Design of a large-core Yb^{3+}:Al^{3+}:silica fibre and its manufacturing with granulated oxides

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Abstract

An Yb^{3+}:Al^{3+}:silica fibre with a small index step of $5.5 \cdot 10^{-4}$ between core and cladding is designed. The fibre is manufactured using granulated dry oxides in silica tubes. Absorption and scattering losses are measured. The designed index step could only be realized approximately. In transmission the fibre shows a granulated appearance that is explained by local variations of the refractive index. These index variations are due to insufficient dissolution or mixing of the different oxides in the glass matrix. Index variations leading to variations of the optical path length can exceed the designed index step and prevent the fibre core from guiding light.

Introduction

High power fibre lasers operated in single transversal mode are limited by their effective core diameter. As a rule of thumb 1 μm^2 of the core cross-section can guide few Watts of light. As an example 3 W/μm^2 corresponds to an intensity of 300 MW/cm^2. This is a typical intensity where nonlinear processes can play a role. These processes can eventually lead to damage in the fibre [1]. With an assumed limit of 3 W/μm^2 a core diameter of about 20 μm is required to guide a power of 1 kW. For a fibre with a core diameter of 20 μm the index step between core and cladding must be very small, in the range of $5.5 \cdot 10^{-4}$ for the fibre to be transversally single mode. The normalized frequency given by $V = \pi \cdot d_{core} \cdot \sqrt{n_{core}^2 - n_{cladding}^2} / \lambda$ must be smaller than 2.4048 for the fibre to be transversally single-mode. With λ = 1050 nm and d_{core} = 20 μm the square root that is the numerical aperture becomes 0.0402. For silica glass the respective index step becomes $5.5 \cdot 10^{-4}$. With a numerical aperture of 0.0402 the waist of the Gaussian beam becomes 8.3 μm nearly the same as the core radius.

It is, however, not trivial to dope the material with such a high precision to realize this index step. This is especially true if the fibre preforms are prepared by direct assembling silica tubes filled with granulated oxides [2]. For a very low dopant level the feasibility could be demonstrated [3]. With a number ratio of Yb^{3+} to Al^{3+} of 1:7 and concentrations of $\eta_{Yb_2O_3} = 2.93083 \cdot 10^{18}\ cm^{-3}$ and $\eta_{Al_2O_3} = 2.05158 \cdot 10^{19}$ cm^{-3} in an un-doped cladding single transversal mode resulted at a wavelength of 632.8 nm in a core of 9.47 μm diameter. The task is much more difficult if a high concentration such as for laser application is required in the core. Then the large index in the core must be compensated by an almost as large index in the cladding. It is not clear to what extent this can be performed with the technique of granulated oxides.

In this report we present the design and the manufacturing of a Yb^{3+} (0.7 at.%):Al^{3+} (4.9 at.%) silica fibre. The produced fibre is characterized with respect to scattering losses and pump-light absorption. The occurrence of index fluctuations due to incomplete mixture of the molten oxides is investigated.

The design of the fibre

It is the goal to produce a heavily Yb^{3+} doped fibre while maintaining the ratio of Yb^{3+} to Al^{3+} = 1:7 to allow for a good solubility and fluorescence efficiency of the rare earth. A concentration of 10 at.% Al^{3+} in the cladding is chosen. For a single-mode core of 20 µm diameter (@ λ = 1050 nm) this leads to the fibre design listed in Tab. 1:

Cladding	$n_{cladding}$ = 1.45951 @ λ=1050 nm [3]	
at.% Al	wt.% Al_2O_3	η_{Al} (Al-atoms density)
10	8.48537	$2.10706 \cdot 10^{21}$ cm^{-3}
Core	n_{core} = 1.460063 @ λ=1050 nm [3]	
at.% Al	wt.% Al_2O_3	η_{Al} (Al-atoms density)
4.96132	2.30156	$1.0536 \cdot 10^{21}$ cm^{-3}
at.% Yb	wt.% Yb_2O_3	η_{Yb} (Yb-atoms density)
0.70876	6.01407	$1.50515 \cdot 10^{20}$ cm^{-3}

Tab. 1: Dopant concentration of Yb^{3+} and Al^{3+} in the core and the cladding. at.% are given with respect to Si, wt.% are given with respect to SiO_2.

The resulting index profile is shown in Fig. 1:

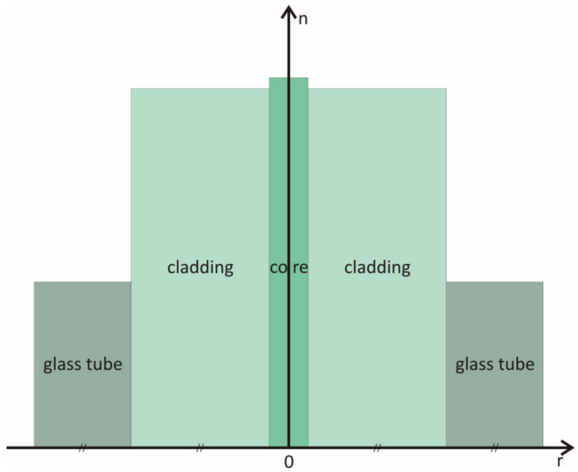

Fig. 1: *Index profile of the fibre with Δn (core-cladding) = $5.5\cdot 10^{-4}$ and Δn (cladding-SiO_2) = $9.64\cdot 10^{-3}$.*

With an index step of $9.64\cdot 10^{-3}$ between cladding (n_{cl}=1.45951) and silica (n_{SiO2}= 1.44987) the fibre is suitable for cladding pumping.

Manufacturing of the fibre

In a first step the future core is manufactured. A silica tube of 21 by 17.6 mm diameter is filled with granulated silica and the dopants given in Tab. 1. The filled tube is mounted in the drawing furnace. After evacuation and preheating to about 1400 °C for one hour, the tube is drawn to a fibre at a drawing temperature of 1850 °C.

A conical piece of fibre with a length of 20 cm and with a thickness of 0.9 to 3.55 mm from just behind the drop is prepared for future use. Since the index step between the core and the surrounding silica tube is far too big, the latter has to be removed. The undoped silica is removed by HF etching. This work was performed at the XLIM-Département Photonique, Faculté des Sciences et Techniques of Limoges university. The etched pure core material with 1.5 mm diameter is then placed in the centre of another silica tube of 21 by 17.6 mm diameter and the remaining space is filled with the cladding mixture (cf. Tab. 1). Again, as in the first manufacturing step, after evacuation and preheating the preform is drawn to a fibre of 150 to 210 µm diameter. The resulting core diameters range from 10.7 µm to 15 µm.

Fibre characterization

After the first drawing step the fibre material of the future core is tested with respect to Yb absorption and scattering losses. The experimental arrangement for this measurement is shown in Fig. 2:

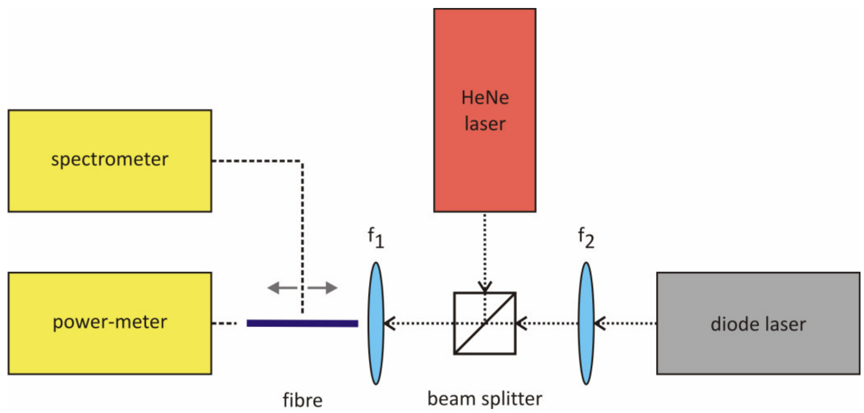

Fig. 2: *Experimental setup for the cutback measurement and the measurement of the absorption length.*

The fibre can be illuminated simultaneously with both, a 633 nm HeNe laser and a 960 nm diode laser. The fluorescence light at a wavelength of 978 nm is observed from the side of the fibre. This allows measuring the extinction in resonance with 960 nm pump-light. The result of the measurement is shown in Fig. 3:

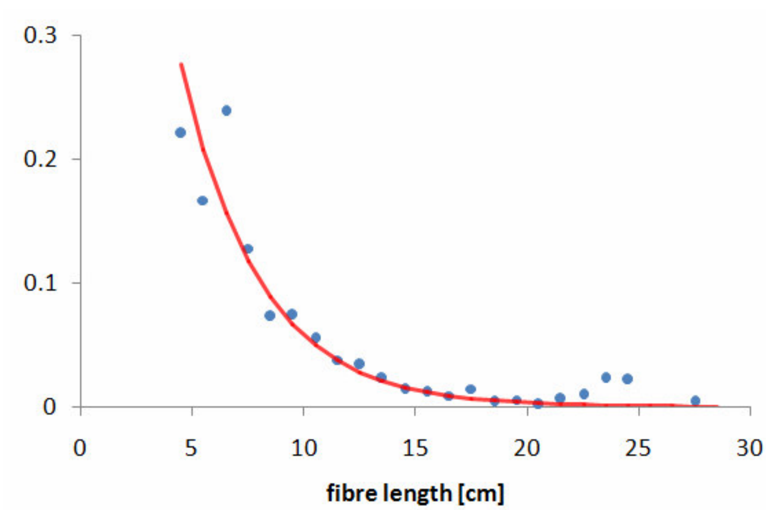

Fig. 3: Extinction in resonance with the 960 nm pump-line. The dots represent measured 978 nm intensity; the solid line is an exponential fit of the measured values.

The exponential fit of the measured values in Fig. 3 shows an extinction length in resonance of 3.5 cm. Scattering losses are determined by a cutback measurement at the HeNe wavelength of 633 nm where no absorption occurs. The result is shown in Fig. 4:

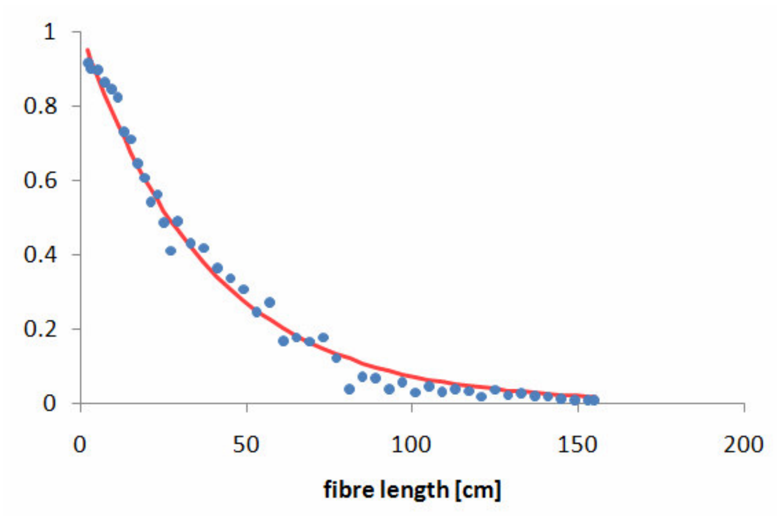

Fig. 4: Extinction due to scattering of light at 633 nm. The dots represent the measured intensity at the fibre output with respect to in-coupled intensity for different fibre lengths. The solid line represents an exponential fit with 38 cm extinction length.

Fig. 4 shows that the scattering losses can be fitted with an exponential of 38 cm extinction length. Assuming Rayleigh-like scattering with a λ^{-4} characteristic this corresponds to an extinction length of 2 m @ 960 nm and 2.88 m @ 1050 nm.

The absorption length combines from extinction length in resonance and scattering according to:

$$\frac{1}{L_{abs}} = \frac{1}{L_{ext}} - \frac{1}{L_{scatt}} \quad (1)$$

With L_{scatt} = 2 m and L_{ext} = 3.5 cm, a value for L_{abs} of 3.56 cm results. With a concentration of Yb^{3+} of $1.50515 \cdot 10^{20}$ cm^{-3} this leads to an absorption cross-section of σ_{abs} = $1.87 \cdot 10^{-21}$ cm^{-2}.

Properties of the waveguide

At 633 nm wavelength no guiding of light could be observed in the fibre. This phenomenon is explained by insufficient mixing of the glass components leading to a granulated structure of the refractive index across the fibre diameter (cf. Fig. 5).

The spatial homogeneity of the refractive index is one of the most important properties of optical glasses [4]. Reasons for inhomogeneities are discussed in [5]. Reference [5] also includes an ISO-classification of different types of inhomogeneities (schlieren, striae).

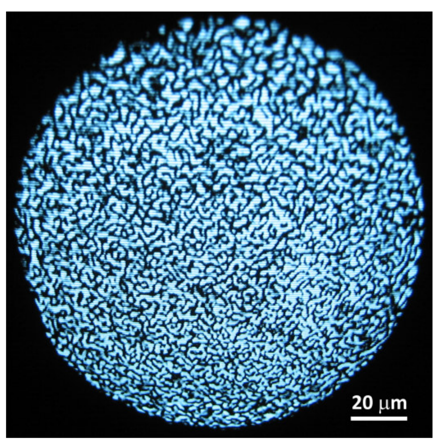

Fig. 5: Speckle pattern from a fibre of 150 µm diameter when illuminated from the rear end with a HeNe laser focused with a 20x microscope objective. The fibre length is 8 cm.

The small size of the speckles (speckles s. [6] and [7]) in the range of few µm suggests very large phase fluctuations. It is therefore interesting to analyze a much shorter sample. A plate of 1.1 mm thickness is cut from the drop, polished and analyzed interferometrically. Fig. 6 shows the interferogram between front and backside of the sample. The regular interference fringes at the left side are from the silica tube, the random speckle pattern originates from the granulated oxides.

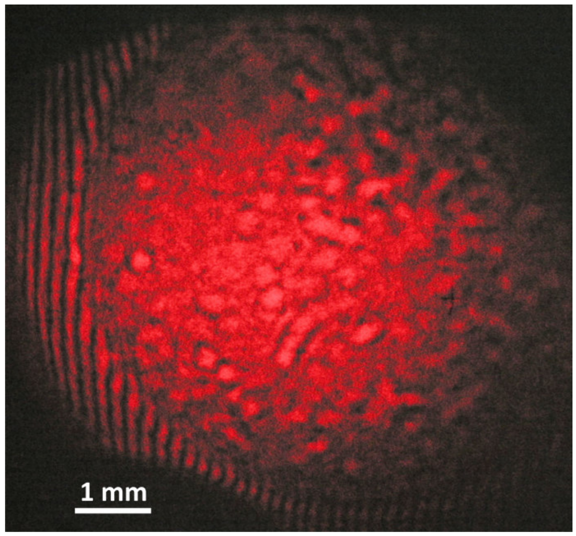

Fig. 6: Interferogram of a 1.1 mm thick sample with a homogeneous zone originating from the silica tube and a granulated zone originating from the vitrified oxide grains.

One fringe in Fig. 7 corresponds to a change in optical thickness of 633 nm. With respect to the optical path of n · 2.2 mm = 3.2 mm forth and back through the sample one fringe corresponds to a change in the optical path of about $2 \cdot 10^{-4}$. Assuming a perfect flat, this path difference corresponds to a variation of the refractive index. Path differences of only 3 wavelengths of the HeNe laser would already equal the designed index step of $5.5 \cdot 10^{-4}$. If we assume that variations of the optical path exceed 3 wavelengths, then an index step of $5.5 \cdot 10^{-4}$ can only approximately be realized with our technique.

To reduce the index fluctuations in the vitrified material oxides with smaller grains could be used. This, however, may lead to problems with evacuation and pre-heating of the preform. The finer the oxides the more challenging it will be to remove gas and humidity. The most promising technique is based on manufacturing the required mixture with sol-gel technique, to dry the material and to mill it to the desired grain size. Efforts to test these solutions are in progress.

Conclusion

In summary we have designed a Yb^{3+} (≈ 0.7 at.%):Al^{3+} (≈ 5 at.%):silica fibre with a small index step of $5.5 \cdot 10^{-4}$ between core and cladding. The fibre is manufactured using granulated dry oxides in silica tubes. Scattering losses with an extinction length of 38 cm @ 633 nm have been measured and the absorption length of 960 nm pump-light has been determined as 3.56 cm. In transmission the fibre shows a granulated appearance that is explained by local variations of the refractive index. The variation of the refractive index is also shown in the interferogram of a 1.1 mm thick sample. The index variations are due to insufficient dissolution or mixing of the different oxides in the glass matrix. Index variations leading to variations of the optical path length can exceed the designed index step and prevent the fibre core from guiding light.

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