Phosphate Yb^{3+} doped air-cladding photonic crystal fibers for laser applications

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Abstract—We present two single-mode photonic crystal fibers with air-cladding for laser applications. We developed PCF structures created by replacing respectively one and seven air-holes with 6%mol ytterbium doped glass. With increasing the mode area you can increase the power level and shorten the fiber length in laser construction. We achieved 53 and 19cm optimum length fiber lasers with 4.7W and 12.4W maximum output power, respectively. The slope efficiencies of the lasers were 15.6% and 42.4%. The use of air-cladding brought a very high numerical aperture of pump waveguides in both laser fibers resulting in the values of 0.72 and 0.91, respectively.

Active fibers are of great interest in the design of lasers and fiber amplifiers. Currently, many commercial structures still base on standard step-index fibers, but there are also many constructions using photonic crystal fiber (PCF). PCF has the properties that allow shortening the length in comparison of standard step-index fibers for laser applications. Shortening the length of the active PCF is possible due to a substantial increase in the absorption of pumping radiation, which is achievable by the application of a Large Mode Area (LMA) core, while maintaining single-mode propagation and therefore achieving an excellent quality of the generated beam [1]. Another PCF technology property that helps to get high pump absorption is a very high numerical aperture achieved by the use of external air-cladding in a double-clad structure [2]. A very high value of numerical aperture of the pump waveguide in PCF technology is not available in step-index fibers.

Air-cladding, due to the sophisticated fabrication technology of photonic crystal fibers, has a slightly irregular shape, which increases the pumping efficiency by reducing the appearance of helical modes, which is characteristic for step-index symmetric circular internal cladding structures. For silica PCF, the laser fiber length can be limited to few meters or parts of a meter [1] but step−index laser fiber needs to be usually tens of meters to provide power operation of the same order [3].

In order to produce shorter lasers, the solutions are based on phosphate glass which allows incorporating more rare earth ions. In the case of phosphate glass, which has much more attenuation than silica glass, shorter fiber not only brings a final size reduction of the device, but it is also important due to the reduction of losses in the laser cavity and thereby increases the laser efficiency. In this paper we present a phosphate fiber laser with a double-clad structure made entirely in PCF technology, i.e. the PCF structure builds the core and internal cladding that is surrounded by a PCF external air-cladding.

For fibers fabrication we used doped and undoped phosphate glass (P_2O_5-Al_2O_3-BaO-ZnO-MgO-Na_2O). The doped glass was prepared using Yb_2O_3 that was soluble in the glass with a density of 6 mol% (15.69×10^{20} Yb^{3+}/cm^3).

The absorption coefficient of the doped glass was measured with a high resolution of 0.1nm for the range of 800-1100nm for a 0.5mm thick sample. You can find the absorption cross section if you divide the attenuation coefficient by the number of active ions [4]. Then using the McCumber method you can calculate the emission cross section of the doped glass [5-6]. The results of this analysis are shown in Fig. 1. The peak emission cross section at 975.2nm is $1.40\times10^{-20}cm^2$.

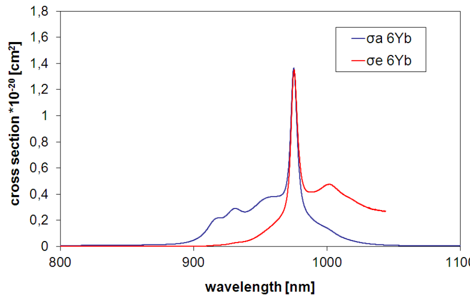

Fig. 1. Absorption (blue) and emission (red) cross section of 6%mol ytterbium doped phosphate glass at 800-1100nm spectrum.

There was also observed lifetime of luminescence of ytterbium ions as a function of level doping. For a doping level of 6 mol% , the lifetime was 0.6ms.

The doped and undoped glass was prepared to match each other with a refractive index and rheological properties. We used doped glass with a slightly negative core-cladding Δn to be sure of the photonic crystal fiber

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way of propagation. A positive Δn could allow the step-index propagation in a photonic crystal fiber structure [7].

The most common method for manufacturing photonic crystal fibers is a stack-and-draw method that is based on stacking a preform of capillaries and rods forming the photonic crystal structure. The preform may also consist of larger elements, for example, glass tubes, which are usually construction elements, the elements to protect the components placed inside or elements to increase the diameter of the final fiber.

The structure of the final fiber maps, usually quite faithfully, the structure of the stacked preform. The core was formed by placing in the center of the preform one or seven doped glass rods surrounded by capillaries creating a PCF structure and inner cladding in a double-clad structure. The capillaries for air-cladding were put in the next layer of the preform. In order to obtain a high numerical aperture of the pump waveguide, the air bridges in the air-cladding in the final fiber should not be wider than half the wavelength of pump radiation, and their length should exceed many times the pump wavelength [8]. In the case of ytterbium doped structures pumped in the spectrum 915-980nm, the bridges width should not exceed 455-490nm, and their length should not be less than a few microns. To fulfill the role of air-cladding there have been used thin wall capillaries. The external layer of the preform was another glass tube.

The preform prepared in the way described above was drawn in the fiber drawing process. Figure 2 shows manufactured fibers: the first fiber with a core created by replacing one capillary with a single doped rod (PCF1) and the second one with an extended core created by replacing seven capillaries with doped rods (PCF7). The fibers were manufactured with similar dimensions. The main difference between PCF1 and PCF7 was the diameter of the core. The PCF1 core diameter was 11.5μm (doped area diameter of 8.5μm) and the PCF7 core diameter was 27μm (doped area diameter of 23μm). The outside fiber diameters were 285μm and 290μm, respectively. The PCF lattice pitch was 7.5μm for PCF1 and 7.0μm for PCF7. The internal cladding diameters for both fibers were about 180μm, which was suitable for coupling effectively the fiber pump waveguide and pumping diode. The waists of glass bridges in air-cladding were 420nm in the PCF1 and 230nm in the PCF7, which allowed to expect a very high numerical aperture of the pump waveguide in both fibers. The lengths of glass bridges were 15μm and 18μm.

The numerical aperture of the fibers was measured at 1064nm wavelength using low divergence laser beam set with different angles to the fiber face. We achieved the value of 0.72 in PCF1 and the value as high as 0.91 in PCF7. The numbers correspond to the analysis reported in [8] that shown that the value of numerical aperture depends on the waist of glass bridges in air-cladding. The value obtained in our experiment is the largest aperture achieved in the structure of phosphate glass and comparable with those achieved in PCF air-cladding structures made of silica glass [1-2].

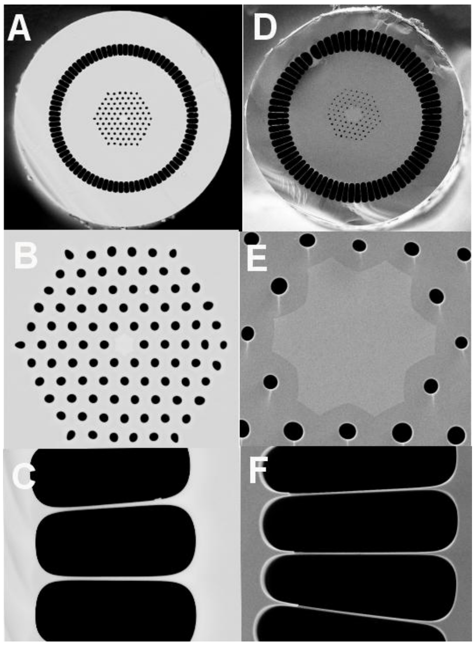

Fig. 2. SEM photos of a cross-section of manufactured double-clad photonic crystal fibers: PCF1 (A, B, C) and PCF7 (D, E, F); overall fiber (A, B), internal cladding (B, E), air-cladding (C, F).

The generation parameters of both fiber lasers were measured in the experimental setup shown in Fig. 3.

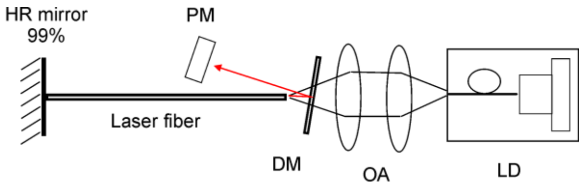

Fig. 3. The experimental laser configuration, where: OA - optical arrangement for forming laser diode radiation; DM - dichroic mirror; LD – pumping diode laser; PM –power meter.

Each fiber was pumped of 975nm with the 100μm core fiber laser diode from the one end of the investigated fiber. The pump radiation at the end of laser diode (LD) fiber was mapped on the surface of the experimental fiber with simple optical arrangement (OA) consisted of two identical aspheric optical lenses (f=25 mm) providing very good coupling. The laser cavity was formed by 4.3% Fresnel reflection and 99% HR butt coupled mirror placed on the opposite site to the pump radiation. The HR mirror reflected also the pump radiation with 99% effectiveness. The laser output was separated from the pump radiation with dichroic mirror.

Referring to the absorption spectrum in the bulk doped glass, the spectrum of pump diodes radiation and the ratio of the doped area to the internal cladding area in the fiber [9], the unsaturated pump absorption in the PCF1 was 12.6dB/m but in the PCF7 the absorption of the pump was more than 91dB/m, which greatly exceeded the value obtained in silica fibers of up to 30dB/m [1].

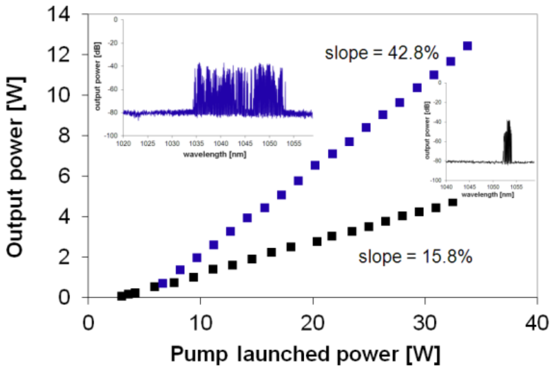

Fig. 4. The output power versus launched pump power in the fiber lasers for the optimal lengths of the PCF1 (black) and PCF7 (blue) with spectrum of both lasers at maximum output power.

Figure 4 shows the laser output power versus the launched pump power calculated in the cw mode for the optimal (according to the slope efficiency) lengths of PCF1 and PCF7. The measurements were done with quasi-cw because we observed thermal fiber damage for higher pump power in the cw mode. The quasi-cw had a frequency of 20.4Hz with a 3ms duty cycle what exceeded few times of lifetime of dopants what indicated the potential of investigated fibers in cw mode. The thermal damage of the fiber was caused mainly by an internal loss of the fiber and quantum defect of the laser. In the case of the cw mode, the fiber should be placed in a cooling arrangement resulting in probably similar laser performance shown in Fig. 4. In the experiment we used a few fibers that differed in length.

In the case of the PCF1, we took fiber from 28cm till 114cm long. We experimentally found that the optimal length of laser fiber was 53cm. In that case the threshold was 2.1W of launched power. The maximum achieved power of a single-mode laser output was 4.7W with no evidence of absorption, probably, a higher value of the output power would be achievable if you used a higher power laser diode. The slope efficiency was 15.8%. The laser generated at 1053nm with an FWHM width of 2.0 nm.

In the case of PCF7, we took fiber lengths from 8cm till 40cm, expecting a shorter optimal length due to much higher absorption in the fiber with an extended core. We experimentally found that the optimal length of laser fiber was 19cm. In that case the threshold was 3.9W of the launched power. The maximum achieved power of a single-mode laser output was 12.4W with no evidence of absorption. The slope efficiency was 42.8%, which is comparable with the best result achieved in phosphate lasers [10]. The laser generated at wavelength 1044nm with an FWHM width of 20nm. The phenomenon of increasing width of a generated spectrum for larger core diameters was reported in silica fiber lasers as well [1]. Lasers in both cases introduced single-mode performance with a numerical aperture of generated mode of 0.07 for the PCF1 and 0.06 for the PCF7.

Tab. 1. The parameters of PCF1 and PCF7 lasers.

	PCF 1	PCF7	
outside fiber diameter	285	290	µm
internal cladding diameter	180	180	µm
core diameter	11.5	27	µm
doped area diameter	8.5	23	µm
glass bridges in air-cladding waist	420	230	nm
NA of pump waveguide	0.72	0.91	
estimated pump absorption	12.6	91	dB/m
experimental optimal length of the laser	53	19	cm
minimum laser treshold	2.1	3.9	W
maximum laser differential efficiency	15.8%	42.8%	
maximum output power	4.7	12.4	W
laser spectrum width	2	20	nm
NA of lasing mode	0.07	0.06	

In conclusion, we presented the ytterbium doped phosphate glass photonic crystal fiber lasers in a single-mode operation. Phosphate glass has much higher attenuation than silica but it can be successful in a short fiber laser arrangement. We compared two fibers that differed in the core area, which had a massive impact on the pump absorption of the fiber, optimal fiber length and generation parameters. Further work on increasing pump absorption in phosphate fiber has been currently undertaken. If we decreased the diameter of an internal cladding, we would achieve the optimal fiber length of a few centimeters for the fiber with an extended core.

Phosphate glass tubes, doped rods and final laser fiber were manufactured entirely in the Institute of Electronic Materials Technology.

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