Light: Science & Applications (2012) 1, e8; doi:10.1038/lsa.2012.8

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ORIGINAL ARTICLE

Yb-doped large-pitch fibres: effective single-mode operation based on higher-order mode delocalisation

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Rare earth-doped fibres are a diode-pumped, solid-state laser architecture that is highly scalable in average power. The performance of pulsed fibre laser systems is restricted due to nonlinear effects. Hence, fibre designs that allow for very large mode areas at high average powers with diffraction-limited beam quality are of enormous interest. Ytterbium-doped, rod-type, large-pitch fibres (LPF) enable extreme fibre dimensions, i.e., effective single-mode fibres with mode sizes exceeding 100 times the wavelength of the guided radiation, by exploiting the novel concept of delocalisation of higher-order transverse modes. The non-resonant nature of the operating principle makes LPF suitable for high power extraction. This design allows for an unparalleled level of performance in pulsed fibre lasers.

Light: Science & Applications (2012) **1,** e8; doi:10.1038/lsa.2012.8; published online 27 April 2012

Keywords: higher-order mode delocalisation; high-power fibre lasers and amplifiers; photonic-crystal fibre; very large mode area

INTRODUCTION

Diode-pumped, solid-state lasers have been utilized in new approaches in areas ranging from fundamental science to industrial production. The canonical architecture of the active medium is a rod, typically of crystalline material, doped with rare earth ions. Such conventional rod-type lasers have been pushed to very high power levels. However, the beam quality of the emitted light degrades with increasing power; therefore, the otherwise excellent focusability of the beam is lost. The reasons for this degradation are so-called thermo-optical problems commonly referred to as thermal lensing and thermally induced birefringence. To mitigate these problems, novel solid-state laser architectures, such as the thin-disk,[1] the innoslab[2] and the fibre concept,[3] have been developed. All of these concepts reduce thermo-optical issues due to their specific geometry. Among them, fibre lasers have the reputation of being highly efficient sources with excellent power-independent beam quality. Moreover, fibres offer unique properties: (i) the heat that is generated by the laser process is distributed over a long length; (ii) the large ratio of the surface to active volume leads to outstanding heat dissipation; and (iii) most importantly, a waveguide structure defines the beam quality and shields the radiation from external perturbations. Consequently, ytterbium-doped fibre lasers with diffraction-limited continuous-wave output powers as high as 10 kW have been demonstrated.[4] However, the performance of fibre laser systems is generally limited by nonlinear effects due to the tight confinement of the light over long interaction lengths in the fibres. Nonlinear effects can destroy the temporal, spectral and spatial characteristics of the laser emission, particularly in the pulsed regime, and this would have a detrimental influence on the targeted application.[5] The most effective mitigation strategy is the scaling of the mode-field area (MFA), which allows for a dramatic reduction of the guided intensity. The effective MFA can be defined as

$$A_{\text{eff}} = \frac{\left[\iint I(x,y)\mathrm{d}x\mathrm{d}y\right]^2}{\iint I^2(x,y)\mathrm{d}x\mathrm{d}y} \tag{1}$$

where $I(x,y)$ is the intensity distribution of the beam. The effective mode-field diameter (MFD), which will be employed in the following considerations, can be defined from equation (1) as

$$\text{MFD} = 2\sqrt{A_{\text{eff}}/\pi} \tag{2}$$

Scaling the MFA of a fibre unavoidably leads to the fibre core supporting several modes. However, the coherent superposition of different transverse modes can induce severe spectral modulations, beam quality degradations and a reduction in the pointing stability. In other words, most of the outstanding properties of fibre-based laser systems can be lost.

Hence, tremendous efforts have been made to design large-mode-area fibres, i.e., fibres with mode sizes beyond the single-mode limit of conventional step-index fibres, which is approximately 15 µm (at a wavelength of 1 µm). Most of these approaches allow for effective single-mode operation, achieved by including discrimination mechanisms for the higher-order mode (HOM) in the fibre design. Prominent state-of-the-art techniques for effective single-mode

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Received: 16 February 2012; Accepted: 25 March 2012

operation in step-index fibres include matched excitation,[6] HOM discrimination by bending[7] and resonant filtering of HOMs.[8,9]

The technique of mode matching is based on the careful injection of the seed radiation so that only the fundamental mode of the fibre is excited.[6] Bulk optics and fibre-based mode adapters can be employed for this purpose. This approach can be used for all types of few-mode fibres and it always results in an improvement in the operation behaviour. However, with growing MFAs, exciting only one mode becomes increasing difficult, mainly due to the collapse of the effective-index space. Therefore, for very large mode areas (VLMAs, >50 μm), this technique can only be used in combination with other mode-filtering strategies. Furthermore, the HOM discrimination by matched excitation is often not sufficient for high-power fibre lasers and amplifiers.

HOM discrimination by bending is another common approach.[7] Bending leads to differential propagation losses between the HOMs and the fundamental mode. Thus, a small bending radius can enforce effective single-mode operation. Unfortunately, with increasing core sizes, the bending-induced discrimination vanishes, and this technique is consequently limited to core sizes below 30 μm.

Resonant filtering can be achieved by cladding structures that have eigensolutions, which are index-matched to the effective indices of HOMs. Consequently, the HOMs can tunnel out of the core, which leads to the filtering of undesired power content along the fibre. Prominent representatives of this approach are chirally coupled core fibres[8] and Bragg fibres.[9] However, any resonant design is very challenging to produce (due to the tight tolerances that have to be normally matched), and it might fail due to some experimental constraints, e.g., a narrow transmission band or the effective-index changes that occur when pumping or bending the fibre. Furthermore, as the MFAs become larger and the effective-index space collapses, resonance matching becomes more challenging.

Most of these approaches struggle in active and effective single-mode operation in step-index fibres with MFDs greater than 50 μm. Therefore, fibres with MFDs in excess of 50 μm represent a new regime, which can be classified as VLMA fibres.

Photonic-crystal fibres (PCFs), i.e., fibres with a micro- or nano-structured cross-section, are one of the most promising approaches for mode-area scaling of effectively single-mode fibres. Their guidance properties can differ fundamentally from standard step-index fibres (**Figure 1a**). In the context of active fibres, the most interesting design is a solid-core PCF with an active-ion doped core that is surrounded by a hexagonal array of air holes. Depending on the surrounding region, three main approaches for effective single-mode operation are possible. First, an endless periodic structure with a single defect forming the core can be theoretically considered. This structure can be analytically described, and single-mode conditions based on the effective V-parameter can be defined.[10] However, every real fibre with finite dimensions deviates from this approximation; therefore, this approach cannot be typically realized.[11] The second prominent approach is obtained when using large holes, and it was introduced as the 'modal sieve' concept.[12] Here, the mode discrimination mechanism is defined by differential propagation losses, as depicted in **Figure 1c**. As the size of the spatial features of the transverse modes decreases with higher modal order, these higher-order modes can escape from the guiding structure more easily and experience an increased propagation loss than the fundamental mode. Effective single-mode operation can be thus achieved by adjusting the fibre parameters to the given device length and to the required higher-order mode suppression. This approach is very feasible for transport or highly nonlinear fibres. VLMA fibres following this concept are known as leakage channel fibres.[13] However, this approach is based on fibres with a leaky cladding, which is typically not present in double-clad fibres required for high-power low-brightness pumping. The third approach is the index-guiding PCF, which consists of very small holes, e.g., structures comparable in size to the wavelength. In this fibre, consideration of the average refractive indices of the glass and of the structured area is sufficient (**Figure 1b**). Averaging over this last region gives a decrease in the refractive index when compared to the core index. Thus, this fibre exhibits a step-index-like guiding mechanism,[10] This approach offers significantly improved index control compared to conventional step-index fibres (e.g., those based on the MCVD manufacturing process). Hence, PCFs with very low numerical apertures are feasible, which heightens the possibility of increasing the effective MFA.

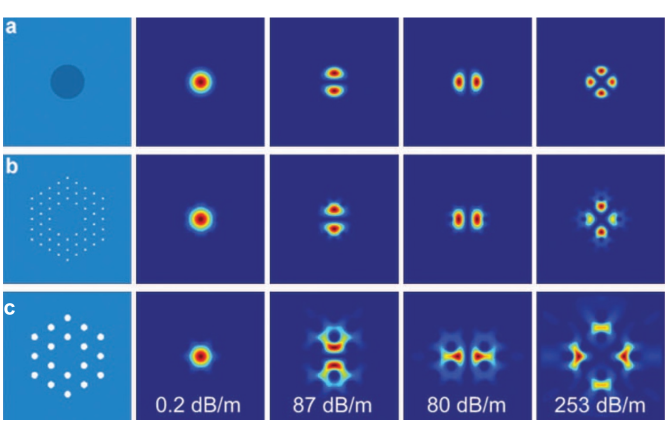

Figure 1 Comparison of different fibre concepts and their corresponding mode profiles. (**a**) Step-index fibre; (**b**) index-guiding PCF; (**c**) PCF incorporating the modal sieve concept (with propagation loss for each mode). PCF, photonic-crystal fibre.

ROD-TYPE FIBRES TO MITIGATE MODE-AREA SHRINKING

Apart from the effective single-mode operation, another effect has to be considered for VLMA fibres: bending a fibre of such dimensions leads to mode shrinking, which will nullify any gains in mode area offered by the fibre design. This effect can be observed in all types of fibres, and it can become the most limiting factor for MFA scaling.[14]

Figure 2 shows the calculated effective mode area of three different fibre core sizes as a function of the bending radius (left). Additionally, a comparison of the mode profiles of a straight fibre and a tightly bent fibre is shown (right). The mode shrinking becomes more severe with

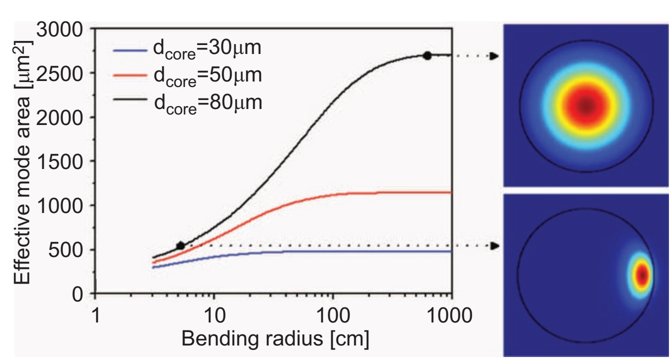

Figure 2 The effect of mode area shrinking in bent step-index fibres with different mode-field diameters (left). Two calculated mode intensity profiles are depicted for the largest fibre (right).

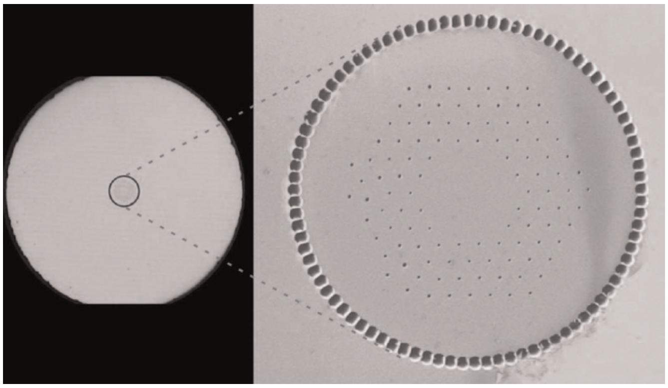

Figure 3 Early rod-type ytterbium-doped photonic crystal fibre with an outer diameter of 1.5 mm and a Yb-doped core of 60 μm.[16]

larger core sizes. Consequently, these initially VLMA fibres lose their gain in the mode area in a bent configuration.

Coiling appears to be an intrinsic and fundamental property of a fibre; however, abandoning this belief is the basis for further increases in the MFA. This approach opens the path towards significant performance scaling combined with robustness and outstanding power handling capabilities. The next step, therefore, is to design the fibre as a rigid rod, a so-called 'rod-type fibre'.[15,16] **Figure 3** shows one of the early rod-type ytterbium-doped PCFs, which was the first representative of VLMA fibres. The ytterbium-doped core is surrounded by an arrangement of tiny air holes, which can be seen as the aforementioned index-guiding PCF. The early design already had an active core diameter as large as 80 μm (a MFA of approximately 4000 μm^2) from which single-mode emission could be extracted, provided that careful excitation of the fundamental mode occurred. A double-clad structure for the guidance of low-brightness pump radiation is formed by a ring of very large air holes, the so-called air-clad. The air-clad can possess a numerical aperture as high as 0.9,[17] which allow a reduction in the core/cladding area ratio. Consequently the small-signal pump light absorption at 976 nm can be increased to approximately 30 dB m^{-1}, enabling the short length (approximately 1 m) of these rod-type fibres. Finally, the microstructured area is surrounded by a very large fused-silica outer cladding, which possesses diameters of up to 2 mm. This outer cladding makes the fibre stiff and self-supporting, i.e., mechanically robust without the need for an additional polymer coating (the typical protective coating of standard fibres and one of the main sources of thermal degradation in high-power fibre lasers and amplifiers).

This early rod-type fibre design enabled enormous performance scaling of fibre-based laser systems, particularly in the pulsed regime. Sub-ten-nanosecond fibre lasers with 100-W-class average power and several mJ of pulse energy became possible.[18,19] Furthermore, these fibres are the basis of mJ-level femtosecond fibre amplifiers, which are routinely operated in state-of-the-art fibre chirped-pulse amplification systems.[20]

The reproducible fabrication of this first VLMA-PCF design with its arrangement of tiny air holes (necessary for the effective single-mode operation of these few-mode fibres) is extremely challenging. This reproducibility issue results in a low yield, which increases the costs. Nevertheless, the concept of a rod-type index-guiding PCF has been a significant advancement. This concept has recently been further developed by incorporating resonant-mode filter structures, a so-called distributed-mode filter design.[21] Finally, this approach combines several common techniques for mode discrimination. However, combining the tiny structure for few-mode step-index guidance with resonant structures for mode filtering is even more difficult for larger mode areas, and appears to be a limitation to this approach.

In conclusion, the rod-type design with its large outer cladding protects the confined radiation from any macro- or microbending-induced perturbations. Therefore, this design was the fundamental component allowing for few-mode designs with VLMAs (MFD> 50 μm). The stiff geometry maintains the large MFA over the entire fibre length. As stated above, the early rod-type index-guiding PCFs were few-mode fibres; therefore, they relied on the careful excitation of the fundamental mode. Often, this few-mode nature resulted in some beam degradation and instability at very high powers, and this prevented the widespread use of this type of fibre because only experienced scientists were able to work with them. Nevertheless, a high demand exists for a fibre design that features the advantages of rod-type fibres and is intrinsically effective single-mode.

DELOCALISATION OF HIGHER-ORDER MODES IN LARGE-PITCH PCFS

Delocalisation of higher-order modes is a novel approach for the effective single-mode operation of a VLMA rod-type fibre. So-called large-pitch photonic-crystal fibres (LPFs) are a first representative of this concept.[22] For a step-index fibre and for a rod-type index-guiding PCF described in the previous section, all of the transverse modes have significant overlap with the core region, i.e., all of the modes are localized in the core. In contrast, the inner structure of a LPF is rather open, which has a tremendous effect on the shape of the eigensolutions. Strong deformations of the higher-order modes result in poor overlap with the potentially doped core region. Thus, only the fundamental mode has a Gaussian-like profile and a large overlap with the core. This difference in overlap results in the discrimination of HOMs due to their poor amplification compared to the fundamental mode, an effect known as preferential gain. In addition, because typically Gaussian-like beams are seeding a fibre, only the fundamental mode possesses good overlap with the input radiation, and it is, therefore, primarily excited.

Figure 4 shows the calculated mode profiles and their corresponding overlap with the active ion-doped core region in a LPF. The core of the simulated LPF is formed from two rings of hexagonally arranged air holes with a hole-to-hole distance (pitch) of 30 μm, i.e., approximately 30 times the wavelength of the guided radiation, and a hole size of 6 μm, i.e., a relative hole size of 0.2. The resulting core has a diameter

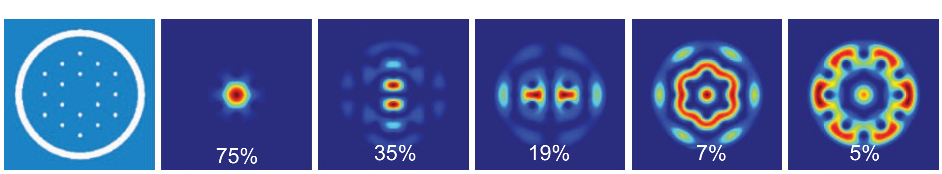

Figure 4 The calculated modal intensity profiles of a LPF and the corresponding overlap of the mode field with the active ion-doped core area. The modes are ordered by decreasing doping overlap. LPF, large-pitch fibre.

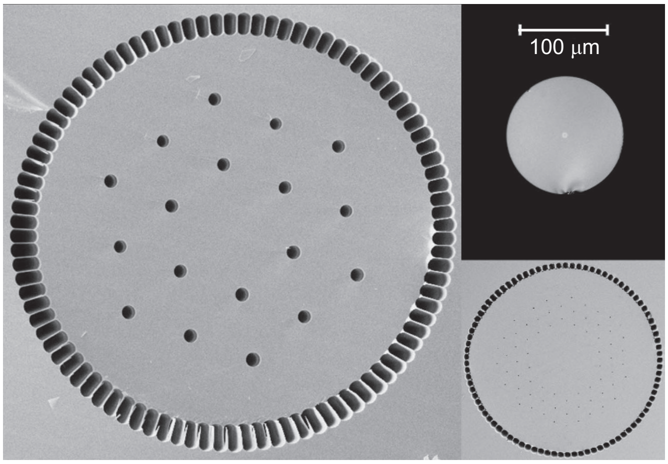

Figure 5 Comparison of a 135-μm core LPF (left) with a 7-μm core step-index fibre (upper right) and a conventional rod-type PCF (lower right). All pictures have the same scale. LPF, large-pitch fibre; PCF, photonic-crystal fibre.

of 54 μm. Furthermore, the inner structure is surrounded by an air-clad with an inner diameter of 170 μm. This air-clad structure represents an integral part of the design as the combination of air-holes and air-clad defines the guided mode set. Experimental findings and numerical simulations show that the operating principle of LPFs is sustained for relative hole sizes ranging from less than 0.1 up to 0.4. Furthermore, the fibre itself is one of the simplest PCF structures. Consequently, the demands on the production are rather low, which allows for a very high production yield and a cost-effective production.

An outstanding property of LPFs is their scalability. Typically, scaling the mode field diameter of a single-mode step-index fiber requires decreasing its numerical aperture, which is technologically limited. In index-guiding PCFs, scaling the mode field diameter implies using smaller structure sizes for larger cores. An analogue condition can be found for a PCF based on the 'modal sieve' concept, where smaller structure sizes are required to compensate for the reduced propagation losses obtained due to the larger mode field diameters. However, the effect of delocalisation is maintained while scaling the structure as the modal shape scales appropriately. Therefore, we were able to obtain rod-type LPFs with pitches ranging from 30 μm (i.e., a 54-μm core diameter)[22] up to 75 μm (i.e. 135-μm core diameter, >10 000-μm^2 mode area)[23] from a single preform. All of these fibres perform effective single-mode and allow for high average powers in the range of several 100 W.[24]

Figure 5 shows the largest LPF (135-μm core diameter) in comparison with a conventional step-index fibre with 7-μm core and the standard index-guiding rod-type PCF (80-μm core). This picture illustrates the simplicity of the LPF structure and the enormous core area scaling possibilities. In fact, the 125-μm outer cladding of the step-index fibre easily fits into the core area of the depicted LPF.

EXPERIMENTAL RESULTS

The LPF design has enabled effective single-mode operation with MFDs exceeding 100 μm, a dimension that has not been reached with any other active fibre design.

For such enormous fibre geometries, effects need to be accounted for that can be neglected for smaller fibres. On the one hand, the index matching between the Yb-doped core and the silica matrix requires an increased accuracy.[25] On the other hand, the formation of a transverse thermal index profile in the core[26] becomes increasingly significant in VLMA fibres in high-power operation.[24] The robust LPF design can cope with both effects. The negative index mismatch of the doped core compared to the silica matrix can be interpreted as pre-compensation for the thermal index profile, which is only possible for non-resonant designs.

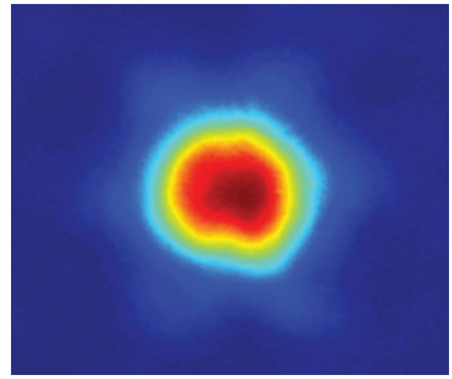

Figure 6 The measured intensity profile of a 135-μm core LPF for an average output power of 100 W. The mode field diameter has been measured to be 100 μm. LPF, large-pitch fibre.

Several high-power experiments have been conducted with ytterbium-doped LPFs of different dimensions. The smallest LPFs with core diameters of approximately 55 μm have been used to demonstrate an average output power of approximately 300 W, while maintaining a near diffraction-limited beam quality (M^2<1.4) and a greater than 50-μm mode field diameter in a fibre CPA system.[22] A LPF with a 108-μm core diameter was used to scale the peak power of ultrafast fibre laser systems to nearly 4 GW.[27] Unfortunately, this experiment was disturbed by an avoided crossing that strongly deformed the fundamental mode of this fibre. However, based on recent experimental observations on thermal waveguide changes,[24] a further increase in the pulse energy and average output power should be possible. Finally, a LPF with a core diameter of 135 μm was implemented as a booster amplifier for a Q-switched fibre laser system. In this experiment, 26 mJ of diffraction-limited pulse energy with an average output power of 130 W has been demonstrated.[23] In **Figure 6**, the output beam profile of this LPF with a measured mode field diameter of 100 μm at approximately 100 W of average output power is shown.

CONCLUSION

LPFs are the first example of a new class of fibres, in which higher-order mode discrimination is based on delocalisation. The effect of delocalisation results in a very strong preferential gain effect and in an intrinsically improved excitation of the fundamental mode. The proposed structure is very simple, and it is based on a non-resonant design. This design enables unparalleled scaling capability and high reproducibility, ultimately leading to high yields and low costs for mass production. The strong HOM discrimination leads to effective single-mode operation, even under misalignment in the launching conditions. For the first time, effective single-mode fibres with mode field diameters exceeding 100 μm can be routinely used in high-power fibre laser configurations. In particular, LPFs with core diameters of up to 135 μm have been demonstrated, enabling 26 mJ, 130 W Q-switched fibre lasers with a near diffraction-limited beam quality.

ACKNOWLEDGMENTS

The research leading to these results received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007–2013)/ERC Grant Agreement No. [240460] and the Thuringian Ministry of Education, Science and Culture under contract PE203-2-1 (MOFA) and contract B514-10061 (Green Photonics). FJ acknowledges financial support from the Abbe School of Photonics.

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