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High-power laser tests of phosphate glass-based bioresorbable optical fibers transmission

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ABSTRACT

Optical fibers and optical fiber bundles are often used for endoscopy and related (minimally invasive) medical methods because they offer good transparency together with flexibility. The ability to perform the operation, monitoring and chemical analysis of tissues with minimal disruption of the skin or internal organs of the patient is very promising in the medical field. Traditionally, silica optical fibers are used. Although silicon oxide is a biocompatible material, its use involves a serious health risk due to its fragility and the fact that potential fiber fragments can freely move inside the body and they are not detectable by conventional methods such as X-ray imaging. A possible solution to this issue can be the development of optical fibers based on biodegradable materials. Important benefit of bioresorbable fibers is that they do not need to be explanted after their use. We report on the optical power transmission tests of recently developed bioresorbable optical fibers based on phosphate glasses. Continuous-wave fiber lasers at 1080 and 1060 nm with output powers up to 7 W and a picosecond laser source at 515 nm with MW pulse peak power were used.

Keywords: biomaterials, biodegradable optical fiber, fiber lasers, laser-induced damage threshold (LIDT).

1. INTRODUCTION

Optical fibers and fiber lasers are highly attractive medium for transmission of light and light sources, respectively, in medicine.¹⁻⁸ Optical fibers and optical fiber bundles are often used for endoscopy and related (minimally invasive) medical methods because they offer good transparency together with flexibility. The bioresorbable and optically transparent materials of optical fibers⁷⁻¹⁰ can bring important benefits for the applications: potential fiber fragments that are unintentionally broken inside the body can dissolve and do not need to be surgically extracted. In some applications it is advantageous to leave the fibers in the body without explanting them out.¹ Despite the fact that the bioresorbable or bioactive materials (bioactive material can form new soft-tissue and bone structures) based on phosphate glass (PG) are known since almost fifty years,^{11, 12} the optically transparent PG fibers have been investigated only recently, including

first in-vivo tests of such fibers.^{7, 8, 10} While the PG fibers have been used since long time for fiber laser applications,¹³⁻¹⁵ the high-power laser tests have not been performed yet for the bioresorbable PG fibers, to the best of our knowledge. In this paper, we report on the optical power transmission tests of recently developed bioresorbable optical fibers based on phosphate glasses. Continuous-wave (CW) fiber lasers at 1080 nm and 1060 nm with output powers up to 7 W and a picosecond laser source at 515 nm with MW pulse peak power and up to 2 W of average power were used.

2. MATERIALS AND METHODS

The phosphate-glass-based optical fiber preform was fabricated by the rod-in-tube method.^{7, 8} The drawn fiber showed a $\sim 40 \mu\text{m}$ multimode core and a $\sim 130 \mu\text{m}$ cladding (Fig. 1a). The fiber refractive index profile and tomography were assessed by the optical fiber analyzer IFA-100 (Fig. 1b and c).^{16, 17} The fiber under test was spliced to a silica-based fiber using the fusion splicer Fitel S178A V2.¹⁰ The phosphate-based fiber of $\sim 20 \text{ mm}$ in length was pigtailed with the single-mode fiber Corning HI1060 and a multi-mode fiber with $105 \mu\text{m}$ core for the fiber-based laser source and free-space coupled laser testing, respectively. Note that the laser radiation was guided in the $40 \mu\text{m}$ core in the case of the fiber laser source, while it was guided in the whole $130 \mu\text{m}$ waveguide structure in the case of the free-space coupled laser. Ytterbium-doped fiber lasers were used for the tests of the PG fiber transmission of the CW-laser light; an example of the in-house developed Yb fiber ring laser is shown in Fig. 2(a). The optical isolator ensured unidirectional operation of the laser. The isolator was located beyond the output coupler to prevent damage of the isolator laser. Since no isolator was placed at the output of the fiber laser, the phosphate-based fiber was cleaved with 7° angle to prevent mode instabilities induced by parasitic reflections from the output fiber end-face.¹⁸⁻²¹ For long-term tests, the commercial Ytterbium fiber laser YLD5000 from IREE Polus Group with external high-power (2 W) optical isolator spliced to the fiber laser output was used. The optical power was measured by the thermopile optical power detectors Gentech UP19K-110F-H5-D0 (incident power up to 100 W, DET 2 in Fig. 2a) and Thorlabs S405C (up to 5 W, DET 1).

The green pulsed laser beam at 515 nm was produced by frequency doubling of the 1030 nm fundamental laser beam at the PERLA C100 laser system²² (Fig. 2b). The pulse duration was 1.7 ps and the repetition rate 92 kHz. A critically phase-matched Lithium triborate (LBO) crystal of $8 \times 8 \text{ mm}^2$ size and 10 mm length ($\theta = 90^\circ$, $\varphi = 12.8^\circ$, XY plane, AR coatings for 1030 and 515 nm) kept at 47°C temperature was used for the frequency doubling. A half-wave plate and a polarizer were used for energy tuning. The beam diameter at the crystal entrance was 2.6 mm ($D4\sigma$). The generated second harmonic beam then reflected on two dichroic mirrors for the wavelength separation and after the second energy tuning system it was coupled into a multi-mode $105/125 \mu\text{m}$ silica fiber spliced to the phosphate fiber via a positive 150 mm focal length lens. The spot focus size was thus $38 \mu\text{m}$. The tuning input power varied from 100 mW up to 2 W (of 40 W available), providing a focus spot fluence from 0.1 up to 2 J/cm^2 .

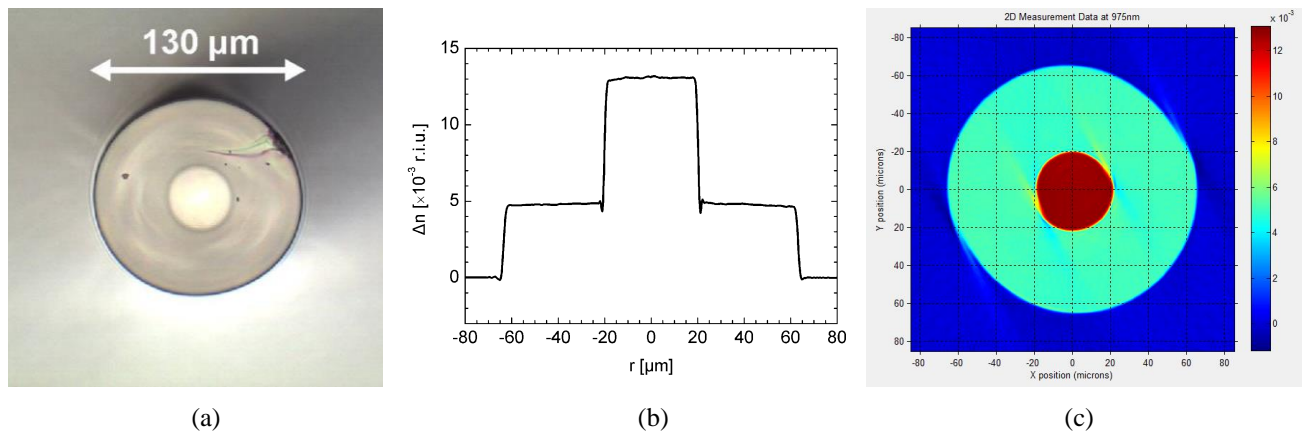


Figure 1. Microscope photograph of the phosphate-glass-based fiber endface (a), its refractive index profile (b) and tomography image (c). Refractive index of the immersion liquid was 1.5150 at 589.3 nm and 25°C .

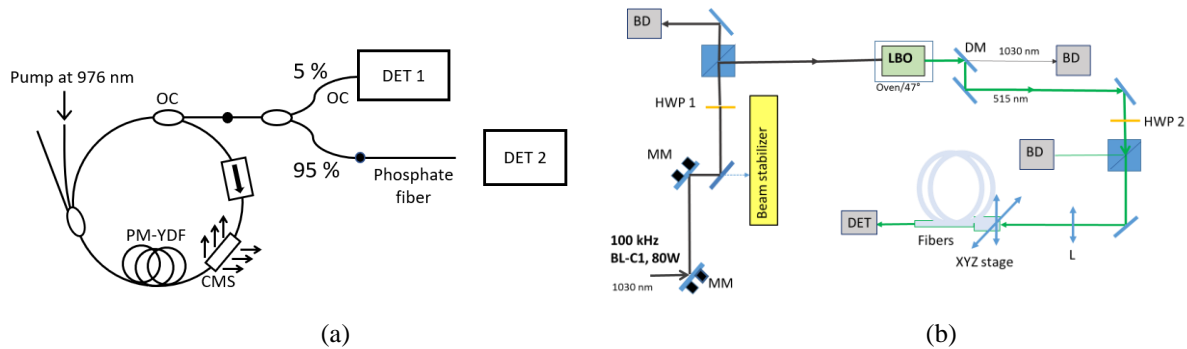


Figure 2. Experimental setups employed for the measurement of the optical power transmission of the phosphate-based optical fiber using two excitation sources: (a) a CW Ytterbium fiber ring laser at $1.08 \mu\text{m}$ and (b) a short-pulse green beam at 515 nm . Legend: PM-YDF, polarization-maintaining Yb-doped fiber; OC, output coupler; CMS, cladding-mode stripper; DET, detector; HWP, half-wavelength plate; MM, motorized mirror; BD, beam dump; DM, dichroic mirror; LBO, Lithium triborate (LiB_3O_5) non-linear optical crystal.

3. RESULTS AND DISCUSSION

The transmission of the CW laser light emitted at $1.08 \mu\text{m}$ by the Yb-fiber ring laser through the PG optical fiber was tested up to an optical power of 6.5 W (Fig. 3a). A linear dependence of the PG fiber output from the input power and the absence of roll-off were observed. Long-term tests were performed by using a commercial Yb-fiber laser at $1.06 \mu\text{m}$ equipped with an optical isolator at the output for two input power levels (Fig. 3b). A relative variation of about $\pm 1\%$ was observed, which falls within the $\pm 3\%$ measurement uncertainty specified by the manufacturer. Indeed, long-term fluctuations of the optical power sensor readings of $\pm 0.5\%$ were found when the measurement uncertainty of the detectors was assessed with a stable laser source. It should be noted that, while the laser monitor (5% branch of the optical fiber splitter) was firmly connected to the S405C detector by using a FC/APC connector, the PG fiber output was directed to the detector in free-space. Therefore, sudden change in the ambient environment may slightly affect the measurement; see the step-wise effect at $\sim 1400 \text{ s}$ for the 1100 mW input power shown in Fig. 3b.

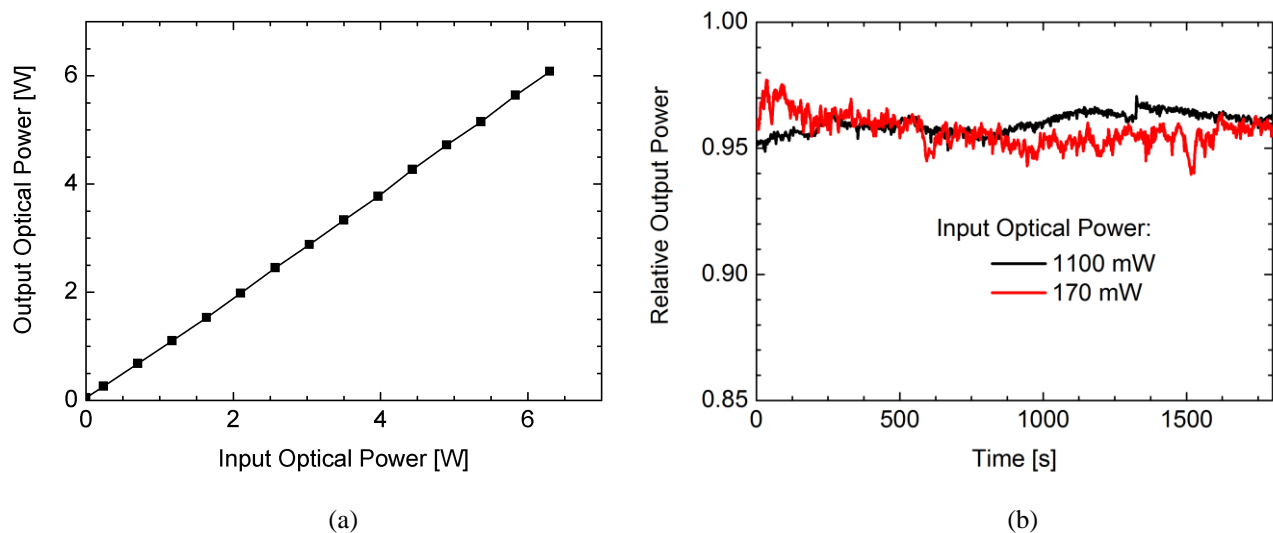


Figure 3. (a) Optical power transmitted through the multi-mode PG optical fiber for the CW Ytterbium-doped fiber ring laser at $1.08 \mu\text{m}$. (b) Stability of the optical power transmitted through the multi-mode optical fiber for the CW Ytterbium fiber laser at $1.06 \mu\text{m}$. Note that the measured time variations are within the stability limits of the used optical power meters.

The tests with the pulsed laser started with the evaluation of the laser induced damage threshold (LIDT) of the all-silica-fiber pigtail using a 19 μm spot size made by expanding the beam two times in diameter by a variable beam expander. A non-linear regression at a fluence of $1.5 \times 10^{-8} \text{ J}/\mu\text{m}^2$ (at an average power of 380 mW and a peak power of 2.4 MW) was obtained, which is an indication of the LIDT value of the silica fiber. The latter resulted to be comparable with other LIDT values reported in literature for bulk silica materials and silica-based optical fibers under ps-pulsed laser light illumination at 1064 nm, where a damage threshold fluence of $\sim 3 \times 10^{-8} \text{ J}/\mu\text{m}^2$ and 1-4.5 MW of self-focusing limit were reported.^{23, 24} The damaged 105/125 μm fiber input end-face after two successive tests with a 19 μm spot size beam is reported in Fig. 4a. No damage was observed for the 38 μm spot focus size within the applied laser power levels (Fig. 4b). In addition, the input fiber end-face was placed slightly out of focus so that the spot size on the fiber end-face was even larger. The defocusing was done at the expense of a lower coupling efficiency, which is estimated to be $> 80\%$. The measurement of the pulsed laser transmission through the PG fiber is shown in Fig. 4c. The slope of the linear part of the curve is 76%, while the attenuation of the 2-cm long PG fiber at 532 nm is about 7% (17 dB/m).¹⁰ Two distinct damage points denoted as A and B can be observed. While the point A designates the transmission curve roll-off, the point B indicates the breakdown of the fiber (see Fig. 5). The damage is attributed to the Kerr-lens self-focusing effect in the PG fiber constituent materials at an input peak power level of about 4 MW. It should be noted that the pulse width was broadened and the peak power inside the PG fiber was lower than the input peak power as a consequence of the dispersion of the 1 m-long multi-mode fiber pigtail. We shall conclude that the self-focusing damage threshold exhibited by the PG fiber is comparable with the self-focusing limit typically observed for bulk silica materials under pulsed laser light illumination at 1064 nm, where self-focusing damage was reported at a peak power of 4.5 MW for a similar beam diameter.^{23, 24}

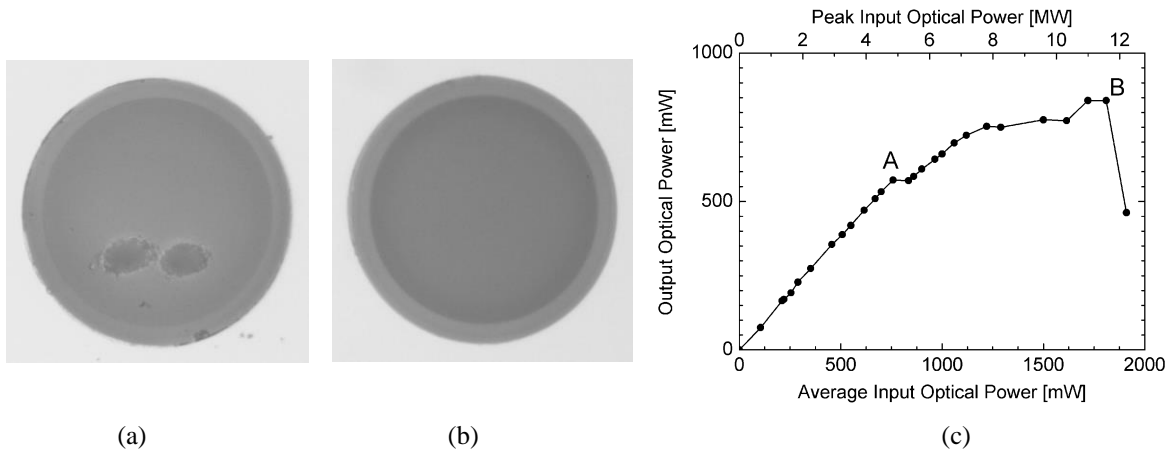


Fig. 4. Microscope photographs of the input fiber connector with the 105/125 μm multimode silica-based fiber: (a) connector damage when using a test beam with a spot size of 19 μm ; (b) the connector after tests with a beam featured by a spot size of 38 μm . (c) Optical power transmitted through the multimode PG optical fiber for the pulsed laser system at 532 nm. The beginning of damage of the fiber is marked as A, while the detrimental break is marked as B.

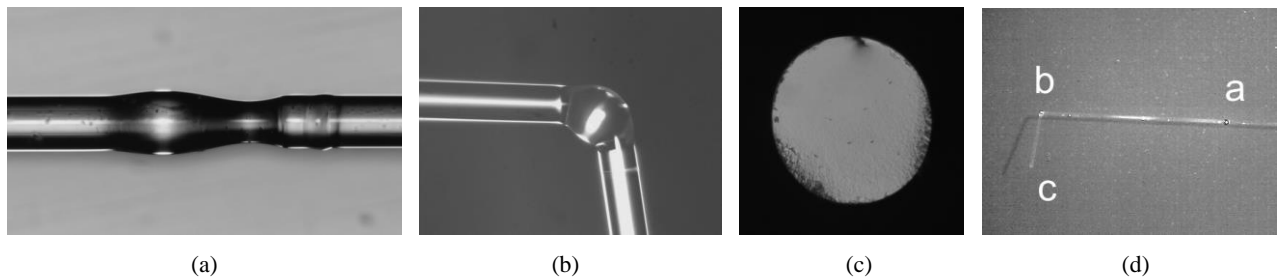


Figure 5. Microscope photos of the PG fiber after the pulsed-laser tests: (a) damaged splice joint between the PG fiber (left) and the silica-based 105/125 multimode fiber (right), (b) the detrimental break of the PG fiber at about 3 mm apart from the fiber end-face, (c) output end-face of the PG fiber. (d) Positions of the respective detailed photos within the fiber under test.

4. CONCLUSIONS

In conclusion, high-power laser tests performed on a multi-mode bioresorbable PG-based optical fiber were reported for the first time. The optical fiber withstood without changes exposition to CW fiber lasers at around 1 μm and 7 W of incident optical power. In the case of ultrashort pulsed regime, the LIDT value was assessed and resulted to be comparable to the respective value in silica fibers. Reported tests indicate that the developed bioresorbable fiber is suitable for high-power laser therapeutic applications in both CW and pulsed operation.

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