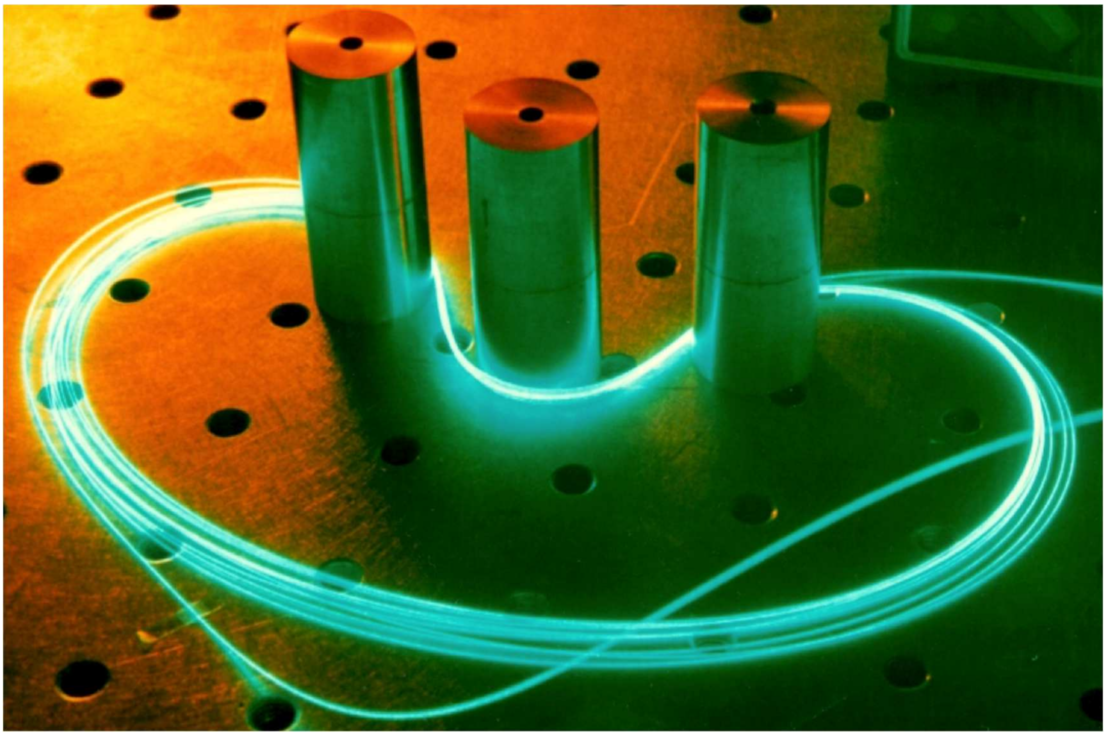
Fiber amplifiers and lasers



Prof. Sébastien Février (sebastien.fevrier@unilim.fr)

An optical fibre can be turned into an active device quite easily. This part of the teaching unit presents:

- the physical principles at stake in fiber amplifiers and lasers

- how to use these physical laws to design telecom amplifiers or high-power amplifiers

- how this laboratory curiosity has evolved into a key-enabling technology for the 21st century.

Fiber amplifiers and lasers

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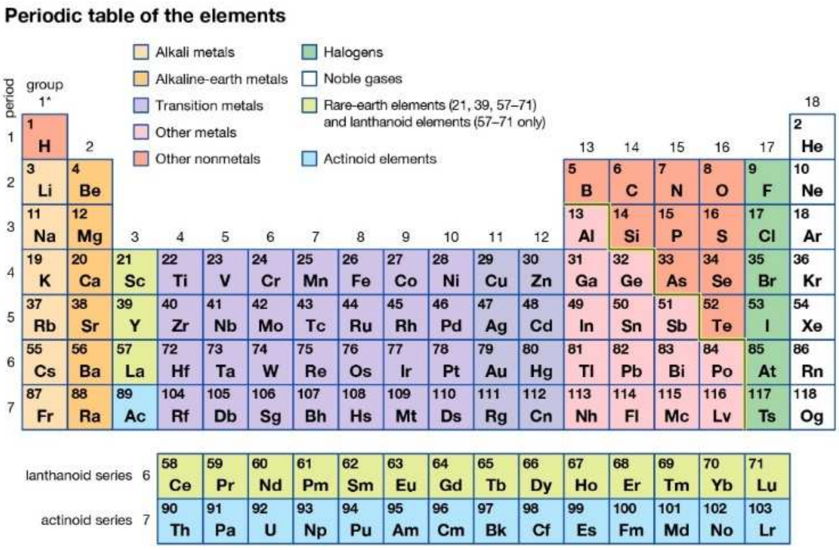
Introduction

Following the discovery by Elias Snitzer in 1961 of the laser action of neodymium in glass, the field of fiber lasers has known rapid and important developments. It has several goals: to obtain new laser transition wavelengths for specific applications (e.g. laser surgery, imaging, communication, atmospheric propagation); to achieve compact and efficient solid-state lasers sources with practical pump wavelengths; and to optimize the physical properties of laser materials for high power or high energy applications (e.g. thermonuclear fusion, machining, laser surgery, range finding, defense). The technology of fiber amplifiers and lasers was driven essentially by the need for optical amplifiers in lightwave communications in the mid-1980s but, since then, has largely spread out to various application fields.

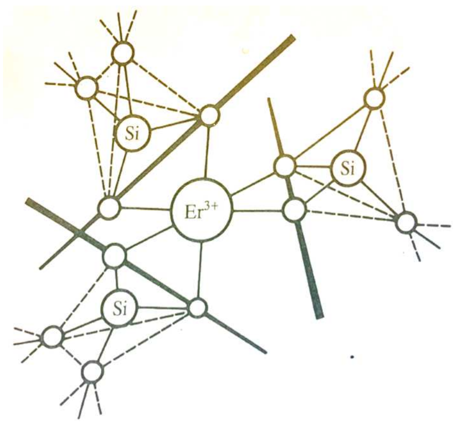
I Fabrication of silica-based RE-doped fibers

I.1 What is a lasing glass?

Glass is an inorganic product of fusion cooled to a rigid condition without crystallization. The structural organization of glass is well defined at the scale of a few atoms but is completely random, asymmetric and aperiodic at a larger scale. The glass lattice is built from basic structural units made of *network former* atoms. The most common is the silica tetrahedron $(SiO_4)^{2-}$. Other usual glass formers are GeO_2, P_2O_5, B_2O_3. The tetrahedron units are connected by their corners through oxygen atoms (bridging oxygens), these random connections form a *disordered* 3D lattice. Other compounds (Na^+, Al^{3+}) can be added to the glass as *network modifiers*. They facilitate the incorporation of lasing elements. Trivalent rare-earths (RE) (light green in the periodic table shown below) are the only ions for which laser oscillation was observed in a glass host, whether in bulk or fiber form. The most commonly used ions are Nd^{3+}, Yb^{3+}, Ho^{3+}, Er^{3+}, and Tm^{3+}, depending on the application. The structure of typical RE-doped silicate glass is shown in Fig. 1b.



(a)



(b)

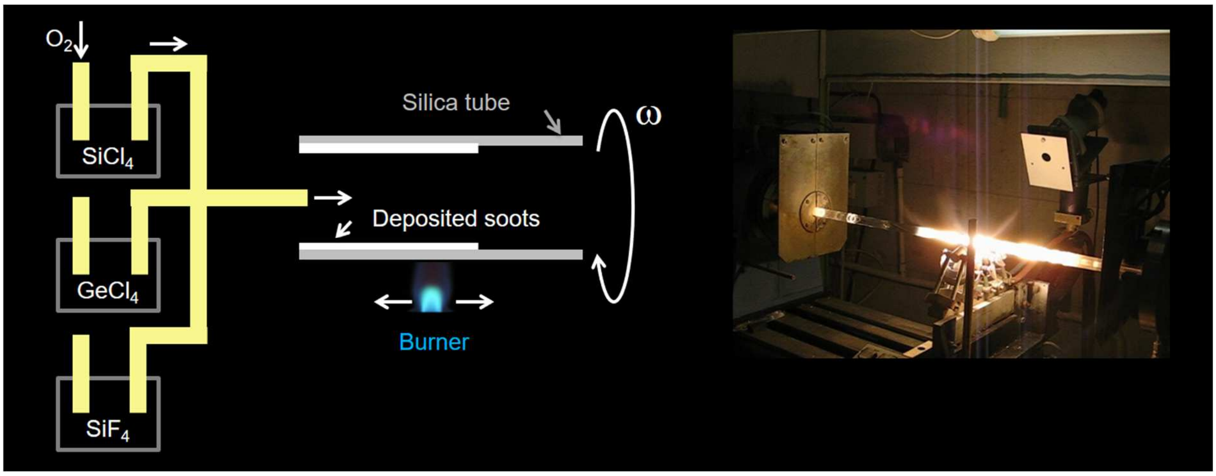
Fig. 1 (a) Periodic table. (b) Possible site for Er^{3+} in basic silicate glass.

A large variety of glasses are suitable as hosts for RE. However, in device applications where the pump is a low-power laser diode, the laser must also be put into the form of an optical fiber. An optical fiber is a thin strand of glass guiding light by the principle of total internal reflection. Passive optical fibers are used to transmit information but also as lighting/collecting elements in endoscopes, for example. By incorporating RE inside the core of an optical fiber, a rare-earth-doped optical fiber can be fabricated and used as an active device, a laser oscillator or an amplifier. Several restrictions and constraints related to the fiber manufacturing technology led to the selection of only a few glasses:

oxide-based glasses (e.g. aluminosilicate and germanosilicate glasses), fluoride-based glasses, and chalcogenide glasses are nowadays used for the fabrication of RE-doped fibers. Oxide-based glasses are by far the most widespread glasses used for fiber amplifiers (telecom) and lasers.

I.2. Fabrication of rare-earth doped optical fibers

The first step in each fiber fabrication method is to realize the fiber preform. The preform can be viewed as a macroscopic replica of the fiber to be fabricated. To reduce the amount of impurities, the preform is composed of synthetized glasses. Modified chemical vapor deposition (MCVD) process is widespread for elaboration of fiber preforms. It is schematically depicted below.

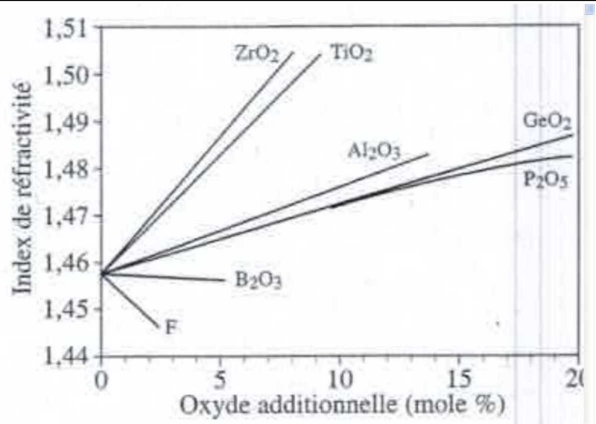


Halide vapors (e.g. $SiCl_4$) react with oxygen thanks to an oxygen-hydrogen flame according to the reaction below:

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

The resulting products are soots of SiO_2, which are deposited inside a rotating quartz tube. The porous $SilO_2$ layer on the inside of the deposition tube is subsequently dried by heating in a chlorine atmosphere, after which it is fused to form a clear nonporous layer. By incorporating doping elements such as GeO_2 and following the reaction $GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$

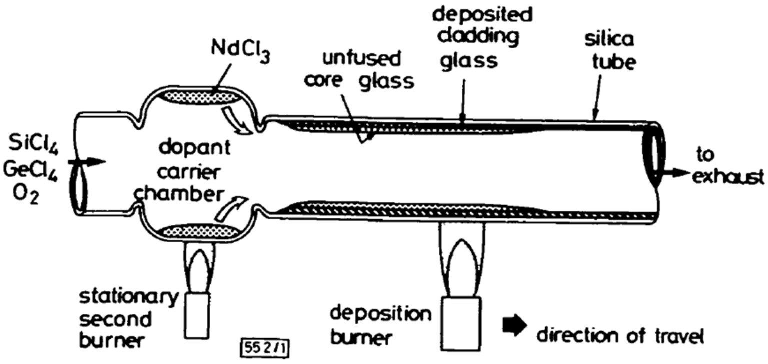
one can change the refractive index. The incorporation of GeO_2 in SiO_2 raises the refractive index. The variation of the refractive index versus the concentration of the doping oxide in the glass is shown below.



SiO_2, referred to as "fused silica", is used as the cladding glass while doped fused silica (e.g. GeO_2-doped SiO_2 glass) is used as the core material. This ensures light guidance in the core by total internal reflection at the core/cladding interface. The picture below shows an MCVD lathe.

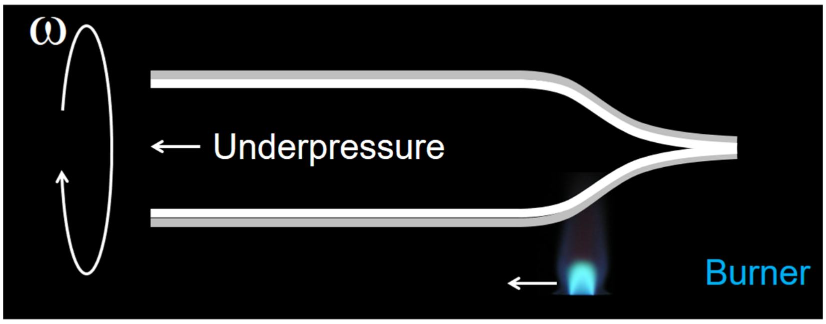
The RE-doped fiber preform is fabricated using the same MCVD fabrication process, with a number of important modifications to permit the incorporation of further dopants into the core glass. Prior to deposition, a conventional deposition tube is prepared by inserting the required dopant $RECl_3 6H_2O$

into a dopant carrier chamber (figure below), where it is dehydrated by heating under a chlorine atmosphere.

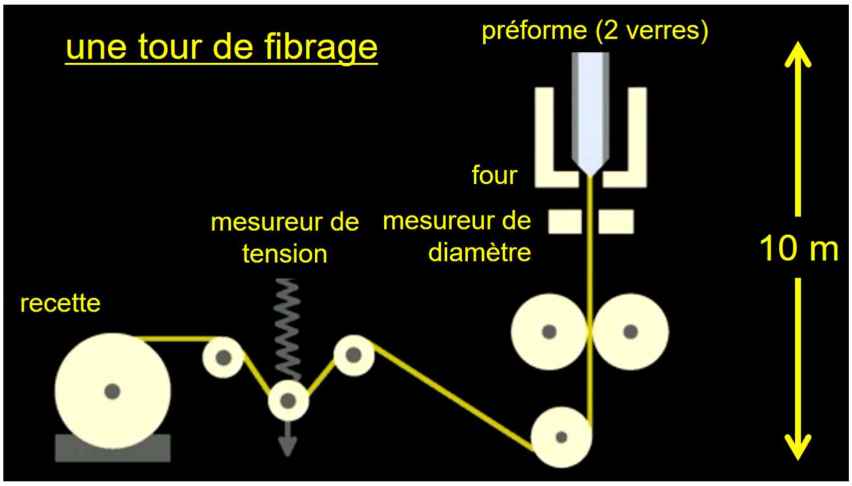


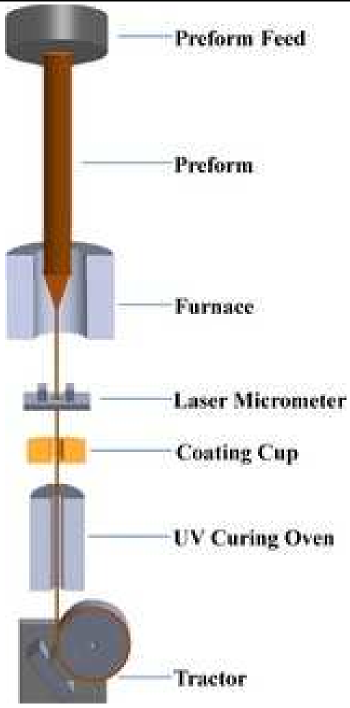
MCVD process for low vapor-pressure dopants. From J. E. Townsend, S. B. Poole and D. N. Payne, "Solution-doping technique for fabrication of rare-earth-doped optical fibres," in *Electronics Letters*, vol. 23, no. 7, pp. 329-331, 26 March 1987, doi: 10.1049/el:19870244.

The cladding glass is deposited in the usual manner. During the core deposition, however, the dopant carrier chamber is heated to around 1000°C by a stationary second burner to produce small quantities of $RECl_3$ vapor. The vapor is carried downstream by the reactant flow, where it is oxidized to RE_2O_3 in the hot zone formed by the deposition burner and incorporated into the core. The porous core layer on the inside of the deposition tube is subsequently dried by heating in a chlorine atmosphere, after which it is fused to form a clear nonporous layer. The tube is then collapsed to form a solid rod.



Next, the drawing process melts the preform (rod) inside a furnace and pulls from it a glass filament of reduced dimensions. Upon solidifying, this filament becomes the fiber. The process also includes the cladding of the fiber by a polymer jacket, which provides enhanced mechanical strength.





In this way, one obtains a rare-earth-doped fiber. The core only is doped with RE. The incorporation of RE does not modify the refractive index of the core. Therefore, it does not modify the electromagnetic modes guided in the fiber. However, it clearly modifies the way light will interact with matter.

Exercise series#1 Modal overlap