Core Size Scaling of Helical-Core Optical Fibres *

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The mode-area scaling properties of helical-core optical fibres are numerically studied and the limit of core size for achievable single-mode operation is explored. By appropriate design, helical-core fibres can operate in a single mode with possible scaling up to 300 μm in core diameter with numerical aperture 0.1.

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Recently, fibre lasers have entered the realm of kilowatt powers with diffraction-limited beam quality.[1,2] One of the key issues for further power scaling of single-mode operation will be to increase the core area to prevent from efficient pump absorption of excessively long fibres and to raise the threshold for unwanted nonlinear processes and optical damage while maintaining robust single-mode operation.[3−5] In practice, the easiest method available is to use multimode large-mode-area fibres with a low numerical aperture (NA) combined with bending loss suppression of higher-order modes.[6] However, scaling to higher power levels will require a larger core diameter and a larger inner-cladding diameter to accommodate more pump power, making it increasingly difficult to coil the fibre with a sufficient small diameter to use bend-induced loss as an effective means for suppressing higher-order modes. An alternative approach to achieve single-mode operation in a large-core fibre laser is to employ a fibre with a helical core trajectory within the inner cladding.[7,8]

The helical-core optical fibre integrates the coiling directly into the fabrication of the fibre itself, as illustrated in Fig. 1. The core radius of the fibre is a. The path of the core axis is at a constant radius Q, called the offset, from the z-axis of the helix; and the pitch or period of the helix, P, is the distance along the z-axis in which the helix repeats itself. We assume a step profile with a core of index $n_{\rm co}$ embedded in a cladding of index $n_{\rm cl}$.[9] Compared to conventional fibres, the helical-core fibre has many attractive features for power scaling. The offset-core can help us to promote efficient pump absorption in a cladding-pumped fibre configuration. The 'helical' loss due to the core trajectory is greater for higher-order modes and hence can be used as a very effective means for suppressing high order modes in a large-core fibre device without resort to bending. Moreover, helical-core fibres, due to their geometry, exhibit circular birefringence which, with appropriate design, can be made large enough for maintaining linearly-polarized or circularly-polarized propagation of laser radiation in a fibre laser or amplifier. Recently, efficient single-mode operation of a cladding-pumped ytterbium-doped helical-core fibre laser with core diameter 30 μm and numerical aperture of 0.087 has been demonstrated. The laser yielded 60.4 W of output at 1043 nm in a beam with $M^2 < 1.4$ for 92.6 W launched pump power from a diode stack at 976 nm. The slope efficiency at pump powers well above the threshold was about 84%.[10]

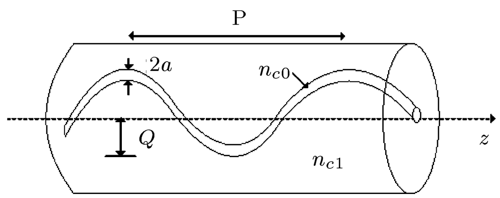

Fig. 1. Schematic diagram of a helical-core fibre.

In this Letter, the properties of helical-core fibres are investigated numerically and the limit of core size where single-mode operation is achievable is explored.

The fundamental quantities required for understanding helical-core fibres are the losses associated with the desired fundamental mode, LP_{01} and the higher-order modes. For these higher order modes, LP_{11} is the mode with the lowest susceptibility to bending loss. Thus, to the first order, the beam quality of the laser is determined by the loss experienced by the LP_{11} mode, while the efficiency of the laser is determined by the loss experienced by the LP_{01} mode.[11]

The curvature loss formula is derived by expressing the field outside of the core in terms of a superposition of cylindrical outgoing waves. By replacing the bending radius with the curvature radius of the helix, the bending loss of the helical-core fibre can be obtained

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from the conventional curvature loss formula:[12]

$$2\alpha = \frac{\sqrt{\pi}U^2 \exp[-2/3(W^3/\beta_v^2)(Q/\sin^2\theta)]}{e_v V^2 W^{3/2}(Q/\sin^2\theta)^{1/2}K_{v-1}(Wa)K_{v+1}(Wa)}, \tag{1}$$

where e_v is 2 for the LP_{01} mode and 1 otherwise, and θ is the trajectory angle of the helix, defined by $\tan(\theta) = 2\pi Q/P$. For other parameters, $U^2 = n_{\rm co}^2k^2 - \beta_v^2$, $W^2 = \beta_v^2 - n_{\rm cl}^2k^2$, $k = 2\pi/\lambda$, $V = ka\sqrt{n_{\rm co}^2 - n_{\rm cl}^2}$, with β_v being the propagation constant and λ the free space wavelength. After α is obtained, the loss can be expressed in dB as $\gamma = 8.686\alpha$. For convenience of discussion, we define modal discrimination ability as

$$b = \gamma_{11} - \gamma_{01}, \tag{2}$$

where γ_{01} and γ_{11} are the losses of the LP_{01} and LP_{11} modes, respectively.

We first calculate the bending loss of the four lowest order modes for the helical-core fibre used in Ref. [10], as shown in Fig. 2. The core diameter, core NA, core offset and the inner-cladding diameter are 30 μm, 0.087, 100 μm and 275 μm, respectively. It can be found that low loss (< 1 dB/m) can be obtained for the fundamental mode while retaining high loss for the other modes. Figure 3 shows the modal discrimination ability of the fibre. It is obvious that the modal discrimination ability is enhanced by increasing the value of core offset. Moreover, the pitch required is heavily dependent on the core offset Q. The larger the Q value is, the larger the pitch range is available for low-loss single-mode operation.

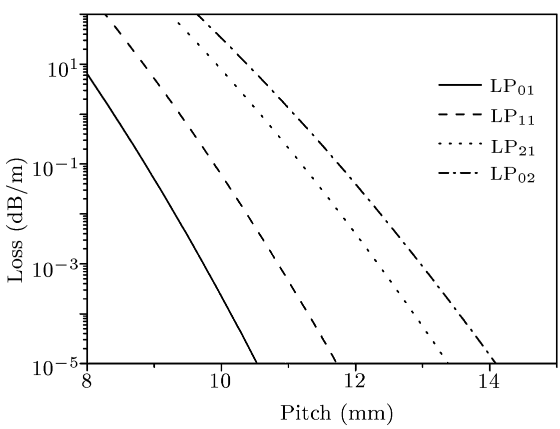

Fig. 2. Bending loss versus pitch for the four lowest order modes. The wavelength, core diameter, NA and core offset are 1060 nm, 30 μm, 0.087 and 100 μm, respectively.

It is instructive to understand the interplay of modal discrimination ability with the loss of the fundamental mode. Figure 4 shows the modal discrimination ability as a function of fundamental mode loss for different values of core diameter. With the increasing core diameter, the fibre can accommodate more modes and the difference of propagation constants between LP_{11} and LP_{01} modes becomes smaller.[13] Therefore, increasing core size leads to smaller modal discrimination and smaller difference between two adjacent modal discrimination abilities. In a previous work, numerical results indicated that core diameter of helical-core fibre can be scaled up to 200 μm under the condition that the available gain in ytterbium-doped fibres is set to be 5 dB/m.[11] Figure 4 shows that in our calculation on the same assumption, the modal discrimination is higher than the available gain in ytterbium-doped fibres for core diameters even up to 300 μm. This plot demonstrates the viability of large-helical-core fibre lasers and amplifiers.

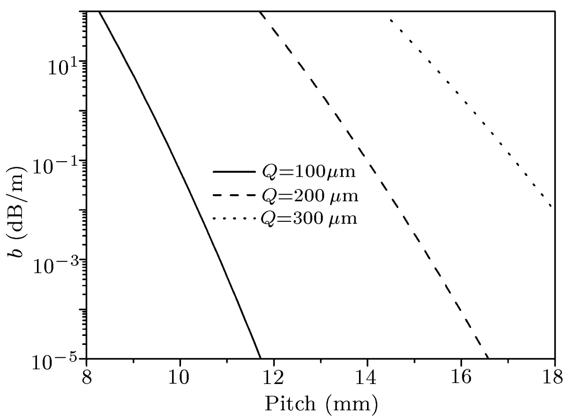

Fig. 3. Modal discrimination ability versus pitch for different values of core offset. The wavelength, core diameter and NA are 1060 nm, 30 μm and 0.087, respectively.

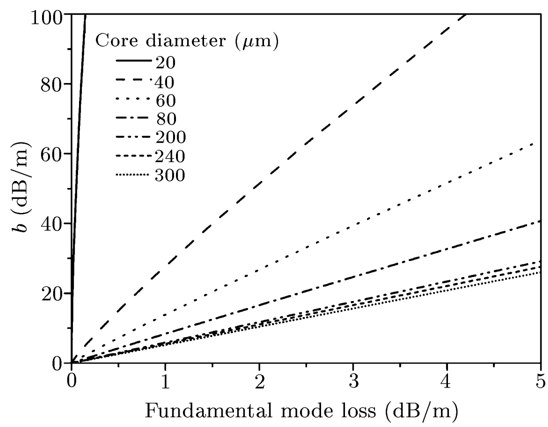

Fig. 4. Modal discrimination ability versus the LP_{01} mode bending loss for different values of core diameters. The wavelength and NA are 1060 nm and 0.087, respectively.

It is evident from Fig. 4 that for large core diameters, good mode discrimination cannot be obtained for arbitrarily low fundamental-mode loss.[11] However, by allowing a tolerable loss for the fundamental mode, e.g. 1 dB/m, core diameters can be scaled up larger than 200 μm. In the following discussion, the fundamental-mode loss is set to be 1 dB/m, and the modal discrimination is calculated as a function of values of core diameter for different NAs. Figure 5 shows that for a given NA, the modal discrimination ability decreases with the increasing core diameter. By calculation, we obtain $b = 5.07209$ dB/m when NA=0.10 and the core diameter is 300 μm. Thus it can be deduced that the modal discrimination is higher than the available gain in ytterbium-doped fibres even possibly up to 300 μm core diameter with NA 0.1.

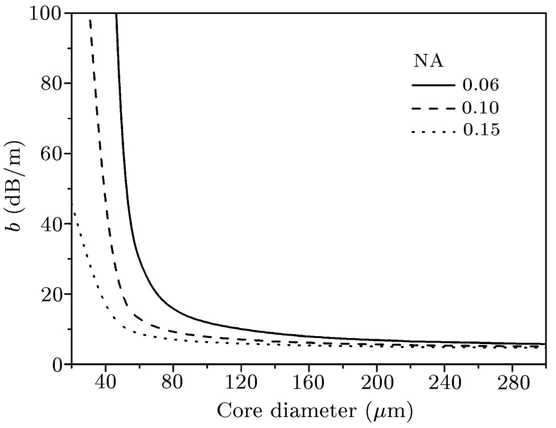

Fig. 5. Modal discrimination ability versus core diameter for different values of NA. The wavelength and LP_{01} bending loss are 1060 nm and 1 dB/m, respectively.

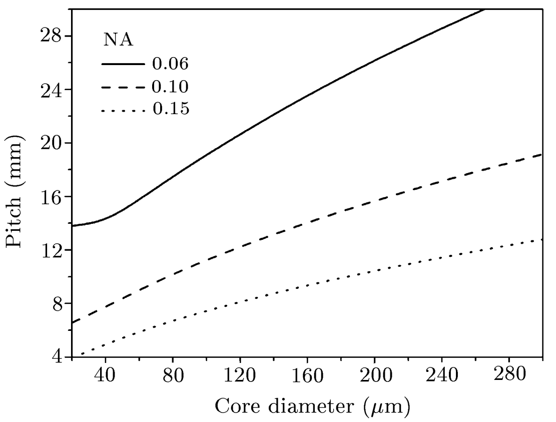

Fig. 6. Pitch versus core diameter for different values of NA. The wavelength, core offset and LP_{01} bending loss are 1060 nm, 100 μm and 1 dB/m, respectively.

Fixing the fundamental-mode loss at 1 dB/m, the dependence of the helix pitch on core diameter and NA are shown in Fig. 6. With the increasing core diameter and decreasing NA, the helix pitch increases. The bending radius required for a straight-core fibre to obtain the same performance as the helical-core fibre can be related to the pitch and the offset by $R = P^2/4\pi^2 Q$ approximately.[9] For the helical-core fibre with pitch 1 cm and offset 100 μm, the corresponding bending radius required for a straight-core fibre to obtain the same performance is about 2.5 cm. Such a small bending radius will possibly lead to long-term fibre degradation, whereas the helical-core optical fibre integrates the coiling directly into the fabrication of the fibre itself. From the discussion, we can find the advantages of helical-core fibres for coiled conventional fibre amplifier designs.

In conclusion, we have obtained the results showing the possibility for helical-core fibres to exceed the performance of current coiled fibre lasers. Typical multimode active fibres have V-numbers in the range 3–6, with 20–30 μm diameters and low NA in the range 0.05–0.06. The helical-core fibres modelled above have a considerably larger diameter than that typically used, which means a significant increase of nonlinear thresholds. By calculation, helical-core fibres are shown to perform in the case that conventional coiled fibres cannot operate, with possible scaling to 300 μm diameter helical cores and with numerical aperture 0.1. If the numerical aperture is less than 0.1, much larger core size can be scaled up possibly.

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