Scaling the mode area of Rare-Earth doped step index fiber under current state of the art MCVD technology

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Abstract: We demonstrate an ultra-low-NA (~ 0.038) Yb-doped step-index-fiber fabricated using conventional MCVD and solution-doping process. The fiber ensures $\sim 700\mu\text{m}^2$ A_{eff} for effective-single-mode operation and 81% laser efficiency with $M^2 \sim 1.1$ at a bend diameter of 32cm.

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1. Introduction

Fiber lasers are important tool for several industrial processing, medical surgeries, space communication, oil and gas sensing, and aerospace industry. Rare-Earth doped step index fibers (SIFs) have played an important role in power scaling of fiber lasers. There is a demand to increase the power level and reduce the cost of fiber lasers for a growing number of applications. Non-linear effects are primary limiting factor for power scaling; increasing the mode area of the fundamental mode while maintaining effective single-mode is one route to avoid non-linear effects. There are several fiber designs that have been proposed to scale the effective area (A_{eff}) of the FM. However, most of these designs require refractive index of the core to be equal to the cladding which poses serious challenge in fabricating Rare Earth ions doped core having refractive index equal to the cladding.

Low NA SIFs under coiled conditions are the simplest and cost effective design for applications in fiber lasers. However, mode area scaling using SIFs is limited due to the challenges in the fabrication of low NA Rare-Earth doped core and restricted to only $\sim 370\mu\text{m}^2$ with NA of 0.06 [1]. Recently, V. Khitrov et. al. demonstrated SIFs with 0.048 NA, nonetheless power scaling is restricted to 3kW [2]. In this paper, we demonstrate for the first time, an Yb-doped SIF with ultra-low-NA (0.038) core thanks to our optimized MCVD process and solution doping process. We did not use any pixelation and microstructuration of core to achieve such a low NA.

2. Numerical Simulations and fabrication

Fig. 1(a) Refractive index profile of fabricated low-NA Yb-doped step-index preform. (b) The calculated loss of LP₀₁ and LP₁₁ modes and effective area of the LP₀₁ mode of a SIF w.r.t. bending diameters at 1060nm for two different core diameters for a fixed core Δn of 0.0005 corresponding to an NA of 0.038.

Fig. 1(a) shows the refractive index profile of an ultra-low NA of 0.038 (that corresponds to a core refractive index with respect to the cladding equal to 0.0005) Yb-doped step-index preform fabricated using our optimized MCVD process in conjunction with solution doping process. The plot shows a flat profile without any considerable dip at the center of the core. Our fabrication process ensures good reproducibility and good yield as well. Table 1 shows the comparative analysis of maximum possible effective area (taking bend induced effective area reduction) for different core NAs. Effective-single mode operation is guaranteed by ensuring larger than 10dB/m loss for the higher order modes while only 0.1dB/m loss for the fundamental mode as shown in Fig. 1(b). Numerical simulations show the feasibility of scaling the effective area of the fundamental mode to $700\mu\text{m}^2$ (taking bend induced distortion into account) at a bend diameter of 32cm for a SIF of 35 μm core diameter and 0.038 NA. On the other hand, for 0.048 NA core, the maximum possible effective area is limited to $\sim 450\mu\text{m}^2$ for a core diameter of $\sim 29\mu\text{m}$ at a bend diameter of $\sim 15.5\text{cm}$ as shown in Table 1. This comparative analysis provides a strong motivation to fabricate ultra-low NA SIFs. In order to verify the effective-single-mode operation, we drew the fiber to a core diameter of 35 μm and outer diameter of 420 μm with low index coating. Before drawing the fiber, preform was milled to D-shape to increase the pump absorption. Fiber shows 2dB/m absorption at $\sim 975\text{nm}$.

Table 1 comparative analysis of mode scaling for different core NAs.

Low NA	Effective area μm^2 (0.1dB/m for FM and 10dB/m for HOMs), taking bend induced distortion into account	Bend diameter (cm)	core diameter (μm)
0.048	~450	~15.5	~29
0.038	~700	~32	~35

3. Experimental measurement

Fig. 2(a) shows the experimental set-up used for the verification of effective single mode operation at 1060nm. A 3m long fiber coiled at 32cm bend diameter is used as fiber under test. Fiber output ensures a Gaussian beam irrespective of the profiles of the launched input beams as shown in Fig. 2(b) and 2(c). Furthermore, the fiber was tested in a 4%–4% laser cavity. A laser diode operating at ~975nm was used as a pump source. A 7m long fiber coiled at 32cm bend diameter was used for this experiment. A maximum output power of ~50W was obtained at ~72W of launched pump power as shown in Fig. 3(a). The output power is limited only by the available pump power. A slope efficiency of ~81% was measured with respect to the absorbed pump power and a M^2 of ~ 1.1. The output spectrum (Fig. 3(b)) shows the free running laser operating at 1040nm.

Fig. 2 (a) Experimental set-up for single mode verification (b) output beam profile with respect to LP_{01} mode launch and (c) output beam profile with respect to mixed mode launch. A 3m long fiber coiled at 32cm bend diameter was used in this experiment.

Fig. 3 (a) Slope efficiency of a 7m long Yb-doped 0.038 NA SIF. Inset shows the profile of the output beam (b) measured output spectrum at an OSA resolution setting of 0.2nm.

4. Conclusion

We have demonstrated an ultra-low NA Yb-doped SIF with enhanced mode area scaling capability of a step-index fiber. Our optimized MCVD process in conjunction with solution doping technique shows the feasibility of achieving the core with a NA of 0.038. This ultra-low-NA fiber can scale up the effective area to $700\mu\text{m}^2$, at 1060nm, while maintaining an effective single mode operation. Experimental results ensure a good laser efficiency of 81% with $M^2 \sim 1.1$.

5. References

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