Yb-doped phosphate double-cladding optical fiber laser for high-power applications

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ABSTRACT

A Yb-doped phosphate glass double cladding optical fiber was prepared using a custom designed glass composition (P_2O_5 - Al_2O_3 - Li_2O - B_2O_3 - BaO - PbO - La_2O_3) for high-power amplifier and laser applications. The preform drawing method was followed, with the preform being fabricated using the rotational casting technique. This technique, previously developed for tellurite, fluoride or chalcogenide glass preforms is reported for the first time using rare earth doped phosphate glasses. The main challenge was to design an adequate numerical aperture between first and second cladding while maintaining similar thermo-mechanical properties in view of the fiber drawing process. The preform used for the fiber drawing was produced by rod-in-tube technique at a rotation speed of 3000 rpm. The rotational casting technique allowed the manufacturing of an optical fiber featuring high quality interfaces between core and internal cladding and between the internal and external cladding, respectively. Loss attenuation was measured using the cut-back method and lasing was demonstrated at 1022 nm by core pumping with a fiber pigtailed laser diode at the wavelength of 976 nm.

Keywords:

1. INTRODUCTION

High power fiber lasers are very attractive due to their potential application in various technological fields including material processing, LIDAR and optical communications. The advantages of fiber lasers for high power applications is related mainly to their efficiency and compactness. The key point in the development of a powerful diode-pump high power fiber laser is the injection of the pump light into the small core of low numerical aperture. This problem can be overcome by using double-cladding optical fiber [1]. In a double-clad fiber laser, the laser-light propagates in single-mode regime into the core, which is surrounded by an inner cladding in which the pump-light is guided. The pump-light is confined inside the inner cladding by an outer cladding with lower refractive index, and it overlaps the fiber core where it is absorbed by the laser-active ions. The inner cladding has a much higher numerical aperture with respect to the outer cladding, so that a larger number of propagation modes can be supported. This allows for using multimode laser diodes as optical pump source, characterized by high power though poor beam quality.

Most of the research studies on high power double-clad fiber lasers have been focused on the Yb-doped fiber lasers [2,3] because of their high power conversion efficiency. These fiber lasers are commonly based on doped silica glasses. However, the ability to dope silica fibers with high concentration of ytterbium is limited by clustering effect. As an alternative to silica-based glasses, phosphate glasses have attracted great interest as host material for rare-earth doped high power fiber lasers because they are easy to fabricate and possess good chemical durability, excellent optical properties, very high solubility of rare-earth ions and no clustering effect [4-6]. In particular, the high solubility of rare-earth ions within phosphate glasses allows for larger concentrations of active ions to be introduced into a small volume: in the case of Yb^{3+} ion, the amount of rare earth that can be incorporated is of $2.10 \cdot 10^{26}$ m^{-3} and $2.12 \cdot 10^{27}$ m^{-3} for silica and phosphate glasses, respectively [7]. The possibility of incorporating a higher amount of rare earth ions allows for fabricating more compact active devices characterized by low nonlinearities.

In this paper, three different phosphate glasses are synthesized and characterized with the aim to fabricate a ytterbium doped double cladding optical fiber. To test the feasibility of the process and materials, a first single cladding phosphate optical fiber was fabricated and characterized. The preform for the fiber fabrication was manufactured by rod-in-tube technique. Rotational casting process was used to obtain the cladding tubes. This process allows to obtain fibers with very good interfaces between core-inner cladding and inner-outer claddings [8,9]. A first demonstration of laser emission is reported with the aim of assessing the quality of the fiber fabrication procedure.

2. EXPERIMENTAL PROCEDURE

2.1 Glass fabrication

Batch chemicals in powder form with very high purity (>99.99%) were used for glass preparation. Three different glasses (core, inner cladding and outer cladding) were manufactured in order to obtain the desired refractive index contrast and then the desired NA between core and inner cladding, and between inner cladding and outer cladding. The chemicals (P_2O_5 - Al_2O_3 - Li_2O - B_2O_3 - BaO - PbO - La_2O_3) were weighted inside a glove box under dried air atmosphere. The core composition was doped with 9 wt. % of Yb_2O_3, corresponding to 8 x 10^{23} Yb^{3+}/cm^3. The raw materials were melted in a furnace at 1300° C using an alumina crucible. A mix of O_2/N_2 gases was purged into the furnace to reduce the hydroxyl ions (OH^-). The melt was then cast into a cylindrical brass mold preheated at 400° C and annealed at T_g-10° for 2h. The glass samples were then cooled down slowly to room temperature.

2.2 Characterization of the glass

The characterization of thermal properties (glass transition temperature and crystallization temperature) of the three samples was carried out by differential thermal analysis (Netzsch, DTA 404 PC) up to 1500° C with a heating rate of 10°C/min. Around 50 mg of fine grain sample were used for each measurement. Their measurement also allowed assessing the corresponding glass stability and thus fiber ability of the glasses, which can be considered proportional to the quantity $\Delta T = T_x - T_g$. Glass samples were cut from the cast glass block sample and then polished for refractive index measurements, which were carried out using the prism coupling method (Metricon, model 2010) at the wavelengths of 632.8, 825, 1061, 1312 and 1533 nm, with a resolution of ± 0.001.

2.3 Fiber fabrication

The most important step for the fiber quality is the preform fabrication. The first step for the fabrication of the preform used in this work was to fabricate the core rod. Core glass composition was melted and cast in a pre-heated cylindrical brass mold. After 2 h of annealing process, a core glass rod of 10 cm long and 1 cm of diameter was obtained. In order to obtain excellent surface quality, the rod core was polished with SiC papers of different grits. The core rod was then stretched in the drawing tower to fit into the cladding tube. The phosphate glass tubes used for the claddings were produced by rotational casting technique from the molten glass at a rotation speed of 3000 rpm using an in-house built equipment. The parameters of the rotational casting process (rotation speed and time, casting temperature and mold temperature) were evaluated and optimized for the inner and outer cladding compositions. The external surfaces of the cladding tubes were polished carefully with SiC papers of different grits. After stretching, the rod was inserted in the inner cladding tube. The obtained core/first cladding structure was then stretched and placed in the second cladding tube. The preform was finally heated in the drawing tower above the T_g and below the T_x to draw the fiber. The fiber diameter was monitored during the drawing process. Two different fibers were produced using this process: firstly a single cladding Yb-doped phosphate fiber was drawn as test of the process and materials. The second fiber that was drawn was a Yb-doped phosphate fiber with a double cladding structure.

2.4 Fiber performances

The morphology of the fibers was analyzed using a Nikon Eclipse 50i optical microscope in order to assess the correct dimensions, geometry and relative positions of core and cladding. The modal profile of the fibers was measured by taking the near field image of the fibers output on a 50 cm long fiber piece at the wavelength of 1310 nm using a butt coupled fiber pigtailed laser diode source.

Laser performance was demonstrated using 25 mm of this Yb double cladding fiber. The experimental set up is shown in Figure 1. The main components used for the experimental setup are the laser diode pump, the WDM combiner; the active fiber, the HR mirror, the Optical Spectrum Analyzer and the computer with GPIB interface.

The pump laser current (i_L) was varied in order to characterize the Yb-doped fiber output power in relation to the pump laser power P_L, and as a consequence, the launched pump power P_p entering into the fiber.

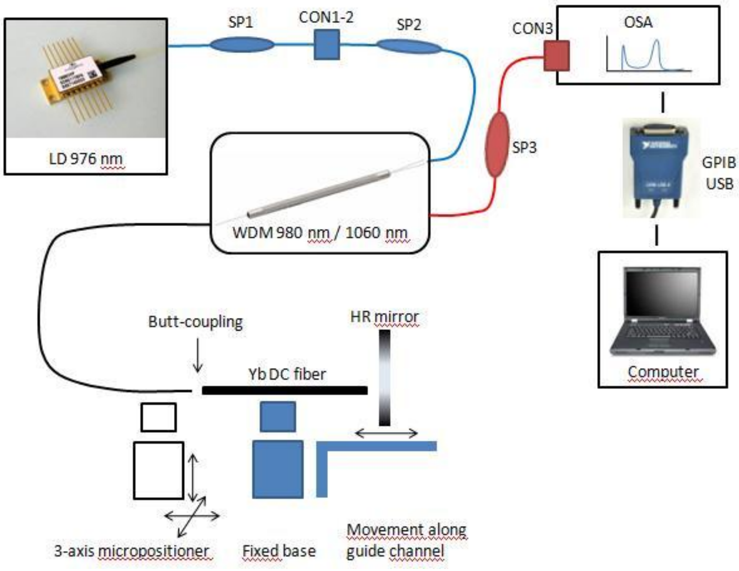

Figure 1. Experimental set-up of the phosphate glass fiber laser.

3. RESULTS

3.1 Glass fabrication and characterization

Clear and homogeneous glasses were obtained for all compositions. Table 1 shows the thermal and optical properties of the three prepared glasses. The difference between glass transition temperature (T_g) and the onset of crystallization (T_x) is related to the glass stability of the system. The values of ΔT were found to be higher than 180° C for all samples obtained, thus showing good stability with respect to temperature increase above T_g.

The refractive indexes of the three samples at the wavelength 1533 nm are reported in Table 1. The numerical aperture (NA) between core and inner cladding and between the inner and outer claddings were found to be equal to 0.16 and 0.39, respectively. The NA for the core and for the inner cladding was calculated by using the equation (1):

$$NA=\sqrt{n_a^2-n_b^2} \qquad (1)$$

where n_a and n_b are respectively the refractive index of the core and inner cladding, for the NA of the core, and the refractive index of CLAD1 and CLAD2 for the NA of the first cladding, both at the wavelength of 1533 nm.

Table 1. Glass transition temperature (T_g), crystallization temperature (T_x), glass stability (ΔT) and refractive index (n) of the prepared phosphate glasses.

GLASS	T_g (°C) ±3	T_x (°C) ±3	ΔT (°C) ±6	n @ 1533nm
CORE	489	672	183	1.564 ± 10^{-3}
CLAD1	481	675	194	1.555 ± 10^{-3}
CLAD2	479	669	190	1.505 ± 10^{-3}

3.2 Optical fibers fabrication

3.2.1 Single cladding fiber

The quality and the efficiency of the optical fiber is strictly related to the quality of the preform, so it is essential to obtain a preform with controlled core and cladding diameter, uniform refractive index contrast between core and cladding along the length of the preform and without defects, in particular at the interfaces between the different glasses. The fibers studied in this work were drawn from preforms made by rod-in-tube technique. Rotational casting technique offers a precise way for obtaining preforms with very good core-cladding interface. More than 200 m of Yb-single cladding fiber were drawn from high quality preform. The fiber was free of crystallization and had a diameter of 125 µm with a core diameter of 40 µm. In Figure 2a an optical micrograph of the core-cladding fiber cross section is shown: the core is circular and concentric and no defects or bubbles are present at the core/cladding interface. The step-index between the core and cladding is evident on the micrograph by the bright coloration of the core as compared to the cladding. The near field image of the fiber output beam was collected on a Grundig electronic SN76 IR video camera. A near field micrograph of the fiber end face illustrating guiding is shown in Figure 2b. The loss measurements were performed by cut-back technique starting from a 2 m long initial fiber. The attenuation value was calculated through linear least square fitting of the experimental data as reported in Figure 3. Attenuation losses at 1500 nm were measured to be 2 dB/m.

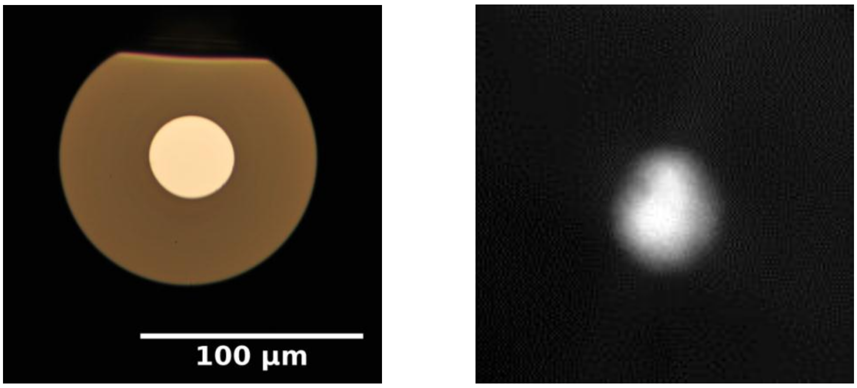

Figure 2. (a) Optical microscopy image and (b) near field image of the SC fiber.

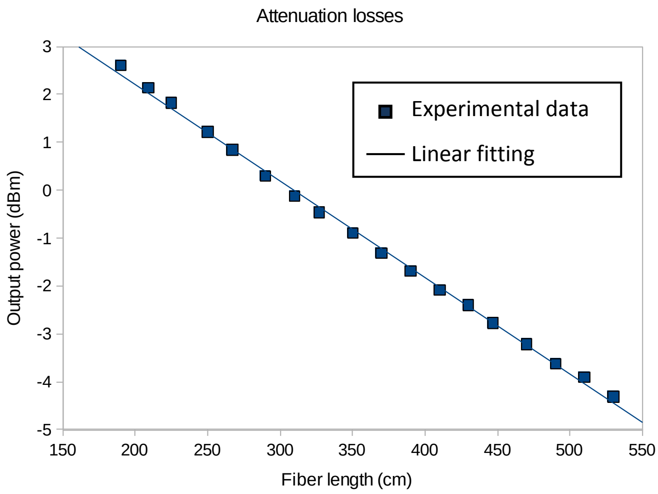

Figure 3. Attenuation losses of the SC fiber at 1550 nm.

3.2.2 – Double cladding fiber fabrication and characterization

After this first step, a Yb doped-double cladding phosphate fiber was drawn. As discussed above, the preform was fabricated by rod-in-tube method with the tubes manufactured by rotational casting technique. The dimensions of the double cladding fiber are: 125 µm for the diameter of the outer cladding, 25 µm for the inner cladding and 7 µm for the core. An optical micrograph of the fiber cross section is reported in Figure 4a. No defects or bubbles was observed at the different interfaces in the fiber section analyzed. Slight misalignment of the core with respect to the first cladding can be observed. A near field micrograph of the fiber end face illustrating the guiding operation is shown in Figure 4b.

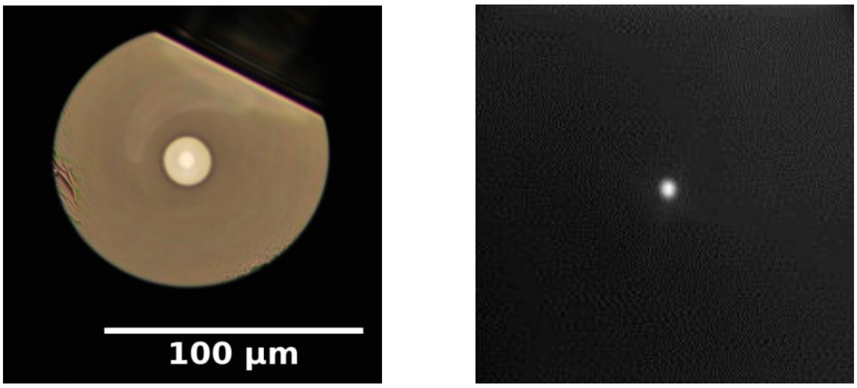

Figure 4. (a) Optical microscopy image and (b) near field image of the Yb-DC fiber

3.3 Fiber laser demonstration

In Figure 5 the spectra for lasing operation at maximum available pump power (blue line) and threshold condition (red line) are shown. The laser threshold was for a pump power of 150 mW. The generation of a lasing peak of 12-14 dBm (15-25 mW) with center wavelength at 1022 nm (see Figure 5) was observed for a pump power of 248 mW. The laser operation was stable for at least 60 minutes (duration of the experiment). The lasing wavelength remained almost fixed and the output power P_{out} presented fluctuations of the order of 5 dB. The bandwidth obtained was 2-3 nm.

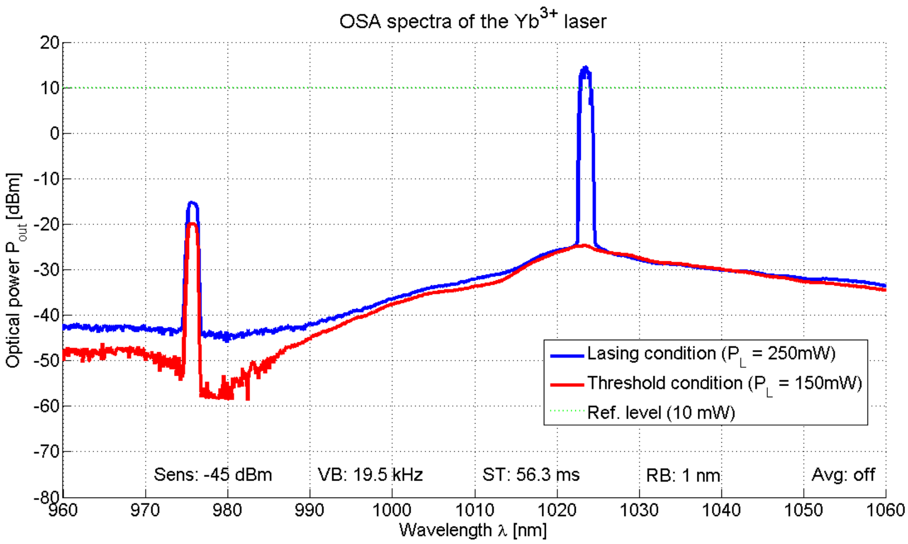

Figure 5. Detail of the Yb^{3+} laser output power peak at 1022 nm.

4. DISCUSSION

Glasses produced in this work showed great stability toward crystallization and good match of thermal properties which made them suitable for the development of an optical fiber. More than 180°C between T_g and T_x values were found for every glass composition. The observed stability is related mainly to the presence of network modifiers (R_2O_3). The presence of B_2O_3 and Al_2O_3 in the phosphate glass helps enhancing the stability against devetrification [9,10]. A good refractive index match between core and first cladding but also between inner and outer cladding is another key point of the glass fabrication. By changing properly the concentration and types of compounds present in our phosphate glass, the refractive indexes of the three glasses were adjusted while minimizing the differences in the characteristic temperatures.

With these glasses, a preliminary single cladding fiber was drawn by using preform fabricated by rotational casting technique. As shown in Figure 1a, a fiber without any visible imperfections or defects on the core/cladding interface was obtained. The attenuation losses obtained by cut-back measurements were mainly due to absorption and scattering effects.

After this preliminary study, gain characterization of the Yb-doped double cladding fiber was made. The Yb-doped fiber laser obtained showed a 6 % overall efficiency. In relation to launched pump power, the efficiency was between 10 and 15 %. Optimal laser performance could have been affected by several factors. Those associated with a non-optimized experimental setup setting could be the following: imperfect alignment between the parts forming the resonance cavity (fiber-guide parallelism, fiber bending, mirror-guide angle), presence of a small gap between the Yb^{3+}-doped fiber and the HR mirror, active fiber end cleaved with an oblique angle or having a bad quality cleaving. In relation with the optical components: the use of a normalized diameter (and NA) would help improving the overall performance of the system. Concerning the WDM: since it is designed to operate with 980 nm and 1060 nm, it could be expected that the power carried at the lasing wavelength (1022 nm) splits between the two ports. In this sense it is possible that some amount of the lasing output power reached the pump laser, and consequently, reduced the power available at the system output (value measured by the OSA). Finally, in relation to the double cladding active fiber: the small distortion and misalignment of the core could lead to coupling losses since the fiber laser was tested using core pumping.

5. CONCLUSION

Three phosphate glasses suitable for optical fiber fabrication were synthesized and characterized. One glass for the core, doped with 9 wt % of Yb_2O_3, two un-doped glasses with lower refractive index for the claddings. The glasses show great stability toward crystallization due to the presence of network intermediate (R_2O_3) and limited glass transition temperature. Preforms with very good interfaces between the different glasses were successfully fabricated by rotational casting technique. From these preforms, a first Yb-single cladding phosphate fiber was drawn and characterized. The fiber presents high quality interface between the core and the inner cladding. Attenuation losses of this fiber were measured at 1550 nm and were found to be 2 dB/m. A Yb-doped phosphate double cladding fiber laser with 15 mW output power at 1022 nm was obtained. The efficiency related to the lunched pump power was between 10 and 15 %. These value of efficiency are affected by different factors, such as experimental set up. In order to improve the laser performance, future work will be focus on the use of a DBG working at 1060 nm instead of the HR mirror and on the cladding-pump scheme instead of the reported core-pump.

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