

From the periodic table to the optical fiber

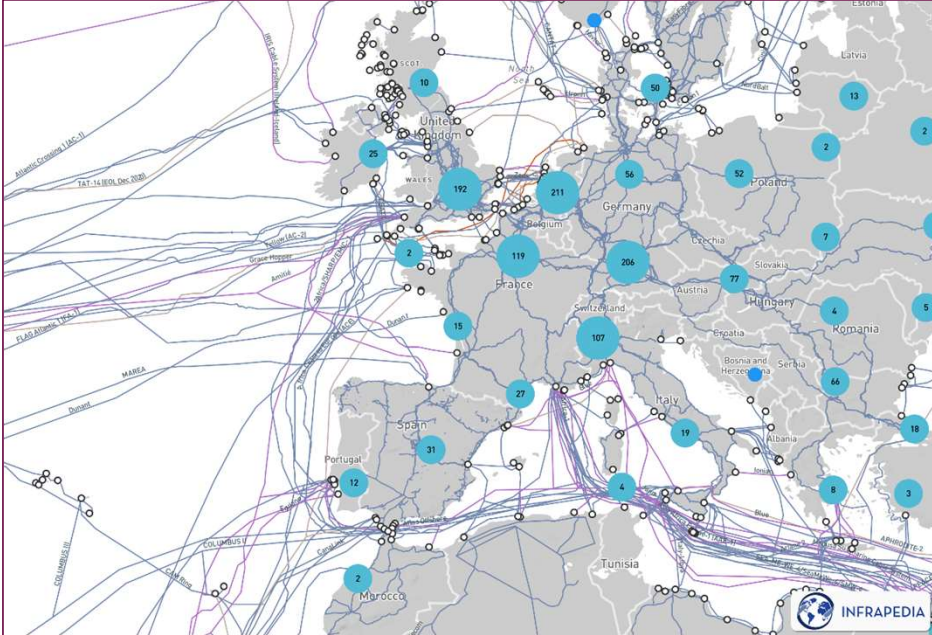
The exciting aspects of the Molten Core Method

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France

Telecom optical fibers: A success, with no doubt!

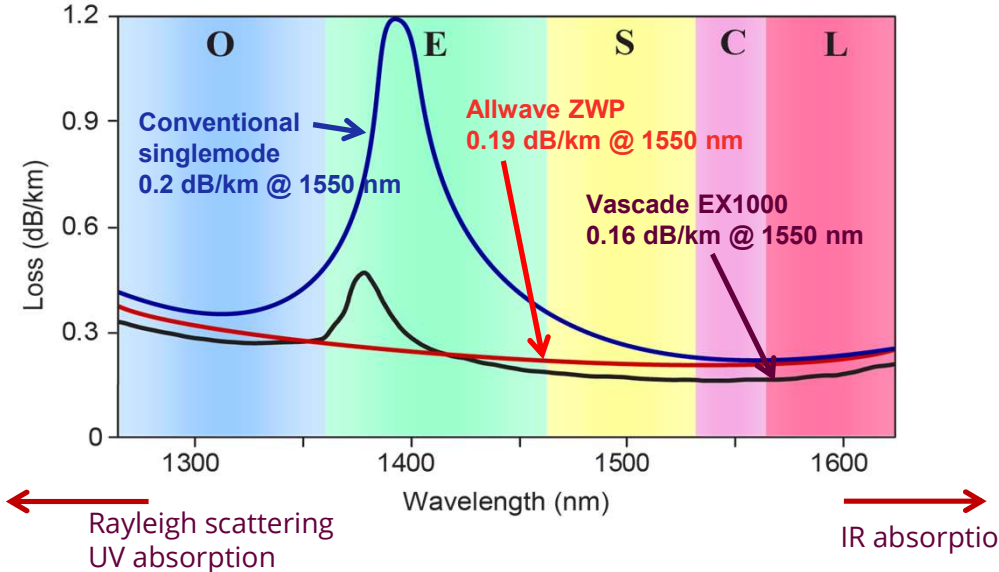
Look at the map...



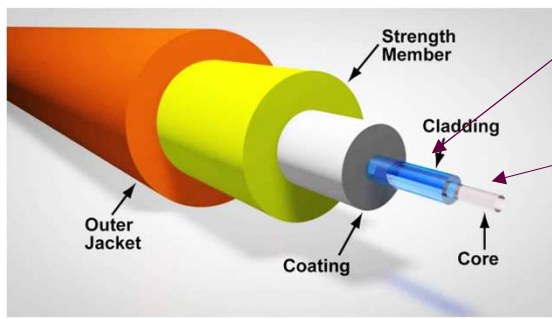
Look at the numbers...

- 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...



Look at the structure...

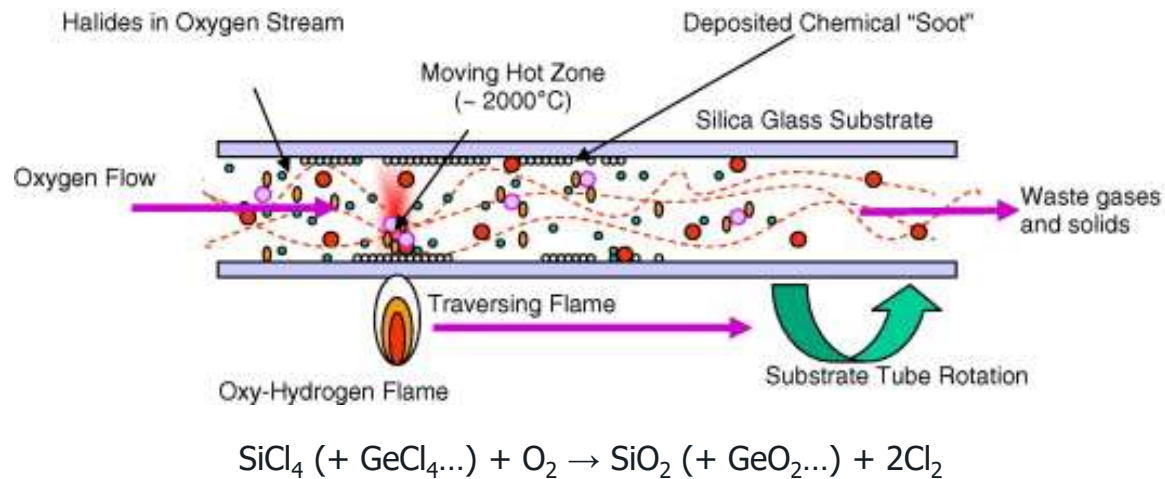


$\Phi_{\text{cladding}} = 125 \mu\text{m}$
Silica (SiO_2)

$\Phi_{\text{core}} = 10 \mu\text{m}$
 $\text{SiO}_2 + 3\text{-}4\% \text{ GeO}_2$

Because silica + CVD techniques work great...

Chemical vapor deposition (CVD) for preform fabrication



Great because...

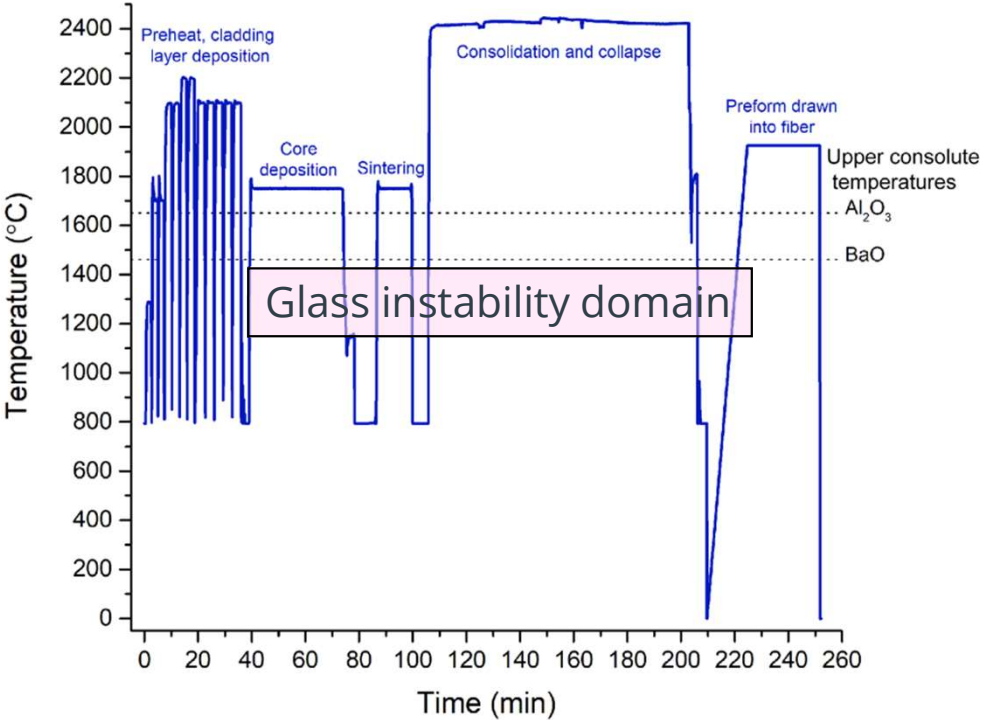
- Nearly intrinsic purity achievable (leads to very low losses)
- Good control of dopant concentration and refractive index profile (tailoring of cross-section)
- High speed (>50m/s), excellent size control, long length

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 ₂ O ₃	8
F	2
Rare earth oxide	2
Alkaline earth oxides	<2

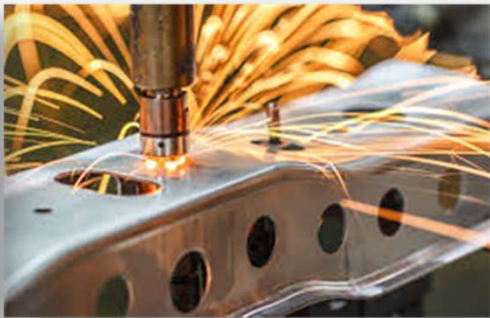
J. Ballato, P. Dragic, *Int. J. of Applied Glass Science*, 13, 2022
 P. Dragic, M. Cavillon, J. Ballato, *Applied Physics Reviews*, 5, 2018

Growing demand for ever more-sophisticated optical fibers

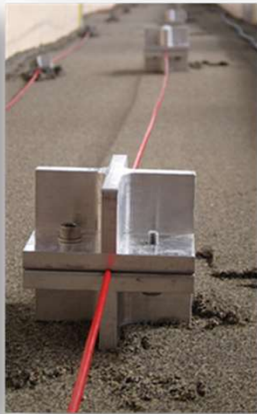
Communications



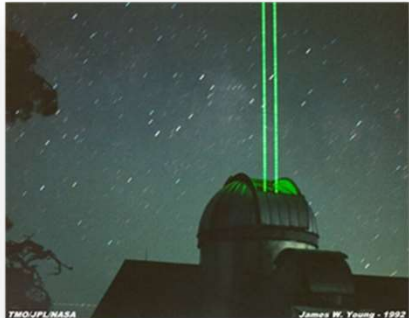
Machining / Manufacturing



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

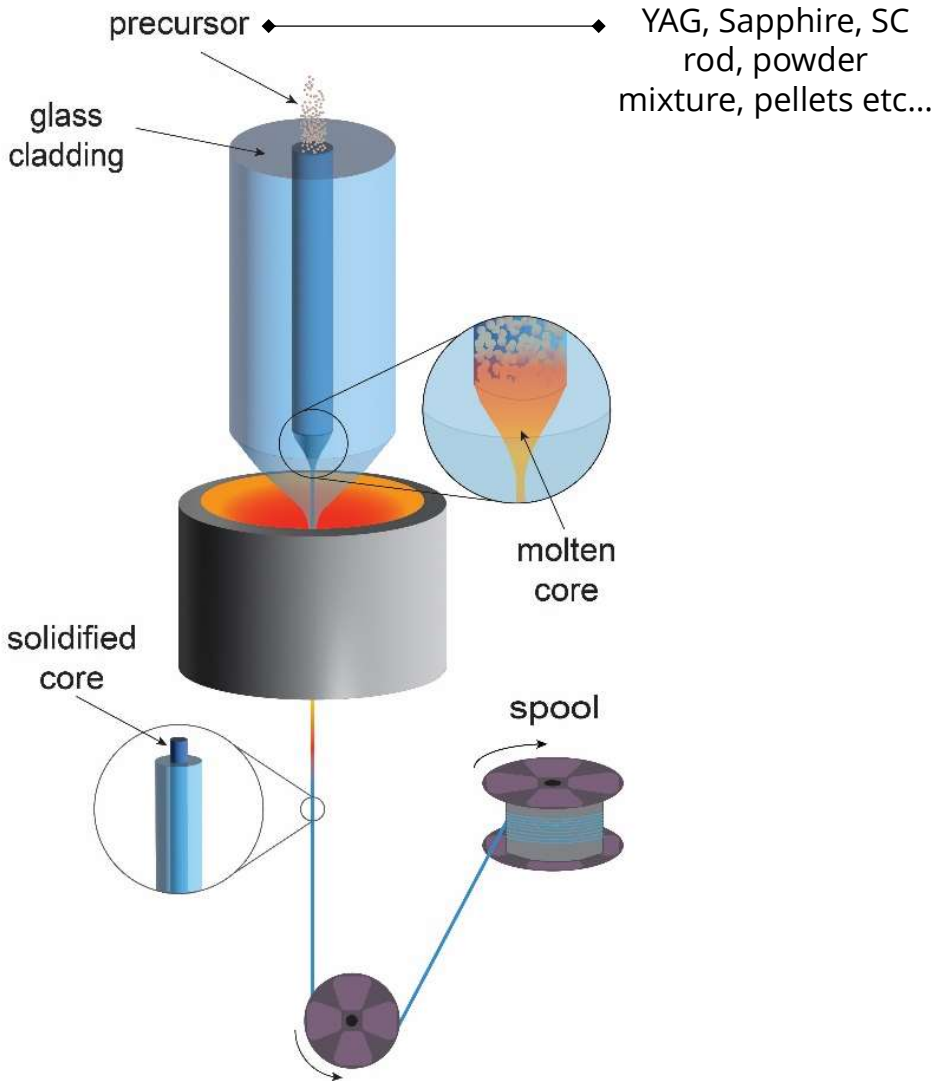
Advantages

- 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)
- Amendable to very wide range of materials

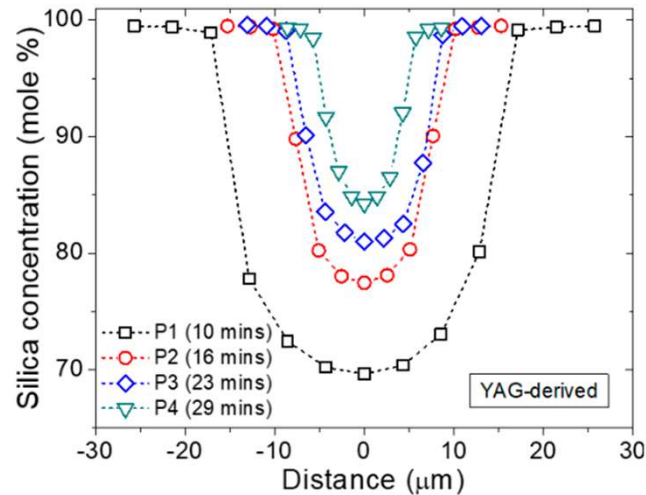
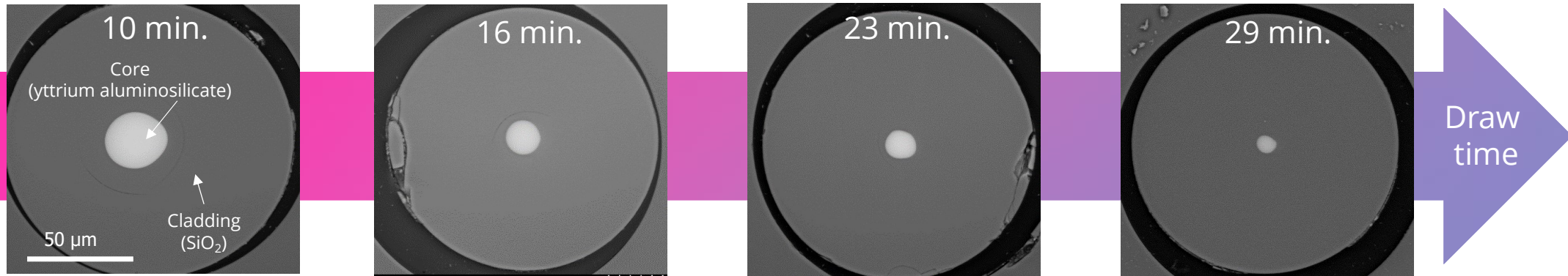
Drawbacks (?)

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

Selected dopants into SiO ₂	Maximum concentration (mol%)	
	CVD	MCM
Al ₂ O ₃	8	54
F	2	8
Rare earth oxide	2	10
Alkaline earth oxides	<2	18 (BaO)



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.

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 SiO₂-Al₂O₃



- Transport (delivery systems)
- Defense and security

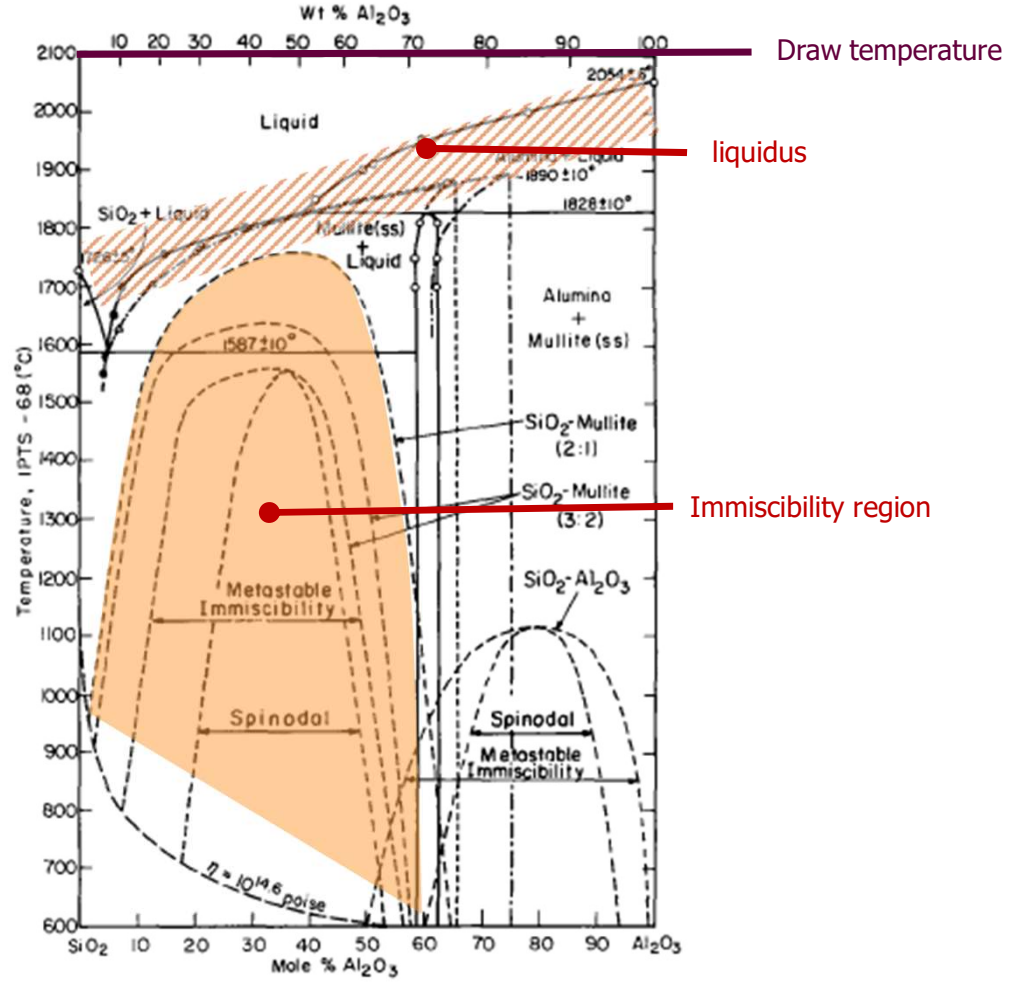


- Machining (cutting, drilling, welding)

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

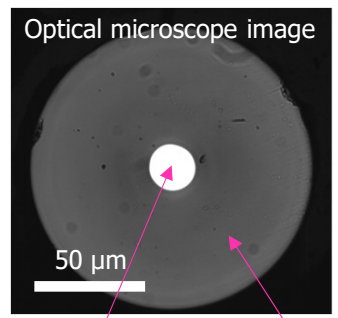
$$BGC = \frac{2\pi n^7 p_{12}^2}{c\lambda^2 \rho V_a \Delta v_B}$$

$p_{12}(Al_2O_3) < 0$
 $p_{12}(SiO_2) > 0$



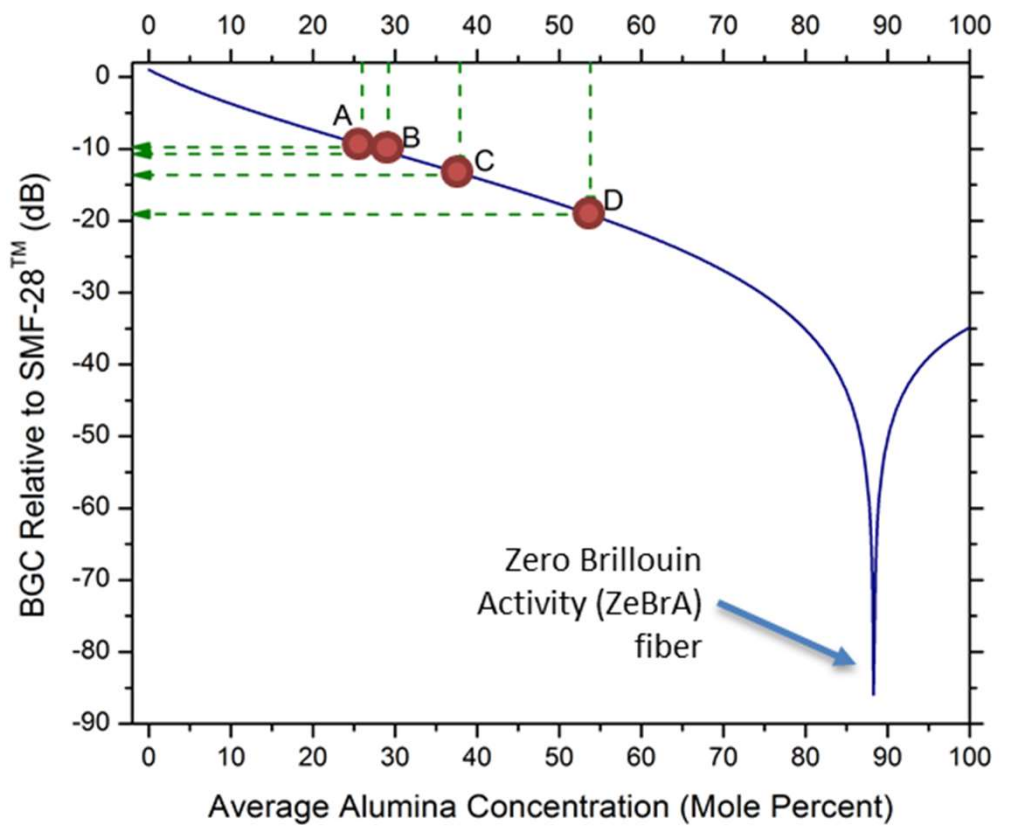
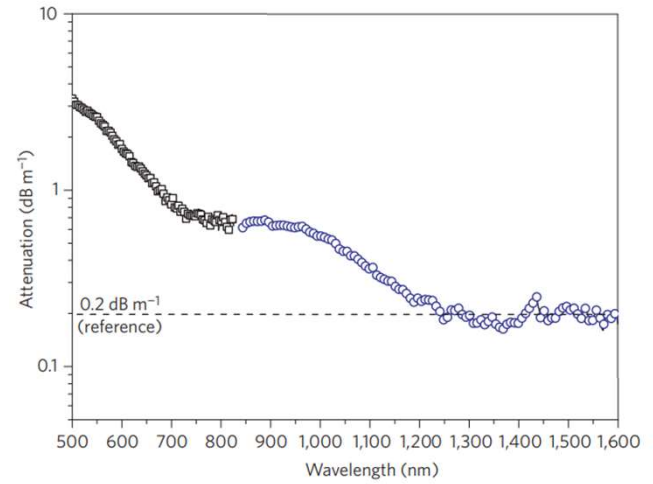
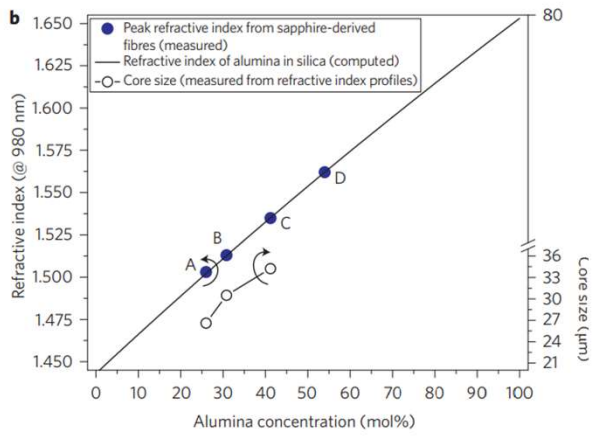
S. Risbud and J. Pask, *JACerS*, **60**, 418 - 424 (1977)
 P. Dragic et al., *Nat. Photonics*, **6**, 627-633 (2012)

Intrinsically low nonlinearity all-glass optical fibers – Case of SiO₂-Al₂O₃



Al₂O₃-SiO₂

SiO₂



Measured BGC ~ 100× lower than commercial SMF!

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

Borophosphosilicate:
 T. W. Hawkins et al., J. of the Optical Society of America B, 38, 2021
 MCVD based but « **MCM-inspired** »! And kW power scaling.

Strontium oxyfluoride:
 M. Cavillon et al., J. lightwave tech., 36, 2018
 Multicomponent glass (also Ca, Ba, etc.)

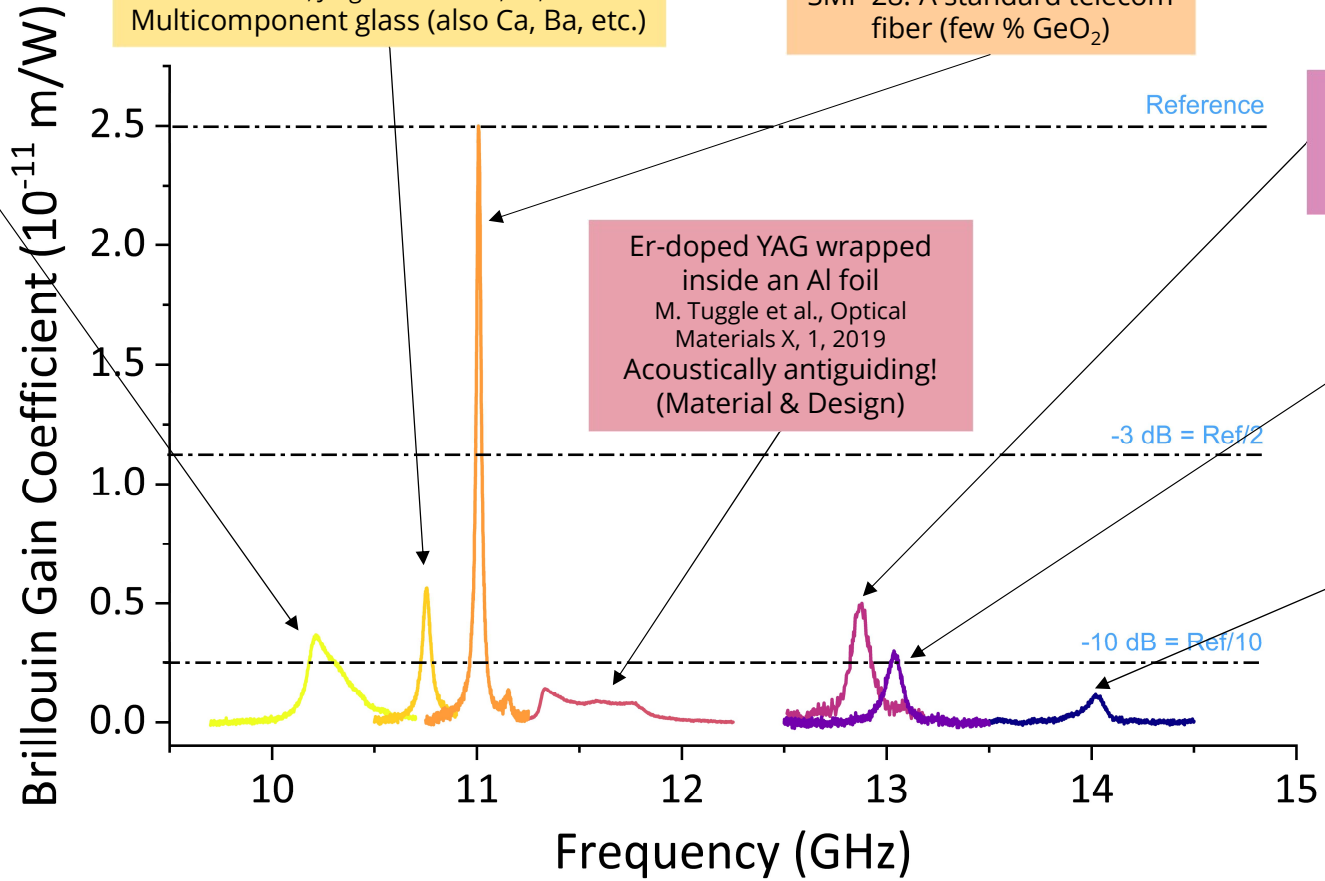
SMF-28: A standard telecom fiber (few % GeO₂)

Er-doped YAG wrapped inside an Al foil
 M. Tuggle et al., Optical Materials X, 1, 2019
 Acoustically antiguiding! (Material & Design)

YAG-derived all-glass
 P. Dragic et al., Optics Express, 18, 2010
 Low p_{12} !

YAG (mixture Al₂O₃-Y₂O₃)
 M. Stone (unpublished work)
 Low Δv_B !

Sapphire-derived all-glass
 P. Dragic. et al., Nat. Phot., 6, 2012
 -20 dB (100x lower than SMF-28!) : Hero experiment



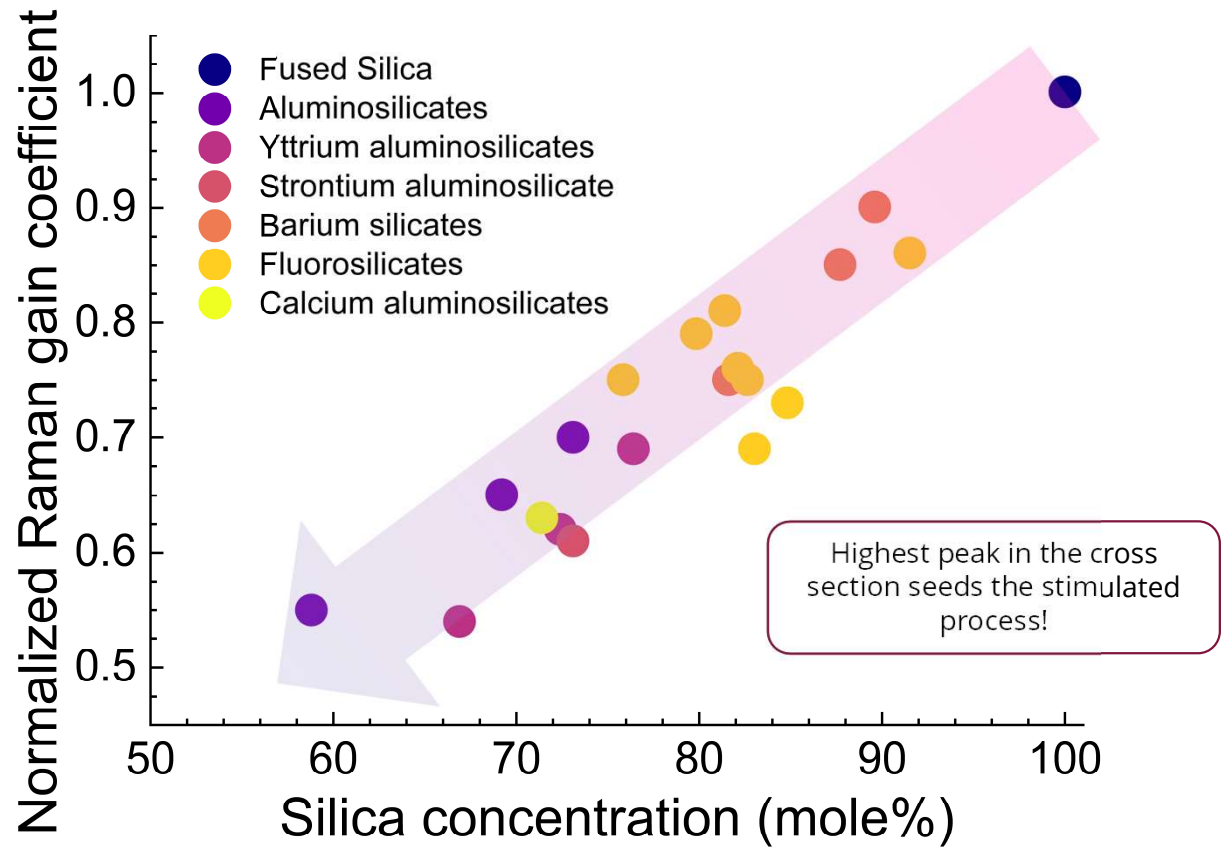
Intrinsically low nonlinearity all-glass optical fibers – More NL effects...

Other nonlinear « parasitic effects »

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

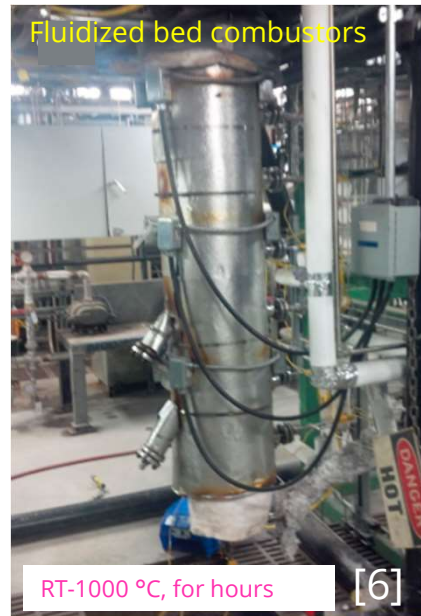
Wave-mixing phenomena (SPM, FWM)
→ “Kerr nonlinearities”, n_2 -driven

Transverse Mode Instabilities (TMI)
→ thermally-driven
→ modal interferences/deterioration of beam quality



Plethora of possible compositions!

High temperature refractory optical fiber sensors



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!

[1]: Laffont et al. Sensors, Vol. 18, 2018

[2]: Willsch et al. , SPIE Vol. 7503 (ICOFs), 2009

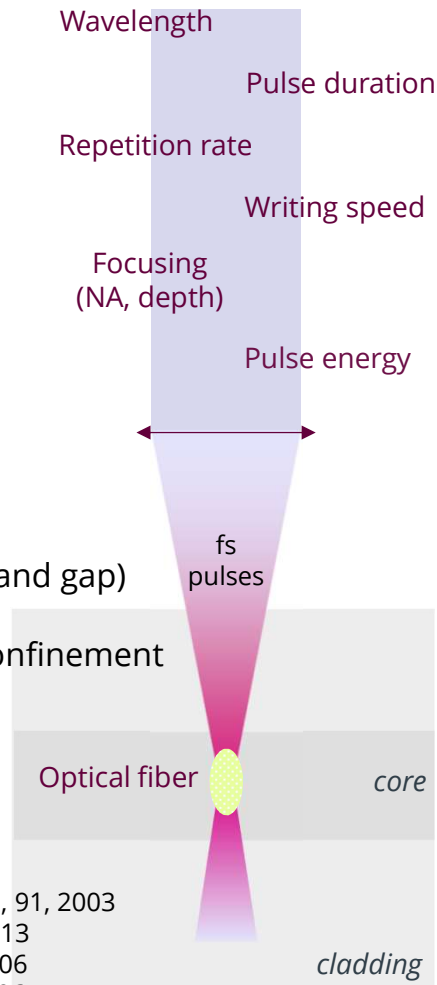
[3]: Bao et al., Sensors, Vol. 19, 2019

[4]: Mezzadri et al., SBMO-CBMag, 2012

[5]: Canagasabey et al. , BGPP Sensors, 2010

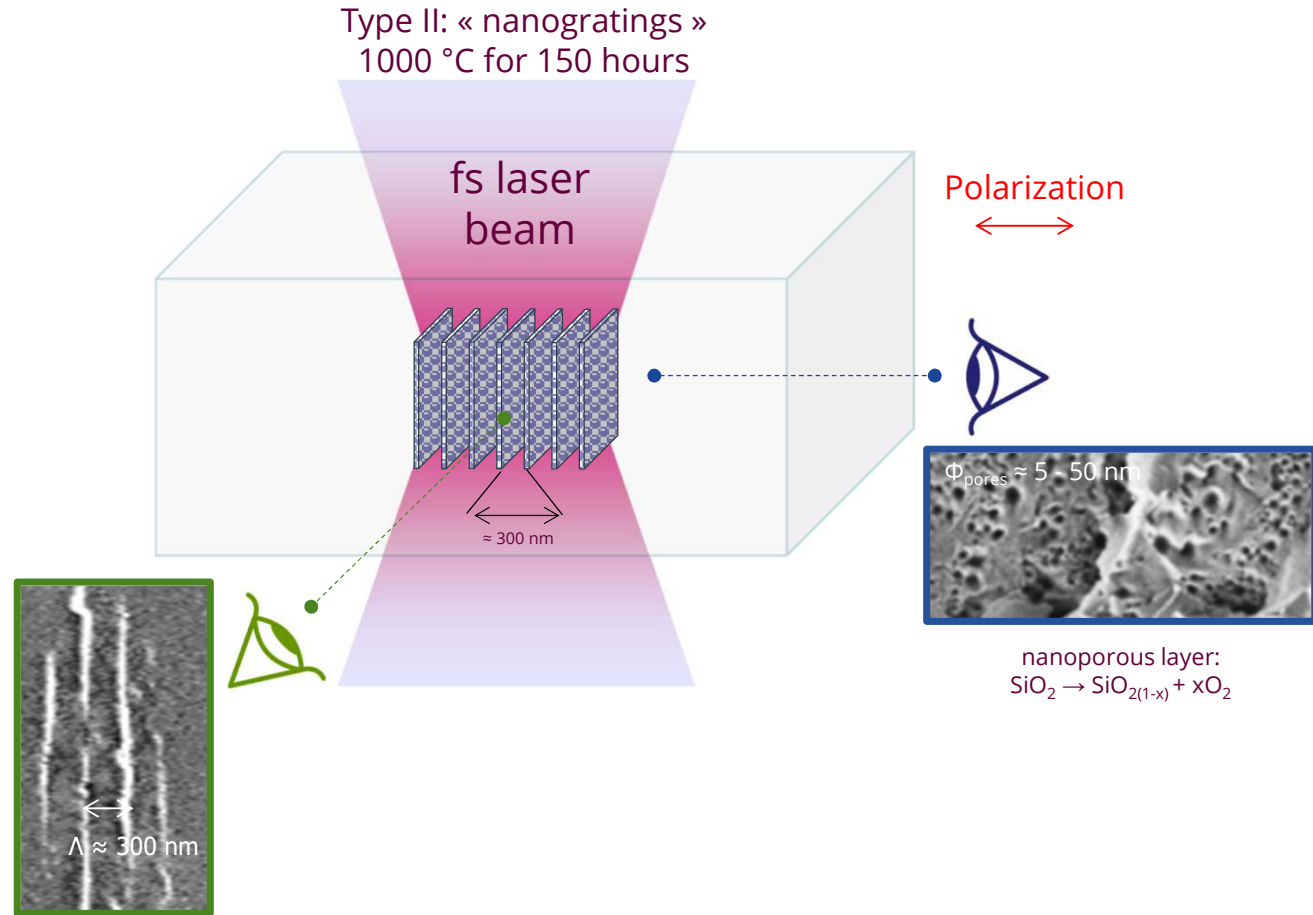
[6]: Mihailov. et al, Sensors, Vol. 17, 2017

High temperature refractory optical fiber sensors



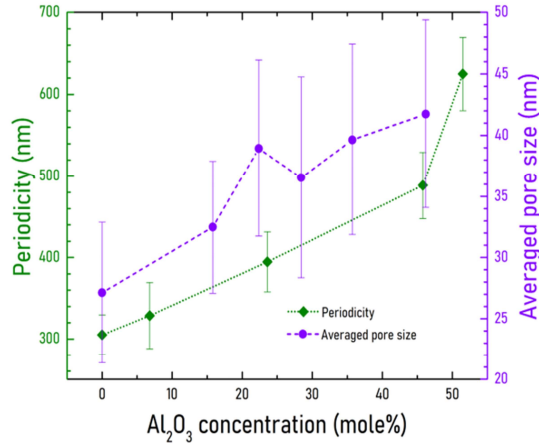
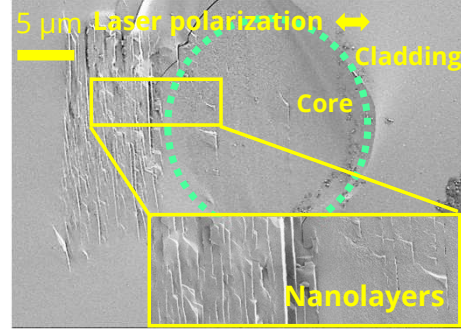
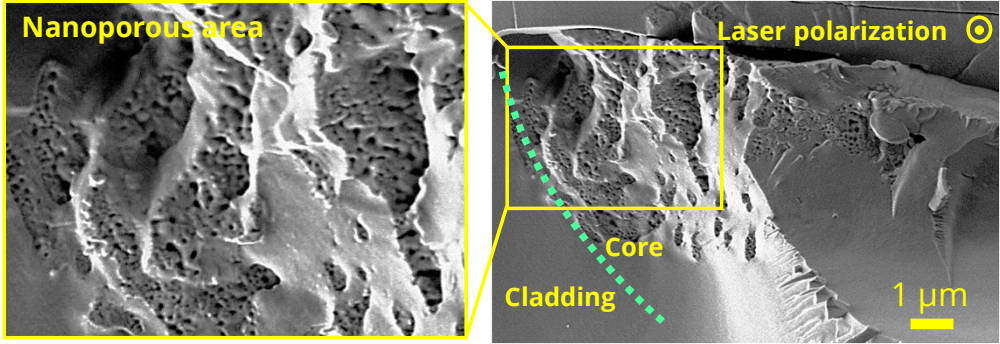
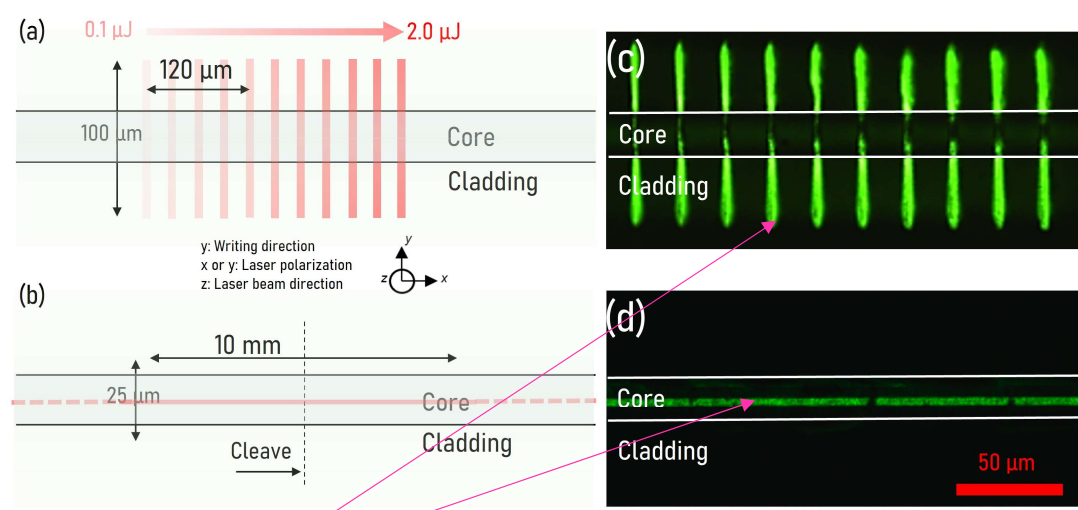
- $h\nu \ll E$ (band gap)
- TW/cm^2
- 3D bulk confinement

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

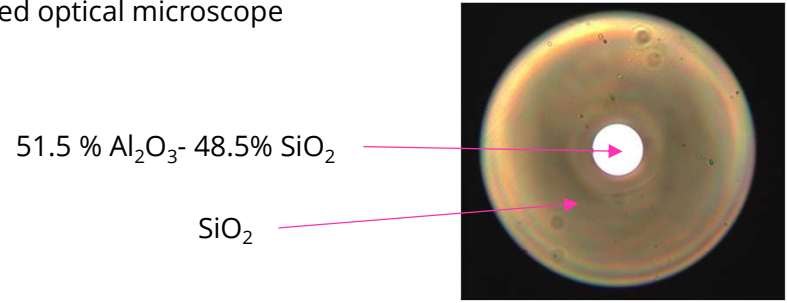


High temperature refractory optical fiber sensors – Case of Al₂O₃-SiO₂ again!

An opportunity to study nonconventional glass compositions



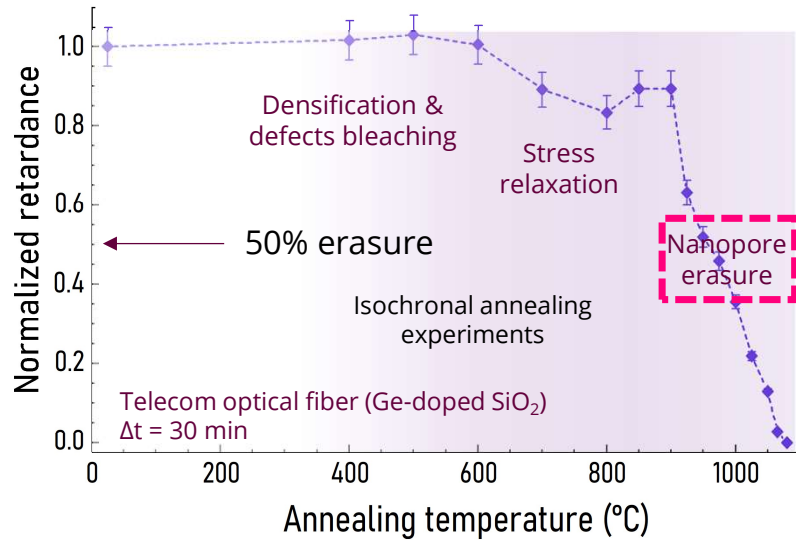
Birefringent structures (Type II) visible under polarized optical microscope



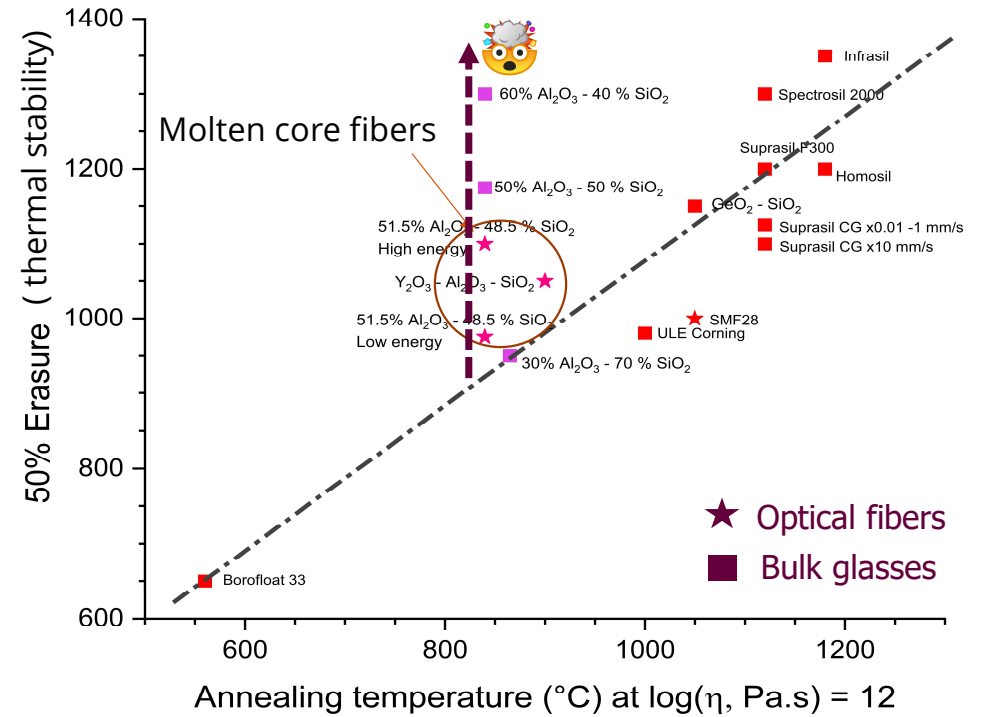
Investigate effect of composition (from 0-50% Al₂O₃) on photo-induced transformations in one fiber!

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!

PERIODIC TABLE OF ELEMENTS

1 H Hydrogen																	2 He Helium																												
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon																												
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon																												
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton																												
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon																												
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon																												
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson																												
<table border="1" style="width: 100%; text-align: center;"> <tr> <td>58 Ce Cerium</td> <td>59 Pr Praseodymium</td> <td>60 Nd Neodymium</td> <td>61 Pm Promethium</td> <td>62 Sm Samarium</td> <td>63 Eu Europium</td> <td>64 Gd Gadolinium</td> <td>65 Tb Terbium</td> <td>66 Dy Dysprosium</td> <td>67 Ho Holmium</td> <td>68 Er Erbium</td> <td>69 Tm Thulium</td> <td>70 Yb Ytterbium</td> <td>71 Lu Lutetium</td> </tr> <tr> <td>90 Th Thorium</td> <td>91 Pa Protactinium</td> <td>92 U Uranium</td> <td>93 Np Neptunium</td> <td>94 Pu Plutonium</td> <td>95 Am Americium</td> <td>96 Cm Curium</td> <td>97 Bk Berkelium</td> <td>98 Cf Californium</td> <td>99 Es Einsteinium</td> <td>100 Fm Fermium</td> <td>101 Md Mendelevium</td> <td>102 No Nobelium</td> <td>103 Lr Lawrencium</td> </tr> </table>																		58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium
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Special thanks to John Ballato & Peter Dragic!

