Depressed clad hollow optical fiber with the fundamental LP_{01} mode cut-off

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ABSTRACT

We propose a depressed clad hollow optical fiber with fundamental (LP_{01}) mode cut-off suitable for high power short-wavelength, especially three-level, fiber laser operation by introducing highly wavelength dependent losses at longer wavelengths. The cut-off characteristic of such fiber structure was investigated. A Yb-doped depressed clad hollow optical fiber laser generating 59.1W of output power at 1046nm with 86% of slope efficiency with respect to the absorbed pump power was realised by placing the LP_{01} mode cut-off at ~1100nm.

Keywords : Hollow optical fiber, fiber laser, Ytterbium, Fundamental LP_{01} mode cut-off.

1. INTRODUCTION

Fiber-based lasers have been extensively researched during the past decade because of their high efficiency, compactness and excellent beam quality. The output power of fiber lasers has been increased significantly over the last few years by adapting the cladding pumping technology, and is now competing with conventional bulk solid-state laser in applications such as micro-machining, welding and material processing. In particular, the cladding pumped Yb-doped fiber laser has already reached kW levels at around 1.1μm with a nearly diffraction-limited output beam [1,2]. In contrast, the power scaling of a three-level laser still remains a technological challenge because of the competing unwanted four (or quasi four) level laser transition which has the lower threshold [3], and becomes even more difficult in the case of the cladding pumped fiber laser owing to the relatively low pump absorption which requires a relatively long device length as compared to core pumped fiber laser. For example, Nd-doped alumino-silicate fibers have two strong emission bands; a three-level around 930 nm and a four-level one centered at 1060 nm. While Nd-doped 1060 nm lasers are relatively easy to realize due to the absence of ground-state absorption (GSA), the interest in this is rather modest because of the superiority of Yb-doped fiber lasers emitting at the same wavelength. However, the 0.9μm Nd-doped fiber laser is still attractive for applications such as blue generation by frequency doubling [4] and water sensing [5]. Similarly, the Yb-doped fibers consist of two broad emission bands at 0.98 μm and 1.03 – 1.1μm respectively. The band at ~ 0.98 μm corresponds to a three-level laser transition and requires a much higher level of the population inversion and also suppression of the other laser transitions between 1.03μm and 1.1μm. Increasing the output power of such fiber lasers is of interest as they have applications as a pump source for erbium-doped fiber amplifiers and fiber DFB lasers [6].

Waveguide design for three-level fiber lasers that produces a distributed loss at longer wavelength, was suggested by some groups [7, 8]. In particular, W-type fiber can efficiently filter out unwanted transition (four-level emission) by the fundamental LP_{01} mode cut-off, in contrast to the normal step index fiber. In the Nd-doped alumino-silicate system, the lasing at 0.9μm was demonstrated, by suppressing the emission at 1.06μm with 47% slope efficiency and 9W of maximum output power [7]. However, the limited controllability of doped-core size, for the LP_{01} mode cut-off to be at the desired wavelength, still puts constraints on improving the pump absorption in cladding pumped W-type fiber lasers. In practice, a large and single mode core is an important design feature for high-power cladding-pumped fiber lasers, since it allows the inner-cladding size, and thus the pump power, to be scaled whilst maintaining acceptable pump absorption.

In this paper, we propose a depressed clad hollow optical fiber (DCHOF), which is composed of a ring-shaped core, an air hole in the center, and a low-index ring in the cladding. The low refractive index (n_{air} = 1) of the hole region produces a negative dielectric volume [9] and the depressed cladding plays a role to increase the mode confinement in the doped core region. These features bestow the DCHOF with the fundamental-mode cut-off required for good suppression of unwanted emission at longer wavelengths, whilst the ring-shaped doped-core will provide the improved pump absorption in the cladding pumped configuration. In a preliminary experiment we have obtained ~ 60W of output power at 1046 nm from a Yb-doped DCHOF with 85% of slope efficiency with respect to the absorbed pump power by filtering of the amplified spontaneous emission (ASE) at longer wavelengths.

2. Depressed clad hollow optical fiber

A schematic index structure of the DCHOF is shown in figure 1. It is composed of a ring-shaped doped core, whose refractive index is n_{co} and outer radius r_{co}, around an air hole of radius r_{air} (n_{air} = 1), and a low index (n_{dip}) ring in the cladding with an outer radius of r_{dip}. Finally, the silica cladding surrounded the low index ring whose refractive index (n_{clad}) is 1.4571.

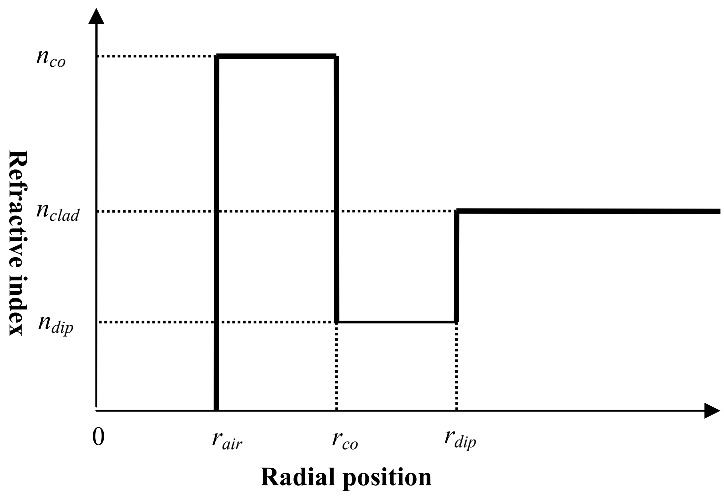


Figure1. A schematic index structure of DCHOF

It is proposed to assume that the modes in this index structure are weakly guided and linearly polarised (LP), because of the relatively large index differences between the air and doped core. However, as far as the mode cut-off is concerned, the difference between the full vectorial calculation and the LP approximation is negligible. Actually, the differences between results from our mode solver assuming LP modes and commercial software (FEMLAB) for full vectorial calculation were within 1% in most cases. Therefore, the weakly guiding and LP mode approximation was used for simplicity. In this case, the radial dependence of the transverse field component is represented by [10]

$$E(r) = \begin{cases} A_0 I_m(vr), & r < r_{air} \\ A_1 J_m(ur) + A_2 Y_m(ur), & r_{air} \le r < r_{co} \\ A_3 I_m(wr) + A_4 K_m(wr), & r_{co} \le r < r_{dip} \\ A_5 K_m(sr), & r_{dip} \le r \end{cases} \tag{1}$$

Here, r is the radial position, $A_i\,(i = 0,1,2,3,4,5)$ is constant, and $J_m(Y_m), I_m(K_m)$ are Bessel functions of first (second) kind and modified Bessel functions of first (second) kind respectively. Mode parameters (v, u, w and s) are defined as $v = \sqrt{\beta^2 - k_0^2}$, $u = \sqrt{n_{co}^2 k_0^2 - \beta^2}$, $w = \sqrt{\beta^2 - n_{dip}^2 k_0^2}$, and $s = \sqrt{\beta^2 - n_{clad}^2 k_0^2}$, where β is the propagation constant of each guided mode and k_0 is the vacuum wave number. The modal effective index (n_{eff}) is determined by the relation of $n_{eff} = \beta / k_0$. According to the boundary condition, the field and its radial derivative must be continuous on the three boundaries, $r = r_{air}$, $r = r_{co}$ and $r = r_{dip}$. From these conditions, the characteristic equation can be written as follows:

$$\begin{vmatrix} I_m(vr_{air}) & -J_m(ur_{air}) & -Y_m(ur_{air}) & 0 & 0 & 0 \\ vI_m^1(vr_{air}) & -uJ_m^1(ur_{air}) & -uY_m^1(ur_{air}) & 0 & 0 & 0 \\ 0 & J_m(ur_{co}) & Y_m(ur_{co}) & -I_m(wr_{co}) & -K_m(wr_{co}) & 0 \\ 0 & -uJ_m^1(ur_{co}) & -uY_m^1(ur_{co}) & -wI_m^1(wr_{co}) & -wK_m^1(wr_{co}) & 0 \\ 0 & 0 & 0 & I_m(wr_{dip}) & K_m(wr_{dip}) & -K_m(sr_{dip}) \\ 0 & 0 & 0 & wI_m^1(wr_{dip}) & wK_m^1(wr_{dip}) & -sK_m^1(sr_{dip}) \end{vmatrix} = 0 \quad (3)$$

Where $I_m^1(ur) = \partial I_m(ur)/\partial r$ and $|\bullet|$ represents the determinant of a matrix. We have solved equation 3 numerically. The parameters for the fundamental LP_{01} mode cut-off wavelength at the desired location are determined by a combination of an air hole size (r_{air}), core thickness ($r_{co} - r_{air}$), the width of depressed clad ($r_{dip} - r_{co}$) and refractive indices of core (n_{co}) and depressed clad (n_{dip}). Figure 2(a) shows the changes of effective indices for different modes for the fiber parameters as listed in table 1. The parameters were chosen in order to obtain the LP_{01} mode cut-off wavelength at ~ 1.03 µm. Figure 2(b) shows the guided LP_{01} core mode at 0.93 µm whereas the figure 2(c) shows that the LP_{01} guided mode is no longer supported by the core after the fundamental mode cut-off wavelength at 1.03µm.

Fiber Dia. (µm)	Dip thicknesss (µm)	Core OD (µm)	Hole Dia (µm)	Core thickness (µm)	Core NA	Dip NA
125	7.82	10.82	3.7	3.6	0.09	0.078

Table 1. Designing parameters for the fundamental LP_{01} mode cut-off at ~1.03µm

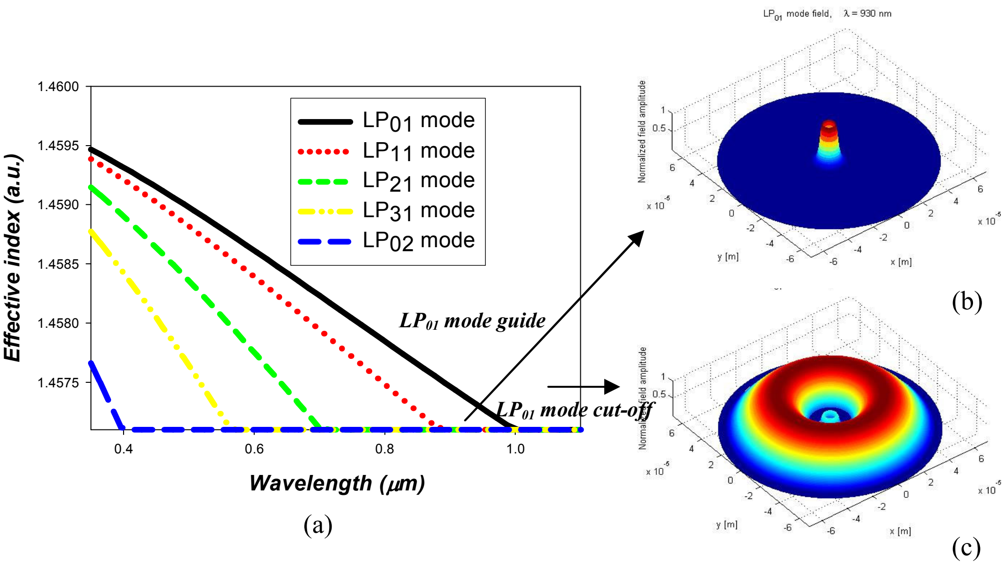


Figure 2. (a) effective index change of different LP modes in DCHOF, (b) the guided LP_{01} core mode field at 0.93µm, and (c) the LP_{01} mode field at 1.06µm which is filtered out of the core.

Thus DCHOF can produce LP_{01} mode cut-off characteristics and good suppression of the unwanted emission is possible in such waveguide structure by controlling the location of the LP_{01} mode cut-off. Using DCHOF, we have demonstrated both high power Nd-doped and Yb-doped fiber lasers operating at 0.9µm and 0.98µm respectively [11, 12]. It is worth mentioning that inspite of the ring-shaped doped core in DCHOF, we obtained a true (Gaussian) single mode output through collapsing the air hole at the output end of the fiber.

3. High power Yb-doped DCHOF laser operating at 1.046µm

In most high power Yb-doped alumino-silicate fiber lasers, the output is shifted towards the long-wavelength side of the emission band, typically ~1.1µm [2]. However, a fiber laser operating at the short-wavelength side of the Yb-emission band would offer an increased scope of further power scaling in the kW regime because of the reduced thermal loading in the fiber (due to the low quantum defect between the pump and the emission photons) as compared to the long wavelength one. DCHOF has the potential of offering short-wavelength lasing, ≤ 1.05µm, by suppressing the ASE at long-wavelength.

We fabricated the Yb-doped DCHOF using a standard MCVD and solution doping technique. At the final collapsing stage, a hole of around 1.0mm diameter was left in the preform. Before being drawn to fiber, the preform was milled to a double D-shape in order to improve the pump absorption in the doped core. This perform was then drawn to a fiber with 170 µm inner-cladding diameter and coated with a low-index polymer outer cladding, which provided a nominal inner-cladding NA of ~ 0.45. The core comprised of a 6.2µm Yb-doped ring (NA ~ 0.07) around an air hole of 18µm diameter, and a depressed ring in the inner cladding of thickness 14µm (NA ~ 0.08). From these fiber parameters, we numerically analyzed the modal characteristics using equation (3). Figure 3(a) shows the effective index change of two LP modes depending on wavelength. The fundamental LP_{01} mode cut-off was ~1.15µm. Experimentally, the fundamental mode cut-off wavelength was verified from the white-light transmission measurement, as shown in figure 3 (b), and found to be in good agreement with our modeling. Figure 3(b) also shows that the induced loss at 1100 nm was ~ 10 dB/m, while the loss at 1040nm was not affected by the LP_{01} mode cut-off.

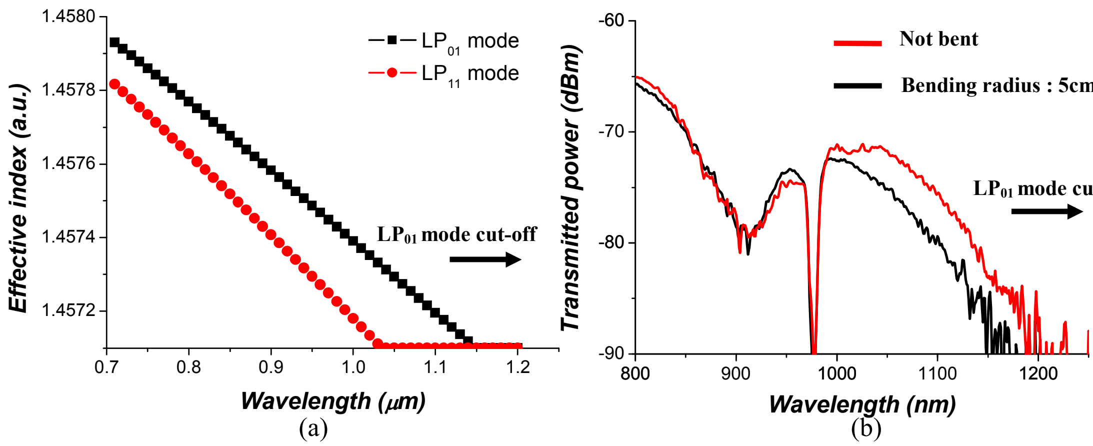


Figure 3. (a) Effective index change of LP_{01}, LP_{11} guided modes in DCHOF and (b) white light transmission through 1m long Yb-doped DCHOF.

The laser configuration is shown in figure 4. A 5m long Yb-doped DCHOF was pumped by a 975nm multimode diode stack through a combination of collimating lenses and dichroic mirrors. A simple laser cavity was formed between perpendicularly cleaved end facets of the fiber, providing 4% Fresnel reflections. Dichroic mirrors (high reflection at 1030 – 1150 nm, high transmission at 975 nm) were used to separate the signal from the pump beams. The operational pump absorption was 2dB/m.

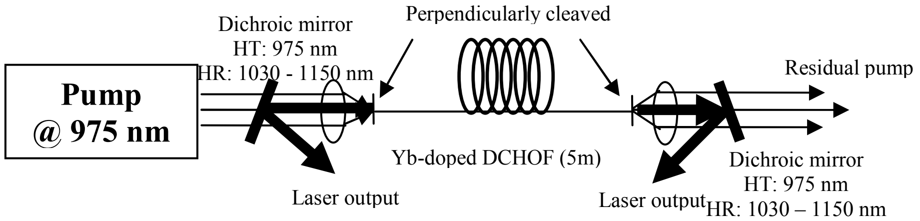
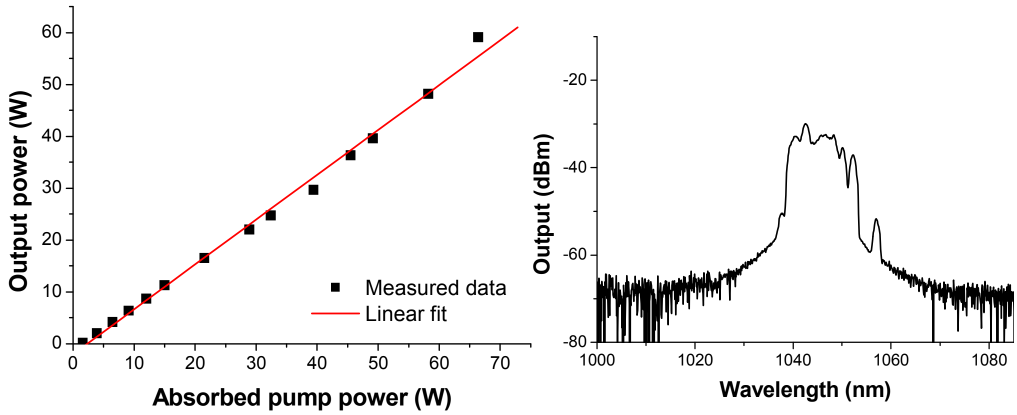


Figure 4. Laser configuration for Yb-doped DCHOF . HR: high reflectivity, HT: high transmission.

Figure 5 shows the laser output characteristics. The output power reached 59.1W with a slope efficiency of 81% with respect to the launched pump power (85% with respect to the absorbed pump power). The central lasing wavelength was 1046nm. The emission at longer wavelength was suppressed successfully by adopting the significant loss induced by the fundamental mode cut-off. Moreover, as shown in figure 3(a), only the LP_{01} mode is supported in the core at a laser wavelength of 1046nm. In DCHOF, because of the ring shaped core, the fundamental mode is expected to have a ring shaped output field distribution. In order to obtain the exact Gaussian output the holes in the output ends of the fiber have to be collapsed, as described in ref. [11, 12].



(a) (b)

Figure 5 (a) Laser output characteristics of Yb-doped DCHOF at 1046nm, and (b) Laser output spectrum (OSA resolution : 2nm)

4. Conclusion

We have investigated the guiding characteristics of DCHOF. The LP_{01} mode cut-off in this waveguide structure can act as a waveguide filter to suppress the undesired emissions. An efficient, short wavelength, Yb-doped DCHOF laser generating 59.1W of output power at 1046nm, with 85% of slope efficiency with respect to the absorbed pump power has been demonstrated. The output beam is expected to be a single mode based on our modal calculation. This initial result shows promising prospects to scale up the output of cladding pumped fiber lasers in a single mode core to kW power level.

5. References

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