From the periodic table to the optical fiber

The exciting aspects of the Molten Core Method

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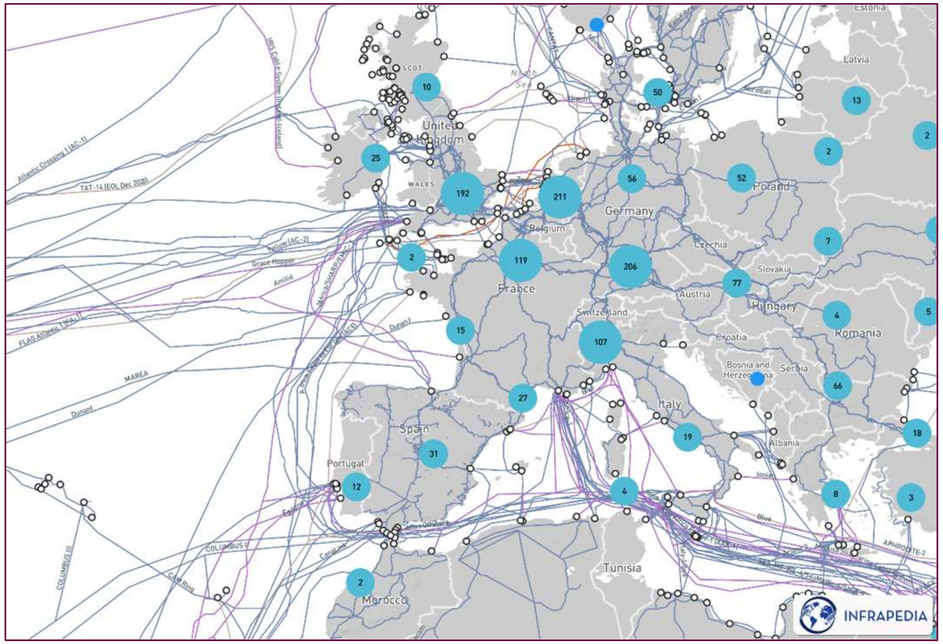
Telecom optical fibers: A success, with no doubt!

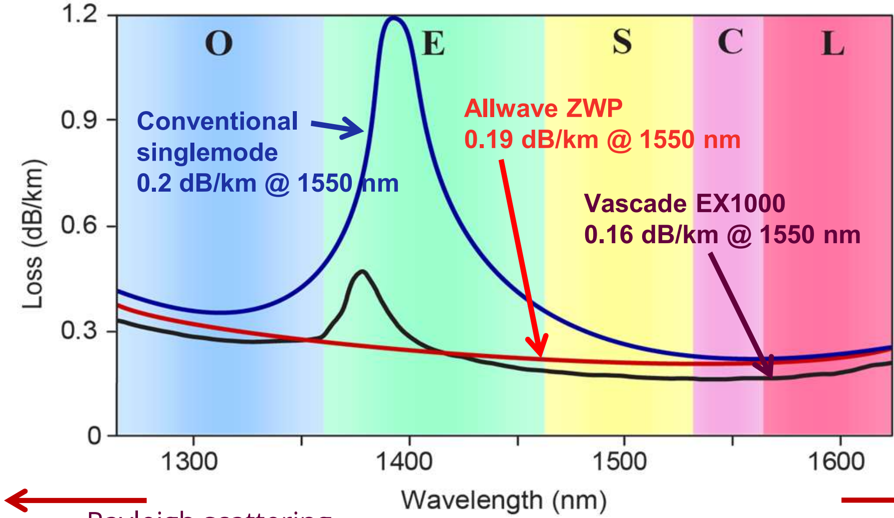
Look at the map…



Look at the numbers…

- 440 submarine cables around the world
- >500 millions km/year (SMF) worldwide (70 m/person/year)
- >50 m/s drawing speeds
- 0.05 USD/m

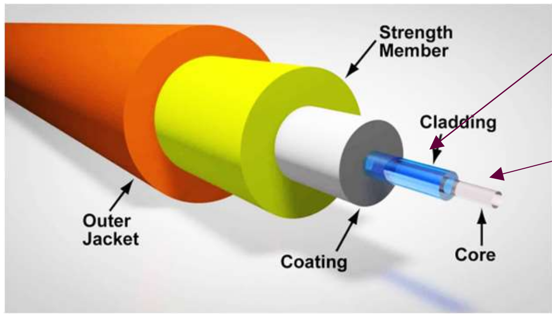
Look at the losses…



Rayleigh scattering
UV absorption

IR absorption

Look at the structure…



$\Phi_{cladding}$ = 125 µm
Silica (SiO_2)

Φ_{core} = 10 µm
SiO_2 + 3-4% GeO_2

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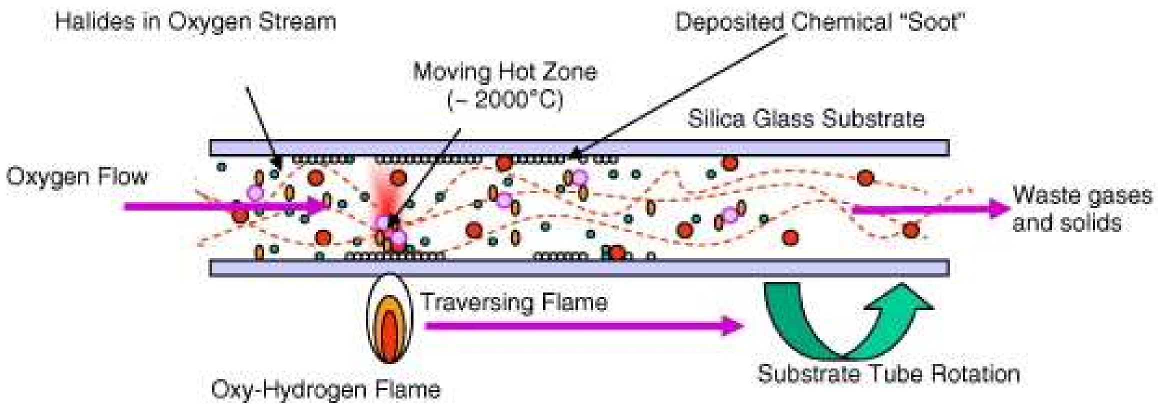
Because silica + CVD techniques work great…

Chemical vapor deposition (CVD) for preform fabrication



$SiCl_4$ (+ $GeCl_4$…) + O_2 → SiO_2 (+ GeO_2…) + $2Cl_2$

Great because…

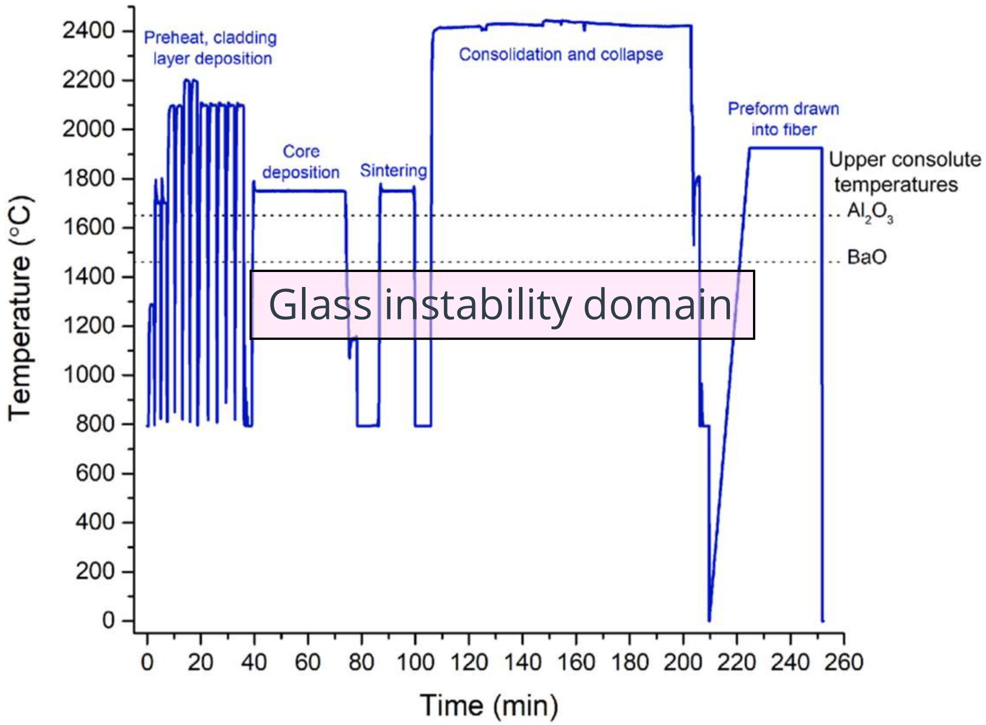
- Nearly intrinsic purity achievable (leads to very low losses)
- Good control of dopant concentration and refractive index profile (tailoring of cross-section)
- High speed (>50m/s), excellent size control, long length

But…

- Doping concentration fairly limited (up to few %)
- Limited in the choice of dopants

… but limited in the choice of dopants and their concentration

Preform fabrication process



Selected dopants into SiO_2	Maximum concentration (mol%)
Al_2O_3	8
F	2
Rare earth oxide	2
Alkaline earth oxides	<2

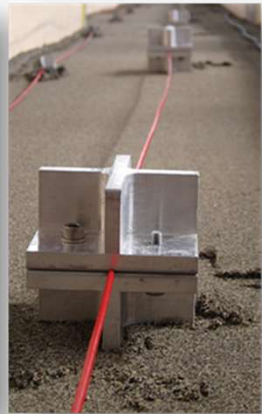
J. Ballato, P. Dragic, *Int. J. of. Applied Glass Science*, 13, 2022
P. Dragic, M. Cavillon, J. Ballato, *Applied Physics Reviews*, 5, 2018

Growing demand for ever more-sophisticated optical fibers

Communications

Machining / Manufacturing

Energy / Sensing / Medicine



Ranging / Science

Directed Energy

One really needs to pay attention to the underlying materials science **to unleash the full potential of the periodic table** on fiber properties and performance!

→ Molten Core Method!

The molten core method - principles

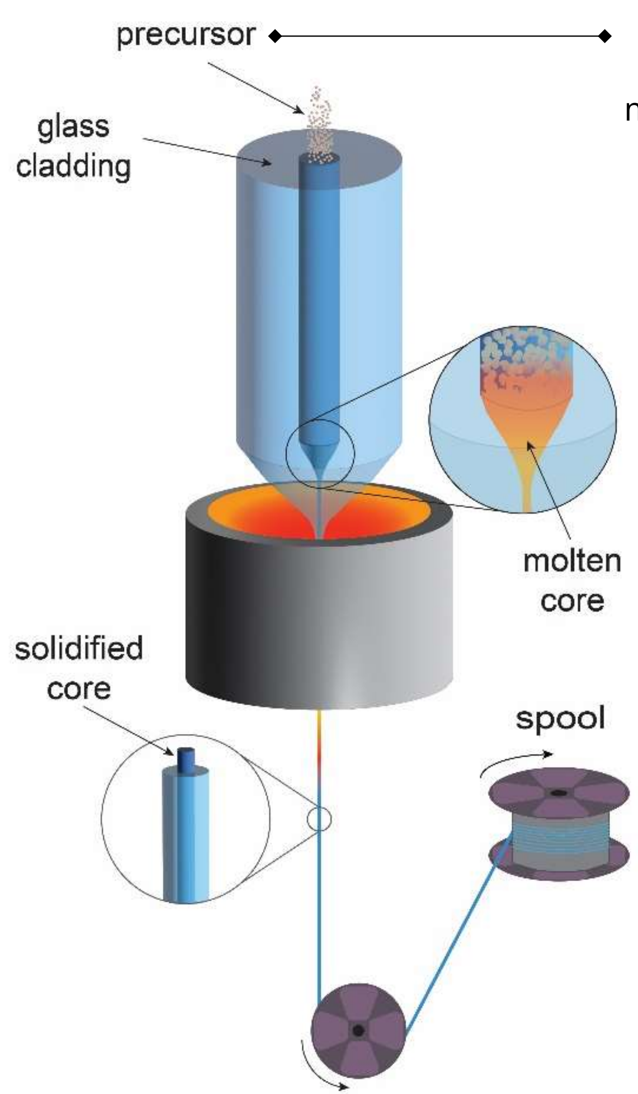
<u>Advantages</u>

- Straight-forward
- Industry-accepted manufacturing (fiber draw) used; no lathe deposition.
- Long lengths (> km) and high-speed manufacturing (> m/s)
- Low temperature (compared to CVD…)
- Can be reactive (liquid-phase chemistry)
- <u>Amendable to very wide range of materials</u>

<u>Drawbacks (?)</u>

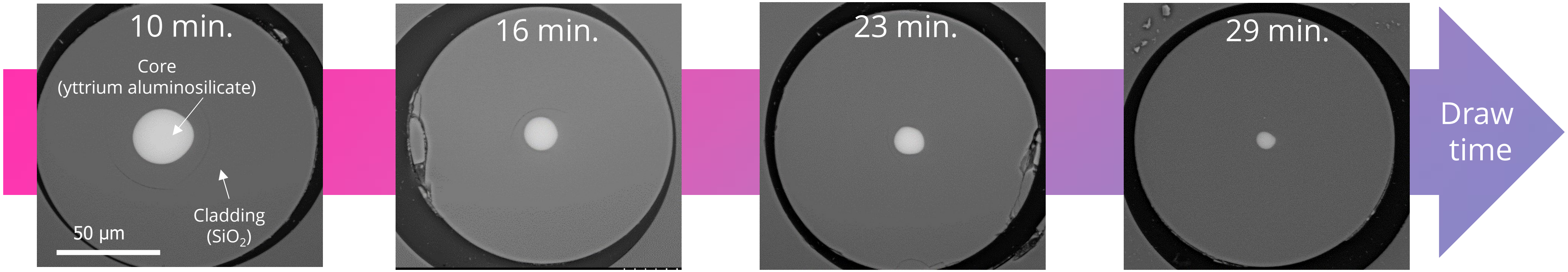
- High temperature (diffusion / dissolution)
- Non-volatile cores
- Losses… (dB/m range)
- *One must understand materials / glass science*

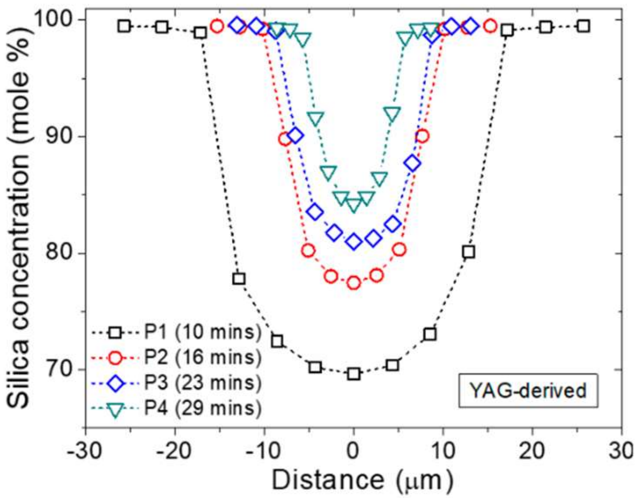
	Maximum concentration (mol%)	
Selected dopants into SiO_2	CVD	MCM
Al_2O_3	8	54
F	2	8
Rare earth oxide	2	10
Alkaline earth oxides	<2	18 (BaO)



P. Dragic, M. Cavillon, J. Ballato, *Applied Physics Reviews*, 5, 2018

The molten core method – Typical features of a YAG-derived fiber





- Prediction of elemental evolution (dissolution / diffusion) possible!
- Difficulties since few samples, strongly material-dependent, process dependent etc.

M. Cavillon et al., *Materials*, **12**, 2019

Opportunities (and challenges) using the MCM through examples

- Intrinsically low nonlinearity all-glass optical fibers
- High temperature refractory optical fiber sensors

Intrinsically low nonlinearity all-glass optical fibers – Case of SiO_2-Al_2O_3

- Transport (delivery systems)
- Defense and security

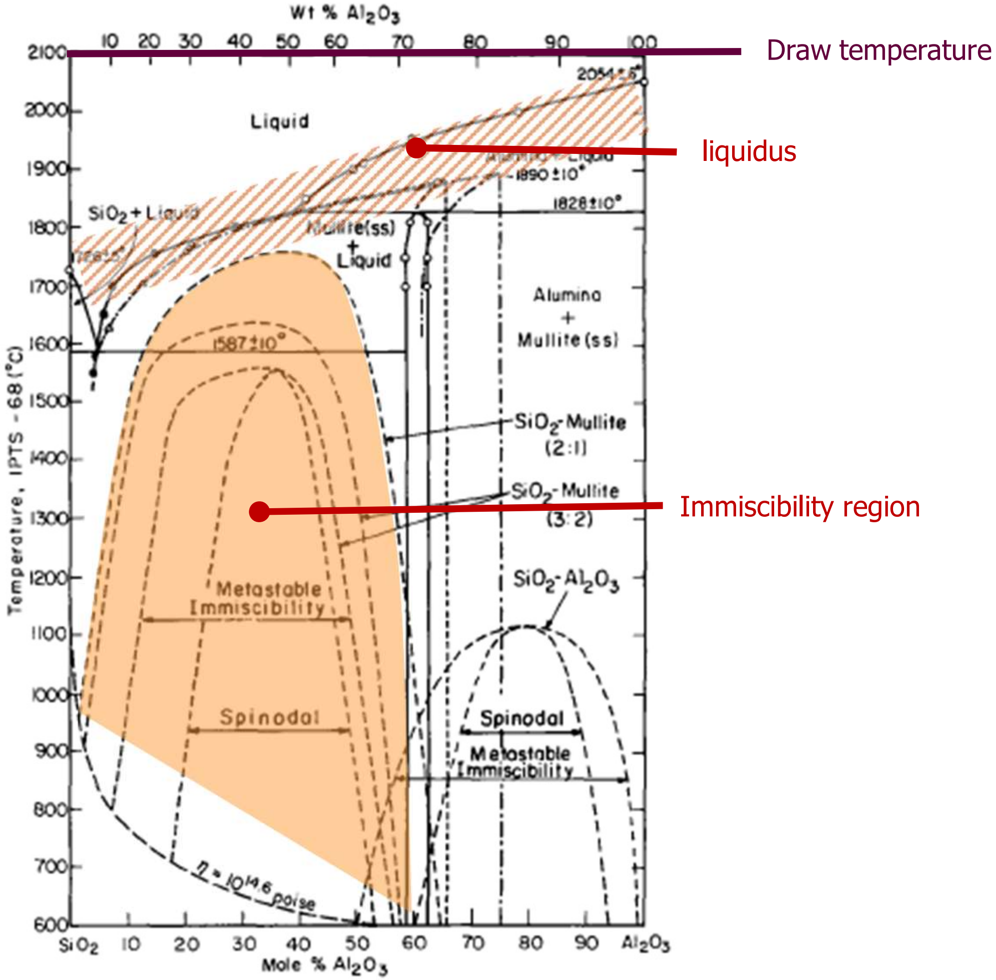
- Machining (cutting, drilling, welding)

Mitigation of stimulated Brillouin scattering (SBS)
→ Parasitic effect in high power fiber lasers

$p_{12}(Al_2O_3) < 0$

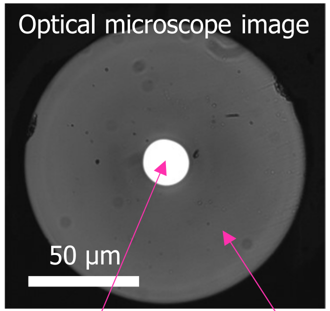
$p_{12}(SiO_2) > 0$

$$BGC = \frac{2\pi n^7 \mathbf{p_{12}^2}}{c\lambda^2 \rho V_a \Delta\nu_B}$$

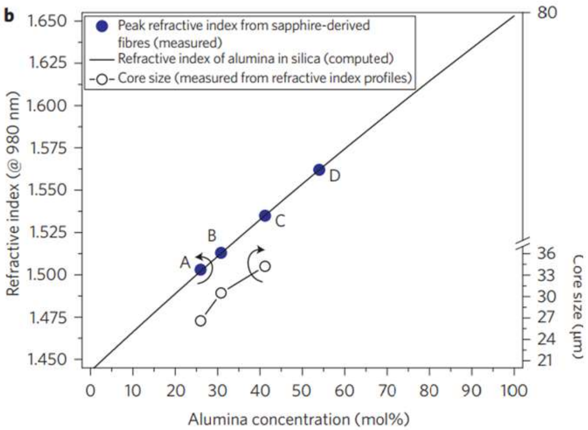


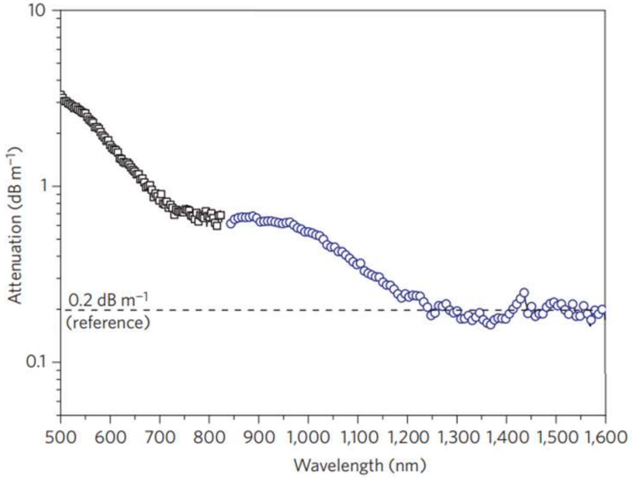
S. Risbud and J. Pask, *JACerS*, **60**, 418 - 424 (1977)
P. Dragic et al., *Nat. Photonics*, **6**, 627-633 (2012)

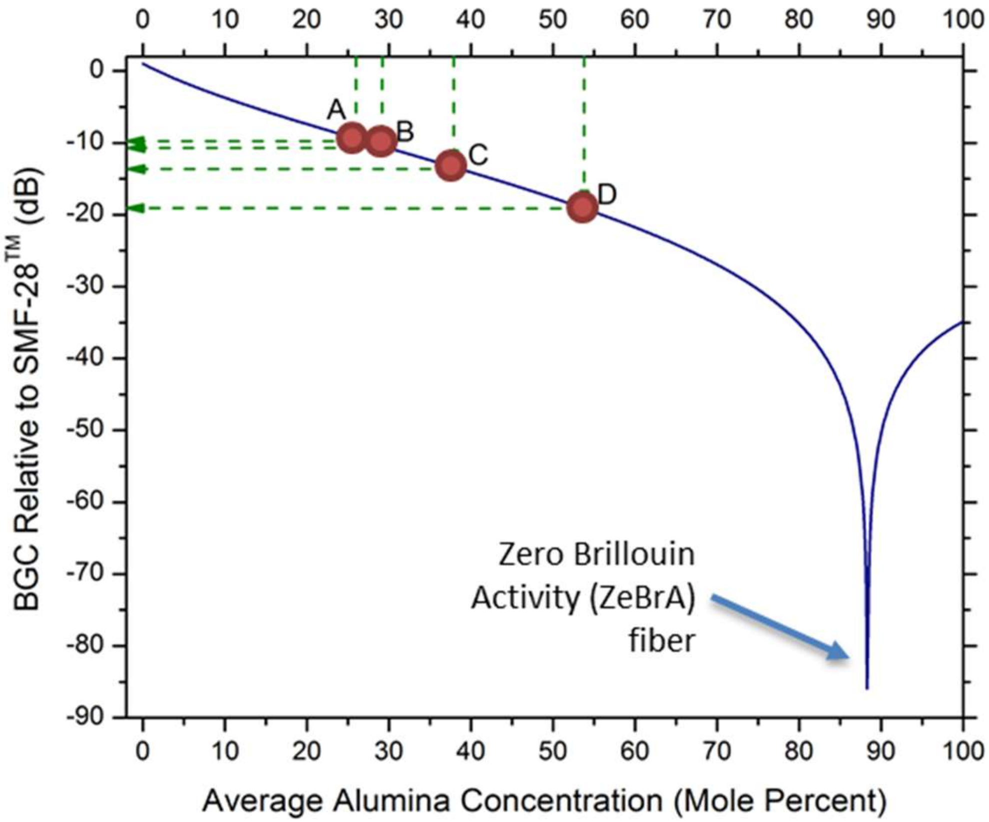
Intrinsically low nonlinearity all-glass optical fibers – Case of SiO_2-Al_2O_3



Al_2O_3-SiO_2 SiO_2



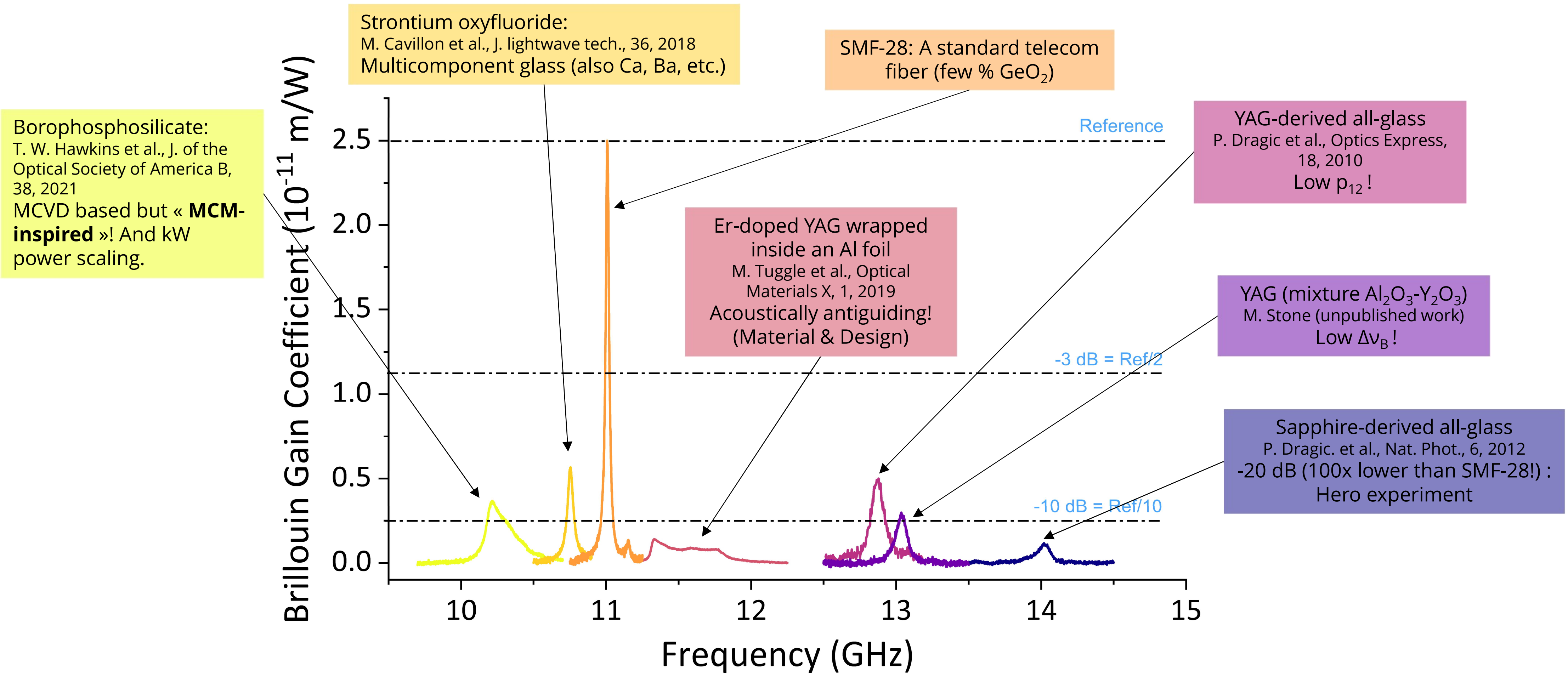




Measured BGC ~ 100× lower than commercial SMF!

P. Dragic et al., *Nat. Photonics*, 6, 2012

Intrinsically low nonlinearity all-glass optical fibers – More compositions…



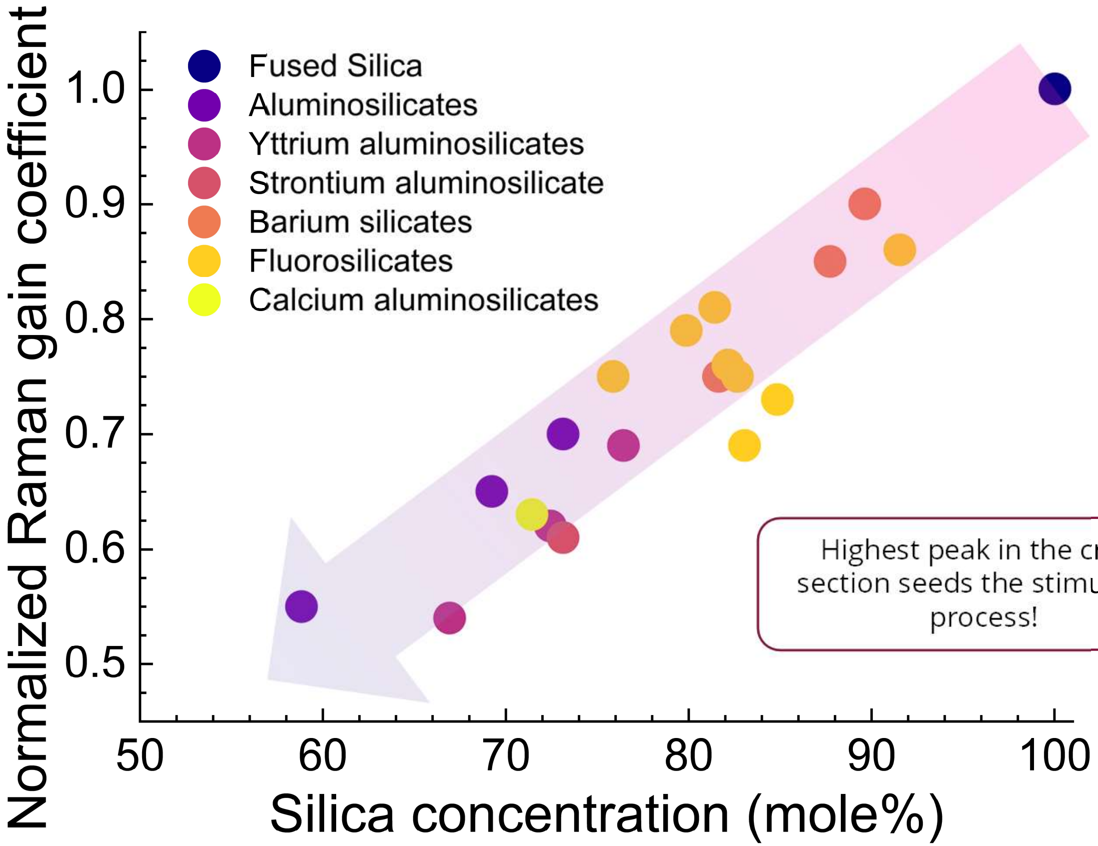
Intrinsically low nonlinearity all-glass optical fibers – More NL effects…

Other nonlinear « parasitic effects »

Stimulated Brillouin and Raman Scattering (SBS/SRS)
⟶ inelastic light scattering

Wave-mixing phenomena (SPM, FWM)
⟶ "Kerr nonlinearities", n_2-driven

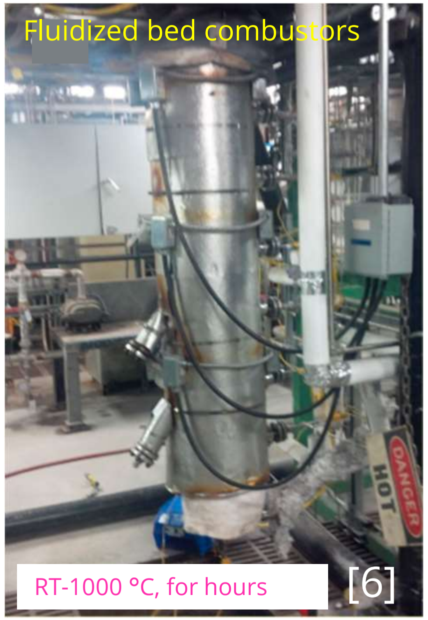
Transverse Mode Instabilities (TMI)
⟶ thermally–driven
⟶ modal interferences/deterioration of beam quality



Highest peak in the cross section seeds the stimulated process!

Plethora of possible compositions!

High temperature refractory optical fiber sensors



[1]: Laffont et al. Sensors, Vol. 18, 2018
[2]: Willsch et al. , SPIE Vol. 7503 (ICOFS), 2009
[3]: Bao et al., Sensors, Vol. 19, 2019
[4]: Mezzadri et al., SBMO-CBMag, 2012
[5]: Canagasabey et al. , BGPP Sensors, 2010
[6]: Mihailov. et al, Sensors, Vol. 17, 2017

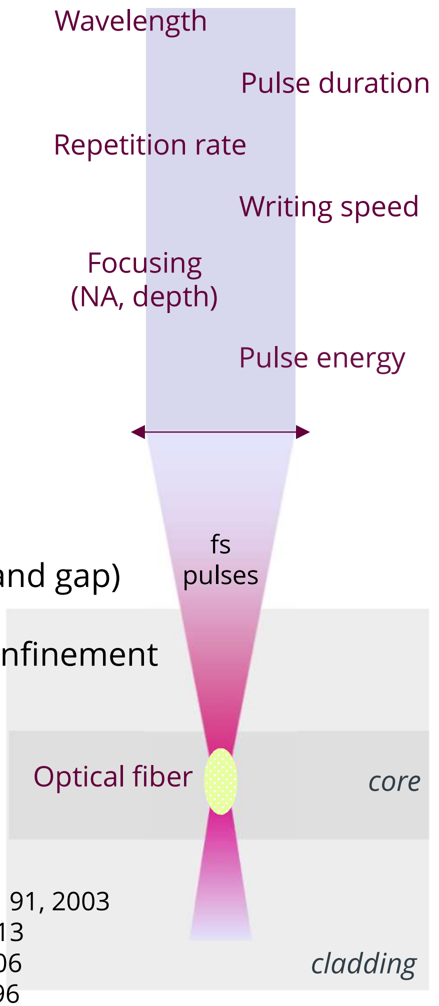
Oxide glass based optical fibers:

- compactness, lightness, flexibility, high-transparency
- chemical / radioactive / electromagnetic resistance
- Optical T/p sensing (FBGs, Rayleigh backscattering, etc.)

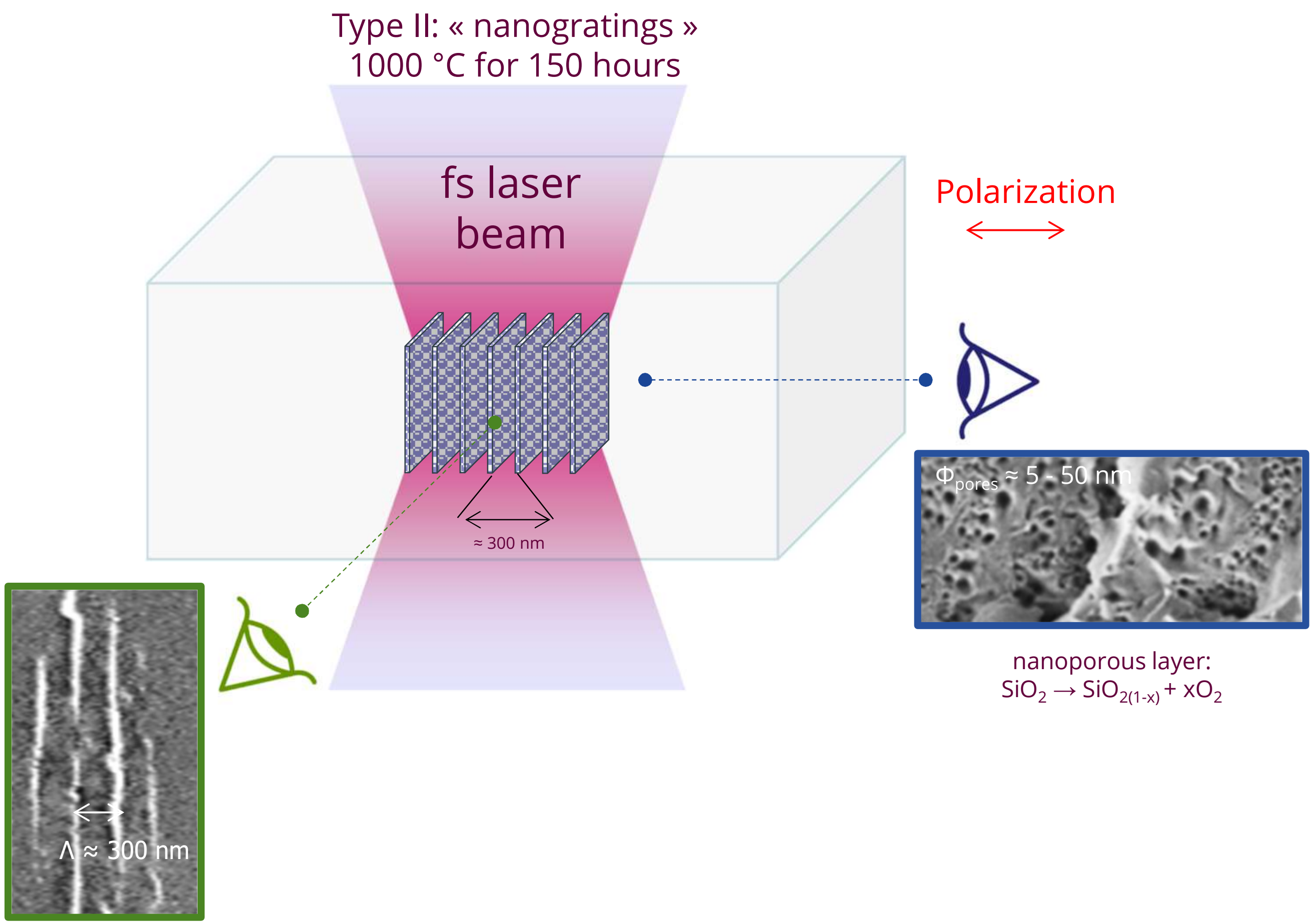
What must be done?

- Functionalization of MCM fibers
- High temperature operation!

High temperature refractory optical fiber sensors



- hν << E (band gap)
- TWs/cm²
- 3D bulk confinement



Shimotsuma et al., *APL*, 91, 2003
Lancry et al., *LPR*, 7, 2013
Grobnic et al., MST, 2006
Miura. al, Opt. Lett, 1996
Bricci et al., APL, 2006

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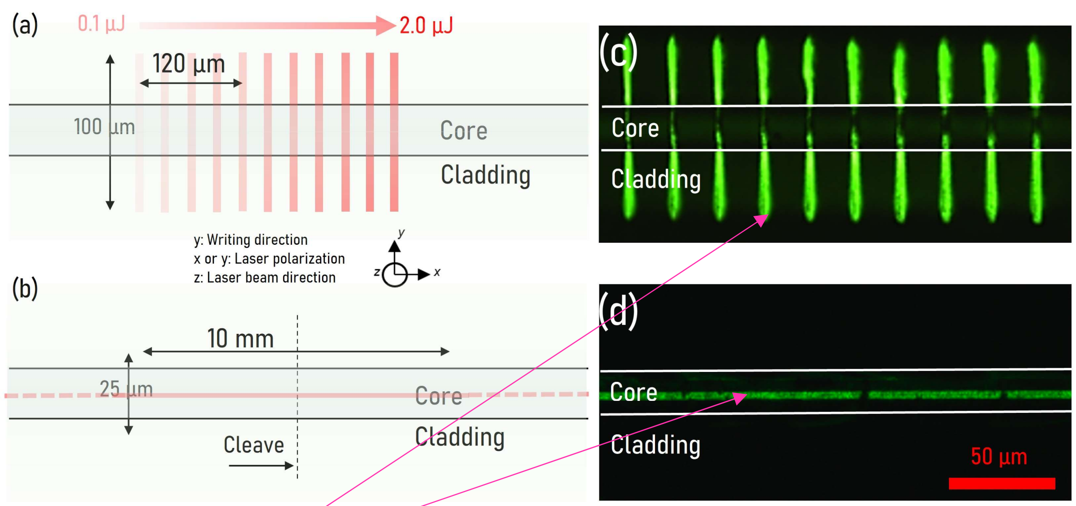
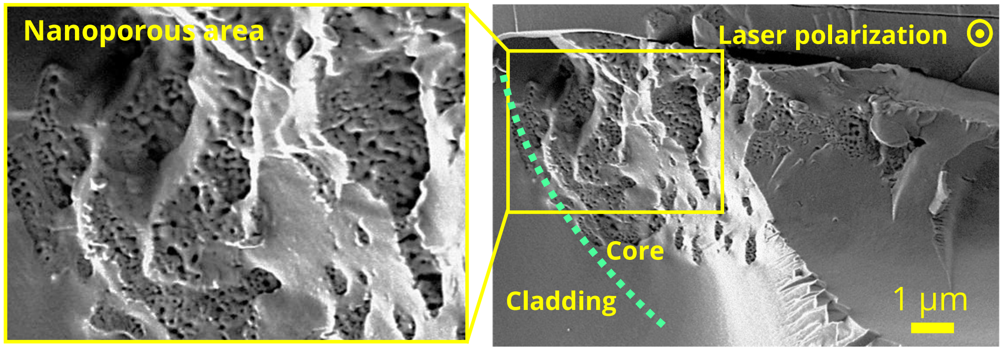
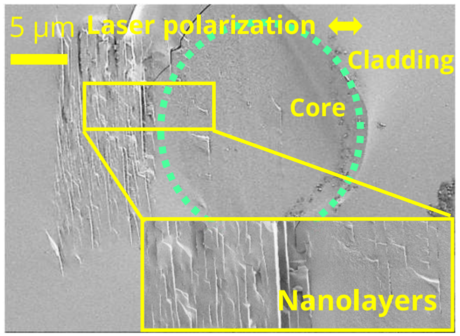
High temperature refractory optical fiber sensors – Case of Al_2O_3-SiO_2 again!

An opportunity to study nonconventional glass compositions



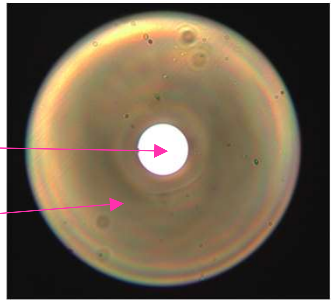
Birefringent structures (Type II) visible under polarized optical microscope

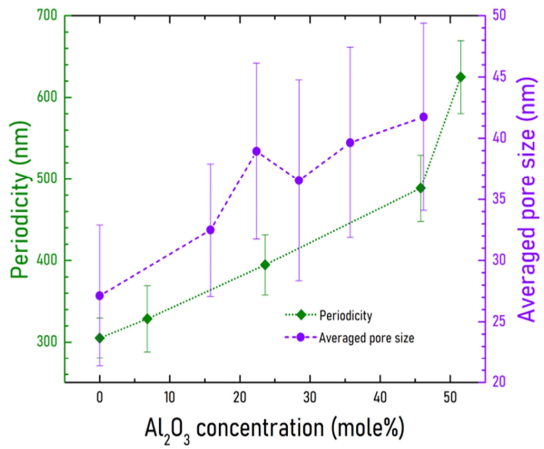




51.5 % Al_2O_3- 48.5% SiO_2

SiO_2



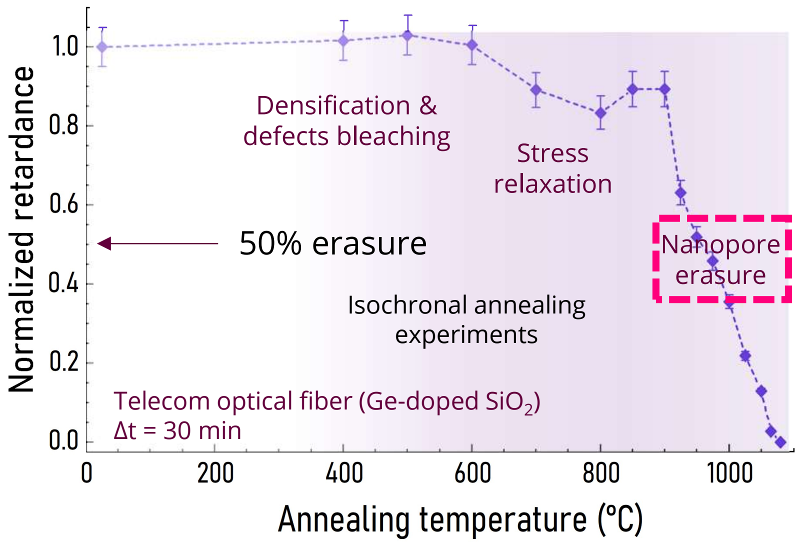


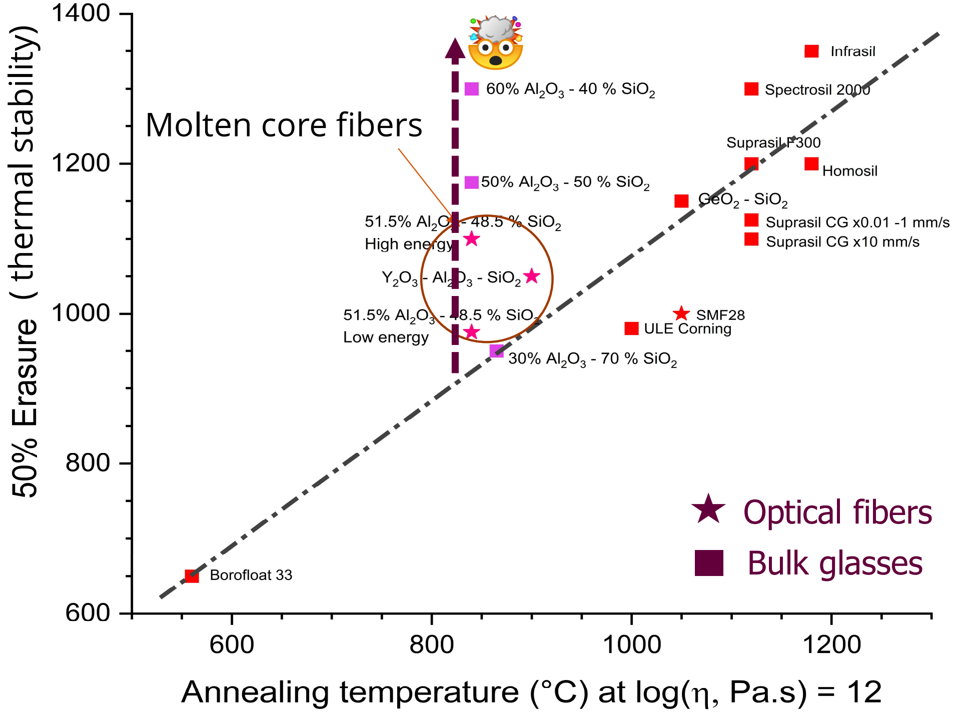
Investigate effect of composition (from to 0-50% Al_2O_3) on photo-induced transformations in one fiber!

Wang et al., AOM, Vol. (N/A), 2022

High temperature refractory optical fiber sensors

Challenging conventional fibers…





- Viscosity is the key player for thermal stability
- But also pore size, surface tension…
- … but also chemical migration, crystallization, etc.
- Recently temperature sensors developed (Rayleigh backscattering, Bragg grating)

$$\rho\left[R\ddot{R}+\frac{3}{2}\dot{R}^2\right]=[p_v-p_\infty(t)]-\frac{2S}{R}-4\mu\frac{\dot{R}}{R}$$

Rayleigh-Plesset equation to predict nanopore erasure

Pressure difference

Surface tension

Glass viscosity

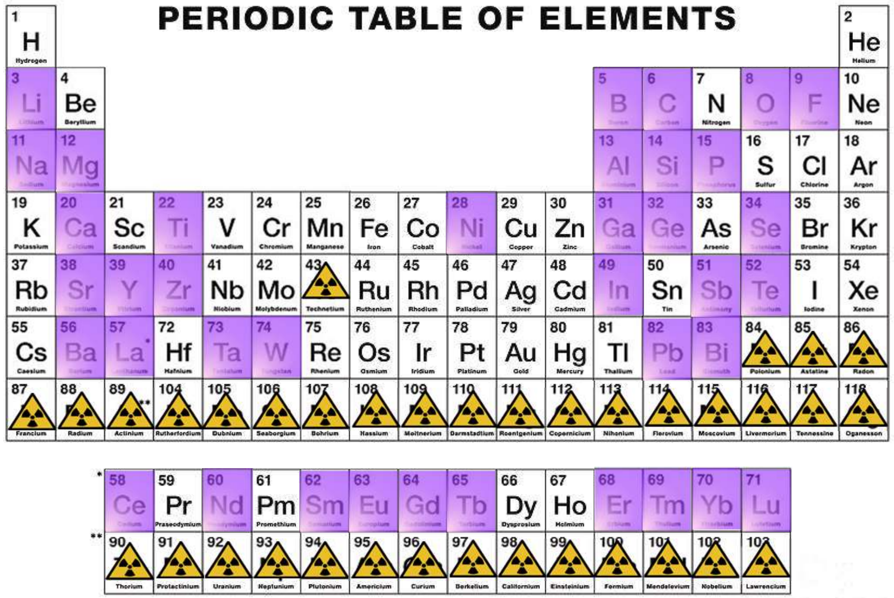
Y. Wang et al., *Advanced Optical Materials*, (N/A), 2022
M. Cavillon et al., *J. Phys. Photonics*, 1, 2019

Y. Wang et al., *JaCerS*, 103, 2020
Cavillon et al., *Appl. Phys. A*, 126, 2020

Conclusions

- Molten core method (MCM) is a nonconventional fiber fabrication technique
- Commercially scalable; process that yields (depending on material family) long lengths at practical speeds.
- all sorts of fun, useful, and novel glass and crystal science; amorphous and crystalline core fibers
- Also crystalline SC molten core fibers…!

Thank you for your attention!



Special thanks to John Ballato & Peter Dragic!