

Measurement of high photodarkening resistance in heavily Yb³⁺-doped phosphate fibres

Y.W. Lee, S. Sinha, M.J.F. Digonnet, R.L. Byer and S. Jiang

The measurement of record-high photodarkening resistance in single-mode phosphate fibres doped with 12 and 6 wt.% Yb₂O₃ is reported. After pumping for 10 000 min at a high population inversion (~47%), the fibre exhibited no photodarkening at 660 nm. Silica fibres pumped to the same inversion did show photodarkening, indicating that the phosphate fibre can be doped with at least six times as much Yb and still show no photodarkening.

Introduction: In recent years, the output power from Yb³⁺-doped fibre lasers and amplifiers has been scaled to well above the kilowatt level. One approach for further power scaling these light sources is to increase the Yb³⁺ concentration to reduce the required fibre length and avoid nonlinear effects. However, pumping Yb³⁺-doped silica fibre with high concentrations can result in excess loss at the pump and signal wavelengths owing to photodarkening, which can significantly reduce the overall conversion efficiency and degrade the long-term performance and reliability of the fibre source [1, 2]. In recent months, photodarkening has been actively studied in Yb³⁺-doped silica fibres [1, 3, 4] and the basic mechanism is now fairly well understood. Photodarkening occurs in two steps [4]. First, energy transfer between inverted Yb ions excites one ion to a high-energy virtual level, from which a UV photon is emitted. This UV radiation then photoionises existing precursors in the fibre host material and generates free holes and electrons, which are trapped at defects in the glass matrix and form colour centres that absorb at visible and NIR wavelengths. Phosphate glass is expected to be more resistant to photodarkening than silica for several reasons. First, the solubility of rare-earth oxides in phosphates is much higher [5], which postpones the formation of clusters that are more prone to energy transfer. Secondly, rare-earth-doped phosphate glasses have a higher resistance to UV-induced photodarkening than rare-earth-doped silicates [6].

In this Letter, we present the first experimental evidence that, even under intense and prolonged pumping, a heavily Yb³⁺-doped phosphate fibre (12 wt.% Yb₂O₃) has a much higher resistance to IR-induced photodarkening than silica fibres. To the best of our knowledge, it can support Yb³⁺ doping levels at least six times higher than the best commercial silica fibres to date without the onset of photodarkening.

Experimental results: We measured the photodarkening resistance to IR-induced photodarkening of two singlemode Yb³⁺-doped phosphate fibres as well as three highly Yb³⁺-doped silica fibres. The relevant properties of these fibres are listed in Table 1. The singlemode phosphate fibres (fibres A and B) were fabricated by NP Photonics. Their cores were doped with 12 and 6 wt.% of Yb₂O₃, respectively. Their cores and claddings were made of alkaline-earth phosphate glasses with a high Al₂O₃ content (~5% mole) to ensure high mechanical strength and good chemical durability. Alkali, Fe and Cu ions were also eliminated to further enhance the glass properties. Fibre C was a commercial silica fibre fabricated by the MCVD technique and doped relatively lightly (~0.36 wt.% Yb₂O₃). Fibre D was manufactured by direct nanoparticle deposition (DND), which shows superiority over traditional processes in mitigating photodarkening [1]. Fibre E was heavily doped with aluminium and exhibits one of the highest Yb³⁺ concentrations of low photodarkening silica fibres reported to date [4].

A measurement method providing a worst-case test of photodarkening in silica fibres has been proposed by Koponen *et al.* [1]. It uses a visible laser to probe the transmission of the core-pumped active fibre under test over an extended period of time (tens of minutes to hours). Unlike tests that monitor the output power degradation of a fibre laser, in which the population level is typically clamped at a low value, this test allows evaluation of photodarkening under the condition of high population inversion that prevails in fibre amplifiers that are not highly saturated. Because higher inversions exacerbate photodarkening [3], this test provides a more stringent evaluation of photodarkening resistance.

Since the probe wavelength must fall within the absorption band induced by photodarkening in our phosphate fibres, which was unknown at the outset, the first step was to measure the photodarkening-induced absorption spectrum. To this end, we compared the optical

absorption of phosphate glass samples measured before and after UV irradiation. This measurement was performed with a UV-VIS-NIR spectrophotometer in phosphate glass samples with the same Yb³⁺ concentrations and chemical composition as the phosphate fibre cores. Fig. 1 shows the photodarkening-induced excess loss spectrum after a 2 min irradiation from a 266 nm, 10 ns, 10 Hz, Q-switched laser with a pulse fluence of 0.552 J/cm². UV irradiation induces colour centres in the Yb³⁺-doped phosphate glass with an absorption peak at 490 nm and a tail that extends to the NIR (>900 nm). Based on this result, a 660 nm probe laser was used for all our photodarkening measurements, as this wavelength falls well within the absorption band of photodarkening-induced colour-centres of both phosphates (see Fig. 1) and silica [1, 3, 4].

Table 1: Experimental parameters of silica and phosphate fibre samples

Fibre	A	B	C	D	E
Material	Phosphate	Phosphate	Silica (MCVD)	Silica (DND)	Al-doped silica
Core diameter (μm)	5	5	6	4	4
Yb ³⁺ concentration (ions/m ³)	1.42 × 10 ²⁷	7.10 × 10 ²⁶	2.55 × 10 ²⁵	1.20 × 10 ²⁶	2.50 × 10 ²⁶
Small-signal core absorption at 976 nm (dB/m)	9032	4516	250	1200	2450
Fibre length (cm)	1.5	3.1	56	11	5.7
Average population inversion (%)	49	48.9	46.4	46.3	45.3
Manufacturer	NP photonics	NP photonics	Nufern	Liekki	CorActive

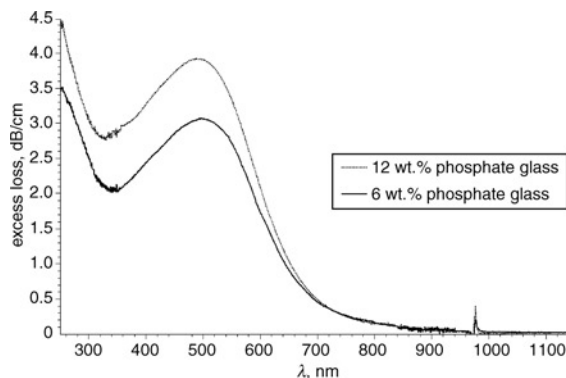


Fig. 1 Excess loss induced by 266 nm irradiation in 12 and 6 wt.% Yb³⁺-doped bulk phosphate glass. Photodarkening induced excess loss at 660 nm is ~16 dB higher than excess loss at 1064 nm

The photodarkening measurement setup is shown in Fig. 2. The Yb³⁺-doped fibres under test were core-pumped with a 400 mW 976 nm fibre-pigtailed laser diode. The probe laser was also coupled into the fibre through a WDM fibre coupler to periodically measure the photodarkening-induced fibre loss. The length of each fibre sample and the pump power were chosen to provide 140 dB of small-signal absorption at 976 nm, so that these fibres had approximately uniform population inversions along their lengths (see Table 1), and about the same average population inversion (~47 ± 2%). All test fibres were spliced to the WDM fibre pigtail except for fibre A, which was butt-coupled instead. To eliminate back-reflections from the junction and to stabilise the junction mechanically, a drop of index matching gel was applied to it.

Fig. 3 shows the normalised 660 nm transmission of these fibre samples measured as a function of exposure time. Even after pumping for over 10 000 min, no sign of photodarkening was observed in the phosphate fibres (fibres A and B). In contrast, we found that fibre C had a small degradation (~4%) in the 660 nm transmission, although its Yb³⁺ concentration was 56 times lower than that of the phosphate fibre. The measured transmission of fibre D dropped rapidly, indicating

significant photodarkening. It decayed by 3 dB in only 12 min, eventually reaching a transmission plateau as low as 30% (5 dB). This photodarkening behaviour is similar to that reported for the same fibre in [1]. Fibre E performed better than the other two silica fibres because of its higher Al concentration, as expected from another report [4]. However, unlike the phosphate fibre, it did exhibit a gradual decay in transmission of 20% in 12 h.

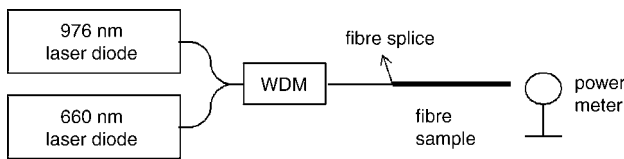


Fig. 2 Experimental setup of photodarkening measurement

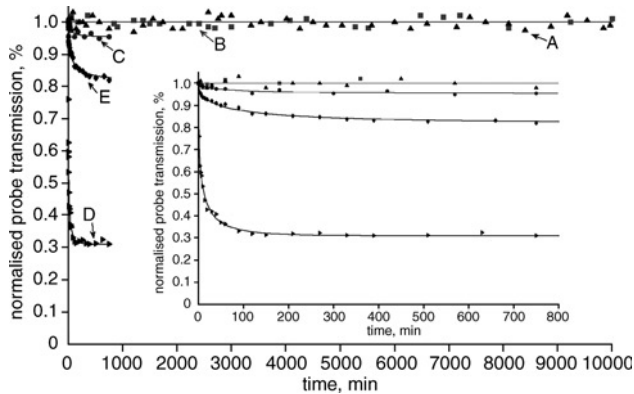


Fig. 3 Measured normalised transmission of fibres at 660 nm against pump exposure time

Fibre A: phosphate fibre doped with $1.42 \times 10^{27} \text{ Yb}^{3+}/\text{m}^3$
 Fibre B: phosphate fibre doped with $7.1 \times 10^{26} \text{ Yb}^{3+}/\text{m}^3$
 Fibre C: silica fibre doped with $2.55 \times 10^{25} \text{ Yb}^{3+}/\text{m}^3$
 Fibre D: silica fibre doped with $1.2 \times 10^{26} \text{ Yb}^{3+}/\text{m}^3$
 Fibre E: Al-doped silica fibre doped with $2.5 \times 10^{26} \text{ Yb}^{3+}/\text{m}^3$
 Exponential fit to experimental data is shown for each curve
 Inset: same four curves with enlarged time scale

This set of measurements shows that the maximum Yb^{3+} concentration allowed in the phosphate fibre before the onset of photodarkening at 660 nm is at least 56 times higher than a standard commercial silica fibre and six times higher than a highly Al-doped silica fibre. Although the excess loss is significantly larger at 660 nm than at the pump and signal wavelengths of Yb^{3+} -doped amplifiers and some fibre lasers do not operate at such high population inversions, this study confirms that phosphate glass is significantly more resistant to IR-induced photodarkening than silica, which puts phosphate glass fibre at an advantage for high-power applications. Since the SBS gain

coefficient of silica fibres is twice as large as that of phosphate fibres [7] and the peak absorption cross-section of Yb^{3+} -doped silica fibres is about 1.5 times higher than that of phosphate fibres, everything else being the same, the maximum achievable output power from a single-frequency phosphate fibre source is expected to be at least eight times higher than from a silica fibre source.

Conclusions: The first measurement of photodarkening resistance of Yb^{3+} -doped phosphate fibres shows no sign of photodarkening at 660 nm after 10 000 min of exposure to a 975 nm pump, despite the high average population inversion along the fibre (~47%). This phosphate fibre can be doped with at least six times higher Yb^{3+} concentration than highly Al-doped silica fibres without the onset of photodarkening.

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