultaneously ensure high coupling efficiencies, minimum dependence on splicing procedure and to avoid pedestal/core modes inter-coupling along the length of the fiber. The new LMA Tm-doped fiber was designed with a 25µm core diameter and a pedestal-to-core ratio of 3. In addition, the pedestal was also designed to ensure a lower core NA at a target of 0.09 in order to reduce the number of transverse core modes from 4 to 2. For this combination of core diameter and core NA, the $LP_{11}$ core modes can easily be suppressed via coiling. Furthermore, the process-related features of the core index profile can be minimized via tighter process control. An example of index measurement of the fiber with improved design is shown in Fig. 4 (green line). A new matched fiber (LMA-GDF-25/400-09M) was fabricated and used to repeat the splice analysis using the same standard and optimized splicing recipes as described in the previous section.

### 4.2 Splice analysis results

The measured refractive indices across the standard and optimized splices of LMA-TDF-25P/400-M with the matched passive fiber were imported in the modeling tool. The indices measured at the splices are plotted in Fig. 4 with red dashed line and light blue line respectively. Compared to the previous fiber design LMA-TDF-25P/400-HE shown in Fig. 3(a) the diffusion observed at the pedestal-core interface is significantly reduced (less than 3µm). As a result, the core index profile suffers less distortion which preserves the characteristics of the $LP_{01}$ mode and favor high coupling efficiencies. Using the software, the 2µm single-mode from the passive fiber was launched in the TDF and the fraction of light coupled in the fundamental mode of the active fiber was calculated across the splice. The final fraction of light coupled and propagating in the TDF away from the splice is summarized in Table 2. When using a standard splice recipe with the 25µm core improved LMA fiber with pedestal B/A = 3 (LMA-TDF-25P/400-M), up to 90% of the light is being guided in $LP_{01}$ compared to only 42% in the former LMA-TDF-25P/400-HE fiber design.

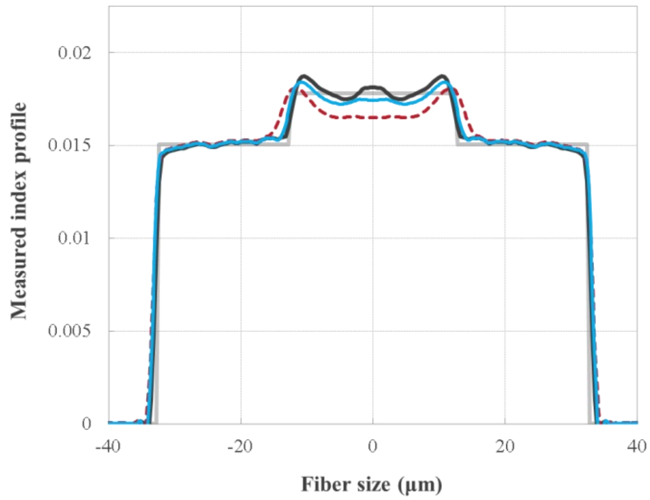


Fig. 4: Measured index profile of the improved fiber design (green line). The fiber index was measured at the splice when using the optimized (light blue) and the standard (dashed red line) splice recipe.

As anticipated, larger pedestal B/A values allow minimizing pedestal diffusion and therefore core distortions in the vicinity of the splice. The result is a high coupling efficiency in the $LP_{01}$ mode which will contribute to deliver high beam quality with minimum dependence on the splice parameters.

Table 2: Fraction of incident light guided in the fundamental mode ($LP_{01}$) of the active fiber

| | LMA-TDF-25P/400-HE | **LMA-TDF-25P/400-M** |
|---|---|---|
| B/A | 1.7 | 3 |
| Standard splice | 42.1% | 89.3% |
| Optimized splice | 97.6% | 99.3% |

Furthermore, it is possible to calculate the total amount of parasitic light being guided in the pedestal as a result of (a) coupling loss or (b) core light leakage in the pedestal due to index profile distortions along the splice. Results are plotted in Fig. 5(a) and (b) through the standard and optimized splices in the former design (LMA-TDF-25P/400-HE) and in the improved fiber design (LMA-TDF-25P/400-M) respectively. Using an optimized splicing program, the amount of light in the pedestal is less than a few percent in both fiber cases. The pedestal B/A of 3 provides the significant advantage to minimize inter-mode coupling as the light propagates down the length of the TDF to preserve high beam qualities [4]. Using a standard splicing program on the TDF with B/A = 1.7, close to 40% of the light is being coupled in the pedestal in addition to the inter-mode coupling which occurs down the fiber length. It becomes extremely challenging to maintain high beam quality in such case.

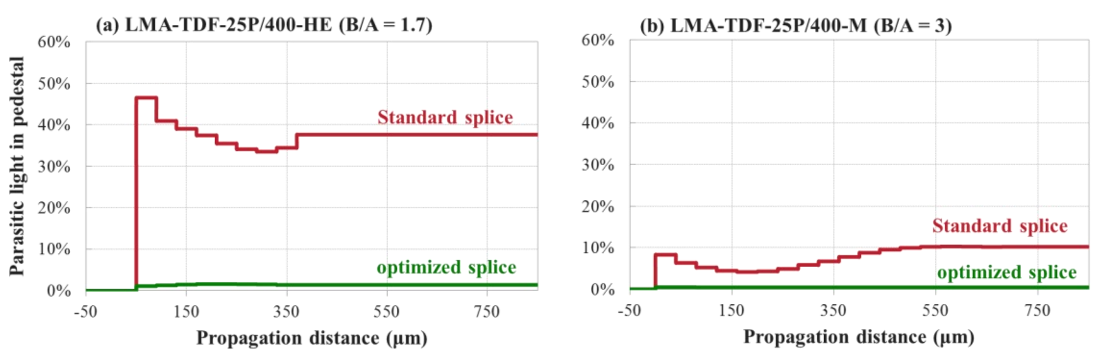


Fig. 5: Calculated fraction of light coupled in the pedestal as a function of the light propagating distance through the splice (z = 0 µm is the splice interface). Results through both the standard splice program and the optimized splice are plotted in the case of (a) the 1.7 B/A Tm-doped LMA fiber design and (b) the new improved fiber design with B/A = 3.

On the other hand, less than 10% of parasitic pedestal light is expected in the B/A = 3 fiber design in the worst case scenario of using a non-optimized standard splice program. As a result, larger pedestal-to-core ratios are good candidates in order to ensure high beam quality in TDF-based systems.

## 5. OUTPUT BEAM PROFILE MEASUREMENTS AT 2µm

An experimental analysis was conducted in order to validate the calculation predictions based on measured index across different splices. To do so, an experiment based on the spatially and spectrally resolved imaging technique ($S^2$ imaging) was performed. A supercontinuum light source emitting from 400nm up to 2.4µm was launched in the matched passive fiber. The light emerging the fiber was magnified and focused using a pair of lenses. The focal plane, a probe fiber connected to an optical spectrum analyzer was used to collect light signal at various "pixels" across the near-field. Spectra were recorded within the wavelength range of 2035 and 2045nm, where the TDF does not show strong absorption bands. After scanning the near-field of the fiber under test, the spectra are integrated and a relative amount of power is calculated at each pixel, resulting in a reconstructed beam profile at the wavelength recorded on the OSA.

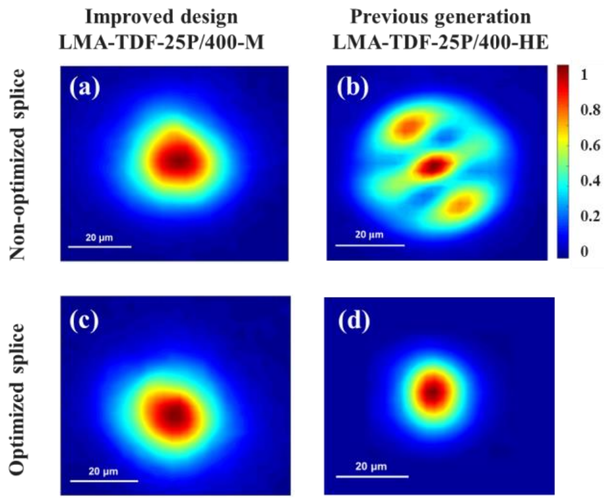


Fig. 6: (a) and (b) depict the measured beam profile at the output of the LMA-TDF-25P/400-M and LMA-TDF-25P/400-HE respectively when a single-mode is launched through a standard (non-optimized) splice. (c) and (d) depict the measured beam profile when light is launched through an optimized splice. A 20 µm scale was added for visual help.

After testing the matched passive fibers and verifying the single mode purity of the beam, the two 25µm TDF's were spliced to the corresponding matched fiber using both the standard splice recipe and the optimized splice recipe. The measurement was performed and results are summarized in Fig. 6. In the case of the standard splice, the measurements confirm the presence of strong parasitic pedestal light in the B/A = 1.7 fiber design (Fig. 6(b)) whereas, for the same experimental conditions, the fiber with B/A = 3 delivers a beam with minimal distortions (Fig. 6(a)). When using an optimized splice program, both fibers deliver high quality beams with no sign of parasitic pedestal light, which is in agreement with the numerical results. As a side note, the beam measured and shown in Fig. 6(d) exhibits a relatively small mode-field diameter (MFD) compared to the beam measured in Fig. 6(c). This MFD trend is related to the center features of the core index profile discussed in Fig. 1(a). Overall, the experiment confirmed that the improved TDF design is well suited to offer high beam quality and improved performances within the 2µavelength range.

## 6. SUMMARY

In summary, a complete numerical and experimental study has been proposed in order to investigate the effect of heat applied via splicing on fibers with different pedestal-to-core ratio designs. Even though this effect is not fully understood yet, both numerical and experimental results indicate that fibers designed with larger pedestal B/A are less sensitive to splicing parameters, especially regarding amount of heat applied. It was experimentally demonstrated that diffusion-induced index profile distortions are significantly less in the vicinity of the splice when using B/A = 3, even when using non-optimized splicing procedures. This results in significantly higher achievable coupling efficiencies and beam quality. These findings were experimentally validated from beam profile measurements. As a result the improved design LMA-TDF-25P/400-M is a good candidate to manufacture high performances 2µm laser and amplifier systems.

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