

Atomic Layer Deposition as a New Method for Rare-Earth Doping of Optical Fibers

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Abstract: A new method enabling engineering of gain materials at an atomic-scale level is for the first time applied to manufacturing of rare-earth doped optical fibers.

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1. Introduction

Fabrication of advanced optical fibers for lasers and amplifiers requires a doping method enabling highly controllable distribution of rare earth (RE) dopants in the glass. Today, the two major techniques at disposal are liquid- and gas-phase doping of MCVD-preforms.

Liquid-phase doping is performed by coating the inside of the substrate tube with a porous silica layer (“soot preform”) that is impregnated with a solution of RE-ions, followed by drying, sintering, and collapse into a preform. This method is well proven, but rather time-consuming as it requires two MCVD-runs separated by a wet-chemical doping step. Furthermore, as the process starts with a two-phase system of silica-soot particles and crystallized RE-precursor, it is strongly reliant on solid-state diffusion to avoid RE-clustering.

Gas-phase doping is performed as a conventional MCVD-process by adding a gaseous RE-precursor to the reaction gas mixture during glass deposition. As this method adds no extra process steps, it is faster than liquid doping. Moreover, as all constituents are mixed in the gaseous state, this can possibly promote the doping uniformity in the final glass. However, the choice of RE-precursor is more or less restricted to metalorganics, which possess relatively low vapor pressures. Condensation in delivery pipes is therefore a risk of poor process control. Thermal decomposition or oxidation of reactants prior to the reaction zone may also deteriorate doping uniformity.

In this paper we introduce atomic layer deposition (ALD) as a new way of making RE-doped preforms. ALD can be described as a surface-controlled CVD process where the reactants are sequentially introduced to the substrate, enabling less-than-monolayer thickness control over large area substrates. This property has proved to be useful in e.g. production of thin-film large-area electroluminescent displays as well as in IC-industry for deposition of thin high- κ gate-oxides [1, 2]. Furthermore, ALD uniquely provides means for coating complex shapes such as high aspect-ratio holes, or even porous structures, where CVD or PVD methods would only clog the outer surface. This feature has been utilized in deposition of catalyst materials on 3-D carriers [3]. We use the same approach to coat the high-surface area particles of a silica-soot with an RE-oxide film, followed by fusing to govern diffusion of RE-ions into the glass. As typical doping levels are below 1 %, a sufficient amount of RE-oxide can be achieved within a reasonable time. Our idea is to combine the well-established soot-preform technology with the ability of ALD to produce uniform and well-controlled coatings over large areas, to make a fiber doped with Er and Al. Solehmainen et al. [4] used ALD to make Er-doped Al₂O₃ thin film ridge waveguides. They deposited pure Er-layers between Al₂O₃-layers at a substrate temperature of 400 °C. The excited life-time of only 0.9 ms did not enable sufficient inversion for net optical gain. It was proposed that the short lifetime was a consequence of locally high Er-concentration due to poor diffusion between the separate Er- and Al₂O₃-layers. In our study, however, the preform collapse is done at a temperature well above 2000 °C, which will greatly promote diffusion and create a homogeneous Er-distribution in the fiber core glass. We believe that careful selection of composition and sequence of the individual ALD-layers may also provide means to tailor the atomic short-range order in the final glass structure.

2. Fiber manufacturing

A porous SiO₂-layer doped with GeO₂ (~18 %) was deposited in a silica tube without inner cladding, using a commercial MCVD-system (Nextrom OFC12). The inner diameter of the substrate tube was 19 mm and the

thickness and porosity of the soot layer were 28 μm and 58 %, respectively. Sections of the preform were cut out and transferred to a separate ALD-reactor (ASM Microchemistry F-120). All ALD-depositions were performed at 1-3 torr and 300 °C. Er-doping was carried out by Er_2O_3 -coating of the soot using $\text{Er}(\text{thd})_3$ and O_3 as precursors. Al co-doping was done as Al_2O_3 deposition from $\text{Al}(\text{CH}_3)_3$ and H_2O . Test runs on three shorter preform sections followed by elemental analysis with ICP-AES, enabled calibration between the number of ALD-cycles and doping levels. The final coating experiment was carried out using four $\text{Er}(\text{thd})_3$ -cycles and ten $\text{Al}(\text{CH}_3)_3$ -cycles.

After the ALD-coating, the preform was re-mounted in MCVD and subjected to a standard recipe of repeated heating traverses in an oxygen and chlorine atmosphere. A section of the collapsed preform was cut out for Energy Dispersive Spectroscopy. Analysis over the whole doped core with 1.4-mm diameter showed $[\text{Er}] \approx 0.05\%$ and $[\text{Al}] \approx 0.7\%$, excluding oxygen from the total count of atoms. After refractive index profiling, stretching and sleeving of the preform were carried out before pulling a 125 μm fiber with 900 nm cut-off wavelength.

3. ALD-fiber characteristics

The ALD-fiber shows peak absorption of 6.4 dB/m and 6.8 dB/m at 980 nm and 1531 nm wavelength, respectively, corresponding to ${}^4I_{15/2} \rightarrow {}^4I_{11/2}$ and ${}^4I_{15/2} \rightarrow {}^4I_{13/2}$ erbium laser transitions. Scattering loss of the fiber is estimated to 0.018 dB/m (measured off-resonance at 1100 nm). Spectral photoluminescence (PL) dynamics was measured by pumping a 50-mm long fiber at 980 nm with modulated on/off laser diode. Exponential fitting of the PL decay dynamics gave an erbium excitation lifetime of 10.5 ms, showing no fast-decay component indicative of Er-upconversion effects.

The gain and noise figure measured in a 10-m long fiber that is co-pumped with 110 mW at 978 nm is shown in Fig.1. The fiber power conversion efficiency is 25 % when the input signal power is -8.3 dBm.

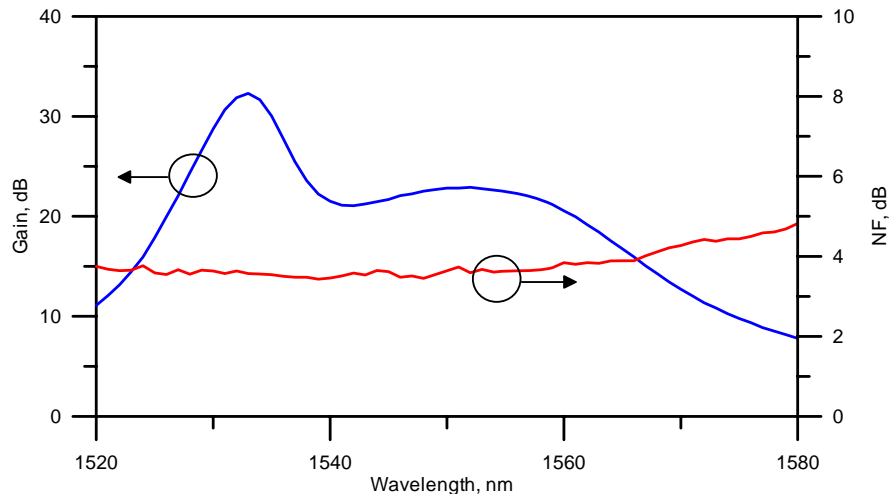


Fig. 1. Gain and noise figure of 10-m long ALD fiber pumped with 110 mW at 978 nm. Input signal power is -8.3 dBm at 1550 nm.

4. Conclusions

As a proof of principle, we used ALD as a new method to produce Er-doped fibers of commercial quality. More work is needed to evaluate the macroscopic doping-uniformity along the preform, possibly motivating an MCVD-ALD hybrid process from a yield point of view. Finally, although luminescence measurements did not reveal any fast-decay component indicative of erbium upconversion, more work with higher Er-concentrations is motivated as these factors normally are becoming very important and limit amplifier performance in highly doped fibers.

5. References

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