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Pixelated-core Large Pitch Optical Fibre Design

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Abstract

This paper is reporting design and simulation of a pixelated-core large pitch optical fibre. With this new design, existence of HOMs, mode instability at high power levels, mode shrinking and gain reduction upon bending were solved and the bending loss is negligible in the frequently used bending radius of 3cm to 5cm. Even down to 3mm bending radius, magnitude of bending loss can also be suppressed by three orders.

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Keywords: Optical fibre, High power fibre lasers, Very large mode area, Photonic crystal fibre, Fibre design and fabrication

1. Introduction

High power fibre laser system has now been playing an increasingly important role in today's industry market because of its outstanding beam quality with M^2 less than 1.2 and an excellent optical efficiency of more than 50%. [1] However, further power scaling of it is limited by nonlinear effects and mode instability which occurs at high power intensity. Currently the most effective mitigation strategy is to scale the mode field area, so as to create a dramatic

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reduction of the guided intensity. However, this will introduce higher order modes (HOMs) and increase the bending loss of the fibre. [2]

In this project, a pixelated-core large pitch fibre (LPF) was designed and simulated, which has a hexagonal core with Erbium-Ytterbium co-doped filaments. With this design, mode instability at high power level can be avoided, HOMs can be delocalized and bending loss can be suppressed by almost three orders of magnitude.

Equipped with this newly designed fibre, fibre laser is expected to have better performances in many industrial areas e.g. fine engraving, marking, stainless steel color printing and ablation.

2. Methodology

2.1. Guiding mechanism of large pitch photonics crystal fibre

Large pitch fibre refers to optical fibres with large effective mode areas. Compared with conventional single mode fibres which normally have an effective mode area of less than 100 µm2, large pitch fibers can usually reach a much higher value of several hundreds or sometimes thousands of µm2. This makes the large pitch fibre own many advantages over the conventional step index fibre.

Firstly because of the large effective mode area, the optical intensities in the core are reduced, which implicitly means this fibre has lower nonlinearities and a better threshold of damage. As a result, large pitch fibre is very suitable for intense pulse and single frequency signal amplifications or delivering such types of light under the case of passive fibers. [3]

Besides, as the large pitch fibre is not designed based on resonant effect, its scalability will be better than tradition fibre designs. Experiments have shown that the pitch distance can be scaled between 30 µm and 75 µm, corresponding to a maximum core diameter of 130 µm.

However apart from that, another important effect also needs to be considered for the usage of fibres, which is the mode shrinking when bending the fibres. Mode shrinking will cause the gains in mode areas to be nullified. And this effect, observed in all types of fibres, has already become one of the most limiting factors for model field area scaling. Although the large pitch fibre performs well in many specified areas, it however loses the advantage of high gains in a bent configuration. On the way pursuing further increase in mode field diameter, large pitch fibre abandons the belief that coiling is the fundamental and intrinsic property of fibre. [4]

a b

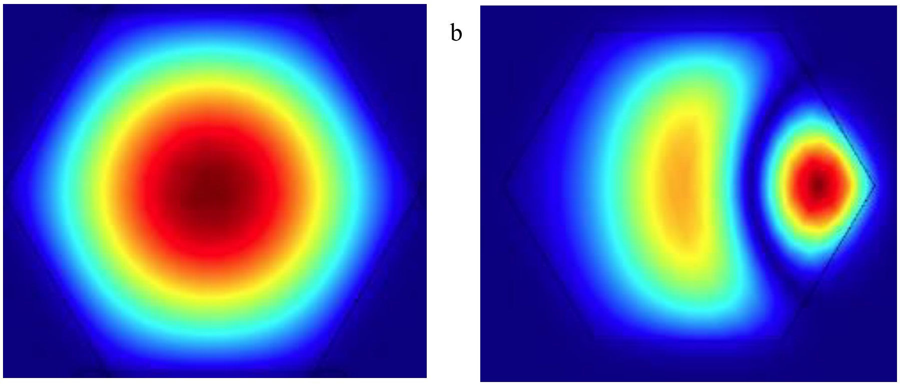

Fig. 1. (a) Large pitch fibre simulation; (b) Large pitch fibre simulation in bent configuration.

2.2. Schematic

The schematic of the pixelated-core large pitch optical fibre design is shown below in Figure 2:

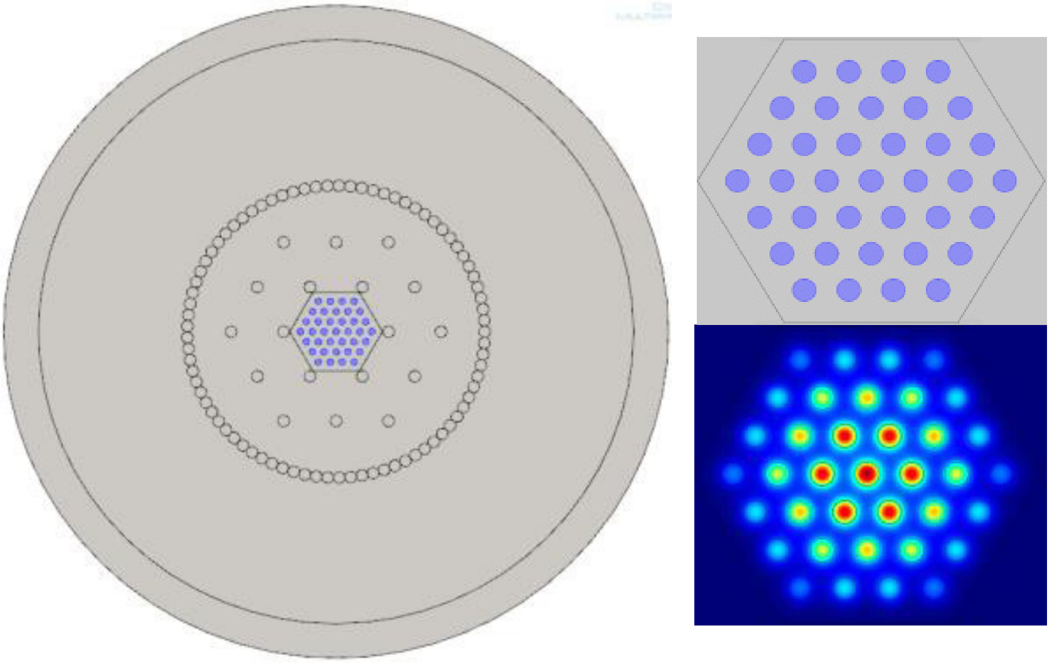

Figure 3: schematic of fibre design in this project

According to the figure above, 37 Erbium-Ytterbium co-doped filaments are inserted into the hexagonal core of the fibre. The hexagonal core is then surrounded by a double-cladding structure. An arrangement of tiny air holes forms the inner-cladding, whereas there is one more ring of air holes, which acts as the outer-cladding. The micro structured area is surrounded by a very large fused silica possessing a diameter of around 2 mm. The purpose of this outer structure is to ensure the fibre is mechanically stiff and robust. This is crucial because the supporting need of additional polymer coatings is one main source which causes the thermal degradation of high power fibre laser.

Refer to the chart below for detailed parameters of the fibre design:

Table 1: parameters of pixelated-core large pitch fibre design

Parameter	Size
Filament pitch Λ	6.2 μm
Filament diameter d	4.8 μm
Core diameter	37 μm
Air-hole diameter	6.6 μm
Inner air-hole pitch	30 μm

2.3. Simulations and analysis

2.3.1. Delocalization of higher order modes

For traditional step index fibres and common photonic crystal fibres, all transverse modes will overlap with the core region significantly. This will cause all modes to be localized in core area. To solve this problem, our new design inherits the large pitch model whose inner structure is quite open to have a huge effect on shape of the eigen solutions. Tremendous deformations of higher order modes will lead to a rather bad overlap with the pixelated core region, which results in only fundamental mode overlapping with core due to its Gaussian like profile. This overlapping difference successfully leads to the preferential gain effect, which means discriminations of higher order modes because of the bad amplifications compared with fundamental mode. Besides, because Gaussian like beams typically seeds the fibre, thus only fundamental mode will overlap well with input radiation and get excited primarily. [5]

2.3.2. Effective mode area

Effective mode area is used to measure the area which a waveguide or fibre mode effectively covers in the transverse dimensions quantitatively.

$$A_{eff} = \frac{\left(\int |E|^2 dA\right)^2}{\int |E|^4 dA} = \frac{\left(\int I dA\right)^2}{\int I^2 dA} \quad (1)$$

where E represents the amplitude of electric field and I represents optical intensity.

Based on simulated results and calculation, the effective mode area of the pixelated-core large pitch fibre is 694 μm^2.

2.3.3. Bending loss

The pixelated core design with 37 Erbium-Ytterbium doped filaments exhibits a very low bending loss at the bending radius down to 1.2mm, whereas typical step index fibre can only reach a bending radius of 5cm.

In this part, the fundamental space filling mode will be used to analyze the pixelated core.

Typical step index fibre guides light by the mechanism of total internal reflection. Hence, as long as a propagation constant β exists such that the effective refractive index of the core $n_{eff} = \beta/k$ is larger than the refractive index of cladding n_{clad}, a specific mode will be able to propagate in pixelated core. Now if the pixelated core radius is supposed to be increased infinitely, the guided light can only recognize a composite periodic medium, whose unit cell is resemble to the pixelated core's unit cell. The light will then travel with the fundamental filling mode propagation constant β_{FSM}. In this case, the equivalent pixelated core refractive index $n_{eq}^{FSM} = \beta_{FSM}/k$.

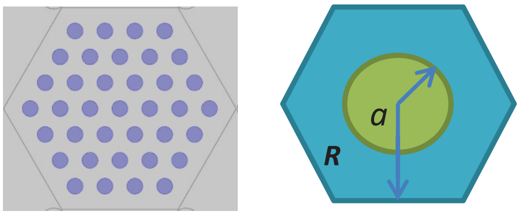

Figure 4: Structural analysis

To simplify the problem, the geometry is considered to be circular with a radius of R.

Different from typical photonic crystal fibre in which the low refractive index air holes are surrounded by higher index silica, the filaments in the pixelated core will have a higher refractive index than the surrounding silica glass. And in both models, the circular approximation will impose a boundary condition, which is
$E_z(R,\theta) = H_z(R,\theta) = 0$.

When treating the pixelated core fibre as an equivalent step index fibre, fundamental mode radius can be calculated by using Marcuse relation:

$$\omega_{eq} = \sqrt{\frac{N\sqrt{3}}{2\pi}}\,\Lambda\,(0.65+\frac{\mathbf{1.619}}{V_{eff}^{3/2}}+\frac{\mathbf{2.879}}{V_{eff}^{6}})$$

The equivalent normalized frequency (effective V number) can be calculated by using the formula

$$V_{eff} = \frac{2\pi}{\lambda}\Lambda(\frac{N\sqrt{3}}{2\pi})^2\sqrt{(n_{eq}^{FSM\,2} - n_{clad}^2)}$$

The effective fundamental mode area can thus be estimated by using the relation of $A_{eff} = \pi\omega^2$.

Meanwhile, the equivalent FSM refractive index cab be calculated by using $n_{eq}^{FSM} = fn_1 + (1-f)n_2$ where f is the filling ratio calculated by $f = 2\pi/\sqrt{3}(a/\Lambda)^2$.

Marcuse equation is also used when calculating the bending loss of the pixelated core large pitch fibre:

$$2\alpha = \frac{\pi^{1/2}u^2\exp(-\frac{2w^3R_{eff}}{3k^2n_{eff}^2})}{2R_{eff}^{\frac{1}{2}}w^{\frac{3}{2}}V_{eff}^2K(wa_{eq})^2}$$ [6][7] where:

$u^2 = k^2(n_{eq}^{FSM\,2} - n_{eff}^{FSM\,2})$ and $w^2 = k^2(n_{eff}^{FSM\,2} - n_{clad}^{FSM\,2})$

To simulate the bending loss of the pixelated-core large pitch fibre design, the effective mode index of the pixelated core firstly needs to be simulated in order to find the confinement loss in bent condition. The formula of the confinement loss is shown as following:

$$L\ (dB/m) = \frac{40\pi \mathrm{Im}(n_{eff})}{\lambda ln10}$$

With this calculated result in bent condition, guiding loss without bending is also needed and the guiding loss difference between these two conditions will be the desired bending loss. [8]

Refer to Figure 6 for the simulation results:

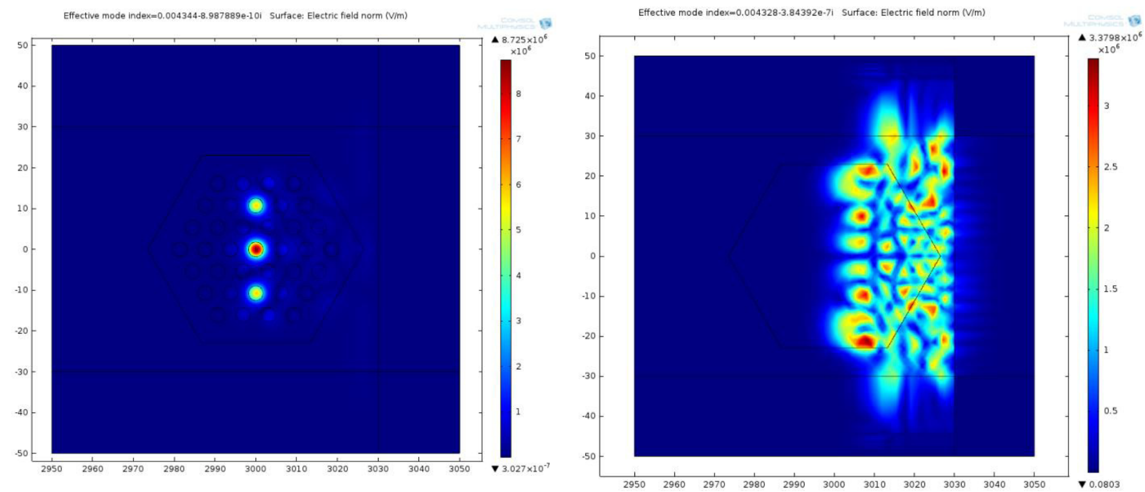

Figure 5: Simulation results of bent configuration in pixelated-core and conventional core

With a bending radius of 3mm, the calculated bending loss is 1.97×10^{-5} for the simulated conventional fibre, whereas bending loss of the new pixelated-core design is 4.61×10^{-8} dB/m.

However, it has to be noticed that the effective mode area also shrinks in this case. Hence, mode area scaling will be the future focus of this design. However, as the bending loss has already been suppressed by two orders of magnitude, this will provide a good potential compensation for the optical intensity reduction caused by the mode area scaling.

2.3.4. Mode instability

When fibre lasers are operated with the high extracted power of a few hundred watts or above 1k watts, mode instability phenomenon will always occur. Mode instability refers to the sudden poor output beam quality when pumping power injected into fibre laser exceeds certain threshold. Simultaneously, when pumping power reaches the threshold value, mode coupling, which means strong power transformation from fundamental mode to the higher order modes, will also arise with unwanted effects. These effects sometimes will even result in the damage of the fibre. [9]

Jauregui *et al.* tried to explain that the thermal-optical effects due to the high extracted average power will result in a periodic-like grating specially being generated in fibre. [10]

In details, this refractive grating can be described to be generated by Kramers–Kronig effect, which emphasizes that modal interference will generate spatially varying intensity pattern and this will lead to variation of the upper-state population of the ytterbium dopant, and thus finally causes the formation of the mode-beating grating along this fibre and changes of the refractive index.

Meanwhile on the other hand, the thermally induced increment of refractive index over the fibre cross section will also have a significant influence on the waveguide mechanism.

These kinds of index perturbations will then cause very large mode area fibers to support higher order modes also in high power applications, which will eventually lead to the mode degradation in the fibre, and finally transverse mode instability will set in at a certain level of power threshold. [11][12]

In pixelated core design, Index-anti-guiding thermally-guiding core was proposed and simulated to help to avoid mode instability, destructive nonlinear effects and thermal damages at high power levels.

Index-anti-guiding thermally-guiding core is mainly realized by surrounding the pixelated core and double cladding regions with silica which has a slightly higher refractive index. Refer to below for details of the guiding mechanism of this design. (Red spot in the figures represents high power region and dark spot represents low power region)

In unpumped status or low pumping power status, because of the high refractive index of the silica in normal temperature, the pixelated core region will not be excited, which is “index-antiguiding” in cold fibre state and the outer silica will provide index-guiding for signal light and pumping light, as shown in Figure 4.

However when coming to the high power operations, refractive index of the pixelated core will increase with a sharper speed than the outer silica. And because of this strong thermal gradient created in transversal direction, localization of modes will predominantly be achieved as shown in Figure 6.

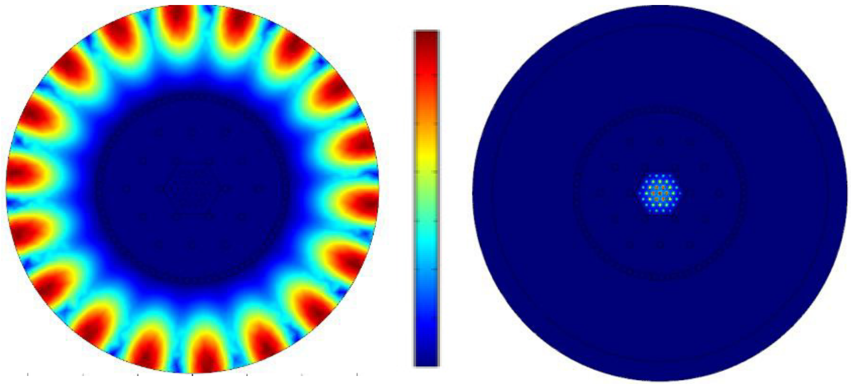

Figure 6: cold and hot fibre simulation

4. Conclusion

In this project, a pixelated-core large pitch fibre (LPF) which has a hexagonal core filled with Erbium-Ytterbium co-doped filaments was successfully designed and simulated. With this design, several intractable problems have been solved including the existence of HOMs, mode instability at high power levels, mode shrinking and gain reduction upon bending. Usually the large bending loss makes it unrealizable to coil the VLMA fibre. However with our pixelated core, the bending loss has been successfully suppressed by three orders of magnitude. At 1064 nm, low bending loss of 4.61×10^{-8} dB/m was exhibited at bending radius of 3 mm. In the normally used bending radius of 3cm to 5cm, the bending loss is negligible.

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References

[1] R. R. Verderber, O. Morse, F. Rubinstein and M. Siminovitch, “*Measurement of optical efficiency of Flourescent Luminaires*,” Annual Illuminating Engineering Society Conference, Scottsdale, AZ, pp. 3-5 (1987)

[2] J. C. Knight et al., “*Large mode area photonic crystal fibre*,” Electron. Lett. 34, 1347 (1998)

[3] N. G. R. Broderick et al., “*Large mode area fibers for high power applications*,” Opt. Fiber Technol. 5, 185 (1999)

[4] J. Limpert et al, "*Yb-doped large-pitch fibres: effective single-mode operation based on higher order mode delocalisation*," Light: Science & Applications (2012)

[5] J. Limpert, N Deguil-Robin, et al. "*High-power rodtype photonic crystal fiber laser*," Opt Express 2005, 13 pp.1055–1058 (2005)

[6] D. Marcuse, "*Influence of curvature on the losses of doubly clad fibers*," Appl. Opt. 21(23), 4208–4213 (1982)

[7] D. Marcuse, "*Curvature loss formula for optical fibers,*" J. Opt. Soc. Am. 66(3), 216–219 (1976)

[8] R. T. Schermer, and J. H. Cole, "*Improved bend loss formula verified for Optical Fiber by simulation and experiment*," IEEE J. Quantum Electron. 43(10), 899–909 (2007)

[9] F. Jansen, F. Stutzki, H.-J. Otto, M. Baumgartl, C. Jauregui, J. Limpert, and A. Tünnermann, "*The influence of index-depressions in core-pumped Yb-doped large pitch fibers*," Opt. Express 18(26), 26834–26842 (2010)

[10] K. R. Hansen, T. T. Alkeskjold, J. Broeng, and J. Lægsgaard, "*Thermo-optical effects in high-power ytterbiumdoped fiber amplifiers*," Opt. Express 19(24), 23965–23980 (2011)

[11] A. V. Smith and J. J. Smith, "*Mode instability in high power fiber amplifiers*," Opt. Express 19(11), 10180–10192 (2011)

[12] F. Jansen, F. Stutzki, H. J. Otto, M. Baumgartl, C. Jauregui, J. Limpert, and A. Tünnermann, "*The influence of index-depressions in core-pumped Yb-doped large pitch fibers*," Opt. Express 18(26), 26834–26842 (2010)