First demonstration of single trench fiber for delocalization of higher order modes

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Abstract: We demonstrate an ytterbium-doped single-trench fiber ensuring a high losses ratio (~1000) and low power fraction (~0.7) between the higher-order-modes and fundamental-mode with excellent bend robustness and 85% laser efficiency at a wavelength of 1040nm.
OCIS codes :(060.2280) Fiber design and manufacturing; (140.3510) Fiber lasers.

1. Introduction

Novel large mode area (LMA) fiber designs have led to significant progress in the development of fiber lasers in the past years. For high power applications, a LMA fiber design should offer characteristics like high suppression of the higher order modes (HOMs), low bending losses of the fundamental mode (FM), and easy fabrication. Several fiber designs such as low NA step index fibers (SIFs) [1], Bragg fibers [2], 2-D all solid photonic bandgap fibers (2D-ASPBGFs) [2-3], and photonic crystal fibers (PCFs) based designs like leakage channel fibers (LCFs) [4] 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. Moreover, PCFs and 2D-ASPBGFs require stack and draw technique. Recently, we proposed multi trench fibers (MTFs), which are easy to fabricate and can provide very high suppression of the HOMs [5]. In this paper, we demonstrate for the first time, a ytterbium (Yb)-doped single trench fiber which is having refractive index of the core higher than the cladding and offers very high suppression of the HOMs with easy fabrication requirements. The fiber exhibited a laser efficiency of ~85% at a wavelength of 1040 nm whilst retaining good beam quality.
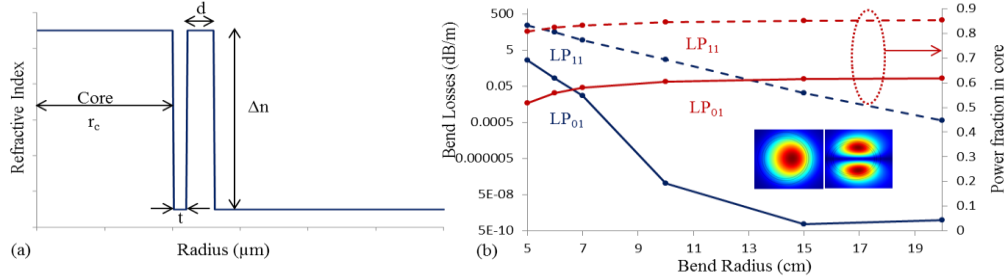
2. Numerical Simulations

Fig. 1(a) Schematic cross-section of the proposed single-trench fiber. (b) Computed bend losses and power fraction of the FM and LP_{11} mode for different bend radius. Inset shows the images of the FM and LP_{11} mode at 7cm bend radius.

Fig. 1(a) presents the schematic of single trench fiber. Fig. 1(b) shows the numerically computed bend losses of the FM and LP_{11} mode (here LP_{11} has lowest losses and highest power fraction among all other HOMs). The fiber parameters considered in our simulations are r_c=10µm, t=1µm, Δn=0.001, and d=2µm. The bending losses of the LP_{11} mode are larger than 18dB/m and for the FM mode it is lower than 0.012dB/m at 7cm bend radius, ensuring a losses ratio of the HOMs to FM larger than 10^3 and the A_{eff} is ~340µm^2. Moreover, power fraction ratio of the HOMs to the FM in core maintains a good ratio of ~0.7 irrespective of bend radius. It is important to note that, in a double clad fiber laser, where all the effective losses are zero, low power fraction of the HOMs in core compared to the FM is an important factor to ensure single mode operation. Due to this low power fraction of the HOMs compared to the FM in core, a single mode output can be ensured irrespective of the bend radius thanks to the delocalization of the LP_{11} mode. Moreover, numerical simulations show that two and three trench fibers can achieve much larger A_{eff} (600-700µm^2) with similar level of suppression, although a compromise with bend radius has to be made [6]. The delocalization of the LP_{11} mode is due to presence of the resonant ring surrounding the core. The best suppression of the HOMs that can be achieved from a SIF with the same core radius (r_c=10µm) and refractive index contrast (Δn=0.001) is only a losses ratio of ~280 and power fraction ratio larger than 0.82 with A_{eff} of ~340um^2 [1, 6]. Moreover, in case of single trench fiber the level of HOMs suppression and the operational range of bending radius is better than other fiber designs like PCFs, W-type fibers, Parabolic fiber etc. [5-7].

3. Experimental Realization of Yb-doped Single Trench Fiber

Fig. 2(a) shows the measured refractive index profile (RIP) of Yb^{3+} and Al^{3+} doped preform fabricated using conventional MCVD and solution doping technique. Preform was milled to D-shaped and drawn to an outer diameter of 240µm (core diameter 20µm) with low index polymer coating. The fiber shows 2.5dB/m absorption at 975nm. Fig. 2 (b) shows the measured Multi-Path Interference (MPI) versus group delay using S^2 measurement. LP_{11} and LP_{21} modes suffer high losses and their power level is 32dB lower than the FM. A significant amount of power for the HOMs is observed outside the core which ensures delocalization of the HOMs. A 6.17m of fiber was used in a 4%-4% linear laser cavity to measure the laser efficiency. Fig. 3 (a) shows the output spectrum of fiber laser at the bend radius of 5cm and 7.5cm. Inset shows the captured output beam image for 5cm bend case. Both lasers show lasing at a wavelength 1040nm wavelength. Fig. 3(b) shows the output power of the fiber laser for different bend radius. The slope efficiency measured is approximately 85% with respect to the launched pump power with $M^2 \sim 1.3$.
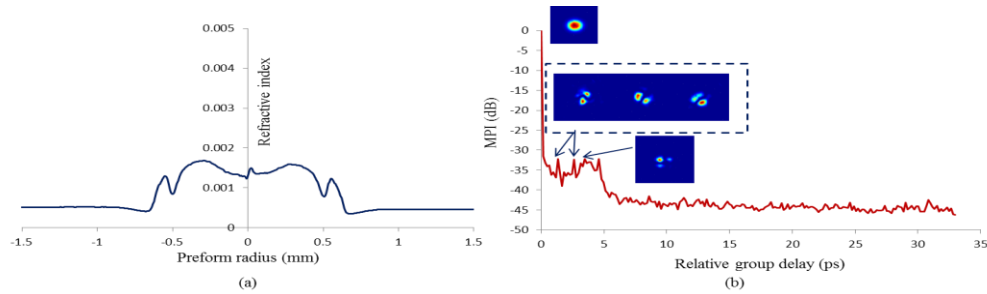

Fig. 2(a) Measured RIP of fabricated preform (b) MPI (dB) versus relative group delay (ps) for fabricated fiber. Inset images show the beam profiles of obtained modes.
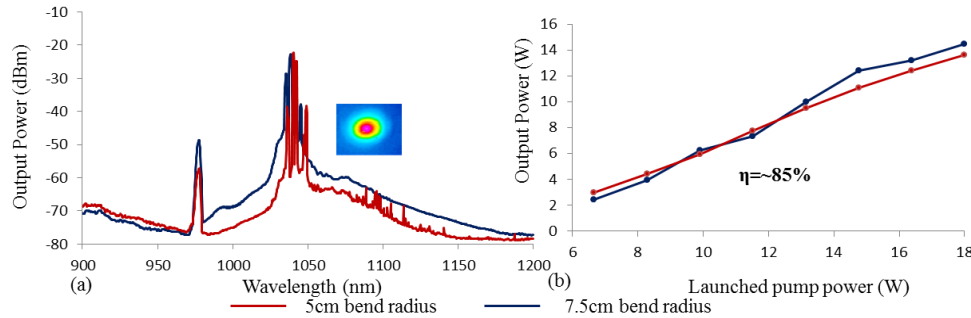

Fig. 3 (a) Measured spectrum of the output beam (b) slope efficiency for two different bend radius of fiber. Inset shows the output beam for fiber laser bent at 5cm radius (shown in red colour).

4. Conclusion

We have demonstrated, for the first time, an efficient Yb-doped single trench fiber in the MTF family. The fiber ensures a single mode operation by offering large losses and poor power fraction of the HOMS in the core thanks to the delocalization of HOMs. The laser yields output at 1040nm with ~85% slope efficiency from a 20µm core fiber. Our proposed fiber design is suitable for mass production using conventional low-loss fiber fabrication techniques.

5. References

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Acknowledgement