Fluoride glass fiber sources: Problems and prospects

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Outline :

1 Introduction

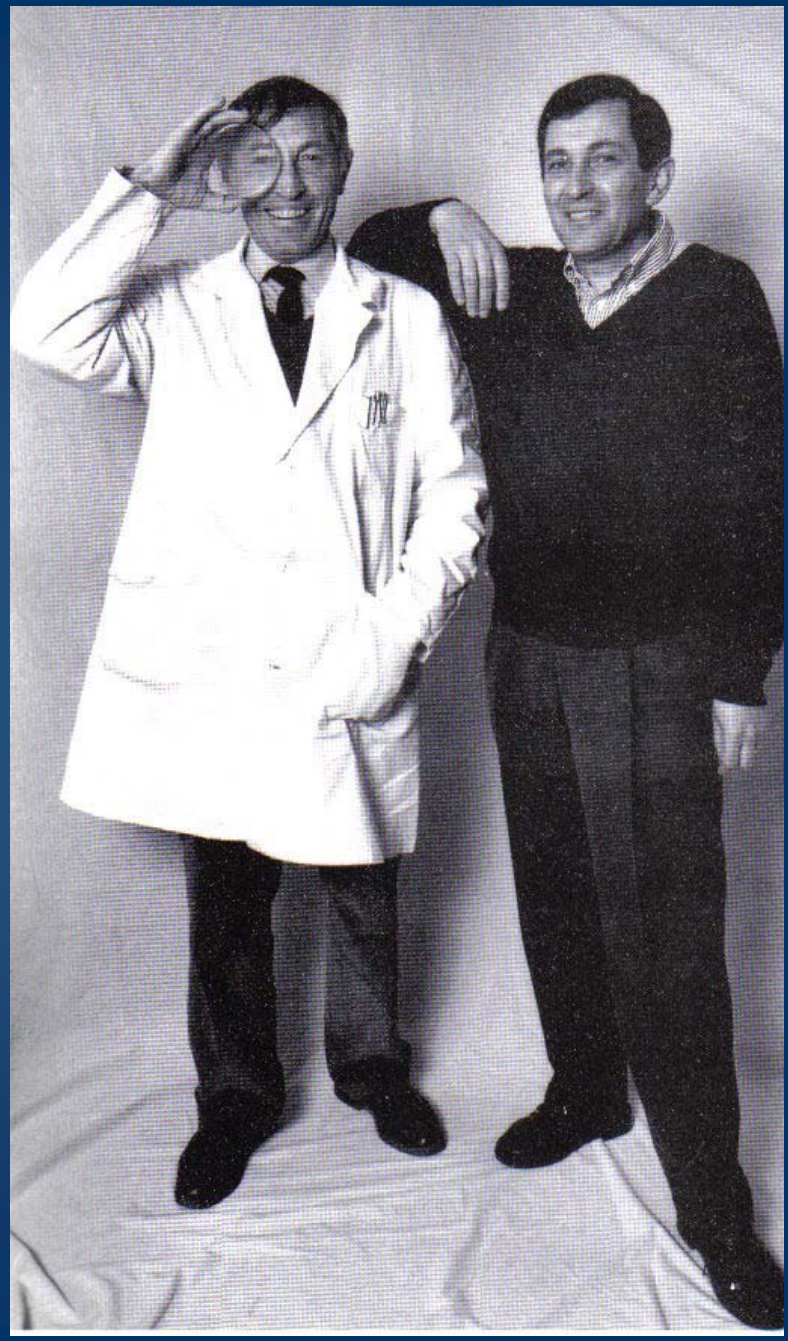
2 Fluoride glass technology

3 Specifications of active fibers

4 Achievements

5 Problems and prospects

6 Conclusion



INTRODUCTION

The privilege of experience…

- 36 years of continuous activity in fluoride glasses, from the discovery to the industrial development
- Pionneering achievements
- Interaction and collaborations with major actors of fiber lasers, optical amplifiers and active devices for more than 20 years
- Very large (and often unexpected) field of expertise.

Pionnering achievements

- Numerous results were not released (confidentiality)
- ZBLAN glass compositions were characterized in 1980. [Furukawa (Shibata & Oshawa) paper appeared in 1984]
- The first ZBLA:Nd laser was made in 1978 in collaboration with P.Brun's laboratory at Rennes University
- Lasing effect was accidentally observed in 1984 in a Nd-doped fiber supplied to the French CEA
- Low loss optical fibers (< 1 dB/km) have been obtained. Development steps have been identified

This talk intents

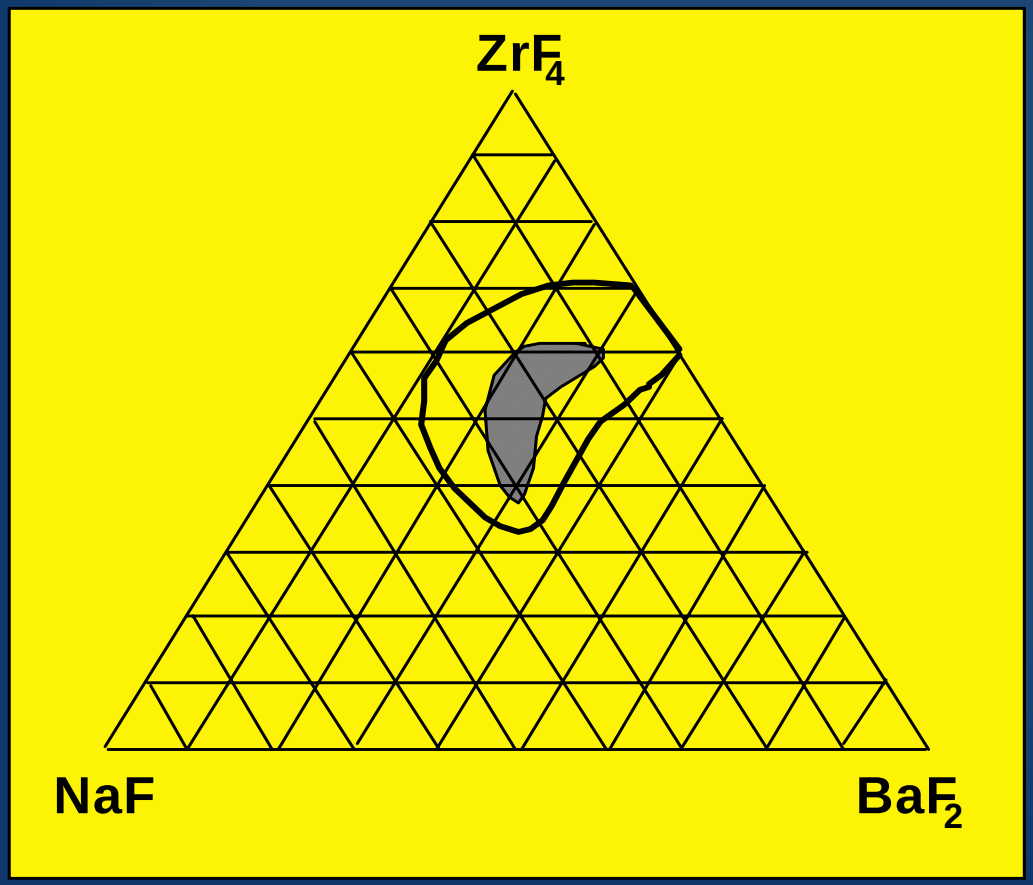
- To outline some achievements (Not an exhaustive review!)
- To discuss problems in relation to fiber lasers, amplifiers and sources.
- To complete ambiguous or misleading informations
- To draw prospects for future realizations
- To make the ground for possible interactions

Interactions, collaborations

- JPL (NASA), large NA fibers (1985)
- France Telecom (CNET), ORC
- Various German companies and universities
- Large astronomic observatories (VLT, Hawaii)
- Researchers and groups from this audience
- Close collaboration with COPL, Laval Univ, Québec

FLUORIDE GLASS TECHNOLOGY

21 Glass composition



Initial system (1975)

Fluoride glass families

- Most studies focused on fluorozirconates based on ZrF_4 and HfF_4

- Other fluoride glasses are formed with AlF_3, GaF_3 and InF_3 as main glass formers

- Significant differences are observed in:
  - Chemical durability
  - Glass stability
  - Mechanical strength & hardness
  - Phonon energy

Typical glass compositions

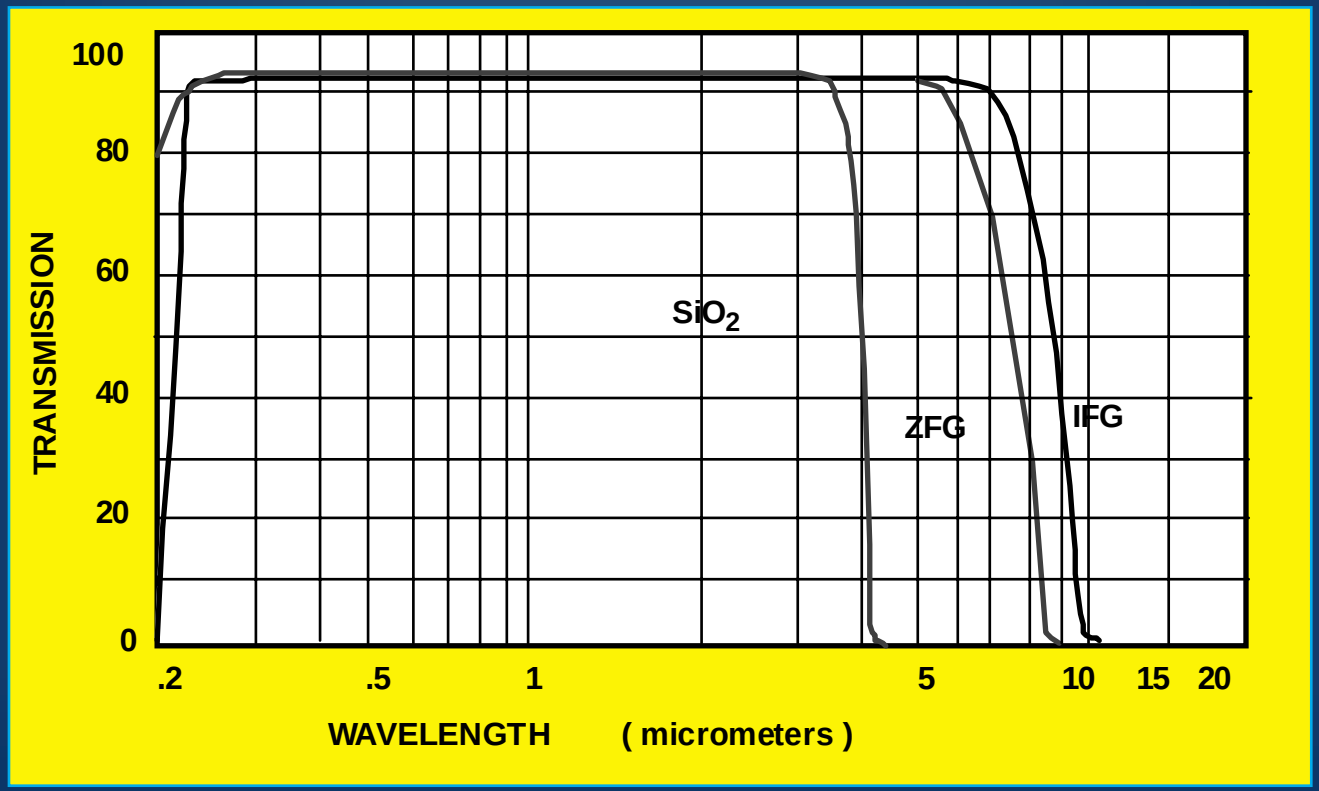
Glass	COMPOSITION (mol %)	n_D
ZBLA	57 ZrF_4, 34 BaF_2, 5 LaF_3, 4 AlF_3	1.519
HBLA	57 HfF_4, 34 BaF_2, 5 LaF_3, 4 AlF_3	1.504
ZBLAN	**53 ZrF_4, 20 BaF_2, 5 LaF_3, 4 AlF_3 , 20 NaF**	**1.498**
ZBSFCl	60 ZrF_4, 20 BaFCl, 20 SrFCl	1.542
YABC	20 YF_3, 40 AlF_3, 20 BaF_2, 20 CaF_2	1.440
IZBS	40 InF_3, 20 ZnF_2, 20 SrF_2, 15 BaF_2, 5 CaF_2	1.495
PGICZ	30 PbF_2, 22GaF_3,13 InF_3,18 CdF_2,13 ZnF_2,2 GdF_3, 2 NaF (n = 1.595)	

General physical properties

PROPERTY	HMFG	ZBLAN
Glass transition temperature (°C)	200-450	260
Coefficient of Thermal Expansion (10^{-7} K^{-1})	140-210	180
Density (g/cm^3)	4-6	4.14
Young Modulus (GPa)	50-60	54
Vickers hardness (kg/mm^2)	200-270	210
Poisson ratio	0.25 – 0.35	0.30
Refractive index n_D	1.45 – 1.60	1.500
Non linear refractive index n_2 (10^{-13} esu)	0.8 – 0.9	0.85
Abbe Index ν	60 – 80	75
dn/dT	1.10^{-5} -2.10^{-5}	$1.5 .10^{-5}$
Cp (J / g at.K)		24.9

Optical transmission

Optical transmission of samples 4 mm thick



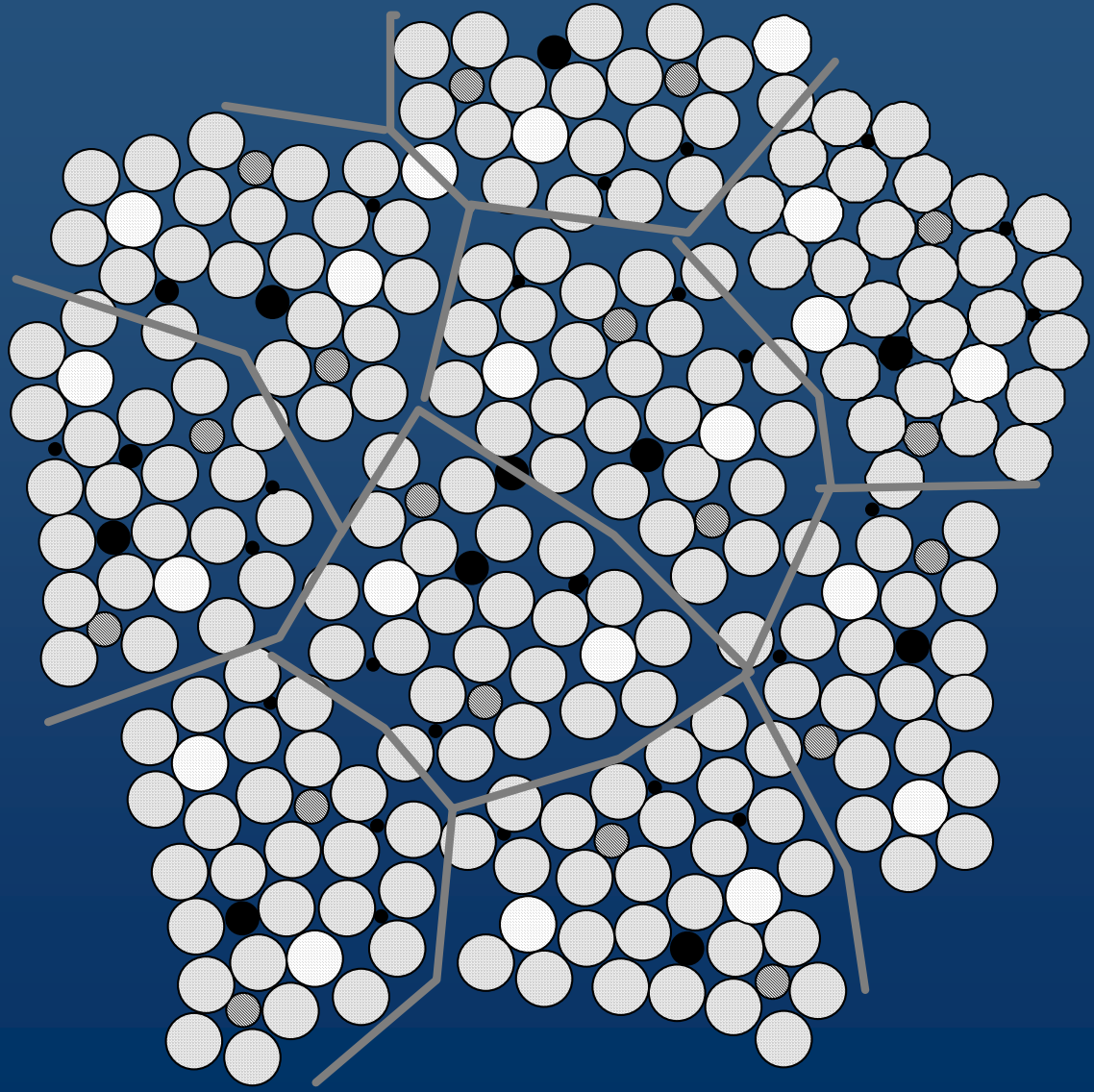
STRUCTURE: the vacancy model

- Numerous structural investigations show the high coordination number of the vitrifying cations: 8 (Zr) or 6 (Al, Ga, In).

- The vitrifying network is constructed from the association of the MF_6 or MF_8 polyhedra with large cations Na^+, Ba^{++} as modifiers.

- The vacancy model offers an alternative description:
  A disordered packing of large ions (F^- and Ba^{++}) in which small cations are inserted. This packing contains vacancies that are mobile in the liquid state.

Bidimensional picture



GLASS PROCESSING

22 GLASS SYNTHESIS

- Fluoride glass synthesis includes melting, fining, casting and annealing steps

- Specific features are low melt viscosity, volatilization, devitrification and hydrolysis.

- Water action is critical. To overcome the problem various solutions have been reported:
  - Reactive atmosphere processing
  - Ammonium bifluoride processing
  - Dry processing

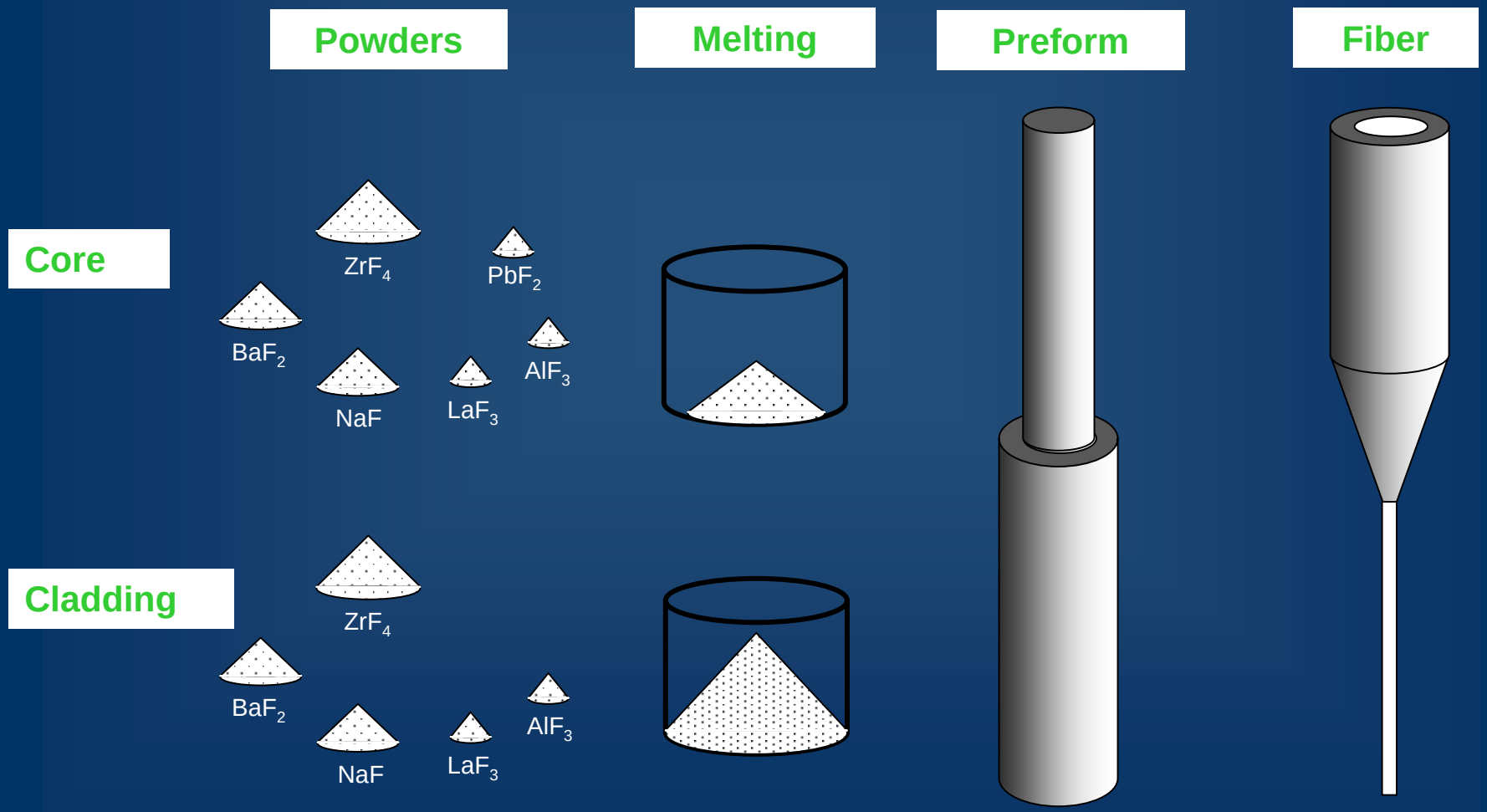
Optical quality samples

- Samples prepared at room atmosphere from current starting materials exhibit numerous defects:
  - Cords and syrups
  -« Stones » and inclusions
  - Bubbles
  - Crystals
  - Composition fluctuations

- Manufacturing of optical quality samples ($\Delta n < 10^{-6}$) is difficult and time consuming.

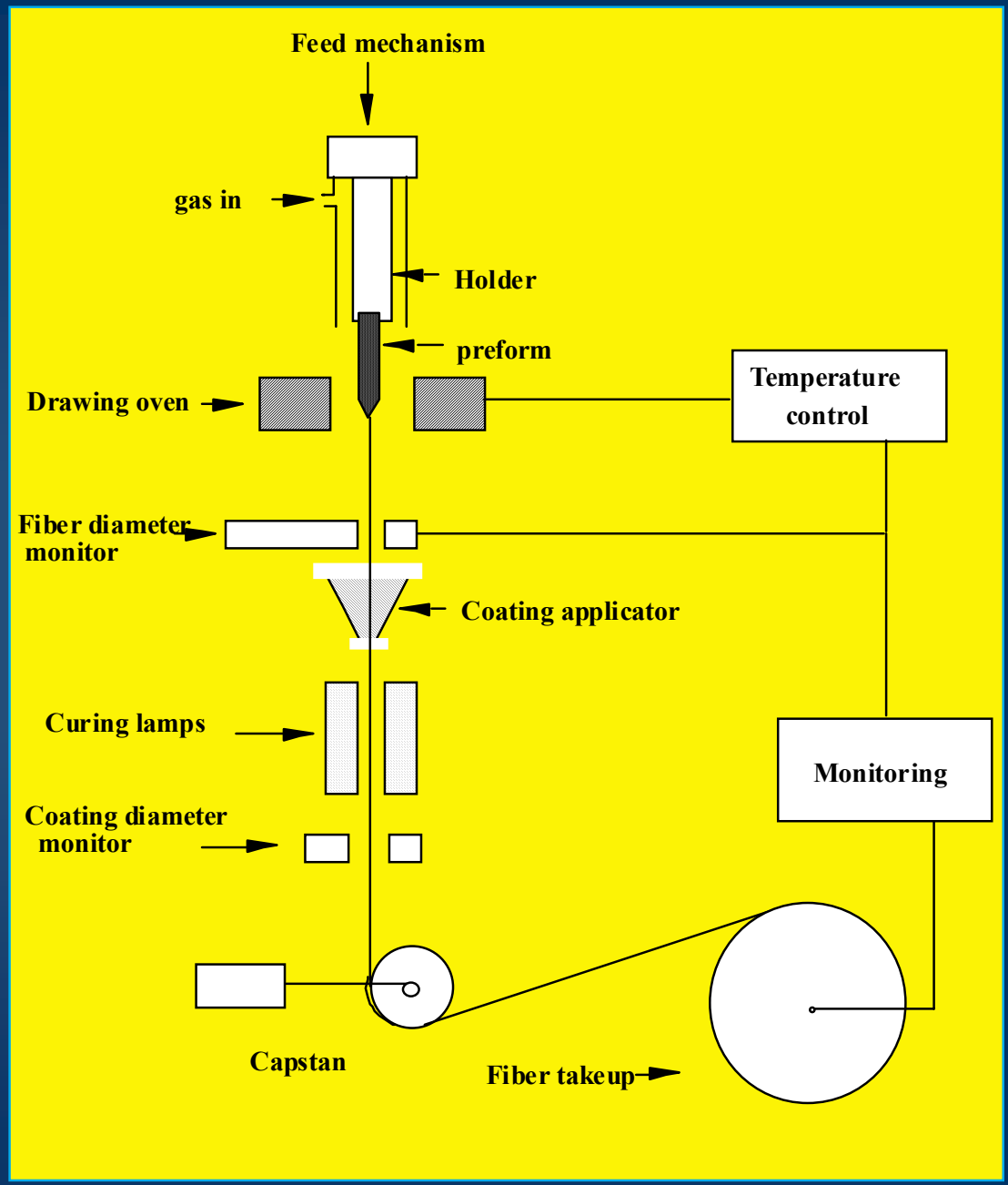
- Several parameters must be considered and optimized

23 Fiber manufacturing



Fiber drawing

Fluoride glass fibers are drawn using glass preforms which are processed from high purity glasses processed in a very dry and clean atmosphere. The optical and physical characteristics of the preform determine to a large extent the structure and the optical properties of the fiber.



Critical aspects of HMFG fibers

- Fiber drawing adds defects to the prexisting defects in the preform
- Various parameters must be optimized:
  Time, temperature, preform size, atmosphere (water, contaminants, dust)
- Main contribution to optical losses arise from core defects
- Quality of core/cladding interface is critical

SPECIFICATIONS

General features:

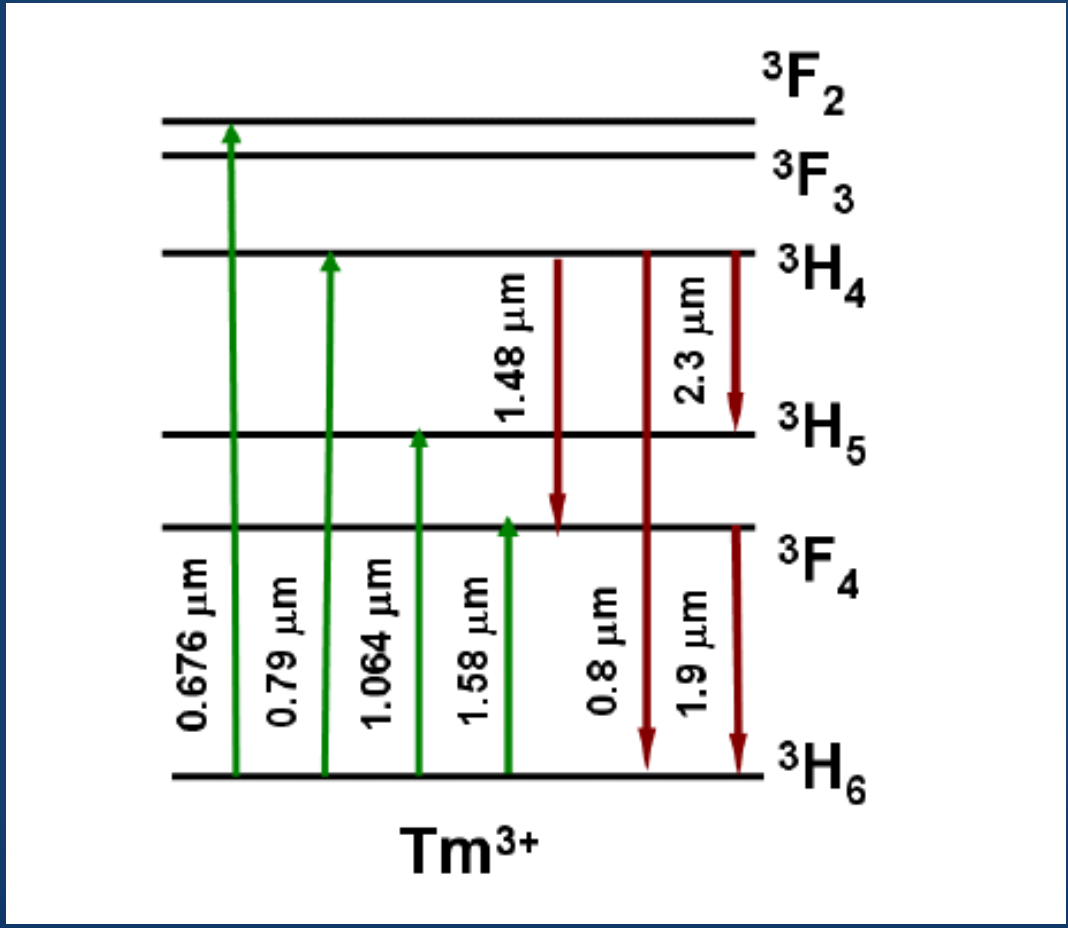
optical fiber must be

- Strong enough to survive in any case
- Transparent in operating window (low optical losses)
- Durable in ambiant air and humidity
- Stable opticaly and mechanicaly *vs* time and temperature
- Comply with optical specifications

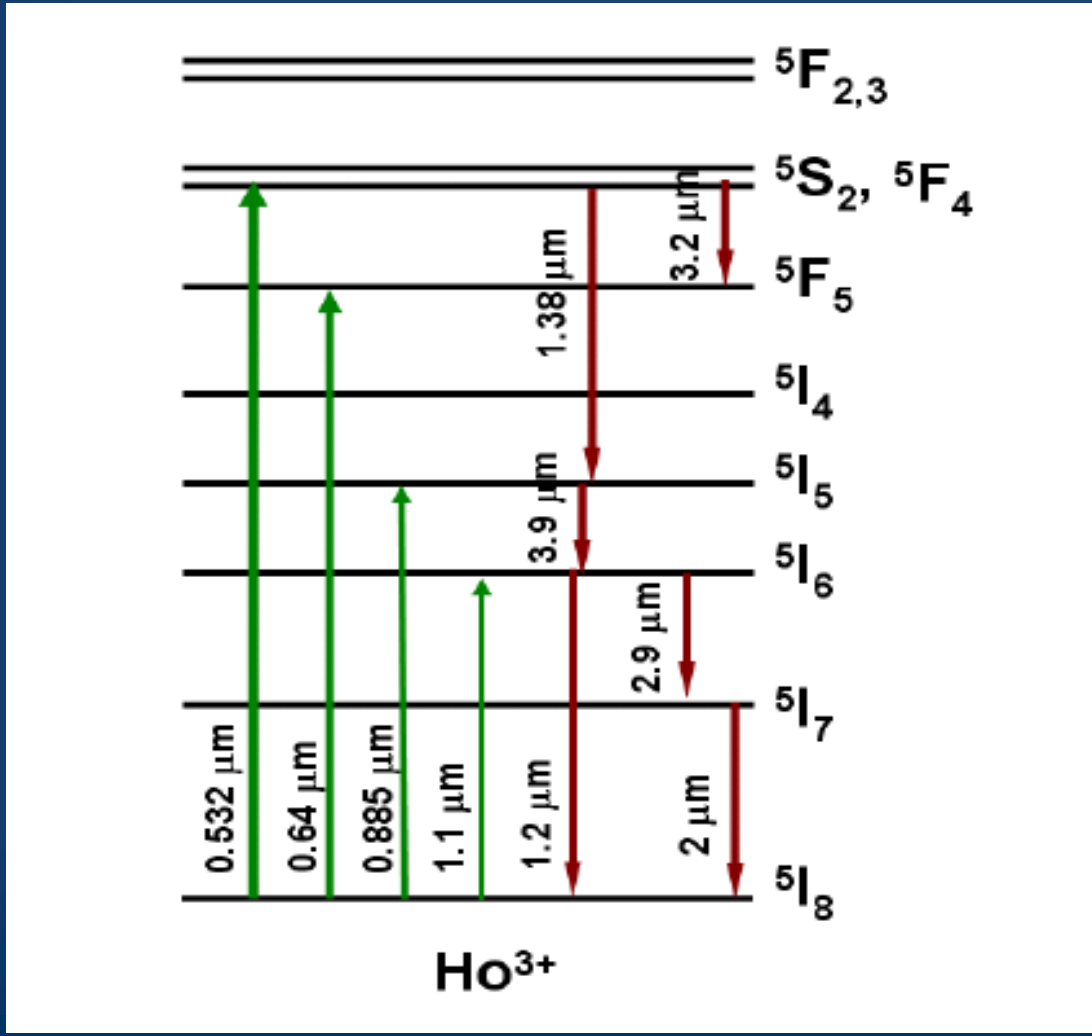
Rare earth doped fibers
must be

- Homogeneous (no clustering)
- Host the convenient amount of active ions.
- Have minimum background losses
- Allow co-doping (e.g. Yb/Er)
- Withstand high energy pumping

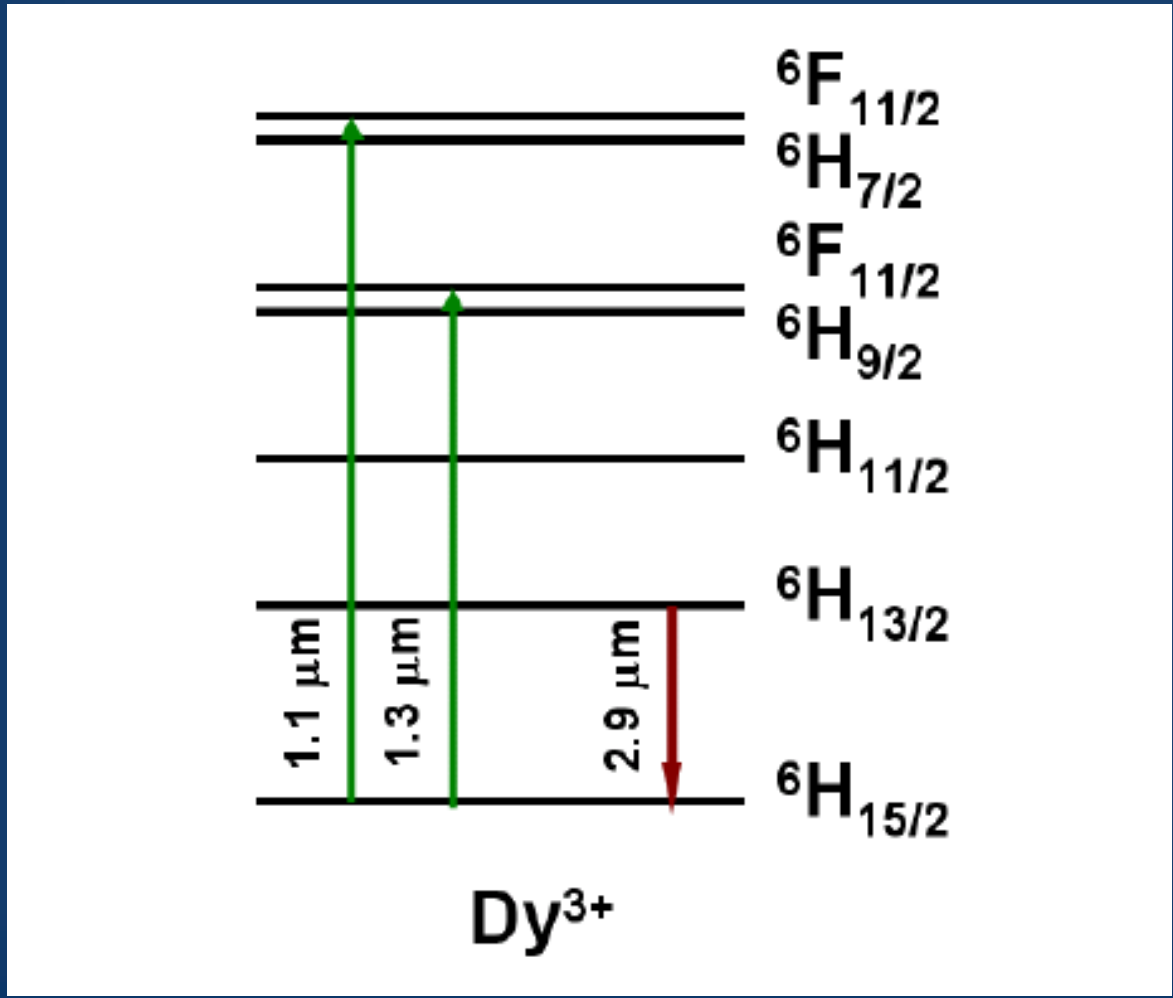
Rare earths for mid IR emission



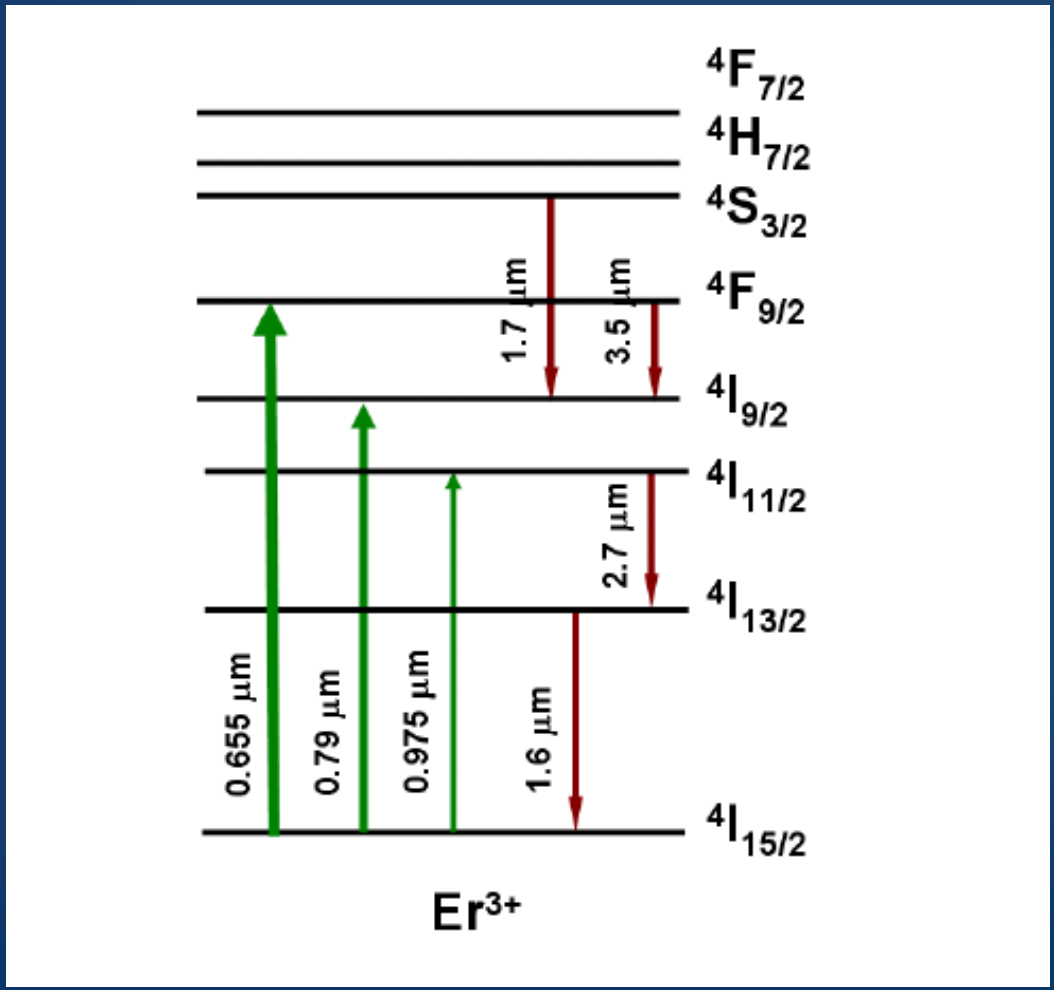
Rare earths for mid IR emission



Rare earths for mid IR emission



Rare earths for mid IR emission



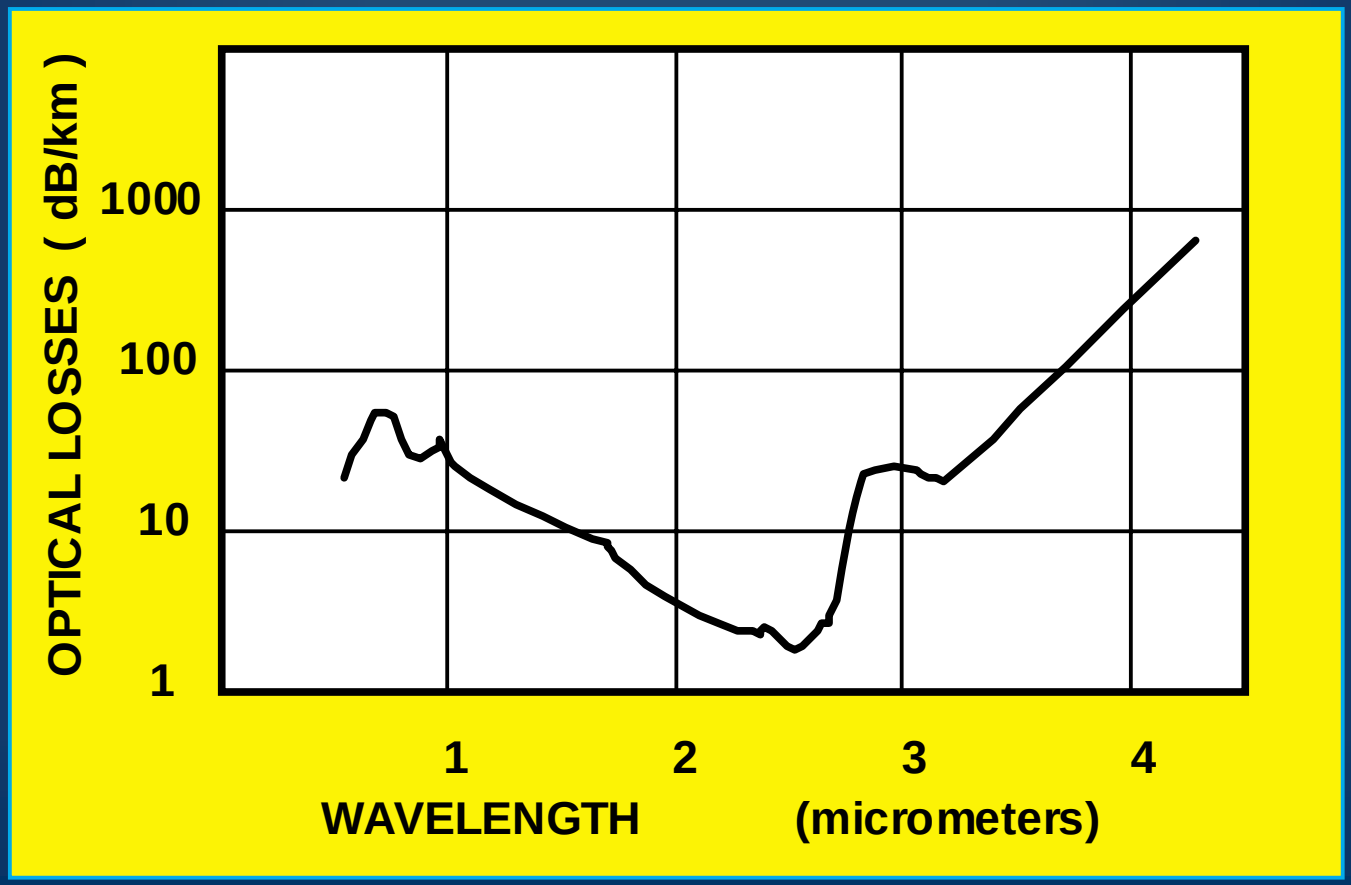
High power and supercontinuum

- Fiber must withstand large pump power
- Limitations arise from extrinsic defects
  (Intrinsic damage threshold is largely unknown)
- Power in cladding must be controlled
- High non linear parameters are desirable
- Reliability of resonator, splicing and end faces

ACHIEVEMENTS

Optical transmission: fibers

Typical losses of a multimode fiber



Optical transmission: fibers

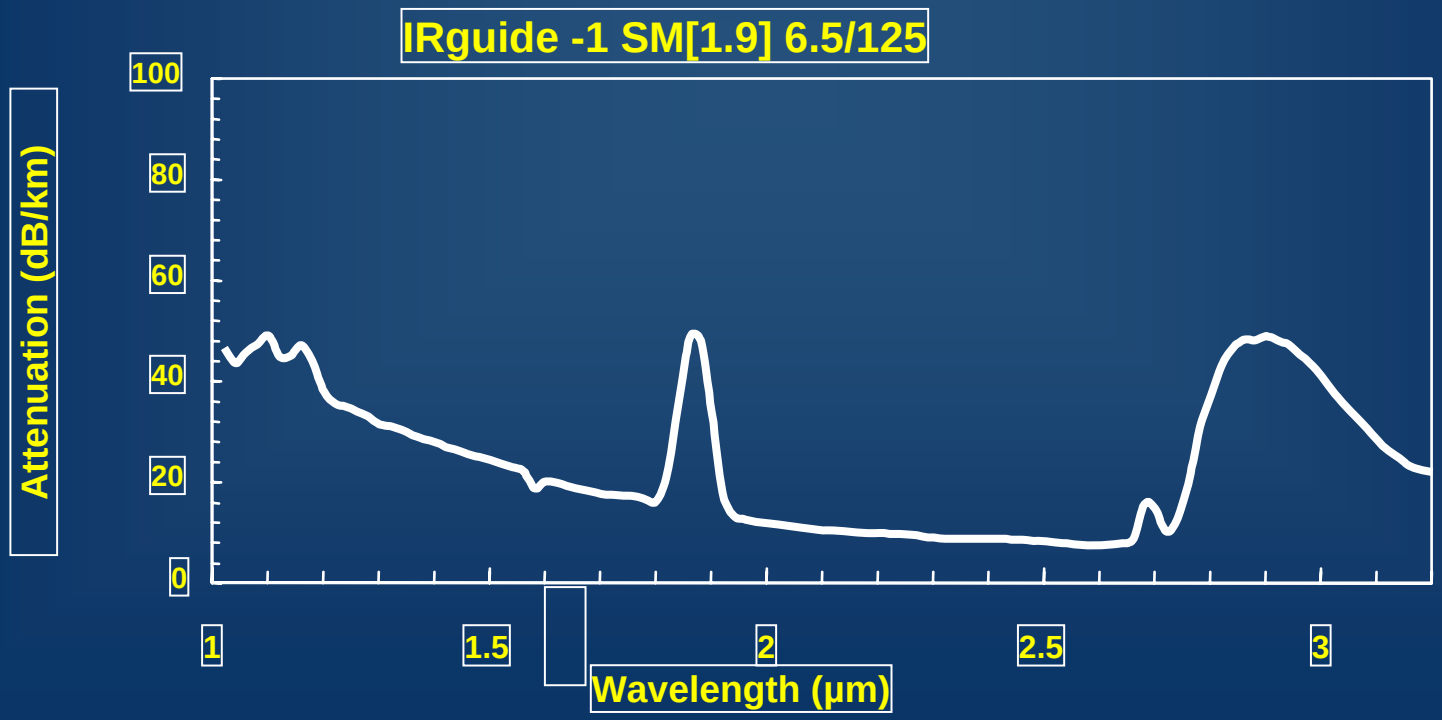
Typical losses of a singlemode fiber

Ø core / Ø cladding : 6.5 / 125 µm

Cut-off wavelength : 1.9 µm

Attenuation at 2.5 µm : 5 dB / km

Attenuation at 3.2 µm : 20 dB / km



Type of fibers

Multimode

Single mode

Polarization maintaining

Low bireringence

Rare eath-doped

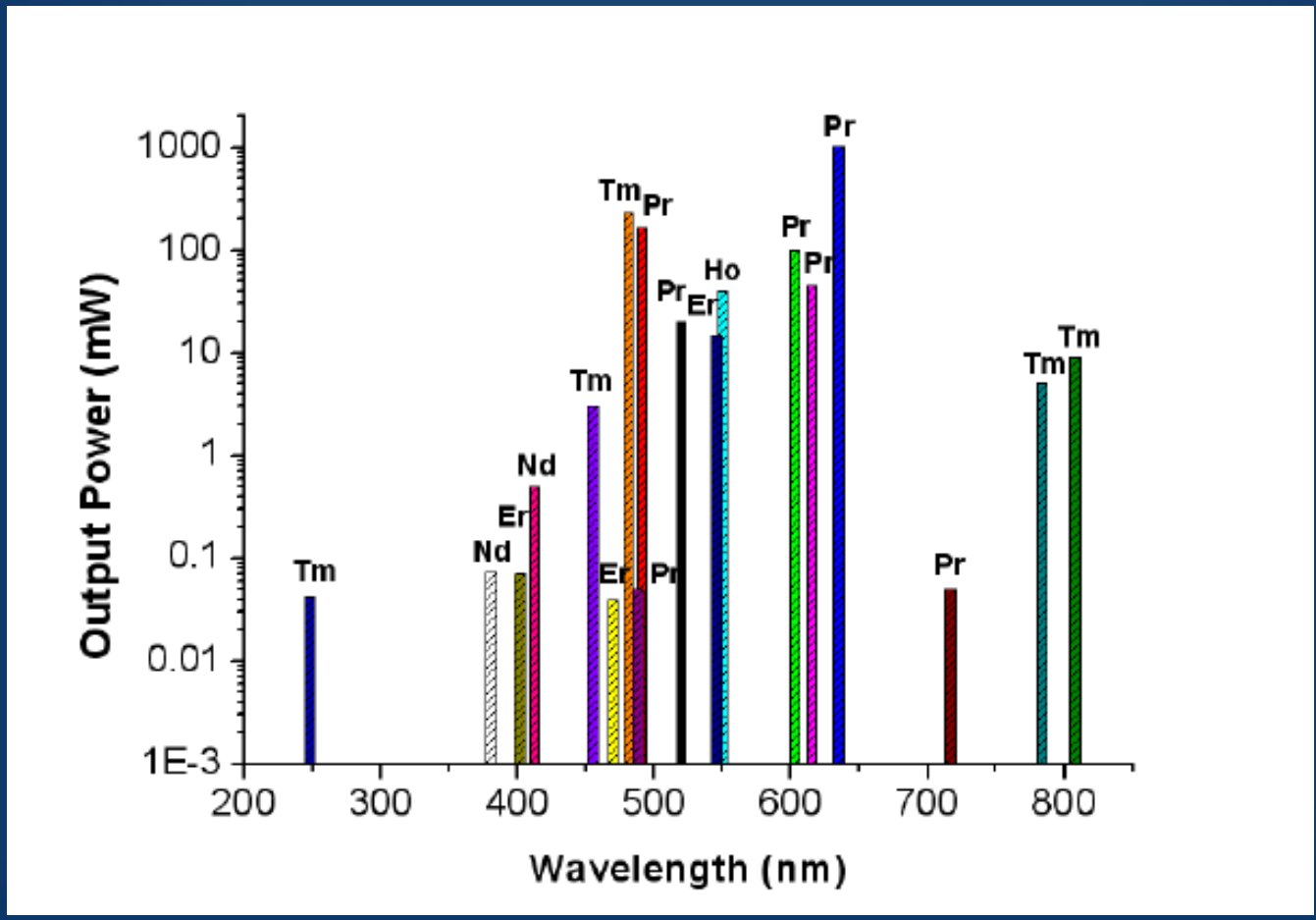
- Double-clad
- D-shasped,
- Ring-core (M-shaped)

High NA

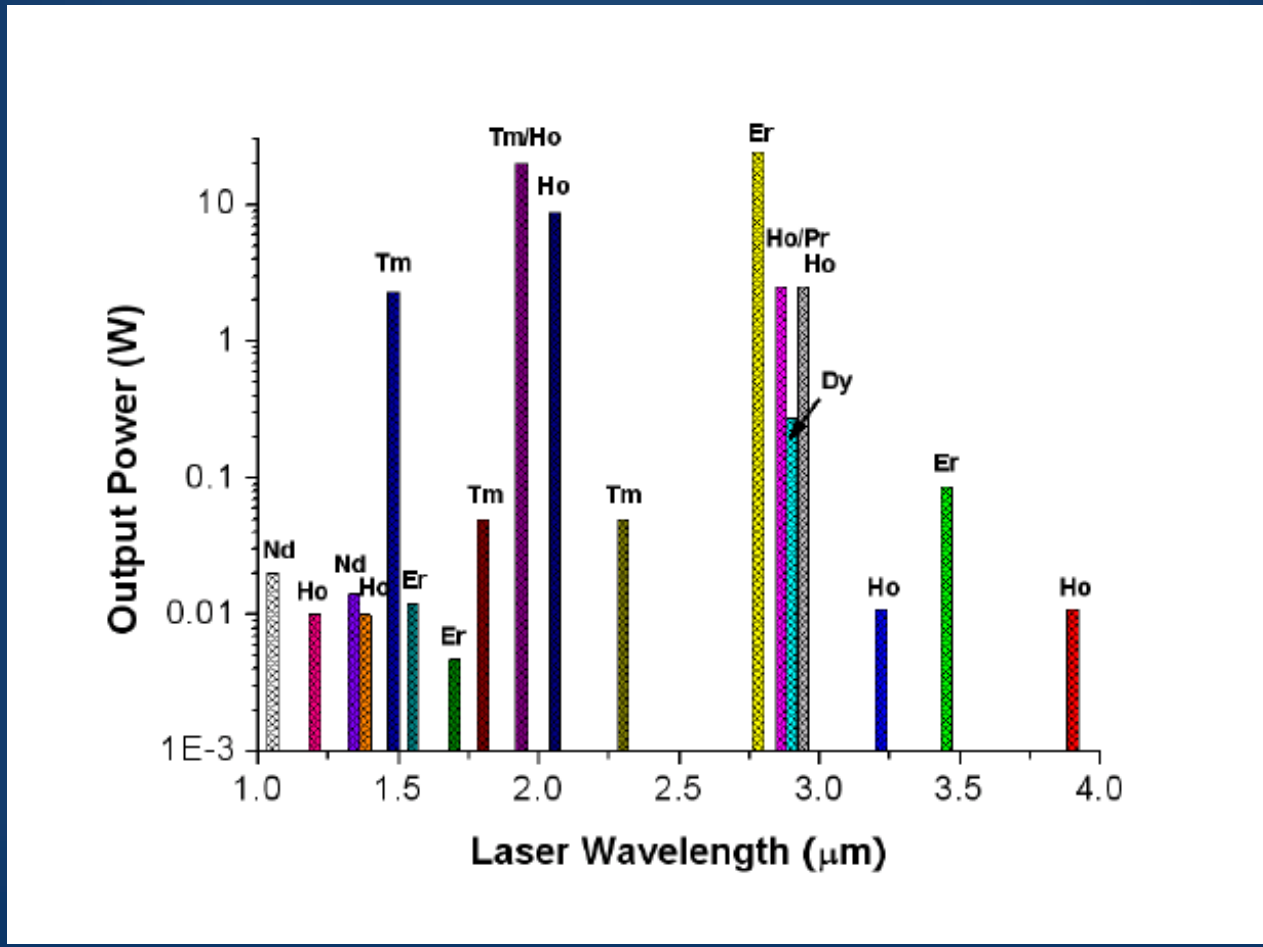
ZBLAN fiber lasers

- Intense activity in the 80's (CNET, BT…)
- Development in various german labs and companies (90's): FSU Iena, Techn. Univ. Berlin, Laser Zentrum Hannover, Laser Zentrum Hambourg, Lasos, Guided Color Techn., Unique Mode, Linos, Philips…
- ZBLAN fibers have hugely increased the number of laser lines
- Marketing issues are heavier than technical problems

ZBLAN fiber lasers: Up conversion



ZBLAN fiber lasers: Mid IR



Supercontinuum

- Significant achievements with ZBLAN fibers
- Various parameters: fiber length, attenuation, pump power, pump frequency, pump wavelength, N.A., dispersion, fiber geometry…
- Laboratory results
- Available systems

Supercontinuum using short fibers

From Toyota Technological Institute (Prof. Y. Ohishi)

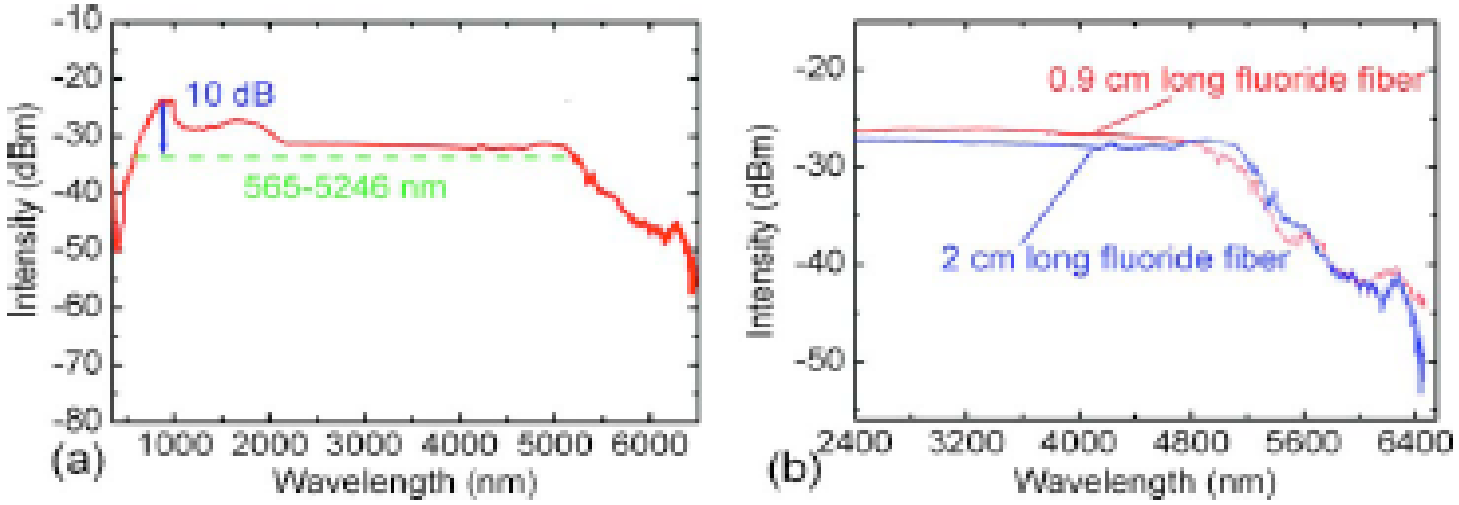
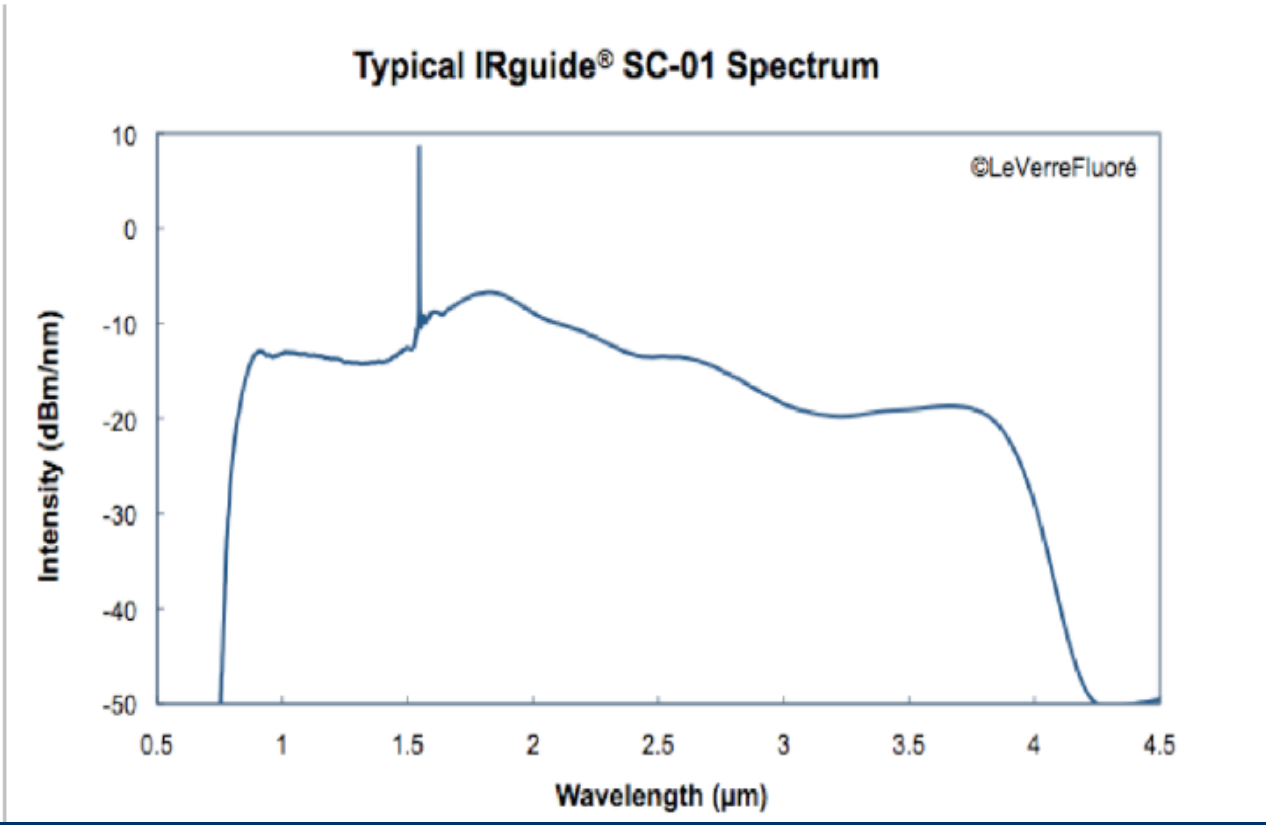


FIG. 2. (Color online) (a) The measured SC spectra from the 2-cm-long fluoride fiber when the average pump power of 1450 nm femtosecond laser was fixed at 20 mW (the corresponding peak power is about 50 MW). (b) A comparison of the long-wavelength edge of SC spectra in 0.9 or 2 cm long fluoride fiber.

Supercontinuum

Current ZBLAN source



PROBLEMS AND PROSPECTS

Practical questions

- Mechanical strength.
- Aging
- Chemical durability
- Thermal stability
- Optical specifications

Fiber strength

- Failure occurs on defects, most of them extrinsic
- Intrinsic strength limted by chemical bonding
- Tensile strength improve by CTE adjustments
- Static fatigue may be controlled by relaxation

Chemical durability

- Water, water, water ….
- Liquid water must not be in contact with glass surface
- Fiber is protected by coatings, jacketing, cabling.
- End faces make problem. Solutions exist !
- Fluoride fibers in use in industrial environment for more than 10 years.

Bragg gratings in fluoride

- Pionneering achievements in CNET (FT)
- But time consuming and Cerium doping
- Reliable Bragg gratings obtained by femtosecond lasers at COPL, Laval University, Québec

Damage threshold

- Is critical for high power lasers and supercontinuum
- Low values have been observed in real fibers,
  in relation to extrinsic defects
- High values measured (ISL)
- Femtosecond experiments implemented at Laval University,
  Suggest that intrinsic damage threshold could be higher
  in ZBLAN than in silica!

Control of fiber defects

- Identification: crystals, bubbles, metal particle, carbon…
- Processing parameters to be adjusted
- Contamination of interfaces
- Glass stability in high NA fibers
- Adjustment of thermal expansion coefficients

Extending optical window

- Requires using Indium-based glasses free of Zr and Al
- Less stable compositions make more difficult to reach low backgroud losses
- Encouraging laboratory results
- Development in progress

Photonic crystal fibers

- Large potential
- May be achieved with ZBLAN glass
- Probably more difficult than silica or chalcogenides
- Thermal properties of ZBLAN offer extended possibilities

CONCLUSIONS

- The potential of fluoride fiber lasers is very large
- … But FG fiber lasers are just emerging
- Most technological problems are identified
- Both laser and supercontinuum sources are available
- Photonic crystal fibers to be developped

ACKNOWLEDGMENTS

- The scientific community for its continuous interest

- All of you for your attention

Application of lacunar model to ZBLAN glass

Molar volume of ZBLAN glass is 8.10 cm^3 and
$\Delta Cp = 14.2\ J.mol^{-1}.K^{-1}$ while I have measured
$\Delta\alpha = 1.2\ 10^{-4}\ K^{-1}$ (dilatometry),
which leads to $e_v = 132\ KJ.\ mole^{-1}$.
The rate of vacancy formation is $8\ 10^{18}\ K^{-1}\ cm^{-3}$.

With 120 K as the estimated difference between Tg and T_K the gross number of vacancies is $N \approx 10^{21}\ cm^{-3}$ at Tg