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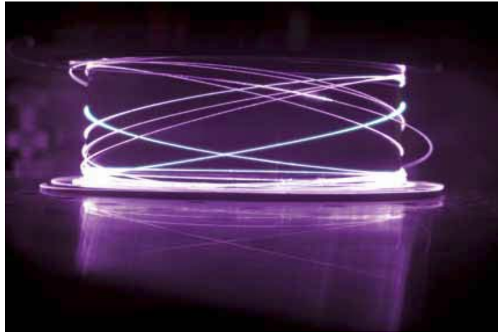

High Tech sand for High Tech optical fibers

Dr. Sönke Pilz

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Applied Fiber Technology - Institute for Applied Laser, Photonics and Surface Technologies (ALPS),

Bern University of Applied Sciences (BUAS), Pestalozzistrasse 20, 3400 Switzerland

In collaboration with:

reseachem more than molecules!

u^b UNIVERSITÄT BERN

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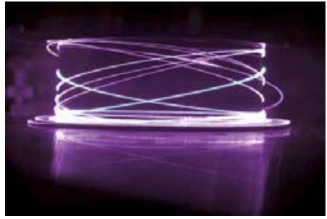
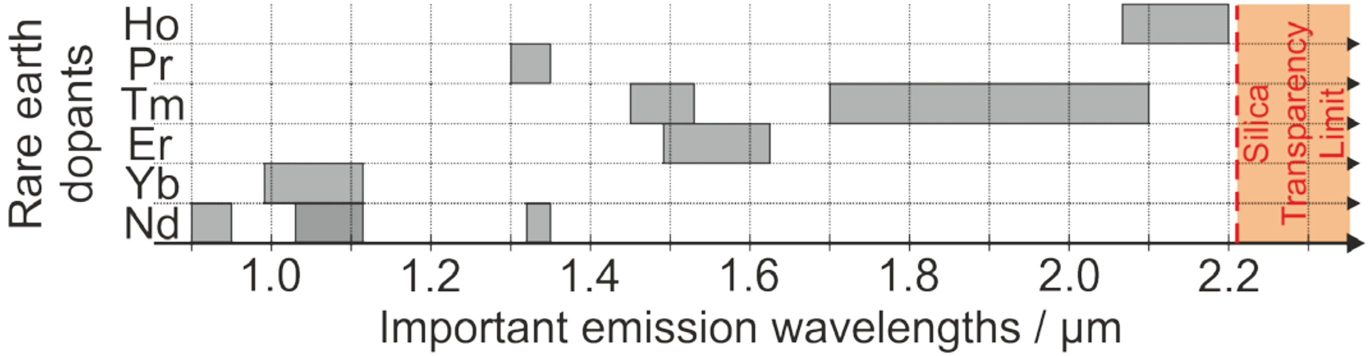
Motivation

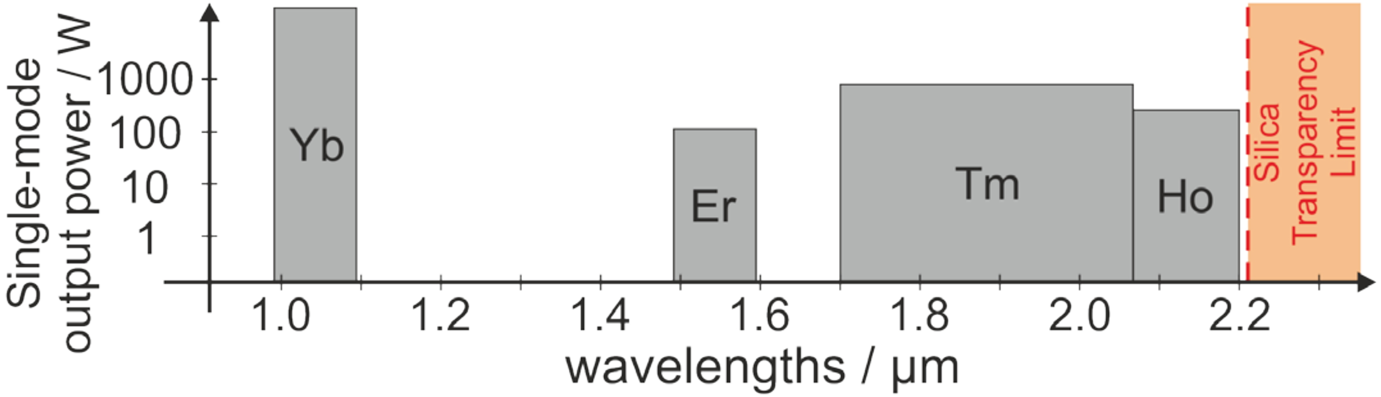


Current technology for active optical fibers:

- Typically based on individual or combinations of **rare earth** (RE):
  - Ytterbium (Yb)
  - Erbium (Er)
  - Thulium (Tm)
  - Holmium (Ho)
  - Neodymium (Nd)
  - Praseodymium (Pr)
  - → only **discrete** emission wavelengths and (relatively) **narrow** amplification windows

- **Efficient high-power** RE fiber lasers and amplifiers:
  - Yb
  - Er
  - Tm
  - Ho





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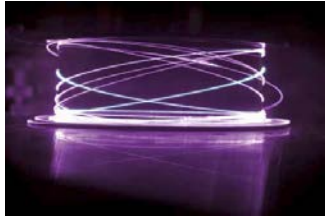

The market has an increasing demand for **specialty optical fibers** which in turn act as innovation driver.

Novel compositions

- **Novel dopants**
  → Expanding emission wavelengths
- **Multi-component doping**
  → Broadband sources and amplifiers
- **Higher doping concentrations**
  → Higher gain/output power
- **Tailoring of the refractive index**
- **New functionality/ properties**
  → e.g.: saturable absorber
- …

Novel geometries

- **Microstructures**
- **Large mode area designs**
  → Higher output power
  → Less non-linear effects
- **Multi-core fibers**
- …

→ An alternative to standard fiber production techniques

→ Modern fiber production methods tailored to the needs of the market

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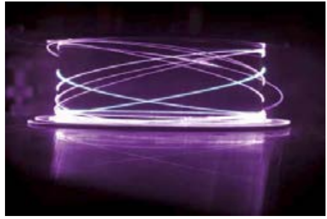
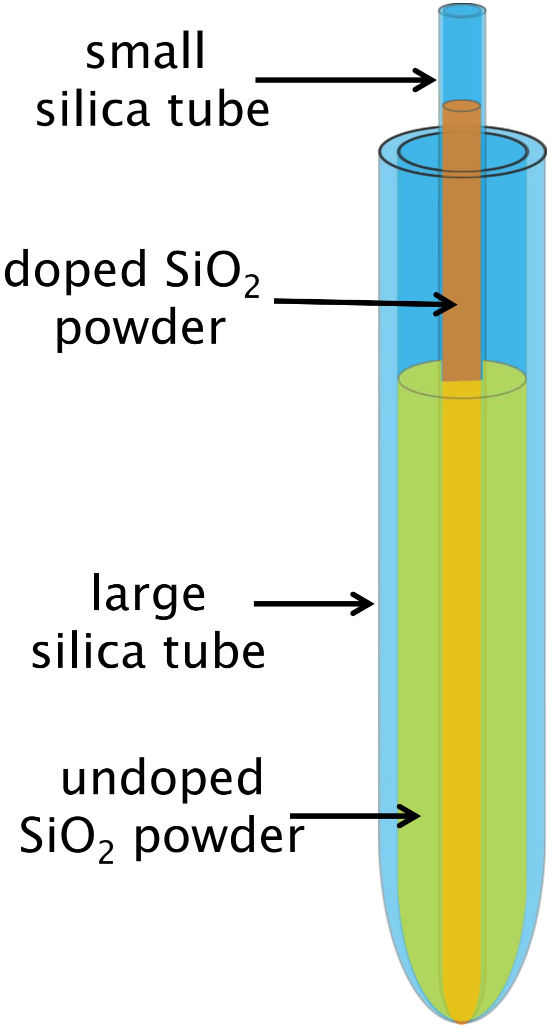


Powder-in-tube technique

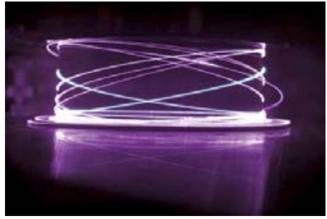
- Introduced in 1995 by **John Ballato** and **Elias Snitzer**[1]
- Different versions of the powder-in-tube were developed:
  - Diverse powder doping techniques and preform assembly strategies

Benefits:

- **Composition**
  - Wide variety of dopants:
    - Arbitrary compositions, high doping concentrations
- **Geometry**
  - Arbitrary designs (no symmetry required), e.g.:
    - no size limitations for doped regions (larger cores, claddings),



(1) J. Balltao and E. Snitzer «*Fabrication of fibers with high rare-earth concentrations for Faraday isolator applications*»; Applied Optics, 34(30), 6848, (1995)



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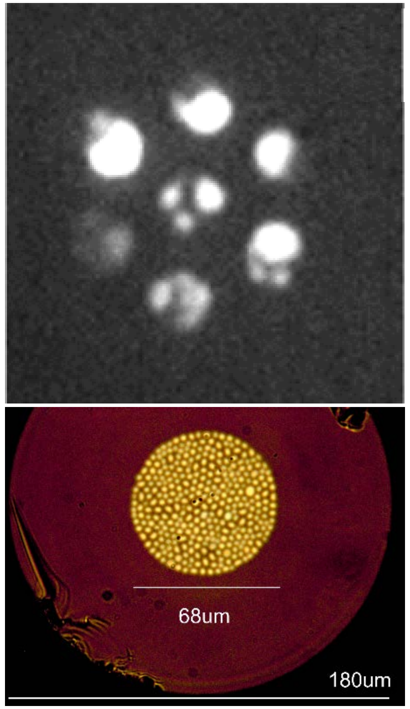
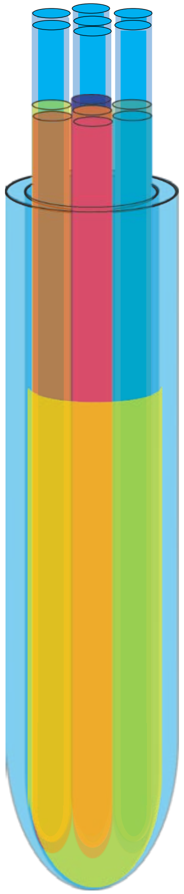


Multi-core



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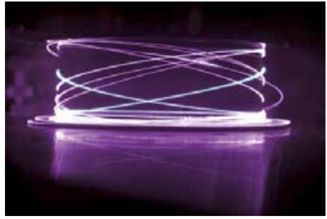

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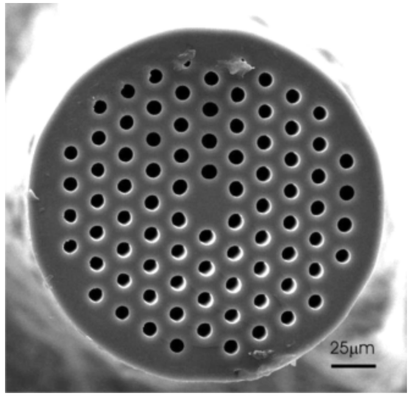
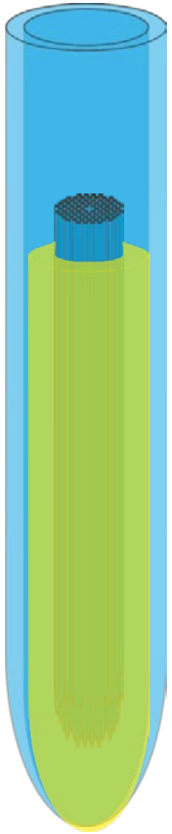


PCF



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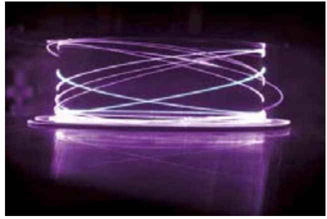
Powder-in-tube technique



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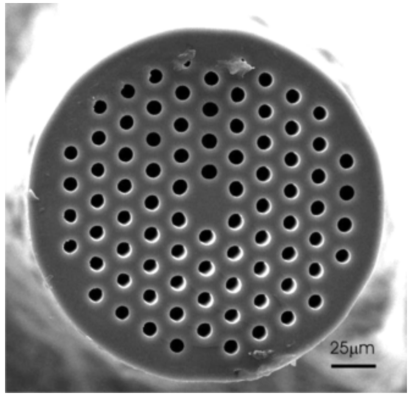
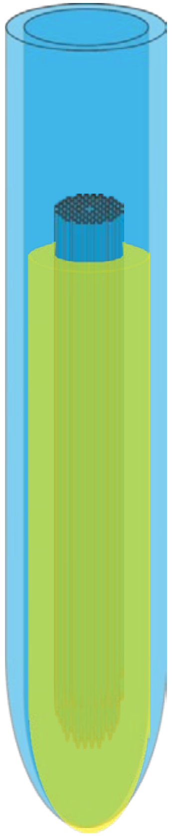
- **Geometry**
  - Arbitrary designs (no symmetry required), e.g.:
    - no size limitations for doped regions (larger cores, claddings), Multi-core fibers, Microstructures (PCF, LCF)
- **Rapid prototyping** from in-stock powder/granulate
- **Cost effective**



PCF



Main drawback:

- **Higher losses** compared to standard techniques

→ Focus is on light sources (laser & amplifier) and not telecommunication

→ For doped fibers losses ≤0.2dB/m @633nm are sufficient for fiber based light sources

(1) J. Balltao and E. Snitzer «*Fabrication of fibers with high rare-earth concentrations for Faraday isolator applications*»; Applied Optics, 34(30), 6848, (1995)

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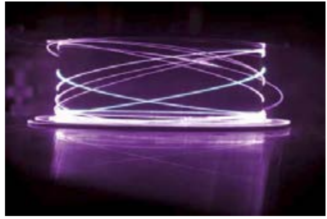
Granulated silica method (GSM)
Overview



- One variant of the powder-in-tube technique
- Developed by the institute of applied physics (IAP) of the university of Bern and the applied fiber technology group (AFT) of Bern university of applied sciences
- Granulated precursors

Granulate doping techniques

Oxide approach

- Large range of dopant(s) in **oxide form**

→ High doping concentrations (up to several at.%)

→ Inhomogeneous dopant(s) distribution

Sol-gel approach

- Large range of **water** or **alcohol soluble** dopant(s)

→ High doping concentrations (up to several at.%)

→ Intrinsic homogeneity

Preform assembly strategies

Rapid prototyping

- "Granulate-in-tube" preform
- Rapid
- Feasibility of doped granulate

→ high losses (≥0.35dB/m @633nm)

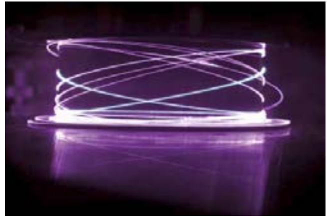
→ only piecewise good fibers

Vitrified preform

- "Rod-in-tube" preform: Pre-vitrified core rod (international project in progress)

→ Reduction of losses

Sol-Gel approach



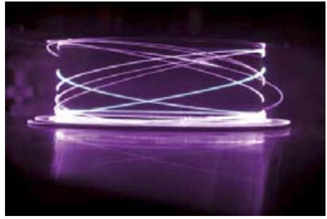
Benefits:

- Wide **variety** of dopants
  - any water or alcohol soluble dopants
  - doping at moderate temperature
- High **intrinsic homogeneity**
  - Homogeneously doped grains
- High **dopant concentrations** (up to several at.%)
- Full control of the **refractive index**, due to freedom of dopants and concentration (e.g. of Al and P)
- **Cost-effective**

Drawback:

- **Higher losses** compared to standard techniques
- Wet-chemical process: **OH-groups** (absorption)

Sol-Gel "Benchmark": Yb/Al/P: Theory

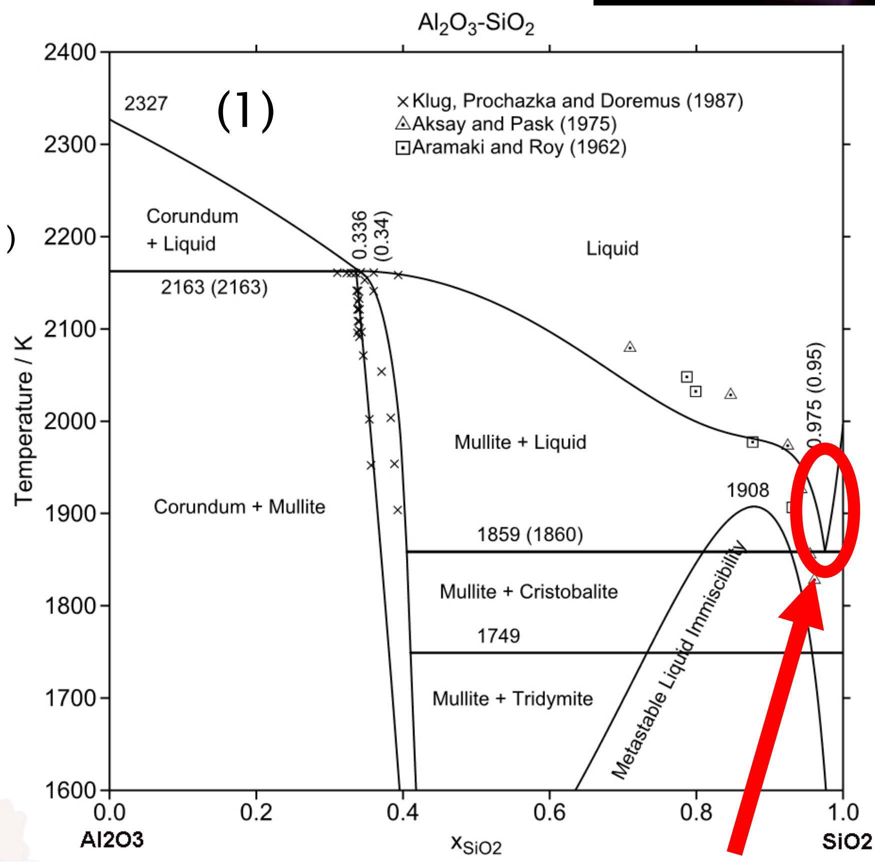


Optical active:

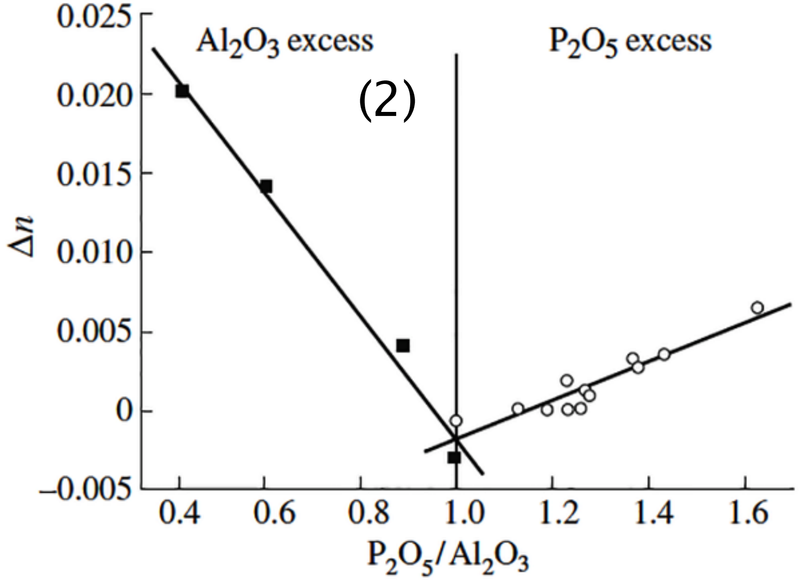
- Rare earth element: Ytterbium

Optical passive co-dopants:

- Aluminum: solubility of RE and control melting temperature(1)
- Phosphorous: photo-darkening (hard to incorporated by standard techniques)
- Al/P: refractive index control(2)



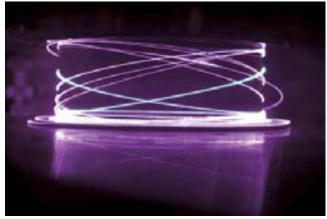
Up to 5 at.% of Aluminum decreases melting temperature of Al_2O_3 – SiO_2 system. Higher Al content lead to a steady increase of the melt temperature.



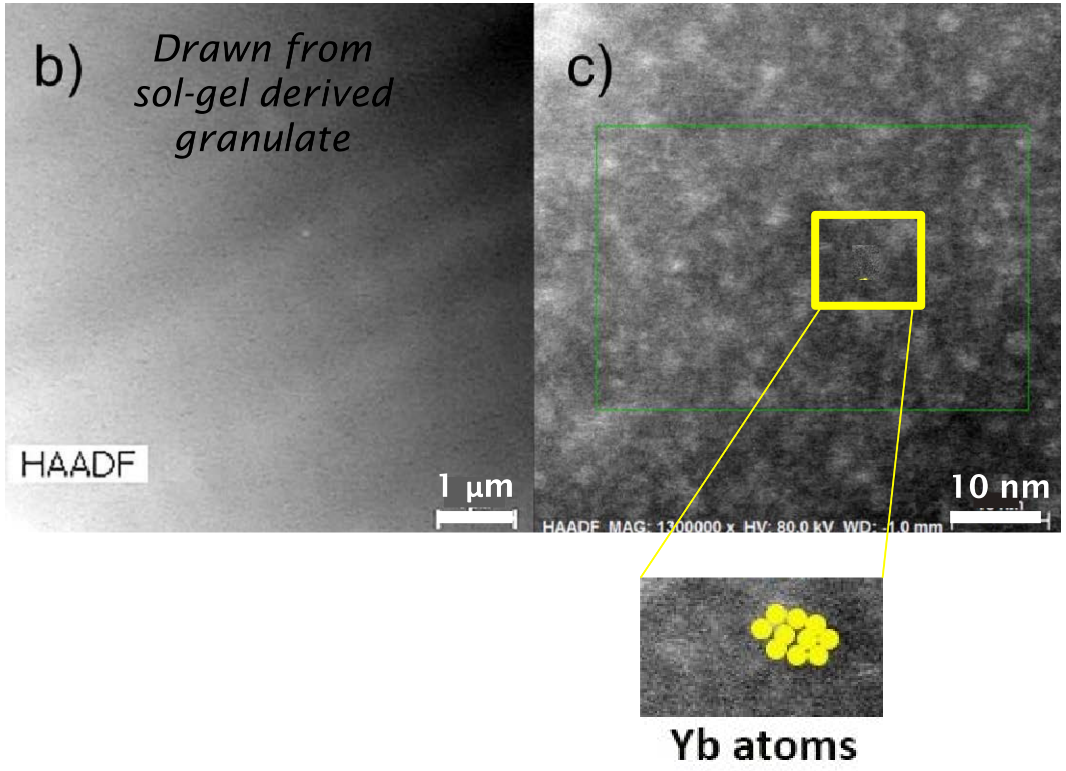
(1) http://resource.npl.co.uk/mtdata/dgox2.htm

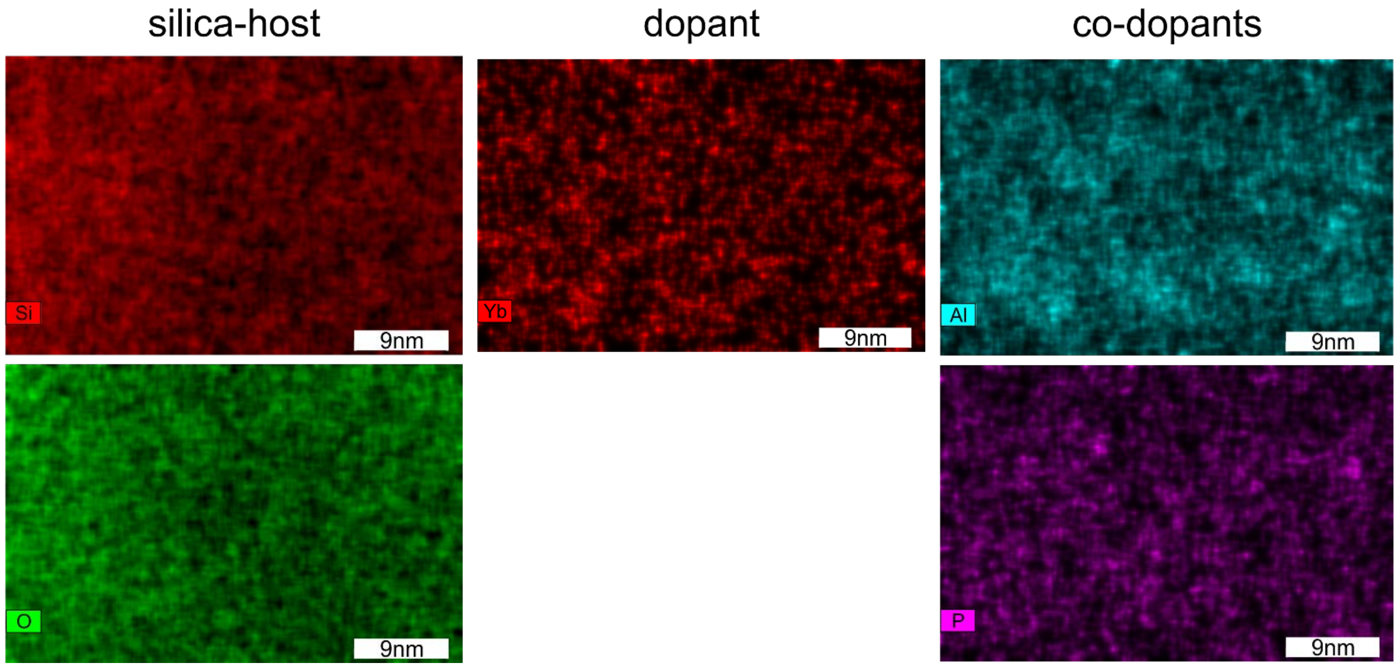
(2) D. J. DiGiovanni et al. «Structure and properties of silica containing aluminum and phosphorus near the $AlPO_4$ join»; Journal of non-crystalline solids 113(1): 58-64 (1989)

Sol-Gel "Benchmark": Yb/Al/P
Achievements



→ Intrinsic Homogeneity:
High Angle Annular Dark Field - Scanning Transmission Electron Microscopy (HAADF-STEM))





Chemical mapping of HAADF-STEM: homogenous distribution of the host, dopant and co-dopants

Najafi, H., et al. «*Atomic-scale imaging of dopant atoms and clusters in yb-doped optical fibers*»; Proc. SPIE 9886, (2016)

S. Pilz et al. «*Progress in the fabrication of optical fibers by the sol-gel-based granulated silica method*»; Proc. SPIE 9886, (2016)

→ Homogeneous distribution in nano-scale

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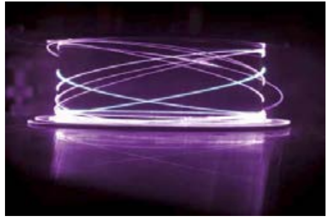
Sol-Gel approach: State of the art & outlook

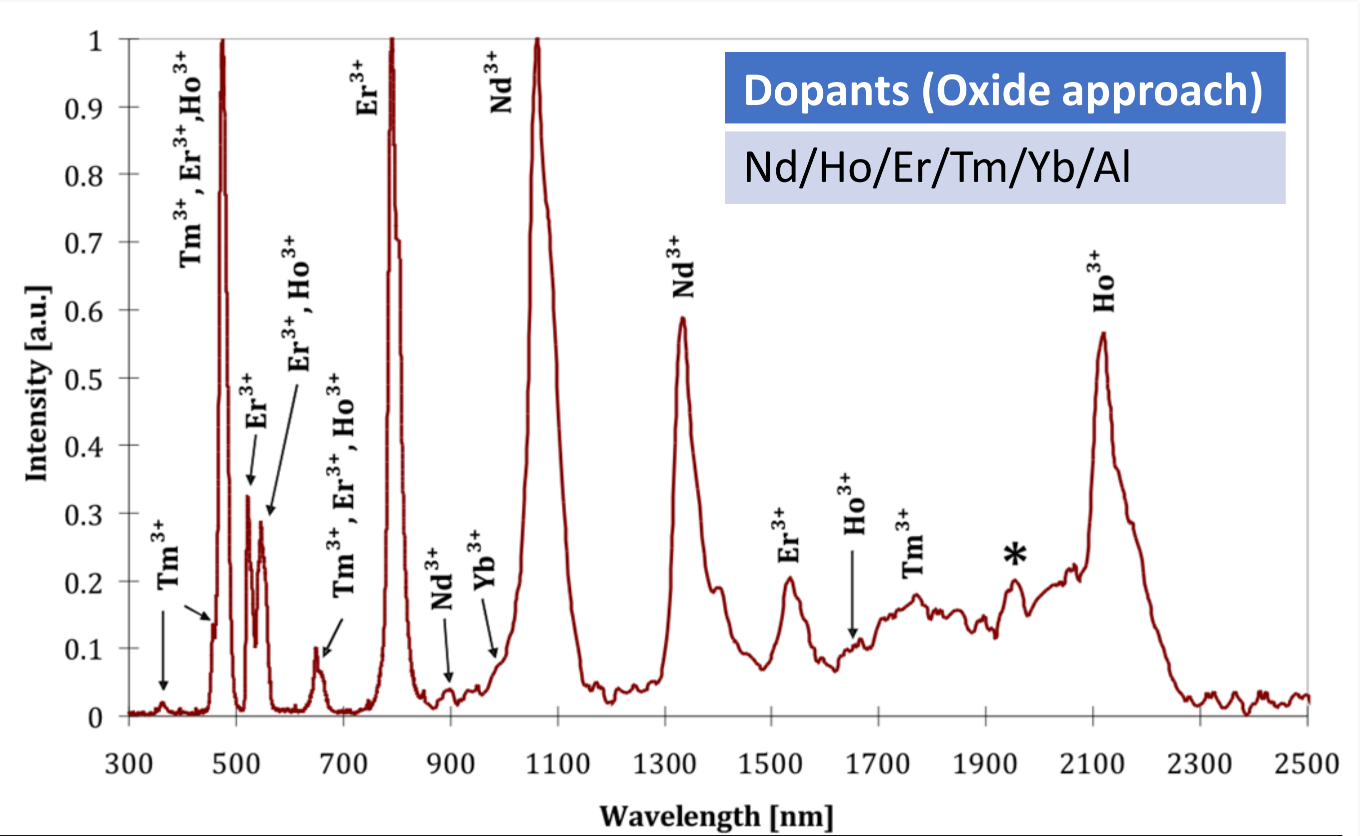


State of the art:
Proof of principle based on "rapid prototyping" for:

Optical active dopants:
- Ytterbium (Yb)

Optical passive dopants:
- Aluminum (Al)
- Phosphorous (P)
- Germanium (Ge)
- Titanium (Ti)

Outlook / vision
"Exotic", novel doping:
→ Adaptation of composition realized by our oxide approach



L. Di Labio, W. Lüthy, V. Romano, F. Sandoz, and T. Feurer «*Superbroadband fluorescence fiber fabricated with granulated oxides*»; Opt. Lett. 33, 1050-1052, (2008)

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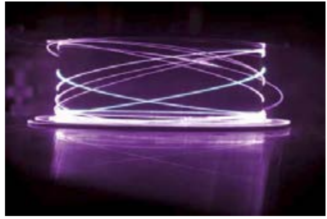

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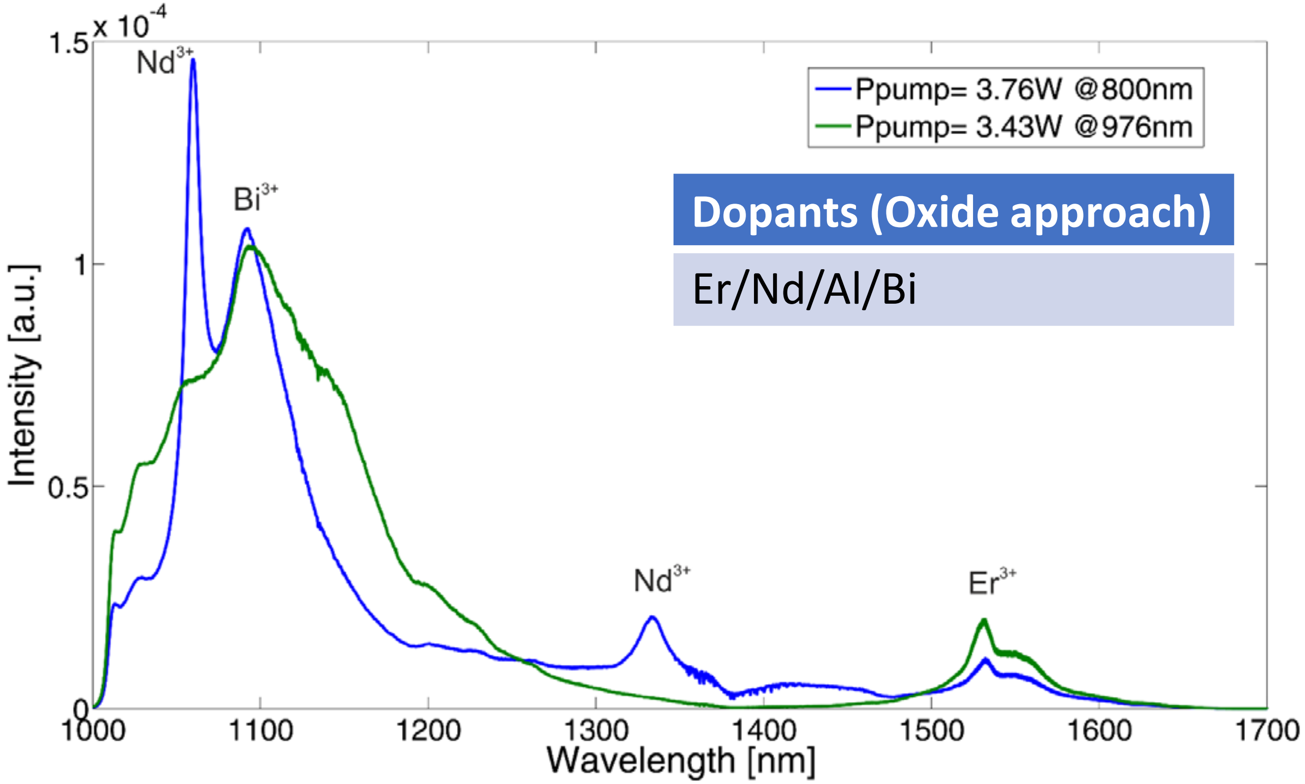

Dopants (Oxide approach)
Er/Nd/Al/Bi

S. Pilz, D. Etissa, C. Barbosa and V. Romano «*INFRARED BROADBAND SOURCE FROM 1000NM TO 1700NM, BASED ON AN ERBIUM, NEODYMIUM AND BISMUTH DOPED DOUBLE-CLAD FIBER*»; Proceedings of the ALT'12, DOI: 10.12684/alt.1.73

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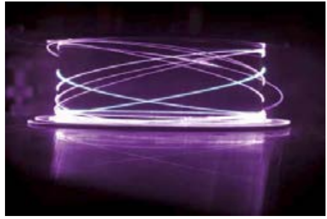
Sol-Gel approach: State of the art & outlook



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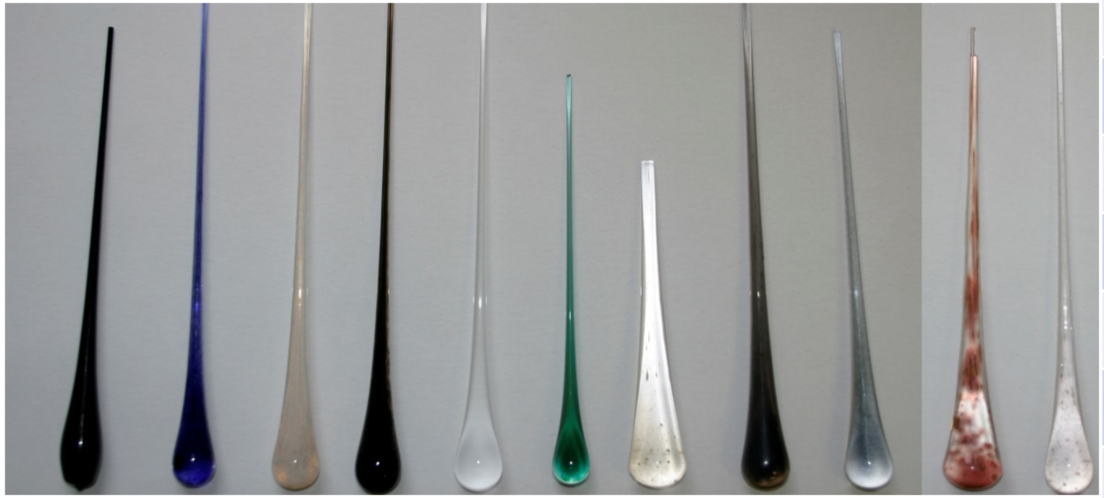
Outlook / vision
“Exotic”, novel doping:
→ Adaptation of composition realized by our oxide approach
- Metal & transition metal doping:
  → novel wavelengths and broadband amplification
- Nonmetals:
  – e.g.: graphene
    → novel functionality: fiber based saturable absorber



Various metal (Bi) and transition metal (V,Cr,Cu,Ti,Co,Zn,Ni,Mn,Sb) preform droplets

M. Neff «*Metal and transition metal doped fibers*», Doctoral thesis, Institute of Applied Physics, University of Bern, Switzerland (2010)

Dopants (Oxide approach)
Bi
V
Cr
Cu
Ti
Co
Zn
Ni
Mn
Sb

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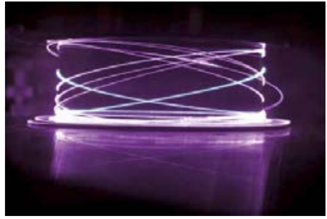
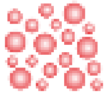


Reduction of losses

Granulate



Rapid prototyping

Preform assembly

Vitrified preform

Granulate-in-tube preform

- High losses (≥0.35dB/m@633nm)
- Formation of micro-bubbles
- Fiber only piecewise good

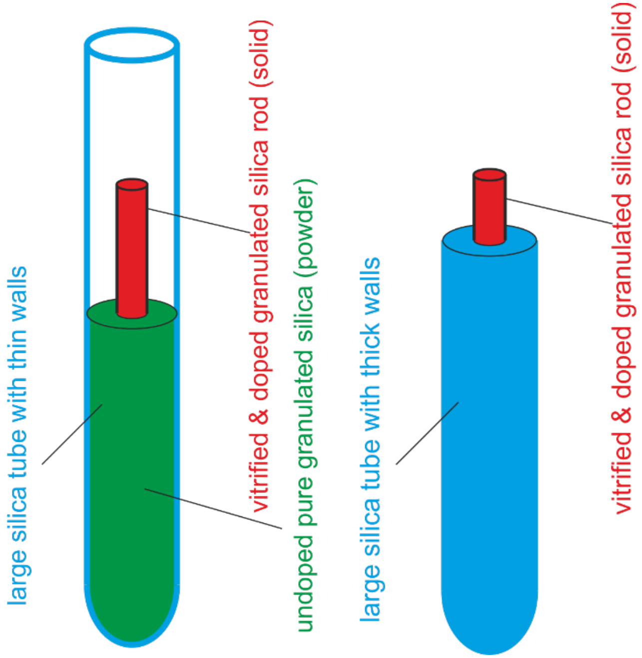
→ pre-vitrification needed!

Drawn directly from granulate

Rod-in-tube preform

- Pre-vitrified core rod

→ Challenge:
pre-vitrification
(international project in progress)



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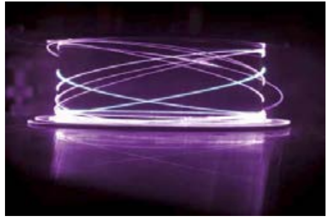
Reduction of losses

Rod-in-tube preform (international project in progress)



Laser-based travelling small zone vitrification (LBTZ developed by APRI/TFO)

First results:

- Bubble free vitrified core rods

→ Significant improvement in losses

→ Background fiber loss:
~0.2dB/m @633nm (Yb/Al/P-doped fiber)

→ Losses are low enough to built up fiber lasers and fiber amplifiers, but not yet efficient

→ In progress: improvement expected in ½-1year

LBTZ vitrification: Vitrified core preform rods (1mm diameter)

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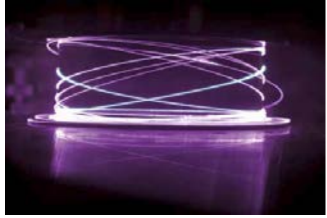
Summery & Conclusion



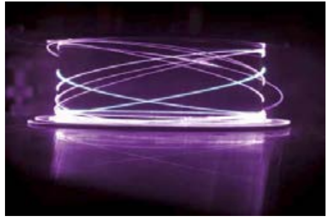
Sol-Gel approach for the granulated silica method
→ Best of both worlds: novel composition & geometry

- Intrinsic homogeneity
- High doping concentration (up to several at.%)
- Refractive index control by the ratio Al/P
- Melting temperature control by concentration of Al
- Freedom of geometry

"Under construction"

- Reduction of losses by pre-vitrification
  → laser-based vitrification (LBTZ): ~0.2dB/m @633nm
- Investigation on novel dopants

	MCVD	Granulated silica method		
		Rapid prototyping		Vitrified preform
		Oxide approach	Sol-gel approach	Sol-gel approach
Arbitrary composition	✗	✓	✓	✓
Arbitrary geometry	✗	✓	✓	✓
Homogeneity	✓	✗	✓	✓
Fiber losses	✓✓	✗	✗	(✓)
Cost-effective	✗	✓✓	✓	✓
Rapid	✗	✓✓	✓	(✓)



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- *Dr. Hyunjoo Kim*
- *Dr. Alexander Heidt*
- *Dr. Manuel Ryser*
- *Prof. Valerio Romano*
- *Prof. Thomas Feurer*

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