Tandem-pumped ytterbium-doped aluminosilicate fiber amplifier with low quantum defect

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Abstract: We show theoretically that a quantum-defect below 1% is possible in tandem-pumped Yb-doped aluminosilicate fibers operating off the gain peak. Experimentally, we reach a quantum defect of 2% and a slope efficiency of 90% or more.
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The fiber geometry offers superb resilience to thermal distortions of the beam profile in lasers and amplifiers, which opens up for high-power single-mode operation. In Yb-doped fibers (YDFs) this is further helped by the low level of quantum defect (QD) heating, as a result of the small energy difference (i.e., QD) between pump and signal photons [1]. Even YDFs, however, are now reaching power levels where thermal distortions become an issue, and tandem-pumping [2] is therefore used at the highest powers [3]. In this case tandem-pumping employs intermediate YDF lasers (YDFLs) emitting at a wavelength somewhere between that of the pump diodes (e.g., ~980 nm) and the final emission wavelength (e.g., 1060 nm). We have analyzed the potential for low QD theoretically [4] and present here also experimental data on a highly-efficient aluminosilicate-host YDF at room temperature. Theoretically we have found that a QD as low as 1% is achievable, which is an order of magnitude lower than in conventional directly diode-pumped high-power YDFLs. Experimentally, we have achieved slope efficiencies of > 90% at a QD of 2%. The pump wavelength was 1020 nm and the signal wavelength was 1040 nm.

Figure 1 shows theoretical gain spectra of an aluminosilicate YDF for different average Yb excitation levels, based on experimentally determined absorption and emission cross-section spectra. Here, and throughout, we assume that the gain is purely homogeneously broadened. The peak gain is scaled to 30 dB, which we take to be the highest gain that can be readily managed. The figure further shows signal wavelengths resulting in 25 dB and 10 dB gain, as well as pump wavelengths resulting in 10 and 40 dB operating absorption, for an excitation level of 7%. The QD is given by the wavelength separation, which becomes smaller for smaller signal gain and smaller pump absorption. A pump absorption of 10 dB (i.e., 90%) may be considered minimum for efficient operation whereas 40 dB is excessive. However, with cladding-pumping the pump absorption decreases approximately in inverse proportion to the inner-cladding-to-core area ratio, so the 40 dB absorption may allow for an area ratio of 4. The smallest QD can be achieved when the pump beam quality is sufficient for core-pumping (i.e., for unity area ratio).

The procedure shown in Fig. 1 for 7% excitation can be repeated for other excitation levels. Accordingly, Fig. 2 shows longest possible pump and shortest possible signal wavelength for different levels of gain and absorption *vs.* excitation level. The QD is given by the wavelength difference, and can be below 1%. In case of core-pumping, pumping around 1020 nm looks attractive, although up to 1040 nm seems good, too, at least for gain up to 20 dB.

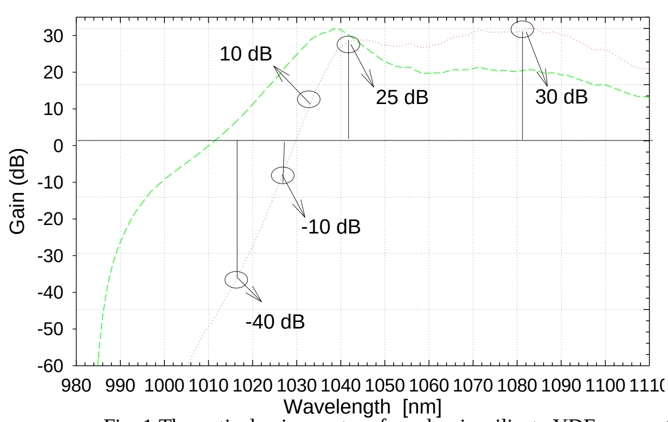

Fig. 1 Theoretical gain spectra of an aluminosilicate YDF for 7% (red) and 20% (green) Yb excitation levels. The vertical lines indicate the wavelengths for different levels of pump absorption and signal gain for the 7% case.

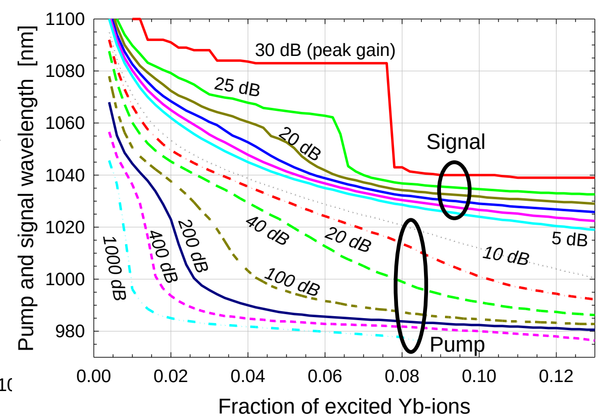

Fig. 2. Longest possible pump wavelength and shortest possible signal wavelength *vs.* fraction of excited Yb-ions at 30 dB of peak gain, for 5, 10, 15, 20, 25, and 30 dB of signal gain and 10 – 1000 dB of operating core pump absorption.

For experimental investigations of the achievable QD we used a simple YDF amplifier configuration, in which an aluminosilicate YDF is core-pumped by a YDFL tunable from ~1020 nm to 1060 nm and seeded by another YDFL tunable from 1038 nm to 1098 nm with around 100 mW of output power. The pump and seed waves are combined in a 1020 / 1060 nm wavelength division multiplexer and then launched together into a 1% tap coupler for monitoring, and finally, via the 99% port into the YDF. See Fig. 3. All fibers are fusion-spliced together. The 0.68 m long YDF was fabricated in-house using an in-situ technique [5]. It is double-clad, with approximately 10 µm core and 120 µm inner-cladding diameter. It also has a waveguiding raised-index pedestal surrounding the core but the pump and signals are launched (mostly) into the core. The absorption was measured at negligible power to 8.1 dB/m at the absorption peak (~ 975 nm) for light filling all three waveguides of a 1.2 m long fiber. From this, we estimate the concentration of Yb^{3+}-ions to 1.2×10^{26} m^{-3}.

The shortest pump wavelength, 1020 nm, was found to work best and allowed for efficient amplification by 10 – 15 dB at signal wavelengths down to 1040 nm, (Fig. 3). The QD is then as low as 2%. Slope efficiencies between 95% and 96% were recorded with these wavelengths, with respect to absorbed pump power. These are very high efficiencies, but similar values have been reported in the literature. However the uncertainty of at least 5% is significant, and more careful measurements are needed in order to confirm slope efficiencies in excess of 90%. Furthermore the lowest achieved pump leakage was 30%, corresponding to ~5 dB absorption. This is considerably less than the 10 dB we would like. This, and the inability to operate efficiently with pump wavelengths longer than ~1020 nm, indicates that the fiber is under-length. We estimate that a fiber length of ~1.5 m would work better for a pump wavelength of 1020 nm, and even longer fibers should be used for longer pump wavelengths, as well as for cladding-pumping. A fiber of optimum length should be able to reach adequate pump absorption without compromising the QD.

A QD of 2% in principle allows for an ultralow thermal load. However, there are also other potential sources of heating, e.g., resulting from impurities or photo-darkening. Given the uncertainty in the slope efficiency measurement, the total heat load may well be closer to 10% than 2%. More precise optical measurements, or direct calorimetric measurements, are needed to determine the thermal load at the percent level.

In conclusion, we have shown that pumping of Yb-doped fibers with higher beam quality allows for a reduction of the quantum defect down to the percent level. This theoretical result, which relies on core-pumping and amplification on the short-wavelength side of the gain peak, is a substantial reduction from the 10% level typical for directly diode-pumped high-power YDFLs. Experimentally we reached a QD of 2%. Fortuitously, the best pump wavelength of around 1020 nm is reachable with high-power YDFLs, which suggests that tandem-pumping is the best architecture for this regime of operation.

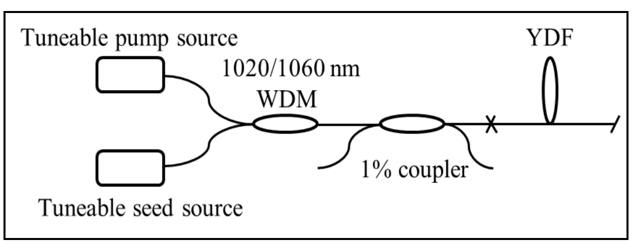

Fig. 3. Experimental setup for tandem-pumped aluminosilicate YDF. WDM: wavelength division multiplexer.

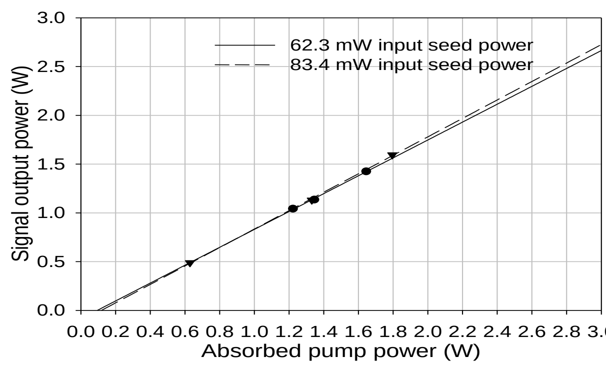

Fig. 4. Amplified output power at 1040 nm *vs*. absorbed pump power of YDF tandem-pumped at 1020 nm.

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