Design and manufacturing of a large-core single-mode Yb^{3+}:Al^{3+}:silica fibre

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Abstract

A large-core Yb^{3+}:Al^{3+}:silica fibre is designed that should guide light of 633 nm wavelength in transversal single-mode with a core diameter of 20 μm (or 35 μm @ 1100 nm). Based on calculated dopant concentrations a preform is produced using the technique with granulated oxides. Fibres with different core diameters are tested with respect to their NA and the cutoff-core-diameter is estimated. The resulting diameter at the cut-off wavelength is only about 20% smaller than calculated, showing that the assumptions made on index enhancing by Al^{3+} and Yb^{3+} are appropriate.

Introduction

In the last years fibre lasers have proven the capability to reach output powers exceeding the kW level [1-3]. A possibly limiting factor is the occurrence of nonlinear effects or damage that will arise if the intensity in the core exceeds some 100 MW / cm^2 [4]. Therefore, in a standard step-index fibre, a large core diameter is necessary to reach high output power. For the fibre to remain transversal single-mode guiding a large core diameter requires a very small index step between core and cladding. Such a small index step requires a very precise dopant concentration. This is especially challenging when the novel technology for manufacturing preforms is used that is based on dry granulated oxides [5].

It is not clear if this technique is suitable to generate very small index differences in the order of 10^{-3} as it is necessary for a transversal single-mode fibre of e.g. 20 μm core diameter. The enhancement of the core index is often realized by co-doping of Germanium or Titanium. Aluminum co-doping is used to enhance the solubility of the rare earths and to avoid clustering. Since in a large-core fibre the index step is very small, co-doping of Aluminum is sufficient to provide for the required index step. With respect to the index enhancement due to co-doping of Aluminum and Ytterbium, only few data on the required concentration are found in literature.

In our letter we report on experiments on manufacturing a large-core fibre with a preform made from granulated oxides. The dopant concentration of the fibre is calculated and compared with literature data. The drawn fibre is tested with respect to its numerical aperture and guided modes with the goal to experimentally determine the effective index step.

Design of the fibre

The refractive index n due to the content of Al^{3+} is assumed to depend linearly from the concentration of Al_2O_3 in vol.% with respect to SiO_2 with refractive indices $n_{SiO_2} = 1.45711$ @ 633 nm [6] and $n_{Al_2O_3} = 1.7659$ @ 633 nm [7].

The same assumption holds for Yb_2O_3 with $n_{Yb_2O_3} = 1.942$ @ 633 nm as interpolated from data of [8].

With this assumption the refractive index of Al and Yb doped silica can be estimated as:

$$n(\eta_{Al_2O_3}, \eta_{Yb_2O_3}) \quad = \quad \frac{V_{SiO_2}}{V_{total}} n_{SiO_2} + \frac{V_{Al_2O_3}}{V_{total}} n_{Al_2O_3} + \frac{V_{Yb_2O_3}}{V_{total}} n_{Yb_2O_3} \tag{1}$$

with η, the molecule density (m^{-3}), and V, the volume of the respective compound (m^3).

Allowing for wavelength dependence and considering $V = N \cdot m / \rho$ with N, the number of molecules, m, the mass of a molecule and ρ, the density of the compound as well as $\eta_{SiO_2(Mixture)} = \eta_{SiO_2} - \eta_{Al_2O_3} - \eta_{Yb_2O_3}$, (1) can be written as:

$$\boxed{\begin{aligned} n(\eta_{Al}, \eta_{Yb}, \lambda) \quad = \quad & n_{SiO_2}(\lambda) + \frac{1}{2}\left(\frac{m_{Al_2O_3}}{\rho_{Al_2O_3}} n_{Al_2O_3}(\lambda) - \frac{m_{SiO_2}}{\rho_{SiO_2}} n_{SiO_2}(\lambda) \right) \eta_{Al} \\ & + \frac{1}{2}\left(\frac{m_{Yb_2O_3}}{\rho_{Yb_2O_3}} n_{Yb_2O_3}(\lambda) - \frac{m_{SiO_2}}{\rho_{SiO_2}} n_{SiO_2}(\lambda) \right) \eta_{Yb} \end{aligned}} \tag{2}$$

With Avogadro's number $N_0 = 6.02 \cdot 10^{23}$ mol^{-1} and the molecular weights of the compounds [7] the molecular masses and densities are:

	m [g]	ρ [g cm^{-3}]
SiO_2	$9.97652 \cdot 10^{-23}$ [7]	2.201 [6]
Al_2O_3	$1.69309 \cdot 10^{-22}$ [7]	3.97 [7]
Yb_2O_3	$6.54385 \cdot 10^{-22}$ [7]	9.17 [7]

Fig. 1 shows an evaluation of (2) in the range of 0 to 0.1 at. % of Al_2O_3 and Yb_2O_3.

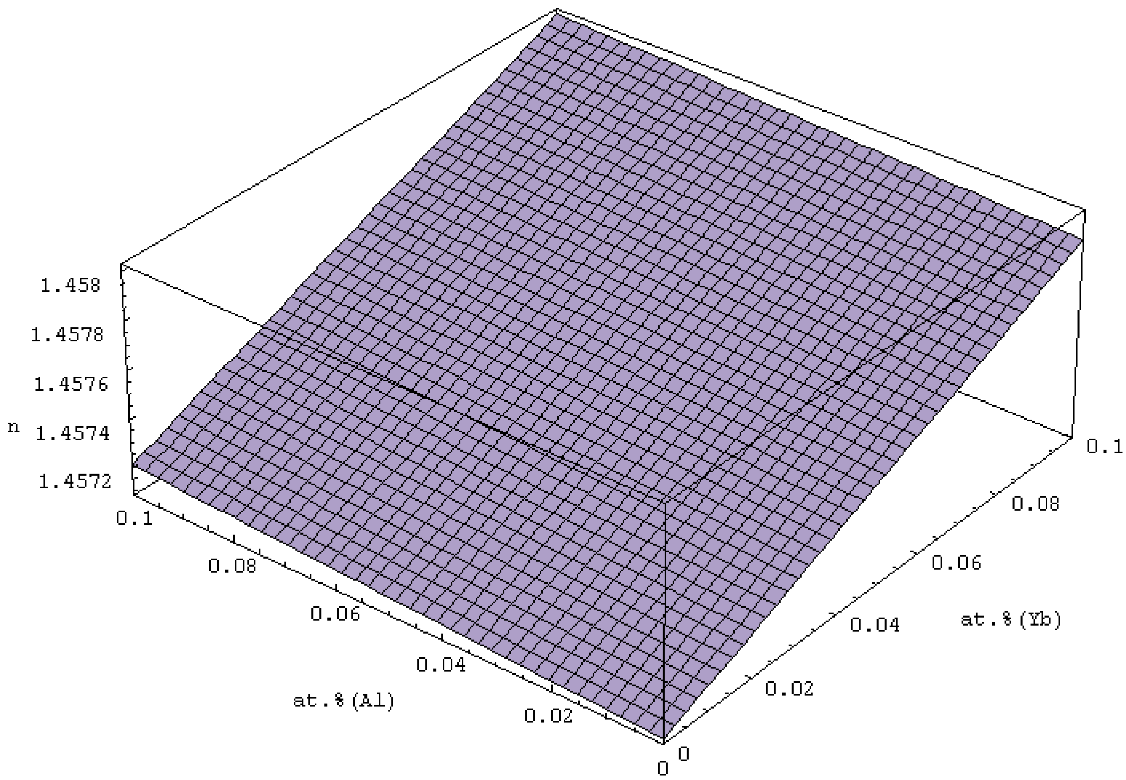

Fig. 1: Refractive index @ 633 nm as a function of the Al^{3+} and Yb^{3+} concentrations (at.% with respect to Si)

The values resulting from (2) have to be compared with literature. The effect of Al-doping is described by Murata [9]. In [9] a SiO_2 refractive index of 1.458 is used. This corresponds to a wavelength close to 633 nm. The values given in [9] perfectly correspond with (2) within 0.1 %.

For transversal single-mode guiding the normalized frequency has to be:

$$V = \frac{\pi d_{core} NA}{\lambda} \leq 2.4048 \tag{3}$$

This requires a numerical aperture NA of 0.02423 for a fibre with a core of 20 μm diameter and a cut-off at 633 nm.

Since

$$NA = \sqrt{n^2_{core} - n^2_{cladding}} \tag{4}$$

the difference between n_{core} and $n_{cladding}$ Δn is 0.0002.

With a number ratio of Yb^{3+} to Al^{3+} of 1:7 concentrations of $\eta_{Yb_2O_3} = 2.93083 \cdot 10^{18}\ cm^{-3}$ and $\eta_{Al_2O_3} = 2.05158 \cdot 10^{19}\ cm^{-3}$ result.

Experimental

A mixture of granulated SiO_2 (120 g), Yb_2O_3 (52.31 mg) and Al_2O_3 (94.74 mg) is prepared. All weights are with an error of 10 μg. A silica tube of 5 mm by 3 mm diameter is filled with about 2 cm^3 of this mixture. The filled tube is inserted into the centre of a larger silica tube of 19 mm by 16 mm diameter. Empty space is filled with granulated SiO_2. This preform is evacuated and drawn to a fibre at a drawing temperature of about 1850 °C. Drawn fibres with different diameter are characterized.

In a first experiment a conical length of the fibre with diameters of 3.4 mm / 2.8 mm is irradiated with the unfocused beam of a He-Ne laser. The doped core region shows strong scattering (Fig. 2). This suggests that vitrification in the central part of the fibre is insufficient.

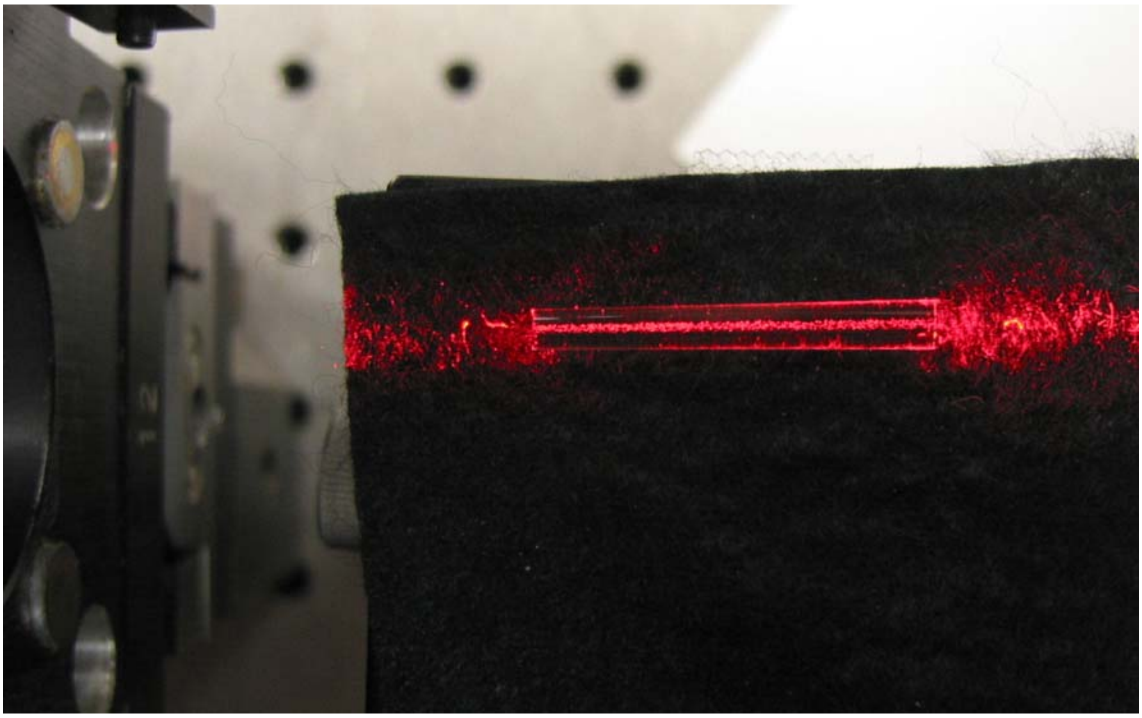

Fig. 2: Scattering of a He-Ne laser beam in the centre of the fibre

In a second experiment fibres of about 10 cm length and diameters of 125 μm, 100 μm and 60 μm are irradiated with a He-Ne laser beam focused with a 20x microscope objective.

The fibres are placed on a metal table allowing the rear end to be slightly bent by gravity. This allows separating transmitted light in the fibre from scattered light of the He-Ne laser. Imperfect separation is responsible for the bright light in the upper part of Figs. 3a and 3c. Light guided in the cladding is coupled out with index matching oil of n = 1.46. The existence of the cores is verified with a microscope equipped with a CCD camera focused to the end of the fibres. The numerical aperture is determined by measuring the spot radius of transmitted light on a screen (Fig. 3).

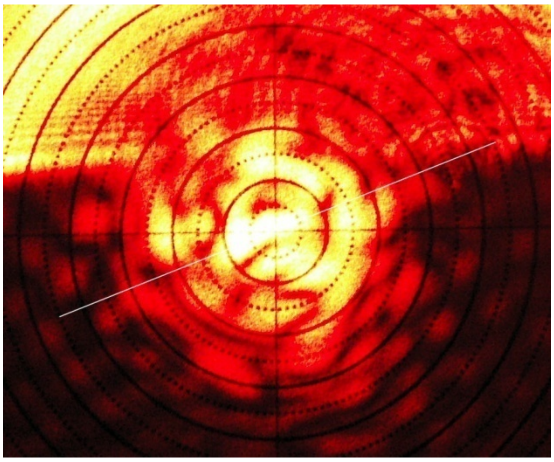

Fig. 3a: Fibre with 125 μm diameter. Spot size with a radius of 2.1 cm on a screen in a distance of 80 cm. The fibre is clearly multimode.

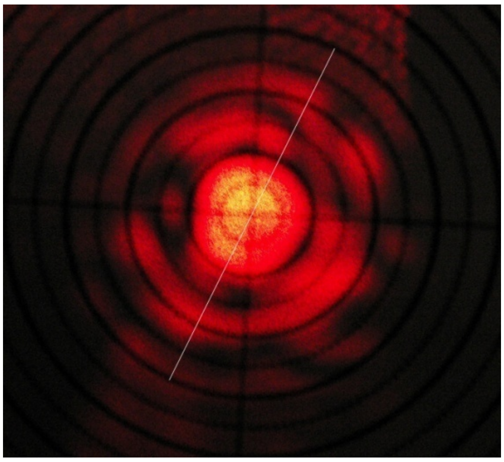

Fig. 3b: Fibre with 100 μm diameter. Spot size with a radius of 0.9 cm on a screen in a distance of 50 cm. The fibre is close to single-mode.

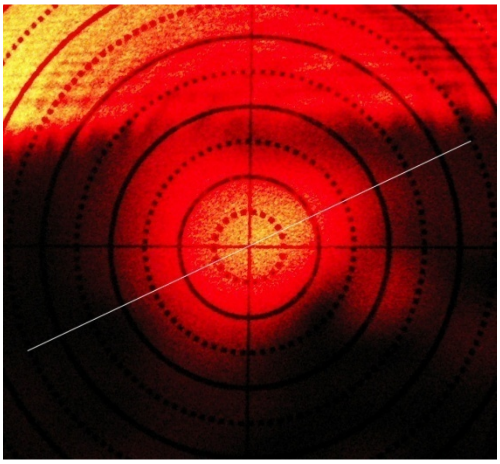

Fig. 3c: Fibre with 60 μm diameter. Spot size with a radius of 1 cm on a screen in a distance of 40 cm. The fibre is single-mode.

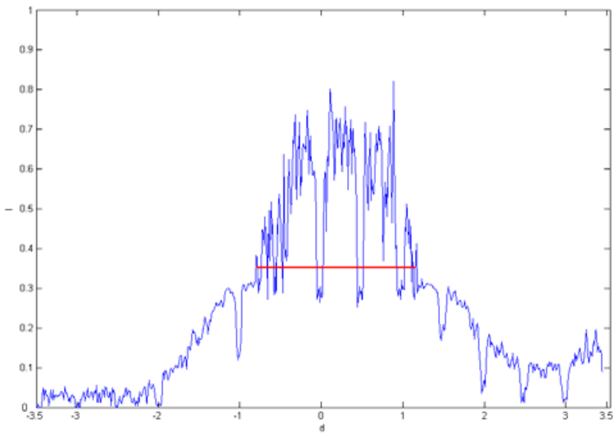

Fig. 3d: Intensity distribution across the spot of Fig. 3c with the spot diameter at FWHM

The results are summarized in Tab.1.

fibre diameter	core diameter	NA	Δn	transversal modes
125 μm	19.74 μm	0.027	0.00024	multi-mode
100 μm	15.79 μm	0.018	0.00010	close to single-mode
60 μm	9.47 μm	0.025	0.00021	single-mode

Tab. 1: Estimated NA and resulting index steps of the tested fibres

The results in Tab. 1 show that the required NA of 0.02423 is reached within +12 % and -26 %. Also the diameter leading to single-mode @ 633 nm is reached with an error of about 20 %.

Possible errors are:

- Possible index difference between fused SiO_2 powder and SiO_2 tube.
- No important error is expected from the purity of the used compounds. The purity of Al_2O_3 is 99.998 % and that of Yb_2O_3 is 99.99 %.
- Also but marginal errors arise from the preparation of the granulated oxide mixture. Weighing of the mixture of granulated SiO_2 (120 g), Yb_2O_3 (52.31 mg) and Al_2O_3 (94.74 mg) was performed with an error of 0.01 mg.
- Local variations due to the distribution of the oxide grains in the drawn fibre. The size of Al_2O_3 grains as well as the SiO_2 grains reaches up to about 0.5 mm. This prevents a perfect mixture of the oxides before fusion.

Conclusion

A large-core Yb^{3+}:Al^{3+}:silica fibre has been designed that should guide light of 633 nm wavelength in transversal single-mode. Based on the calculated dopant concentrations a preform was produced using the technique with granulated oxides. Fibres with different core diameter have been tested with respect to their NA and the cut-off core-diameter was estimated. The resulting diameter at the cut-off wavelength is only about 20% smaller than the calculated diameter, showing that the assumptions made on index enhancing by Al^{3+} and Yb^{3+} were appropriate. Variations in the refractive index are assigned to the large size of the SiO_2 and Al_2O_3 grains preventing a homogeneous mixture.

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