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More than 100 W, 18 cm Yb-doped phosphate fiber amplifier

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ABSTRACT

Phosphate glass is an attractive material for rare-earth-doped fiber manufacturing because high doping levels are possible without introducing negative effects such as up-conversion or increased non-radiative recombination. In this paper we present a novel PM heavily Yb-doped polarization maintaining large mode area phosphate fiber and a > 100 W power level amplifier based on this fiber. The fiber was fabricated by a rod-in-tube technique. An 18 cm long piece of the fiber was used to build a high-power all-fiber amplifier. 106 W of output power at 1030 nm was achieved with 55 % slope efficiency with respect to the launched pump power. To the best of our knowledge, this is the highest average power ever demonstrated for short phosphate fiber lasers.

Keywords: High power lasers, phosphate glass, Yb-doped fibers, Fiber amplifiers

1. INTRODUCTION

Yb-doped pulsed fiber amplifiers are in a great demand for many scientific, military, and commercial applications. The peak power of such amplifiers is mainly limited by nonlinear effects arising from pulse propagation along an active fiber. These effects, such as self-phase modulation, Raman and Brillouin scattering, lead to the distortion of temporal and/or spectral pulse characteristics. Their threshold in a fiber can be increased by the enlargement of the core area and by heavily Yb doping to reduce the length. Increase of the core diameter by itself might lead to a multi-mode operation and beam quality degradation. To date, a variety of approaches have been proposed to develop fibers with a large mode area (LMA) working in a single-mode regime; and high average and peak power amplifiers were realized based on these fibers. These approaches include: photonics crystal fibers [1] and rods [2], Bragg [3], chirally coupled core (CCC) [4], higher order mode (HOM) [5], and tapered fibers [6]. Another less explored approach to suppress nonlinearities is to decrease the fiber length by heavily Yb doping. The problem is that the silica glass, which is most often used as a fiber material, allows relatively low doping levels of rare earth (RE) elements. High RE concentrations result in such detrimental effects as a photodarkening [7] and a life-time quenching [8].

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Multi-component phosphate glasses are attractive alternatives for manufacturing of active fibers with high RE content [9]. A consequence of the disordered matrix structure is a several 10x increase of RE doping level compare to that of the silica glass [10-14]. Another advantage of a phosphate glass technology is that the refractive index can be varied over a large range with a high accuracy and repeatability. First, this enables a stable production of single-mode fibers with a very large core size and ultra-low numerical aperture (NA). Second, it makes possible to realize all-glass double clad fibers with high NA (>0.46) glass outer claddings as an alternative for low-index polymer coating. However, phosphate fibers has a lower (~500° C) glass transition temperature compared to that of silica fibers (~1000° C). This complicates a silica-to-phosphate fiber splicing process as well as complicating thermal management of an active fiber and a splice point. To date, the highest average power demonstrated from a phosphate fiber laser is 57 W [15]. However, this result was obtained in a free space-coupling oscillator scheme with an active fiber length of 70 cm. Attempts to use this fiber to make an amplifier resulted in only 16 W of output power [15]. Concerning all-fiber phosphate fiber amplifiers, the highest power of 32 W was presented by our group using 45 cm fiber in 2014 [16]. In this paper we present a monolithically-built laser system based on an 18 cm long phosphate fiber with more than 100 W of output power at 1030 nm

2. FIBER MANUFACTURING AND SPLICING

Using the rod-in-tube technique we manufactured a new large mode area double-cladding PM heavily Yb-doped fiber (YDF). The fiber core has 32 μm diameter and NA as low as 0.022 that results in a single-mode operation in the 1 μm wavelength range. The inner and outer claddings have 130 μm and 156 μm diameters. Their refractive indexes were designed to provide 0.46 NA for a pump radiation. The fiber has two low-index stress rods to maintain the polarization and provide cladding modes mixing.

A Fujikura LZM-100 laser system was used for splicing. A special splicing program was developed by our group to splice the developed fiber to a passive commercial double-clad LMA fiber with 20/125 μm core/cladding diameters. Image of the spliced fibers is presented in Fig. 1. To simulate the pump radiation the 1310 nm diode was spliced to a 105/125 μm (NA~0.22) pump fiber of a 6+1 to 1 combiner and the fiber was tightly coiled, so light filled the fiber NA. The combiner output fiber was spliced to the chain under test and loss of the cladding-propagating light was measured to be <0.24 dB per splice. The loss for core-propagating light was estimated by launching the 1310 nm light into the core of the passive fiber. The passive fiber was coiled with a small bending diameter to remove higher order modes from the fiber core. The loss was measured to be <2.5 dB per splice that is mainly caused by the significant difference in mode field diameters between two fibers. Lower loss splices are possible with better mode matched fibers and improved splice recipes. The signal splice loss might be optimized by making a mode field adapter, however, it is well known, that the input signal loss does not affect an amplifier performance until it operates in the saturated regime.

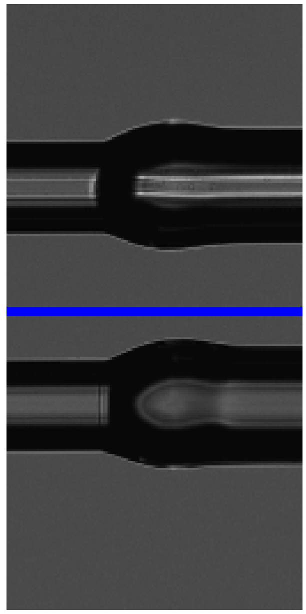

Figure 1. Image of the splice point. Left fiber: passive silica fiber, right: developed phosphate fiber.

Theoretically, there is a danger of a silica-to-phosphate fiber splice breakout during a high-power operation because of the difference in thermal expansion coefficients. To explore that, we performed series of tests with consecutive heating (to more than 200 °C) and cooling (to the room temperature) of the splice point. No evidence of any splice degradation was observed. It is also worth to note that the splice point demonstrated good mechanical strength and stability. The splice could be handled in the same manner as usual silica-to-silica fibers splices; and no special precautions were needed to avoid the splice breaking.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The manufactured fiber was tested in a power amplifier scheme presented in Fig. 2. A continuous wave Yb-doped fiber laser with the output power of 3 W at 1030 nm was used as a seed source. The seed and the pump radiation were launched into the active fiber through a commercially available 6+1 to 1 combiner. Three 976 nm non-wavelength stabilized fiber coupled diode lasers were used for pumping. Maximum combined power of these diodes was 200 W. The output of the combiner was directly spliced to the 18 cm piece of the developed LMA heavily-doped phosphate fiber. The other end of the amplifier was angle cleaved to avoid the back reflection. The active fiber was placed into a water-cooled at 20 °C V-groove. The output beam was collimated using an anti-reflection coated lens with f=25.4 mm. A long-pass filter (LPF) with a cutoff wavelength of 1000 nm was used to remove an unabsorbed pump power.

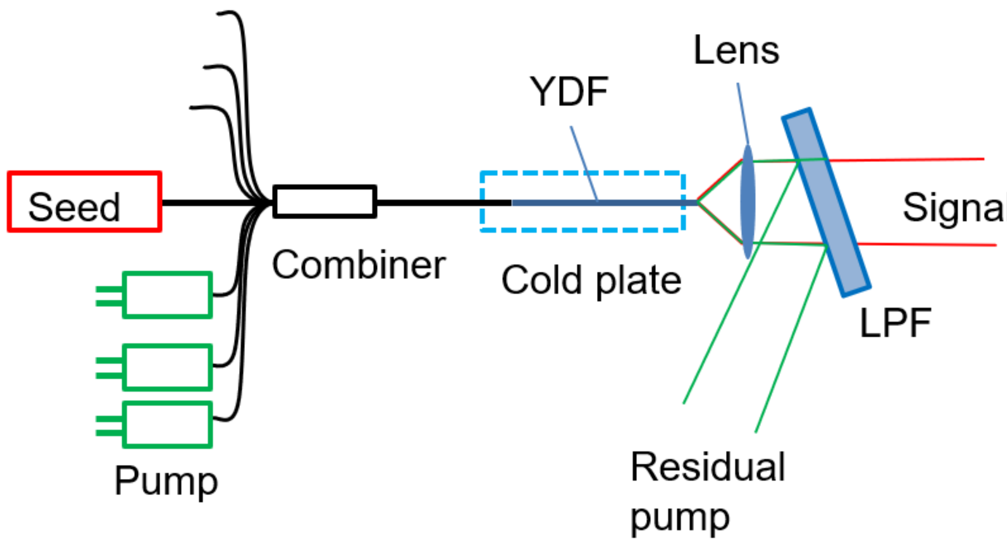

Figure 2. Experimental setup.

106 W of output power at 1030 nm was achieved with 55 % slope efficiency with respect to the launched pump power (Fig 3). Most of the launched pump power was absorbed in the amplifier. The spectra of the seed laser and the amplifier operating at full power are presented in Fig 4a. As can be seen, the signal spectrum was not affected by the amplifier. A 1-hour test at full power was performed and no power degradation was observed (Fig 4b). The polarization extinction ratio of the amplifier was measured to be >13 dB. The M^2 factor was <1.25. The output beam shape measured with a scanning slit profiler is presented in the inset in Fig. 3.

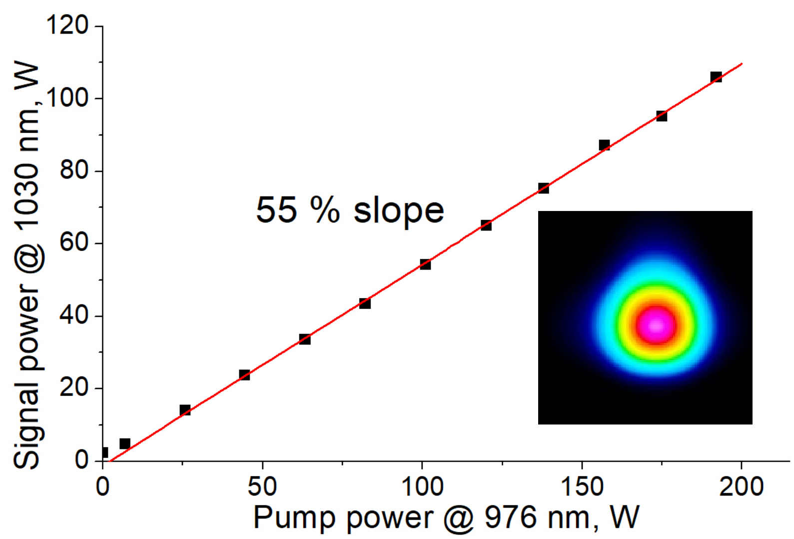

Figure 3. Output power of the amplifier. Inset: beam profile.

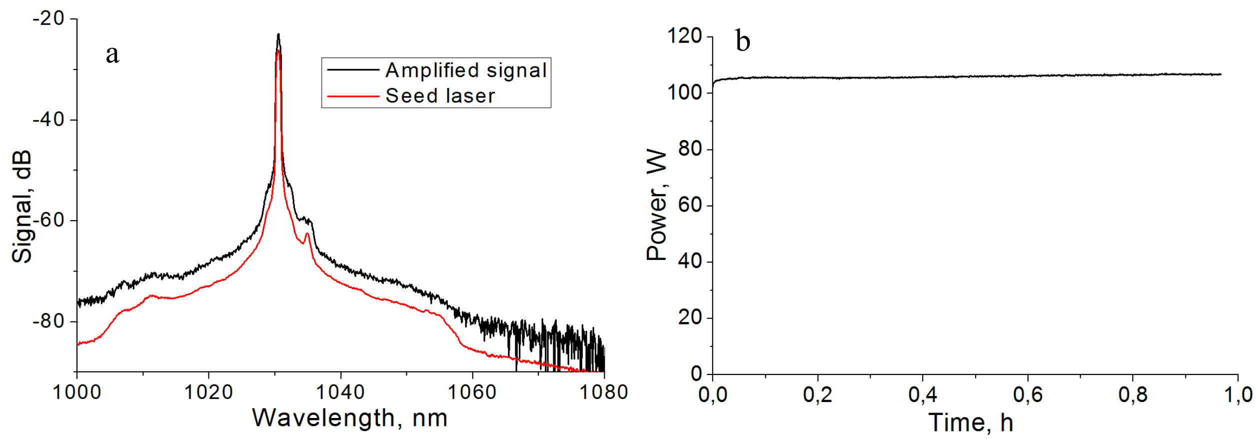

Figure 4. a-Spectra of the seed laser and the amplifier; b-Power stability.

To the best of our knowledge, 106 W is the highest average power ever demonstrated for highly-doped phosphate fiber amplifiers. Further power scaling will be performed in future works. However, the 100 W power level is already sufficient for many applications. At the same time, thanks to the short fiber length (18 cm) and the large core (estimated MFD is ~38 µm) the developed amplifier will provide capability to reach very high peak powers. In Table 1 active fiber lengths and mode field diameters of different state-of-the-art single-mode high peak power fiber amplifiers are presented. It can be seen, that all approaches, except for HOM and rod-type fibers, have similar mode field areas of ~30-40 µm. Rod type fibers and HOM have ~2 times larger mode diameter that corresponds to ~4 times higher threshold for nonlinearities. At the same time our approach allows to use 4.4-21 times shorter fiber than others. Thus, compact monolithically built phosphate fiber amplifiers, as presented in this work, will enable peak power that is higher or at least comparable to that demonstrated for other state of the art fiber lasers.

Table 1. Fiber lengths and mode field diameters for different high peak power amplifiers.

Concept	Fiber length	MFD
PCF rod type fibers [2]	0.8 m	65 µm
HOM fibers [5]	3.8 m	63 µm
PCF LMA fibers [1]	1.8 m	31 µm
Bragg fibers [3]	2 m	26 µm
CCC fibers [4]	3.5 m	42 µm
Tapered fiber [6]	1-2 m	36 µm
This work	0.18 m	38 µm

In conclusion, we presented the novel highly Yb-doped large mode area double-clad phosphate fiber. The fiber was used to build a compact all-fiber amplifier. 106 W of average power at 1030 nm with 55 % slope efficiency was obtained. This power, to the best of our knowledge, is the highest average power ever demonstrated for phosphate glass-based fiber amplifiers. Moreover, the fiber fabricated in this work potentially has the highest nonlinear effects threshold among other solutions for high peak power amplifiers. Further power scaling, as well as a demonstration of high peak power amplifiers based on this fiber, will be presented in future.

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