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## **Drawing optical fibers: elongating bubbles, breaking nanoparticles**

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**Summary:** Optical fibers are the basis for applications that have grown considerably in recent years (telecommunications, sensors, fiber lasers, etc). To fulfill the characteristics required for these applications, optical fibers are obtained by drawing high-purity silica-based preforms. This drawing step is usually assumed to be a homothetic transformation of the preform. However, at this stage, the glass is heated at temperature higher than its softening temperature. Then the glass flows which can induce the transformation of heterogeneities. In this presentation, we highlight the elongation of bubbles and even break up of oxide nanoparticles during the drawing process. These phenomena allow new route to prepare optical fibers with light transport induced by transverse Anderson localization of light or new amplifying properties.

**Keywords:** Optical fibers, Drawing, Nanoparticles, Bubbles.

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### **1. Introduction**

Optical fibers are now part of an everyday technology, usually associated with telecommunications and high-speed internet. Far from being confined to this single use, optical fibers are deployed in many fields of applications, such as lasers (for marking, machining, cutting, laser remote sensing (LIDAR), etc.) or sensors (civil engineering, gas and oil extraction and storage, temperature sensors, etc.).

These key applications rely on the qualities of silica glass: mechanical and chemical stability, high optical damage threshold, low cost, etc. To fulfill the characteristics required for these applications, many processes have been developed to prepare high purity silica-based preforms: MCVD (Modified Chemical Vapor Deposition), OVD (Outside Vapor Deposition), VAD (Vapor Axial Deposition), DND (Direct Nanoparticle Deposition), Rod-in-tube and powder in tube.

All these processes aim at preparing homogeneous preforms in the longitudinal direction in order to prepare many kilometers of fiber with constant opto-geometrical characteristics. Indeed, during the process of optical fiber fabrication, the drawing step could be considered as a homothetic transformation of the transverse section from the preform to the fiber: same ratio core diameter/external diameter and same refractive index profile. However, during the drawing step, the glass is heated above its softening temperature (typically 1650 °C for silica) and quenched within few seconds. This high quenching rate leads to residual stress which affect the refractive index profile. Structural modifications were also reported such as preferential orientation of small-sized silica rings [1].

During this presentation, we will discuss about the effects of the drawing step on the shape of the nanoparticles and bubbles.

### **2. Elongation and breakup of nanoparticles**

Rare-earth doped nanoparticles embedded in the core of optical fiber are proposed to overcome some limitations imposed by silica glass (high phonon energy, low solubility of rare-earth ions, ...) [2]. A route of interest consist of preparing nanoparticles in the preform. Then, to be able to prepare specified nanoparticles in the fiber, we have to understand their modifications during the drawing step.

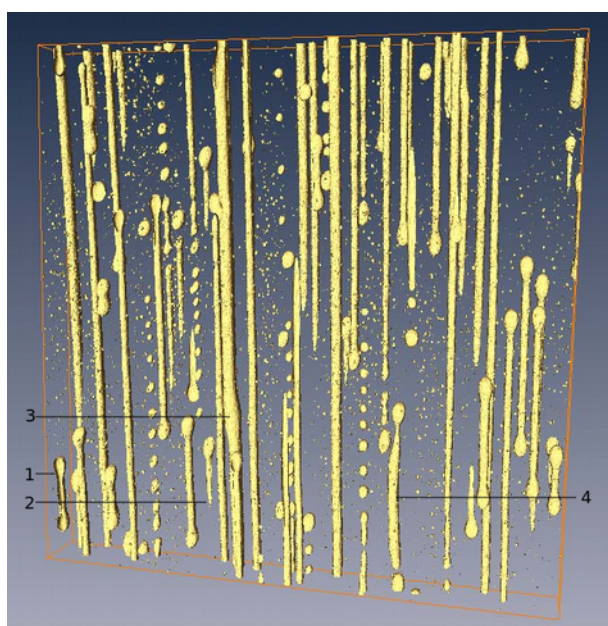
To investigate the role of the drawing step, an optical fiber containing La-rich silicate nanoparticles was etched with a Focus Ion Beam (FIB) to looking at a longitudinal section of the core with Scanning Electron Microscopy (SEM). Figure 1 is the volume reconstruction of the core obtained by using a FIB/SEM tomography [3]. Particles with radius smaller than 10 nm and glass matrix surrounding particles are not plotted in Figure 1. Particles can be sorted according to three sets: (i) nanoparticles with diameter in the 10-40 nm range which are almost spherical, (ii) larger particles with long axes ranging from 65 nm to 230 nm and (iii) highly elongated particles.

From rheology of emulsion and polymers, it is known that the deformation of particles is induced by the competition between the viscous stresses on particles and the surface tension. The study of the deformation is based on the capillary number ( $Ca$ ):

$$Ca = \frac{\sigma R}{\gamma} \quad , \quad (1)$$

where  $\gamma$  is the surface tension,  $\sigma$  the viscous stresses from the flow and  $R$  the radius of particles. It is reported that if  $Ca < Ca_c$  (critical capillary number), an ellipsoidal stationary shape exists, if  $Ca > Ca_c$  the particle elongates into a long cylinder until it breaks due to Rayleigh instabilities or until viscous stresses are decreased.

Based on this approach, we can interpret the sets of particles observed in Figure 1. Long elongated particles (cylinders) are present because the flow was not maintained long enough to initiate break up. It would need more deformation to reduce their diameters and to amplify the instabilities. When the amplitude of growing instabilities is comparable to the radius of the cylinder, cylinder can break up. It is evidenced by the presence of particles with the same size, periodically spaced and aligned in the direction of the flow (Figure 1). These newly formed particles and particles smaller than 40 nm can not break up (under this drawing conditions) because  $Ca < Ca_c$ . Then, the break up of initial large particles is restricted to a range of diameters. These phenomena clearly offer new possibilities for the control of the size and shape of particles. These observations are of a great interest for light scattering issues.



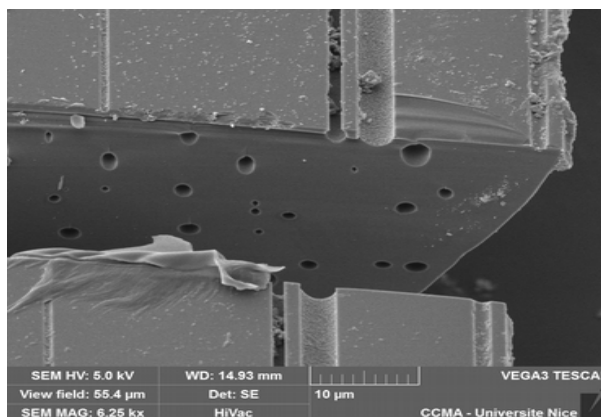
**Fig. 1.** Partial volume reconstruction of the core of the optical fiber imaged by FIB and SEM. The drawing direction is vertical. Width of the picture is 5  $\mu\text{m}$ .

### 3. Elongation of bubbles

In conventional optical fibers, light is guided in the core due to its higher refractive index compare to the one of the surrounding cladding. Recently, a new route to light transport was demonstrated and is based on transverse Anderson localization of light in an optical fibre with transverse refractive index fluctuations [4]. The Anderson localized fibre allowed for the simultaneous propagation of multiple beams in a single strand of disordered optical fibre with potential applications in optical, biological and medical imaging, and beam-multiplexed optical communications. A directional random laser mediated by transverse Anderson localization in a disordered glass optical fiber was reported also [5].

To obtain the transverse refractive index fluctuations, the starting preform was a ‘satin quartz’,

which is a porous artisan glass. The diameter of the final fiber is  $\sim 250 \mu\text{m}$  and the average air fill-fraction is about 5.5%. In the transverse section, the air-hole diameters varying between about 0.2 and 5.5  $\mu\text{m}$ . By polishing a longitudinal section of the fiber (Figure 2), the elongation of these air-holes over several millimeters was measured.



**Fig. 2.** SEM image of a fiber with elongated bubbles.

### 4. Conclusions

The drawing step is usually considered as a homothetic transformation from the preform to the fiber. However, the flow of the glass can be used to induce elongation of heterogeneities such as bubbles and even the break up of nanoparticles.

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