Femtosecond laser induced refractive index changes in fluoride glasses

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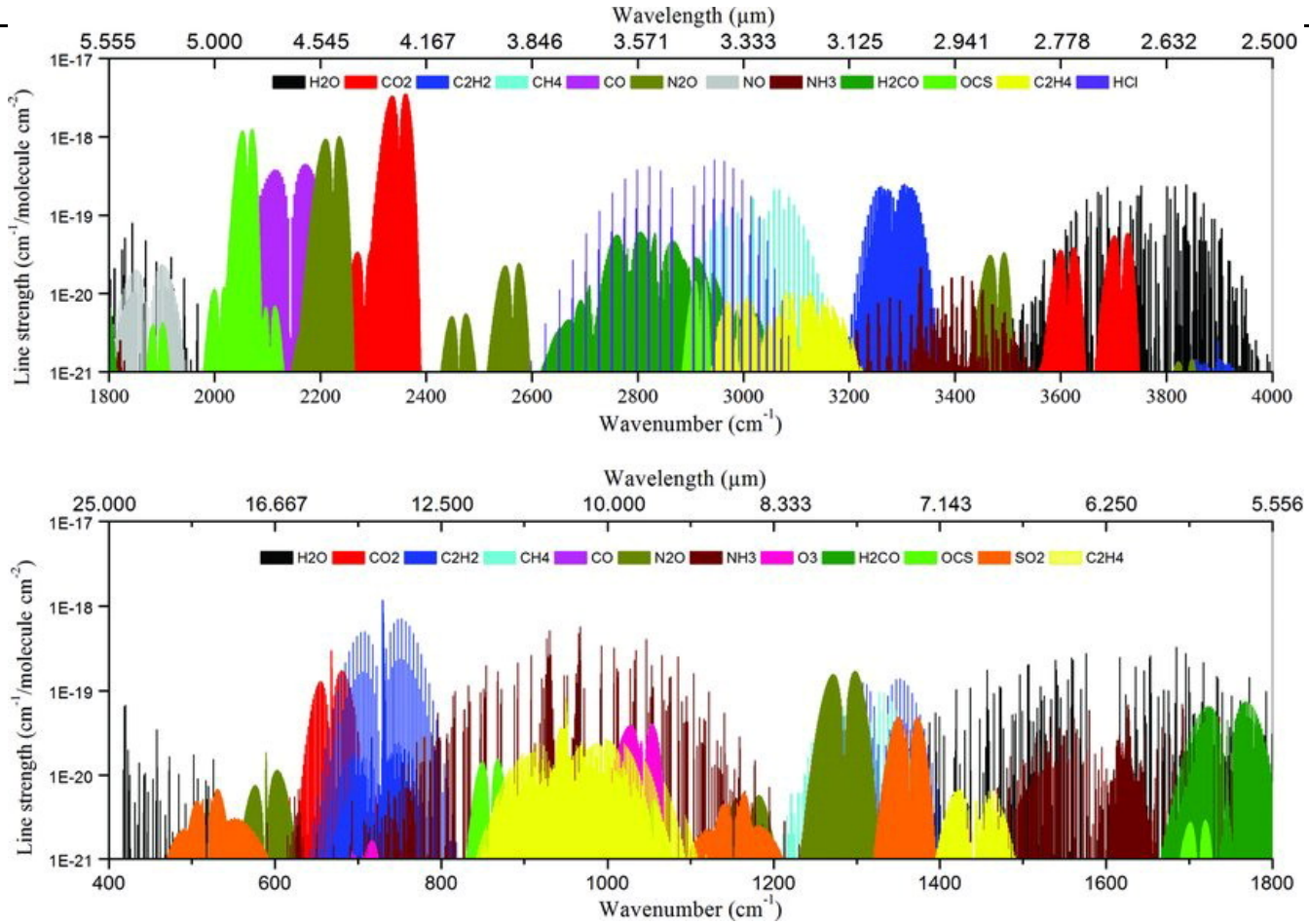
Mid-infrared light



J.S. Li et al, Applied Spectroscopy Reviews **48**, 523 (2013)

Field-resolved infrared spectroscopy of biological systems

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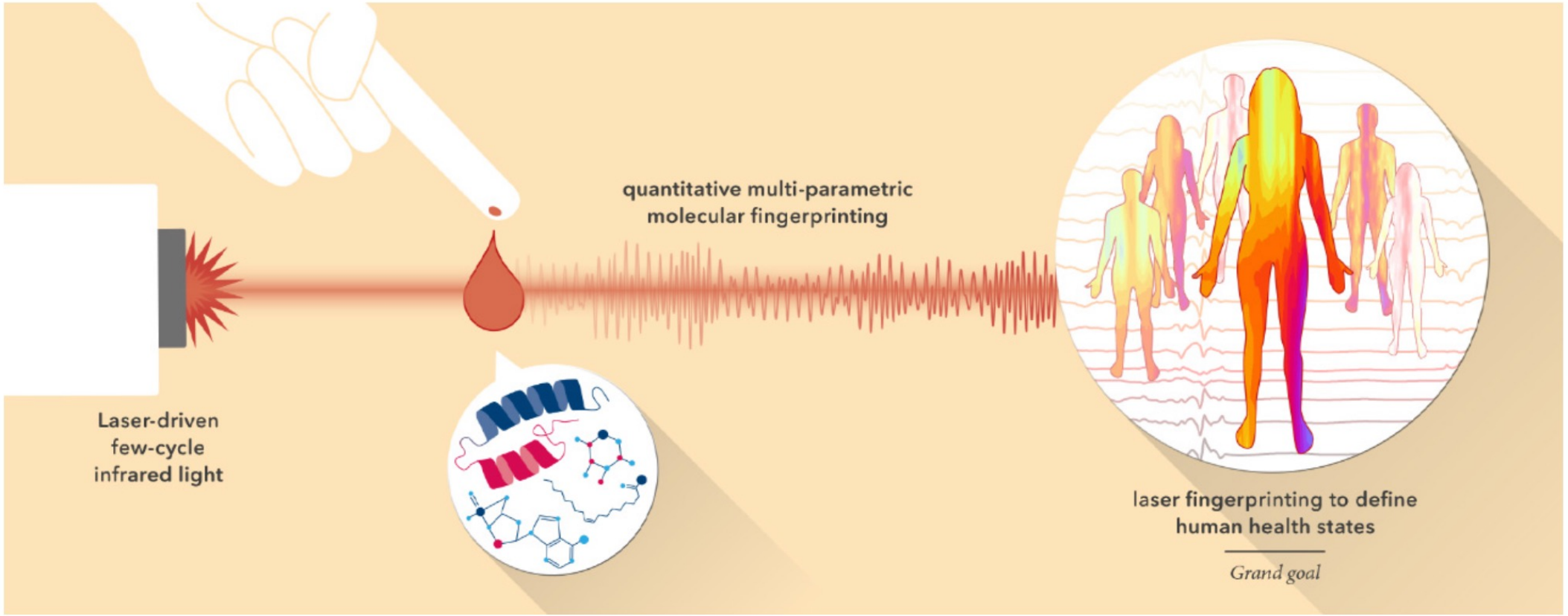
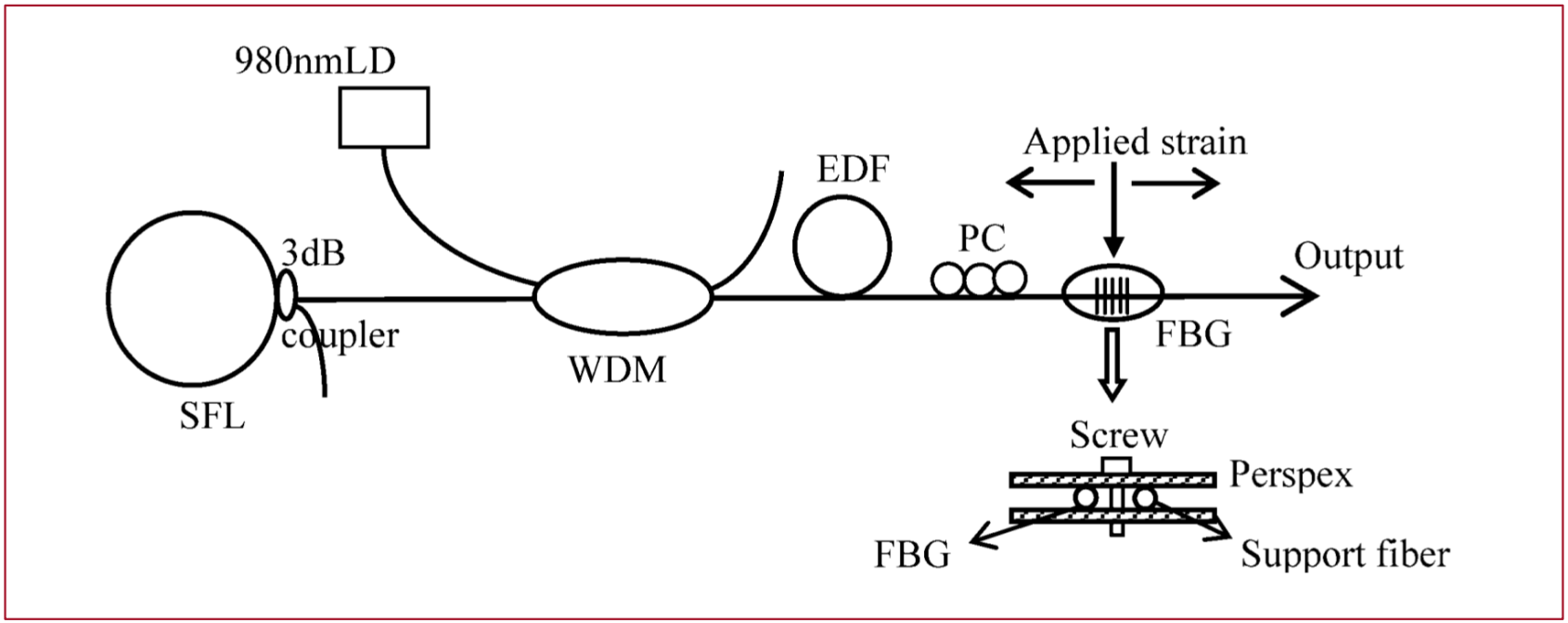
FÜR QUANTENOPTIK



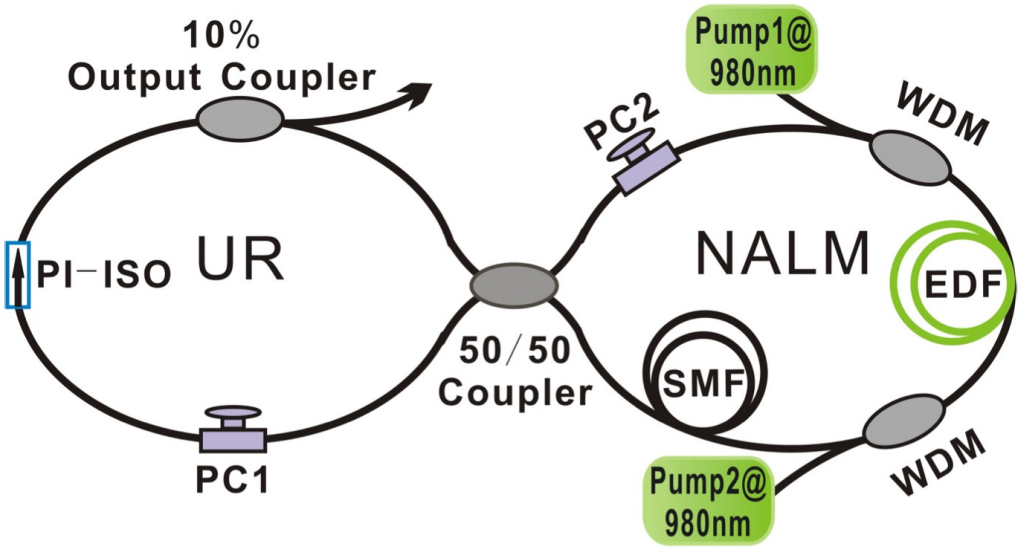
All-fibre near-infrared laser sources

Switchable and tunable dual-wavelength erbium-doped fiber laser based on one fiber Bragg grating

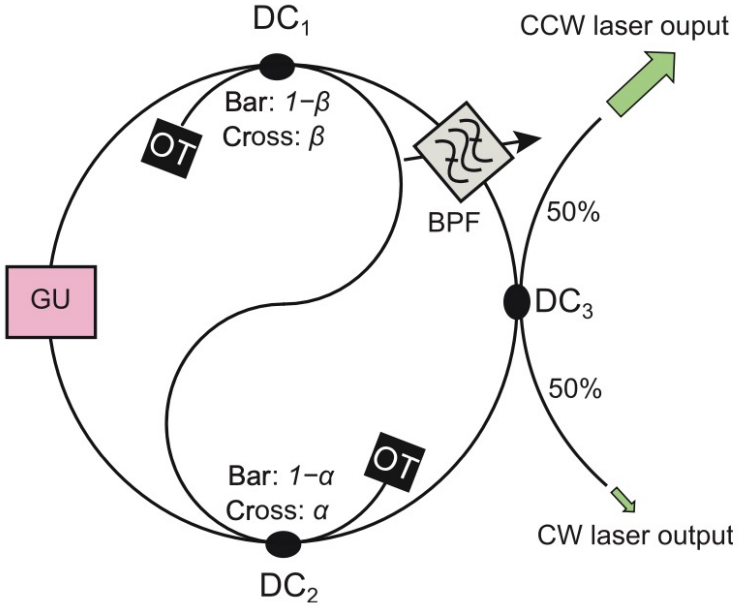
Feng et al, Optical Fiber Technology **10**, 275 (2004)



All-fibre ultrashort-pulsed lasers

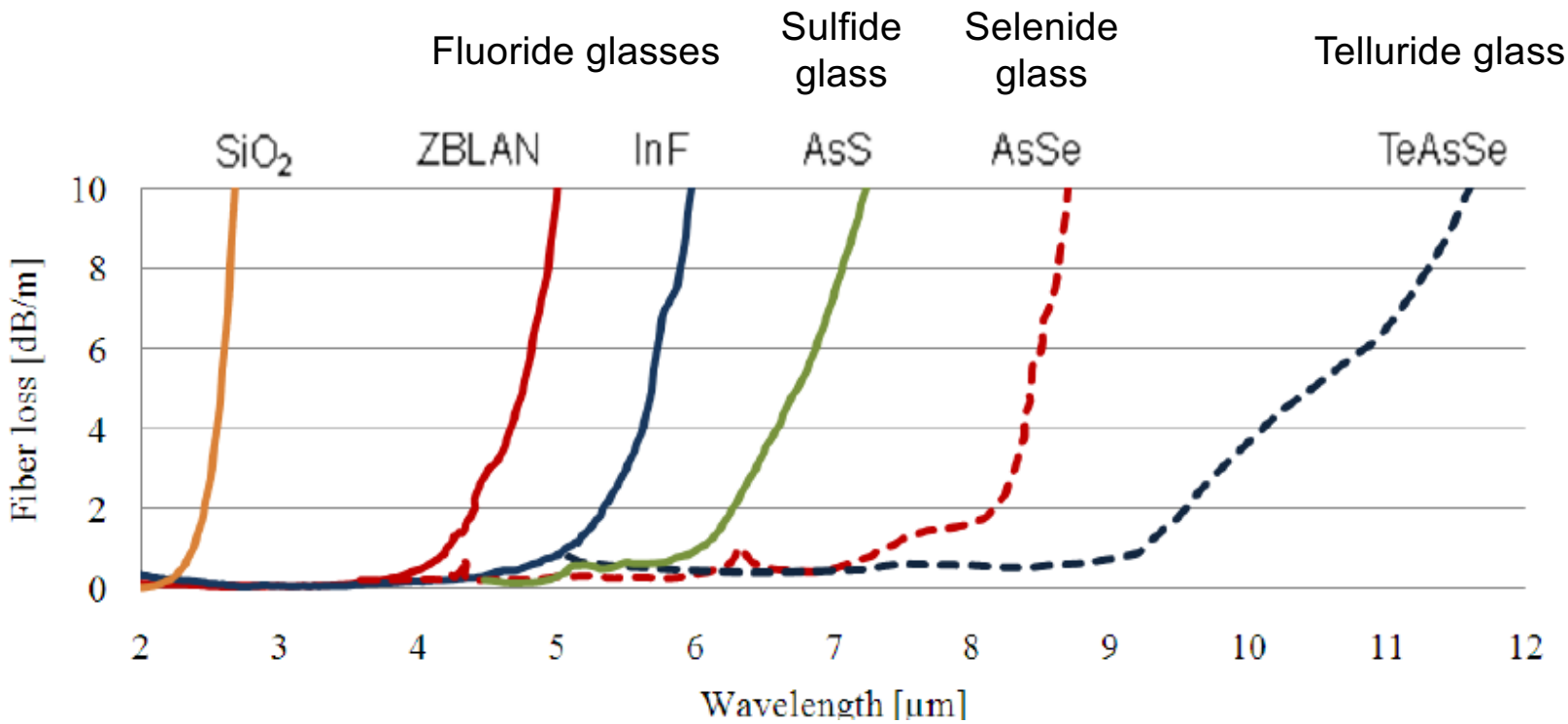


Wang et al, Optics Express **21**, 2402 (2013)



Kharitonov and Bres, Light: Science & Applications e340 (2015)

Material Challenge



Mouselund et al. Proceedings of SPIE, May 2012

Femtosecond laser direct-write technique

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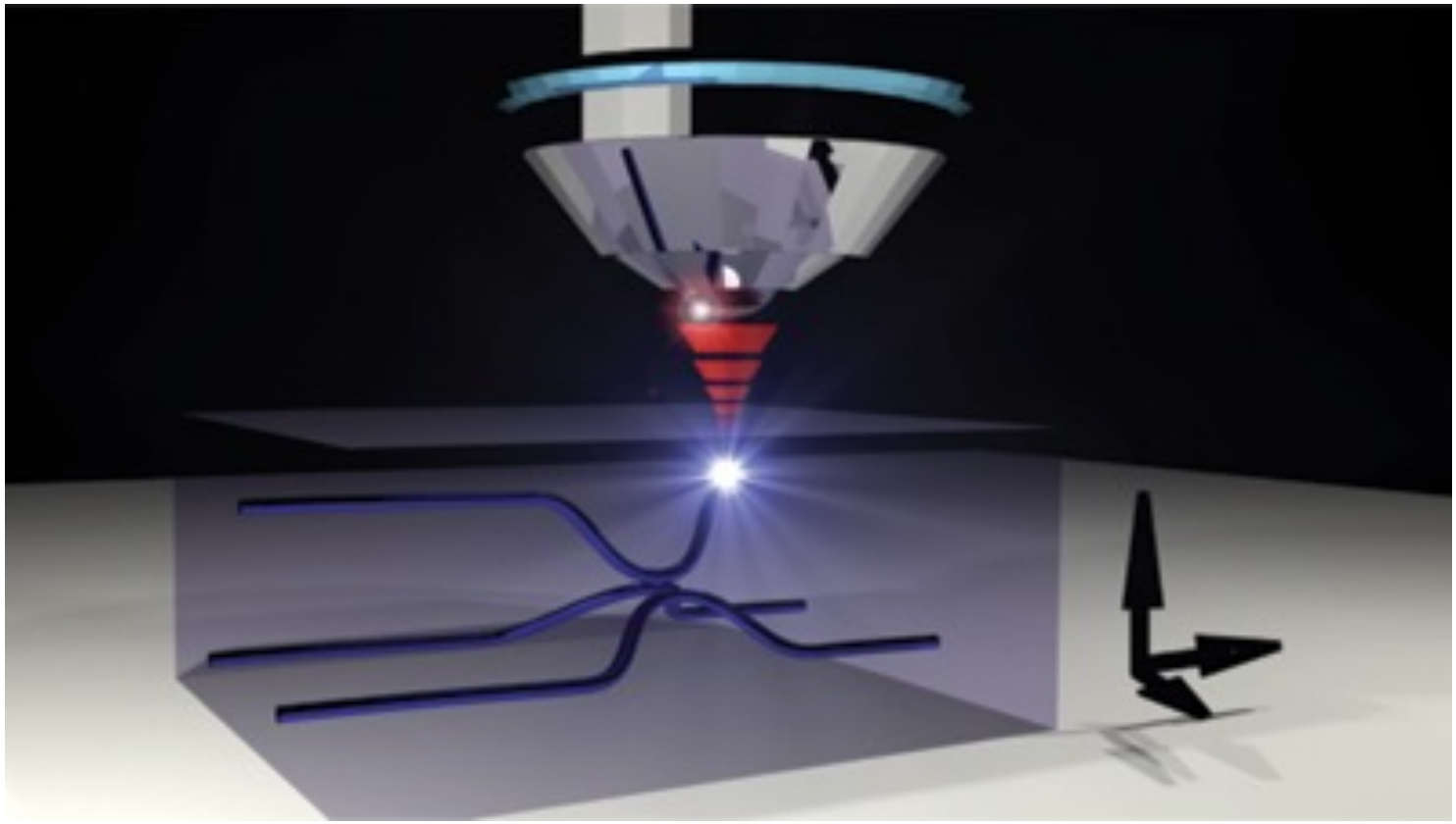
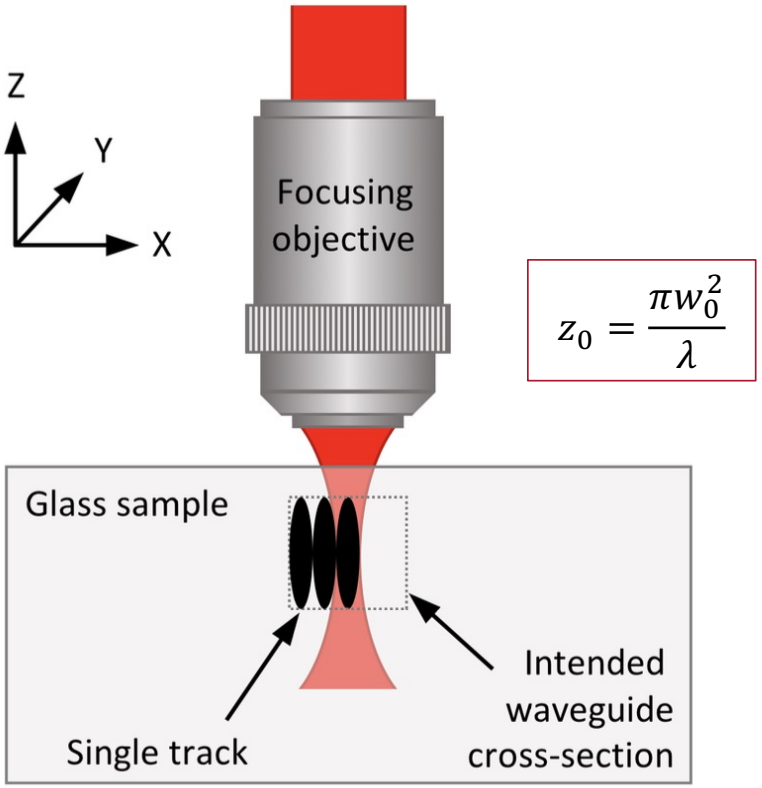
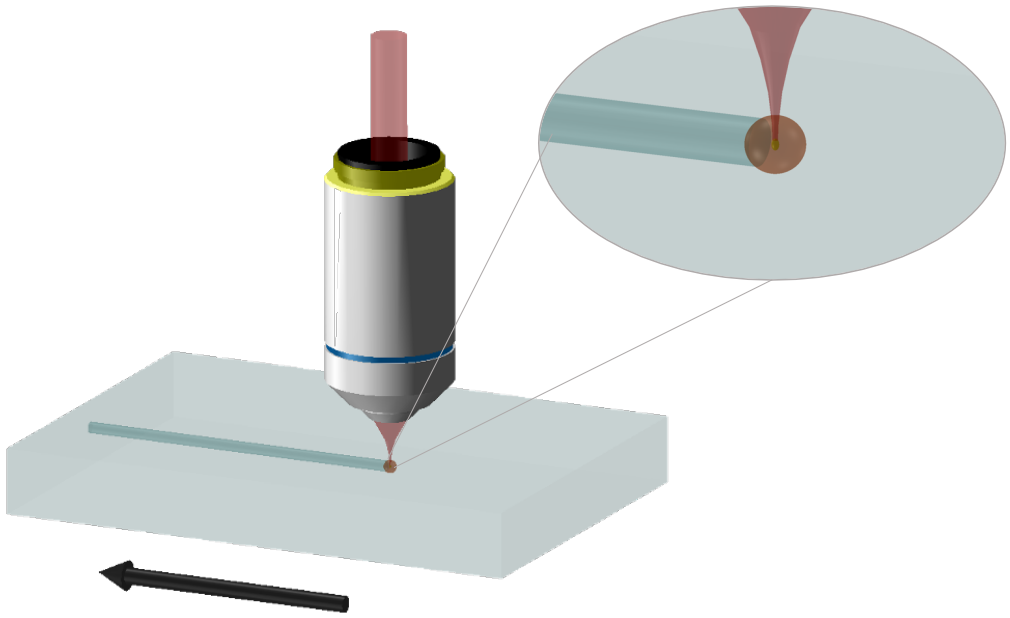


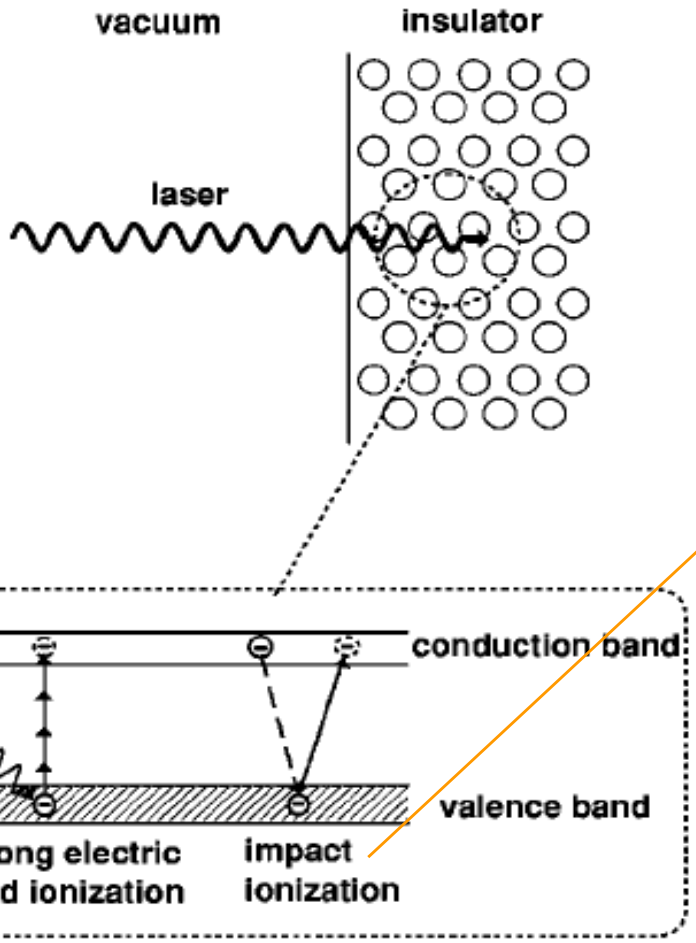
Multiscan vs. cumulative heating



$$z_0 = \frac{\pi w_0^2}{\lambda}$$



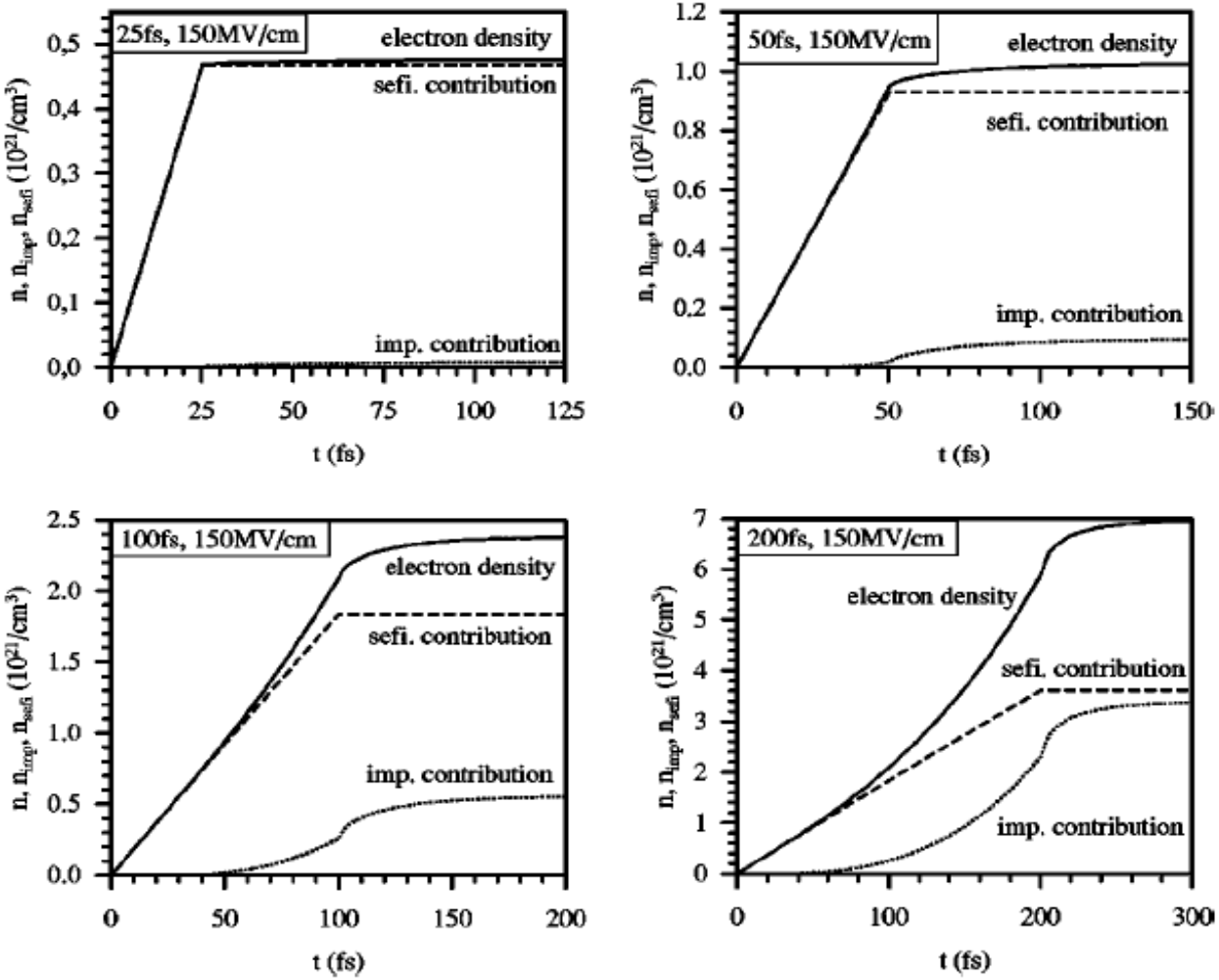
1st: Generation of a free electron gas



Multiphoton ionisation
and
Tunnel ionisation

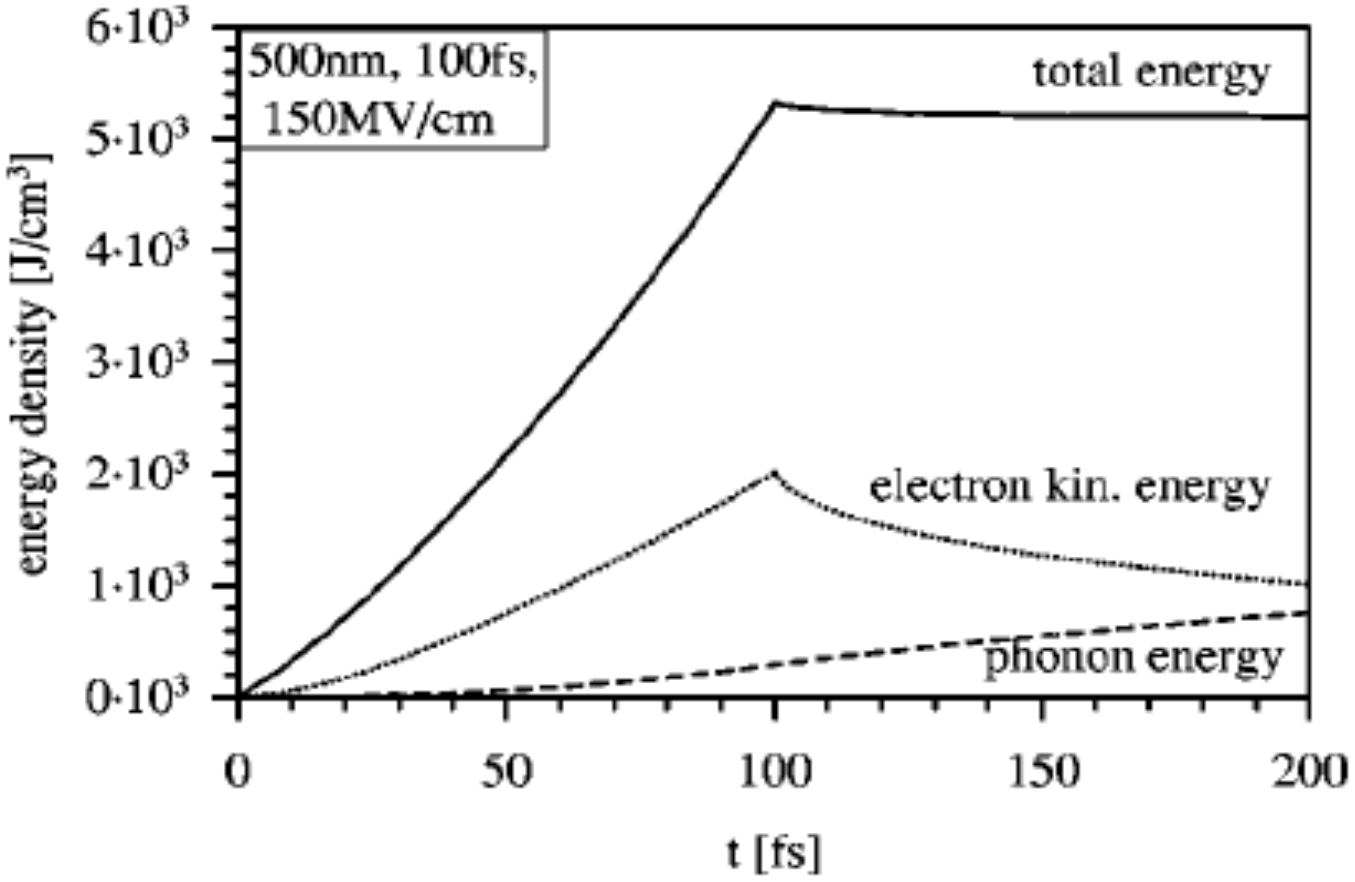
Relies on the existence of a free electron in the conduction band → stochastisch

Ionisation mechanisms



Kaiser et al, PRB 61, 11437 (2000)

2nd: Electron – Phonon collisions



3rd step: Refractive index change

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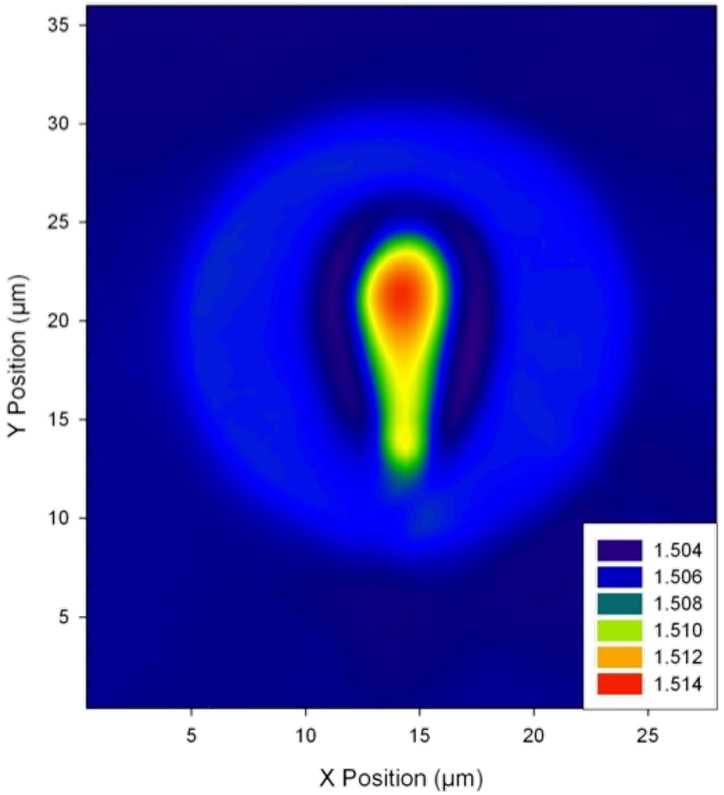
- Many unknowns
- Depends highly on the material
- Depends on the process-parameter, e.g. laser repetition rate
- Structural changes in the glass-matrix are induced
- Atomic species migration in and out of the focal volume
- Stress-induced index change
- Generation of laser-induced defect centres



Early work in ZBLAN

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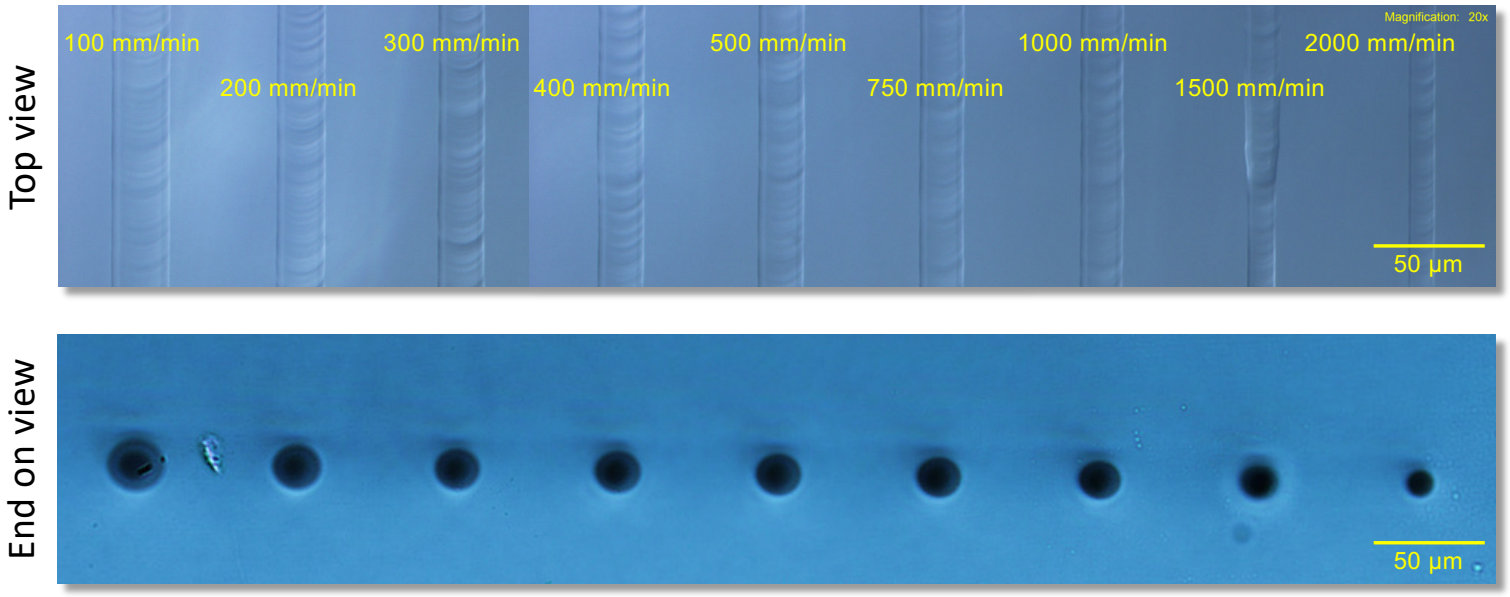
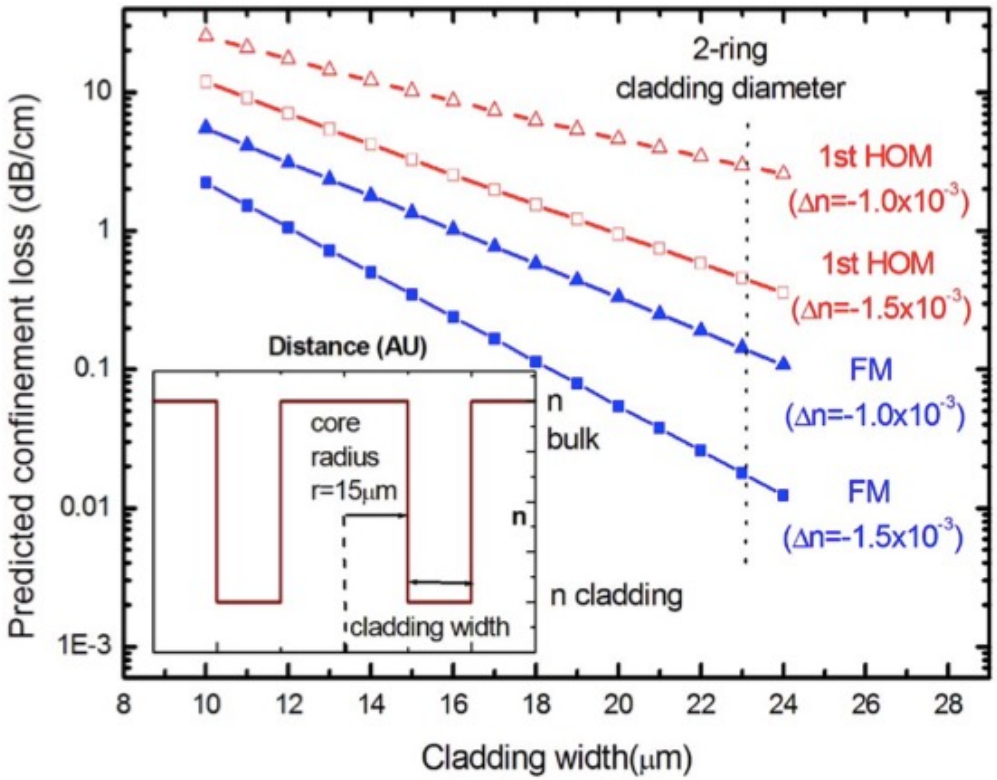
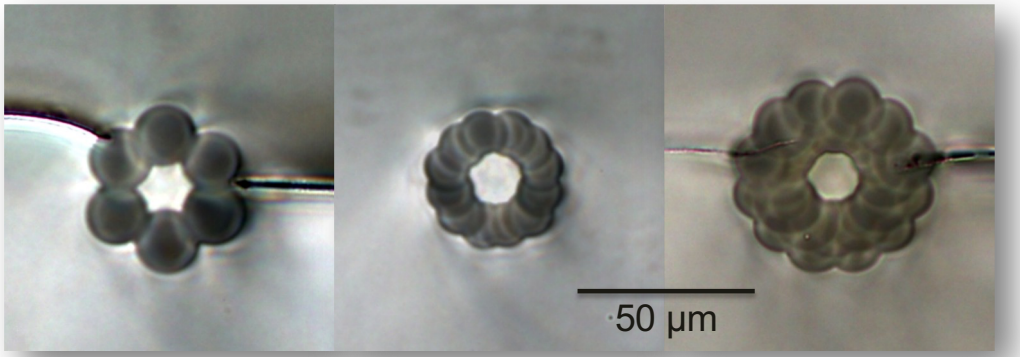


$$\Delta n \cong -1.5\,x\,10^{-3}$$

Depressed-cladding waveguides

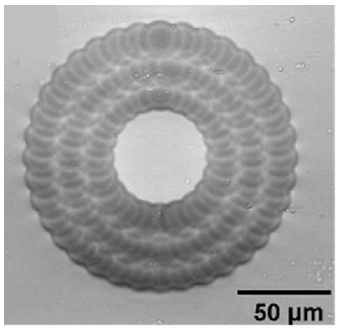


6 cylinders | 12 cylinders | 24 cylinders



0.2 ± 0.1 dB/cm
at 1.5 μm

0.22 ± 0.06 dB/cm at
1.9 μm



0.2 dB/cm
at 2.9 μm

Raman microscopy

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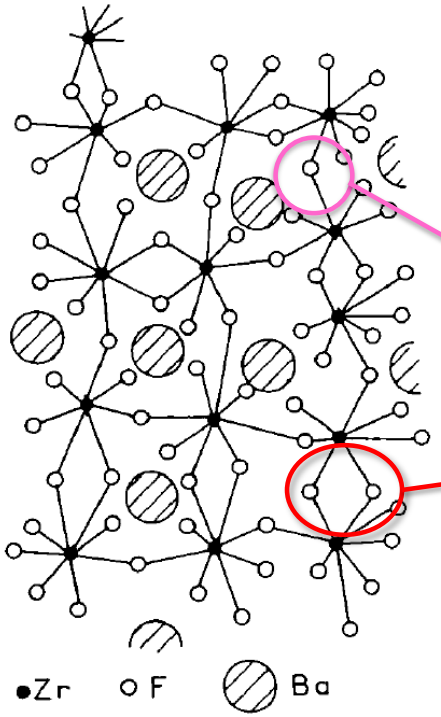
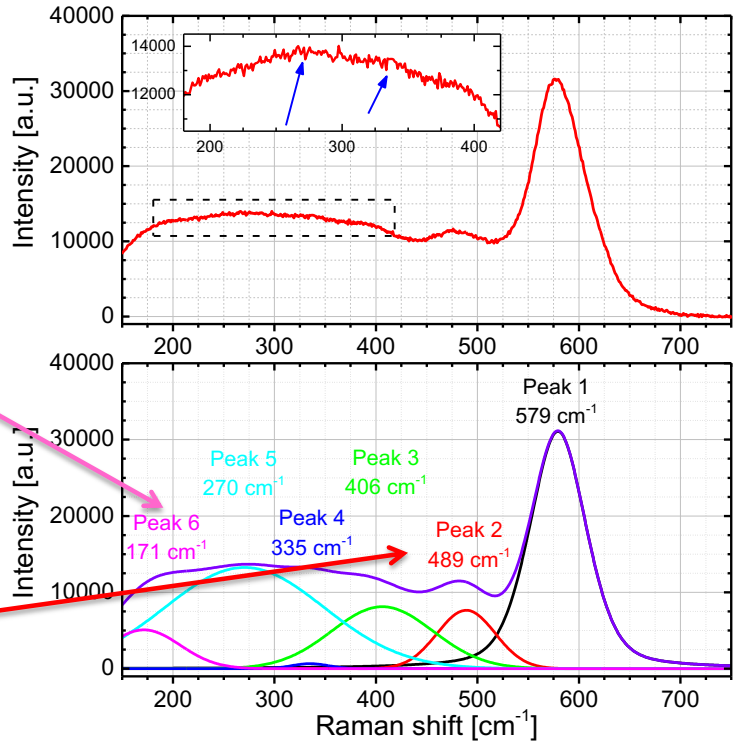
Glass structure

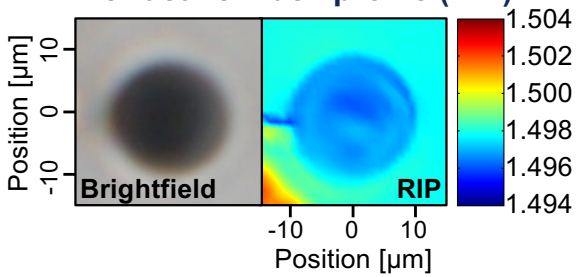


Raman spectrum

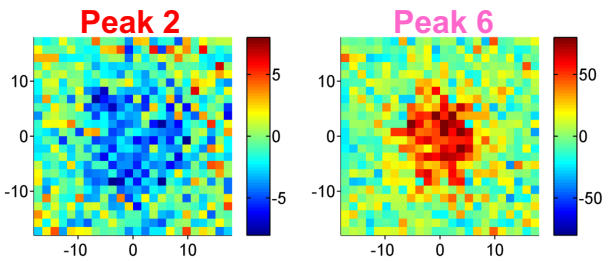


- Decrease of double bridging bonds
- Increase of single bridging bonds

Microscope image and refractive index profile (RIP)



Mapped Raman band strength



Gross et al, Opt. Mat. Express 3, 575 (2013)

H/ZBLAN

LE VERRE FLUORÉ
FIBER SOLUTIONS

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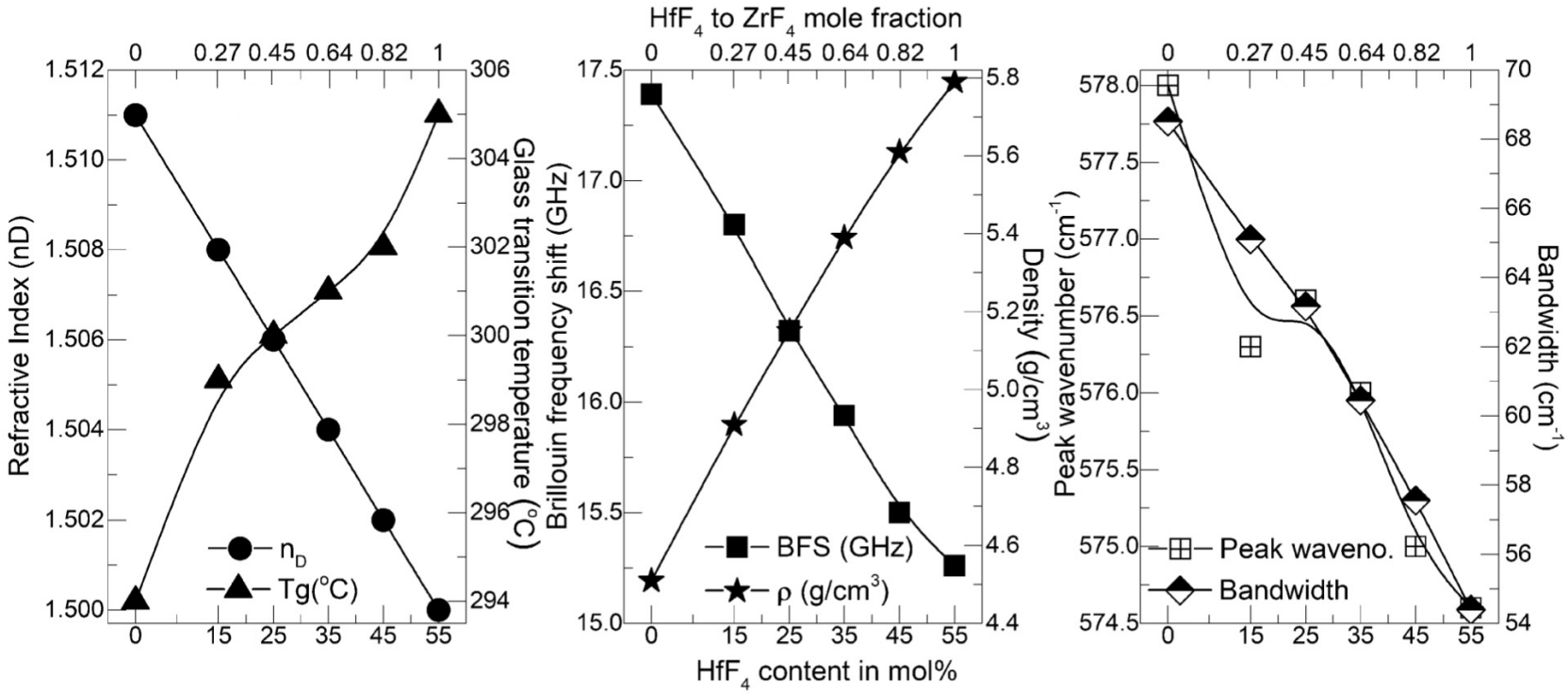
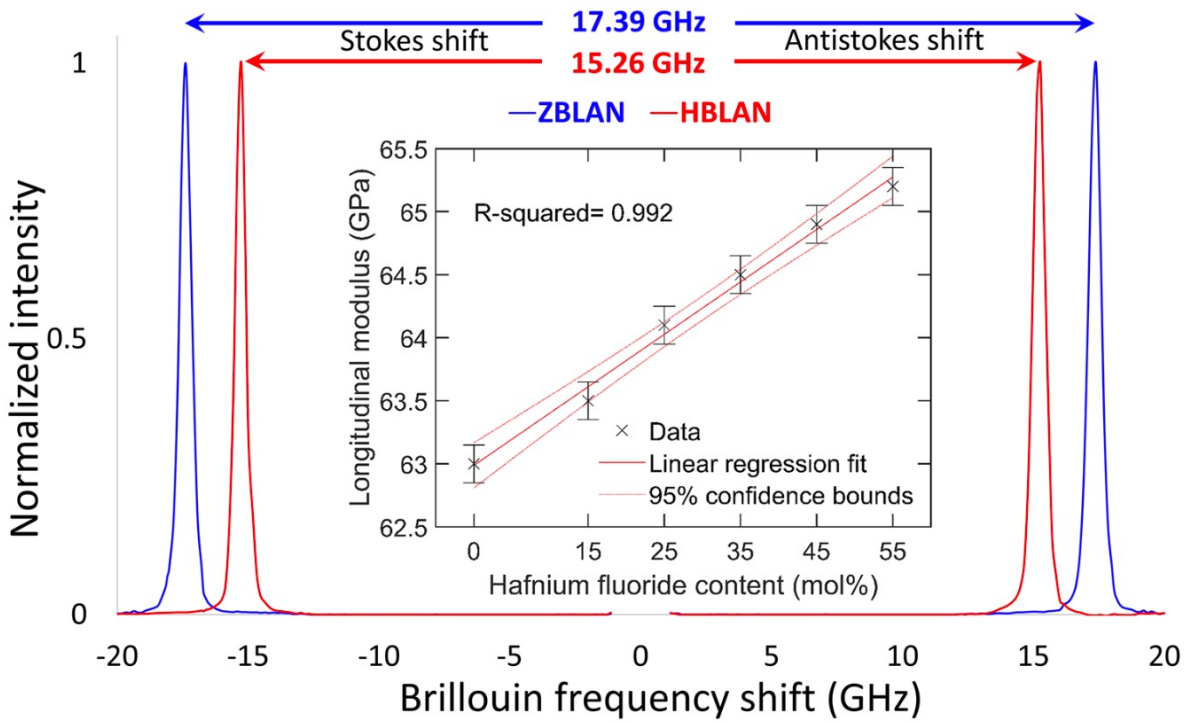
Ba, La, Al, Na

55%ZrF_4 + 45%BLAN



Brillouin frequency shift (BFS)



$$BFS = \frac{2n}{\lambda}\sqrt{\frac{M}{\rho}}$$

Multiscan waveguides

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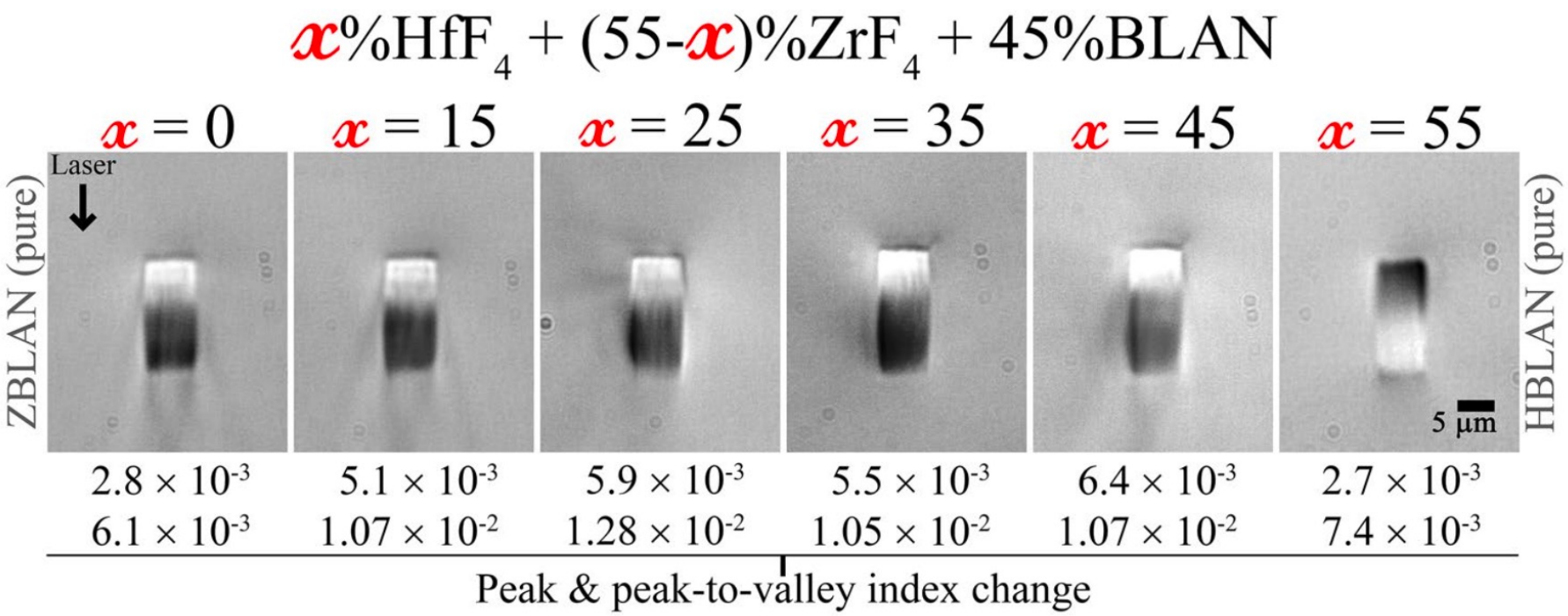
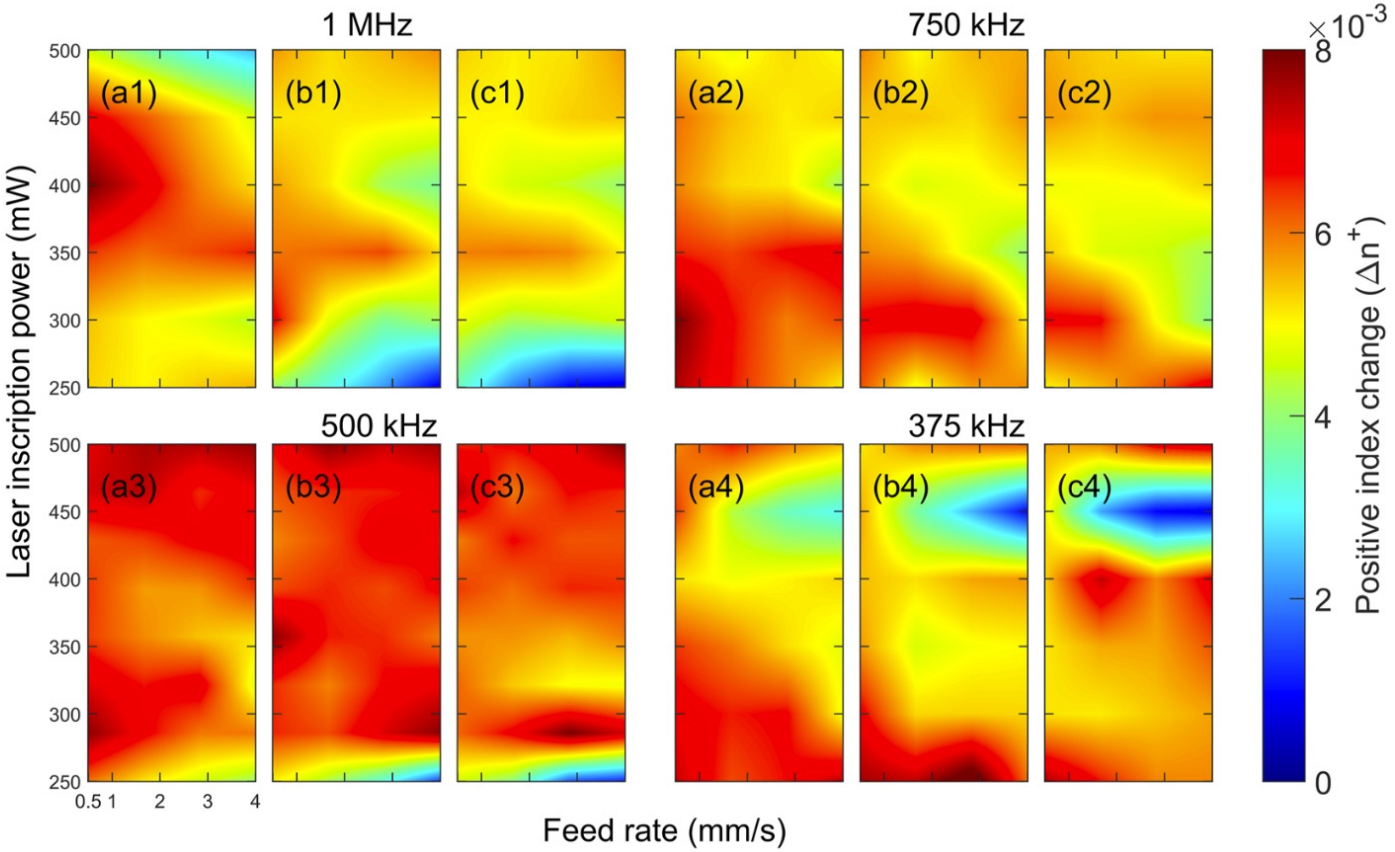
$5\ kHz$
$1030\ nm$
$240\ fs$
$0.6\ NA$
$detuned$



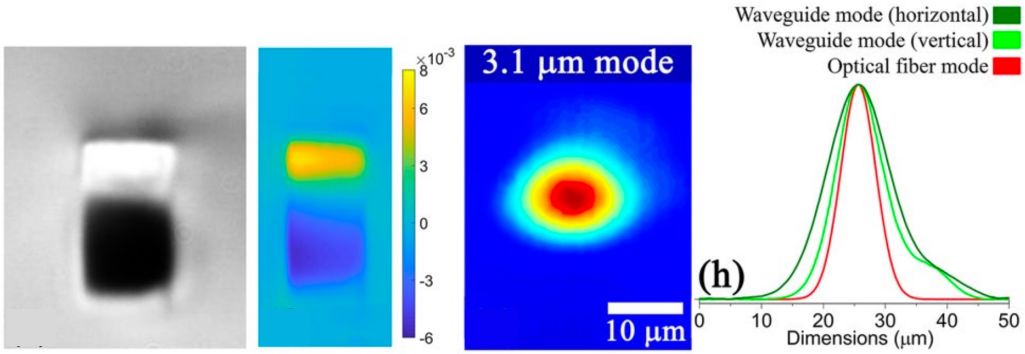
Multiscan Waveguides in Suprasil

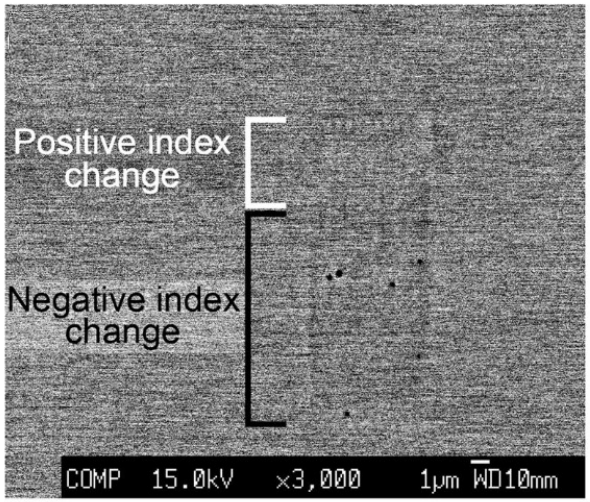


$1030\ nm$
$240\ fs$
$0.4\ NA$
$detuned$

Fernandez et al, APL Photoncis **7**, 126106 (2022)

Mid-IR guided mode



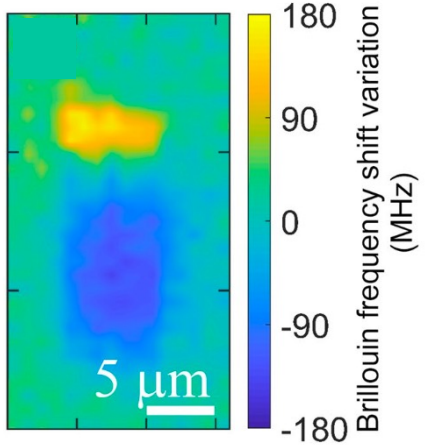


Backscattered electron microscope image

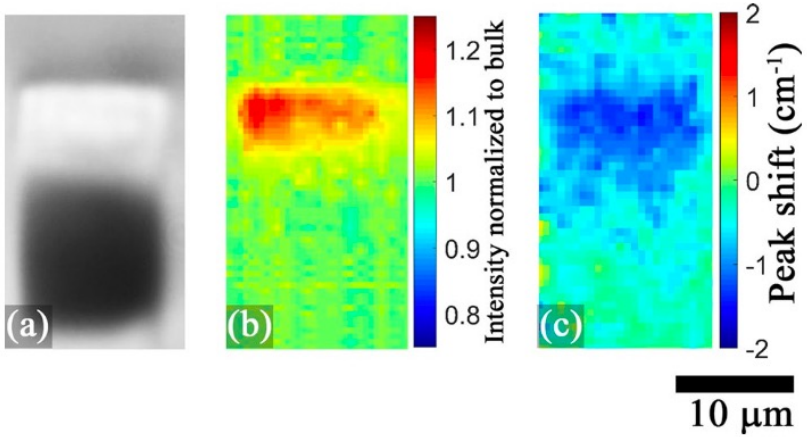
Elemental mapping: featureless

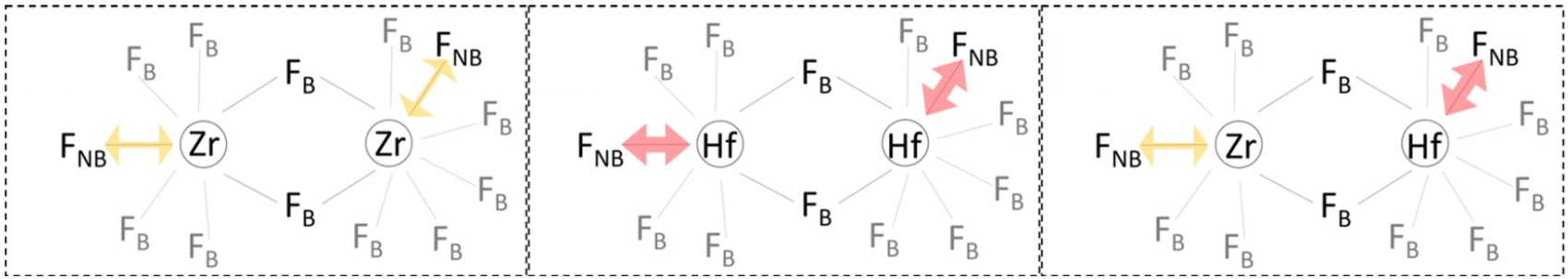
Brillouin and Raman microscopy

$$BFS = \frac{2n}{\lambda}\sqrt{\frac{M}{\rho}}$$



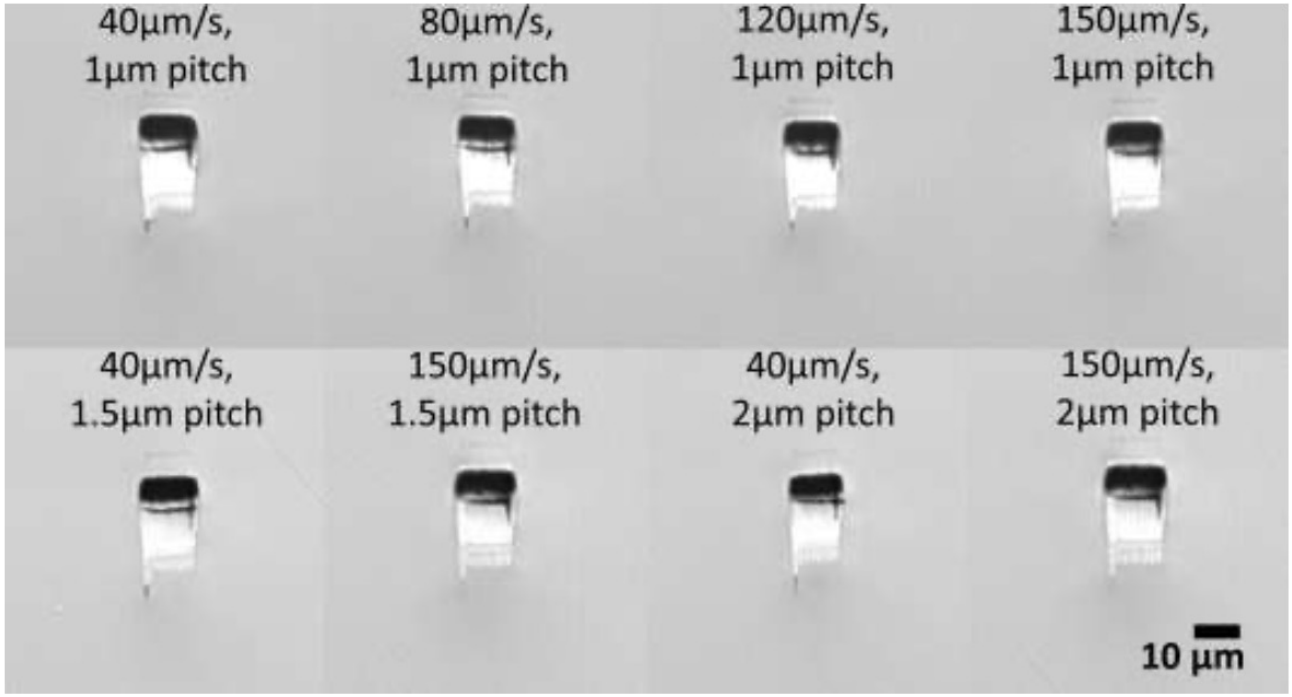
Fernandez et al, Sci. Reports **12**, 14674 (2022)

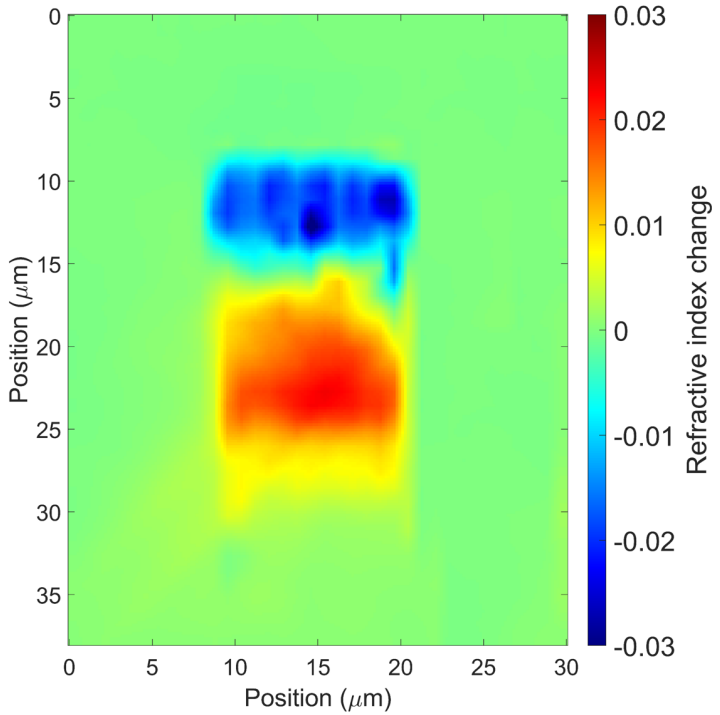




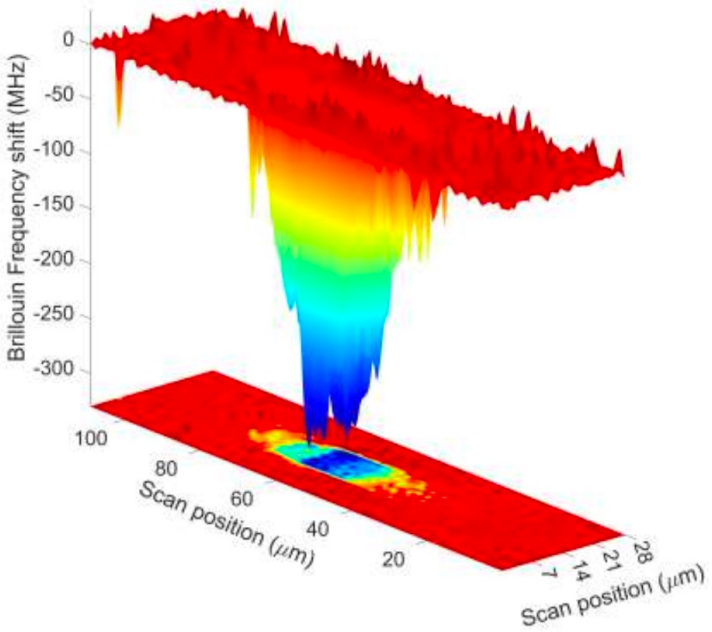
Electron cloud distortion effect that is driven by the existence of two glass formers with contrasting polarizability

Highest index change in ZBLAN

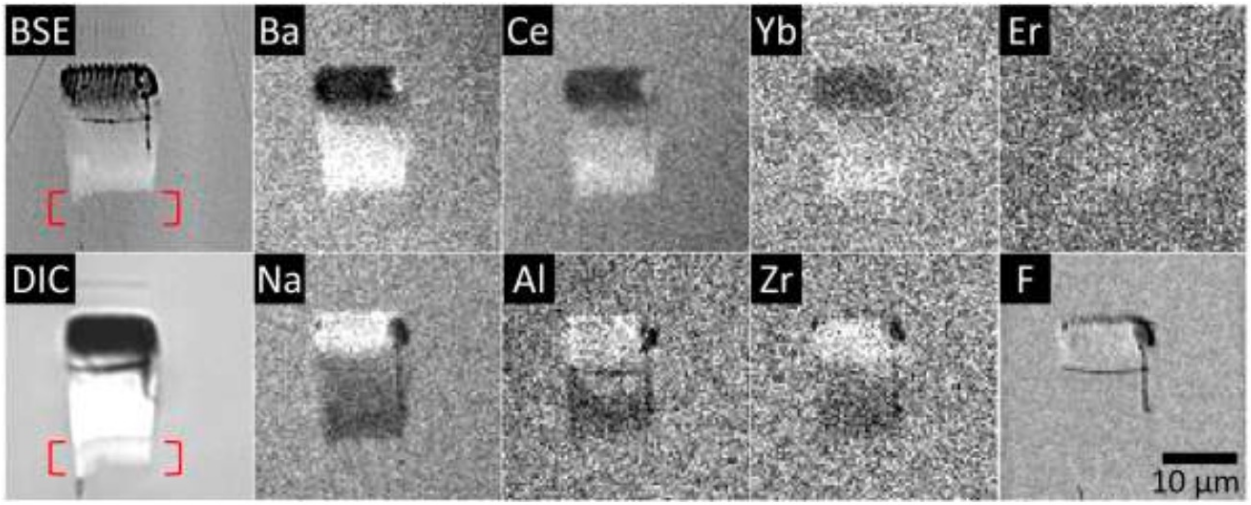




Densification via ion migration

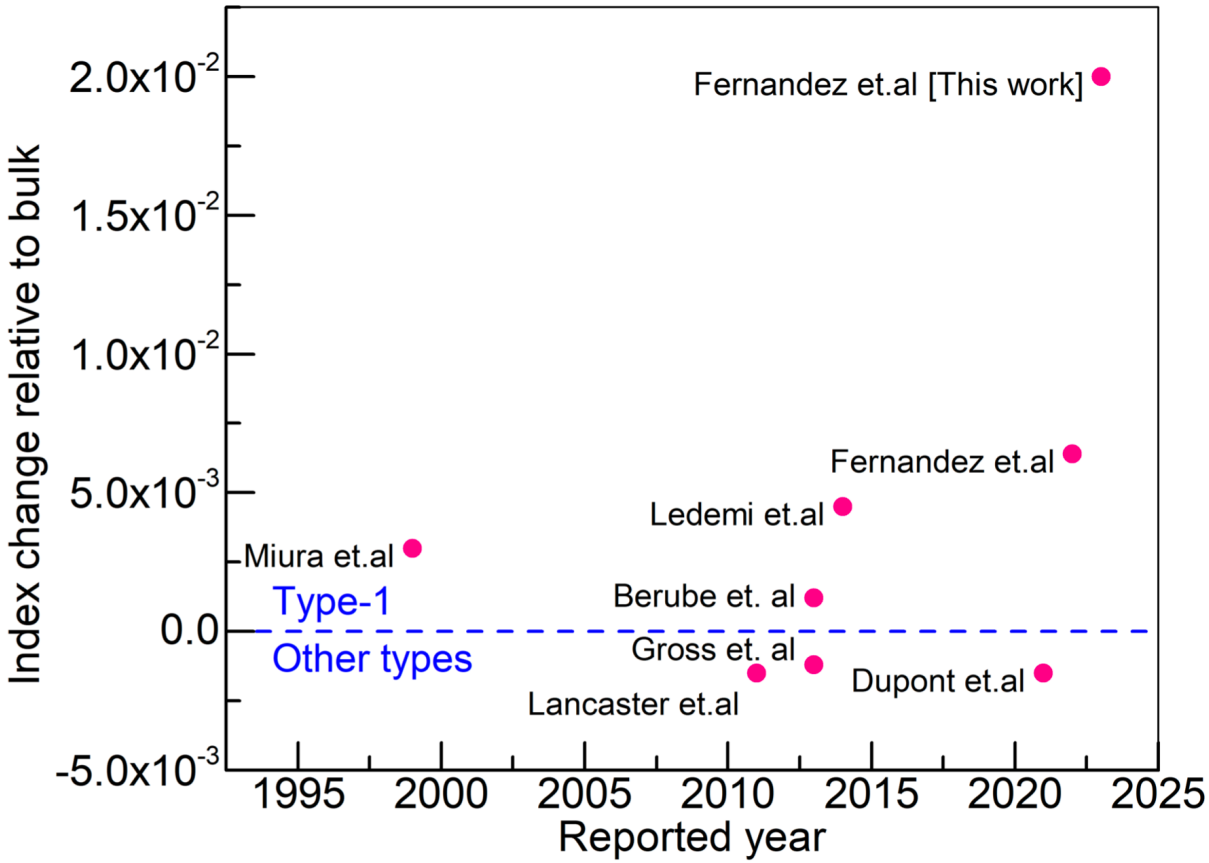


Electron Probe Micro-Analysis - EPMA

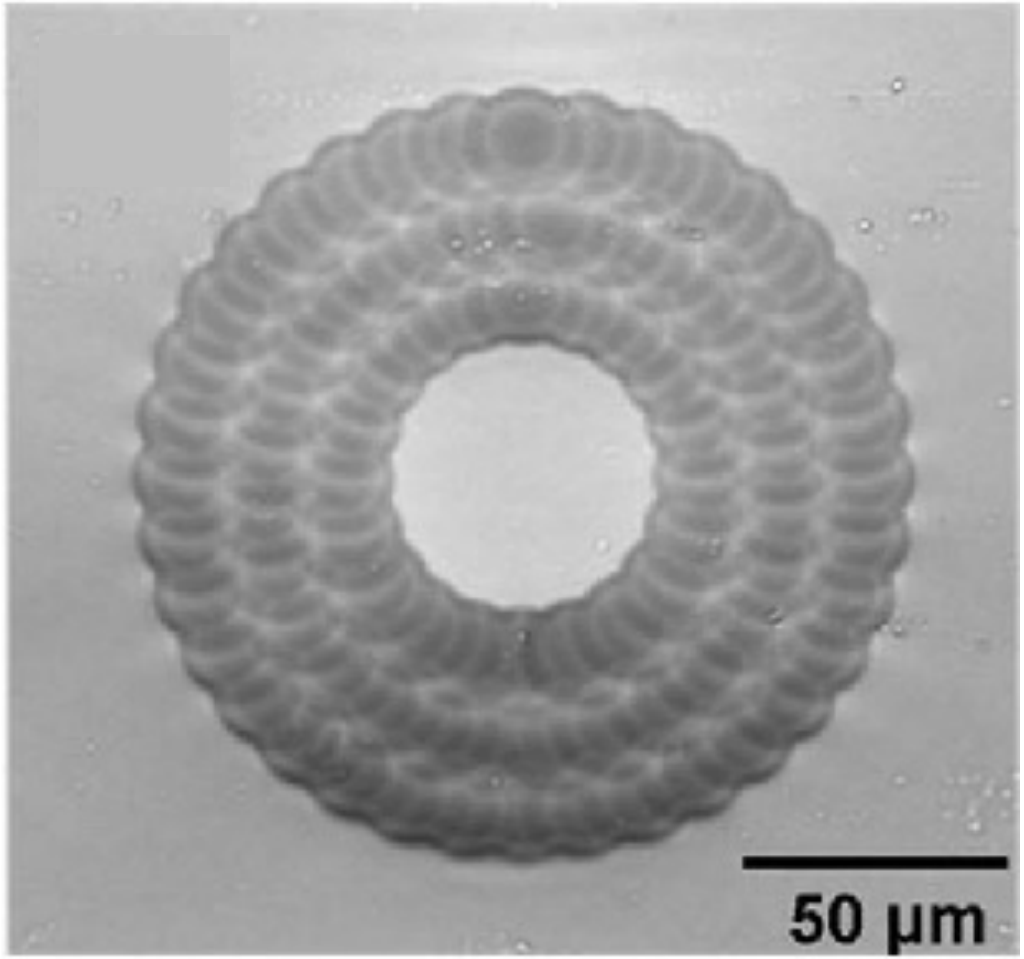


Development of index change

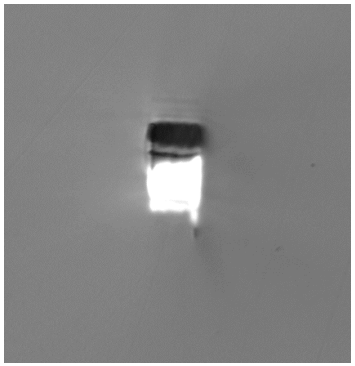
Fernandez et al, Opt. Express **32**, 42938 (2024)



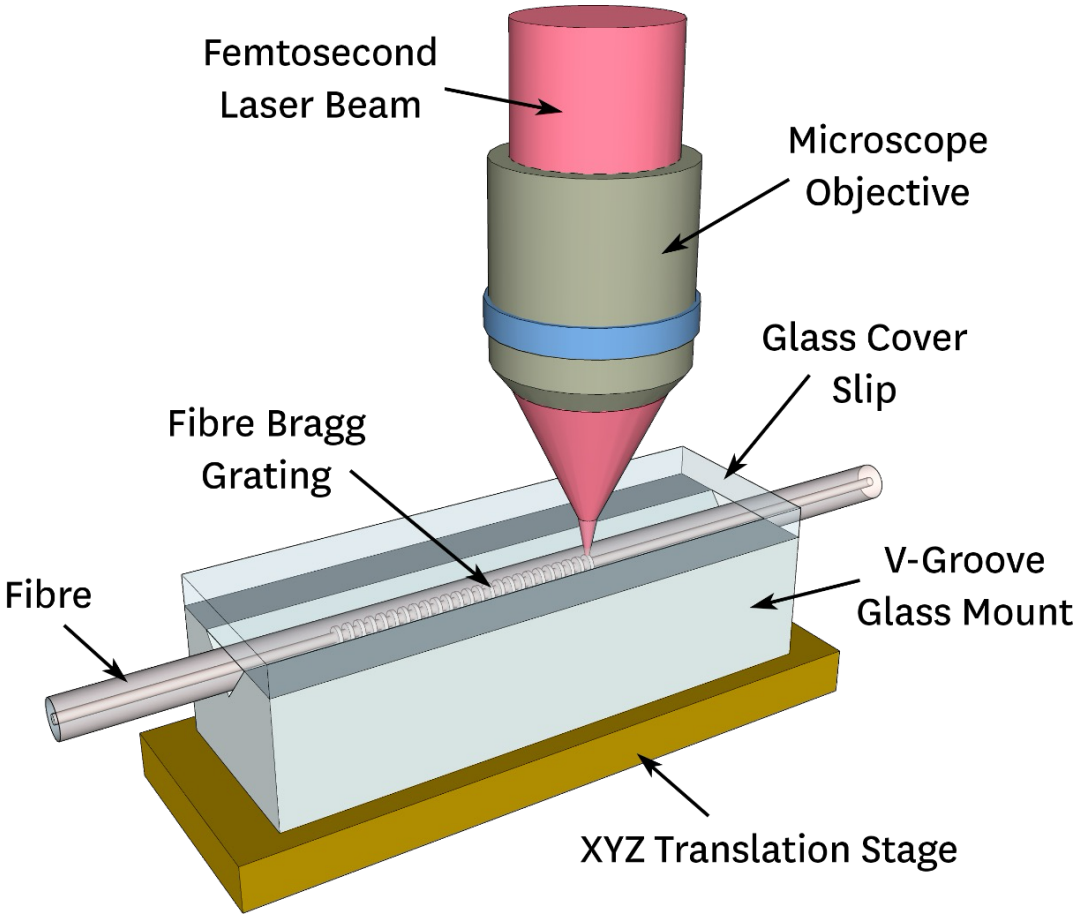
Mid-IR waveguides

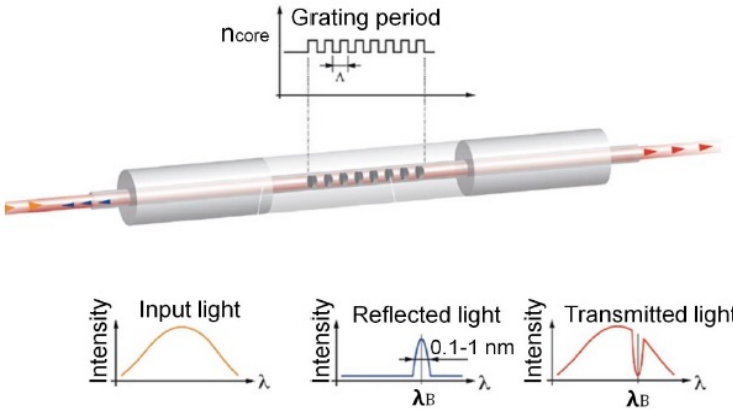


Solution by glass composition redesign



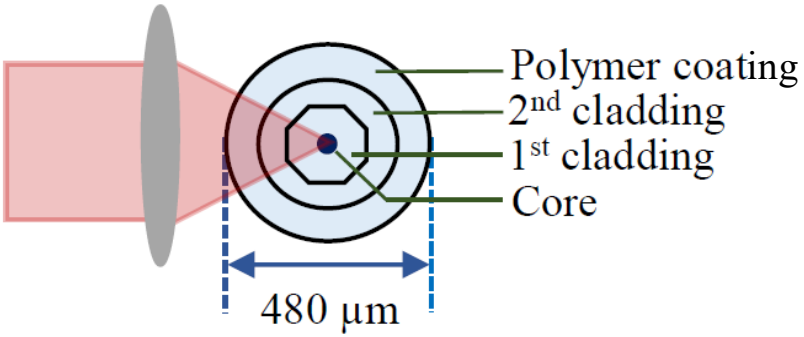
Fibre Bragg Gratings (FBG)

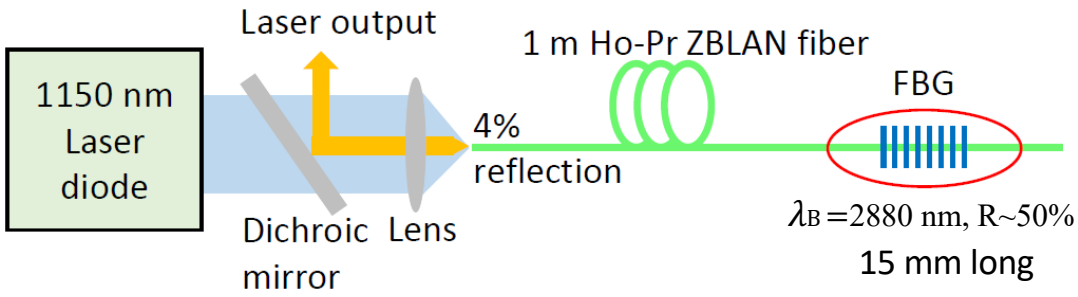


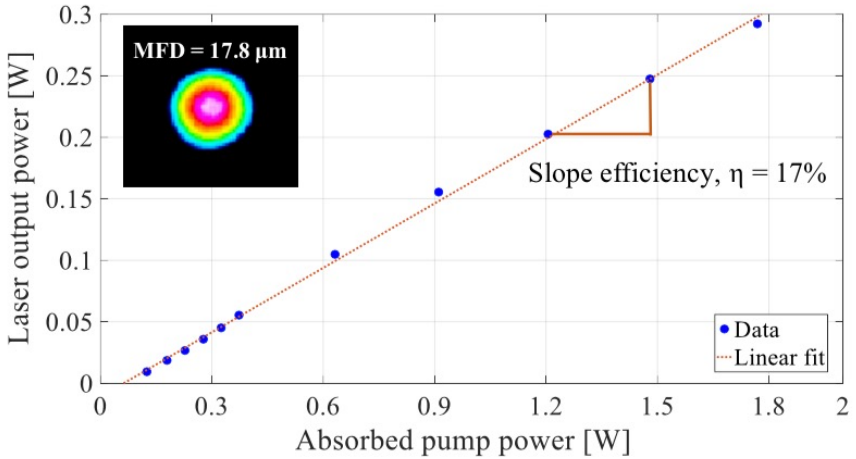


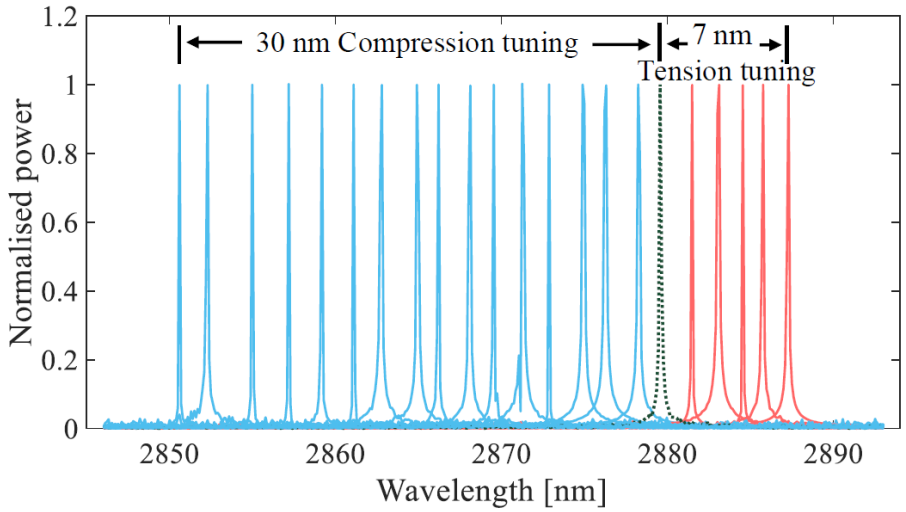
$$m\lambda_B = 2n_{eff}\Lambda$$

ZBLAN – Inscription through the coating









Bharathan et al, Opt. Express 25, 30013 (2017)

Optimisation of inscription

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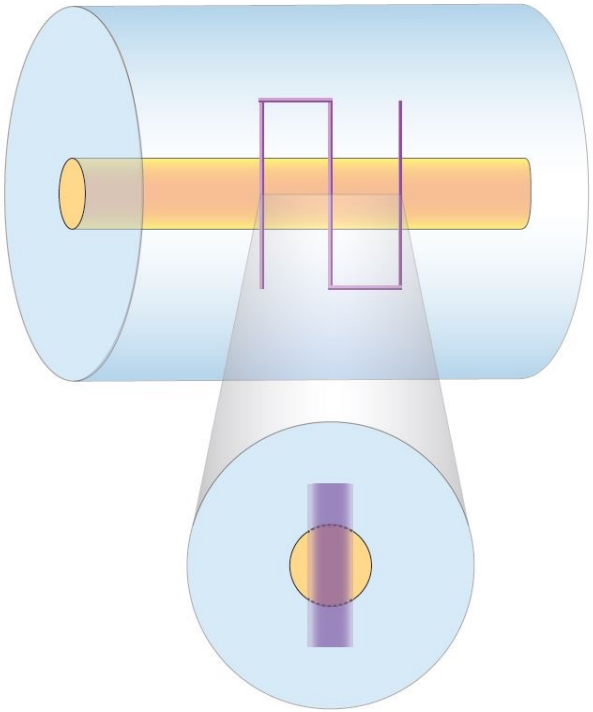
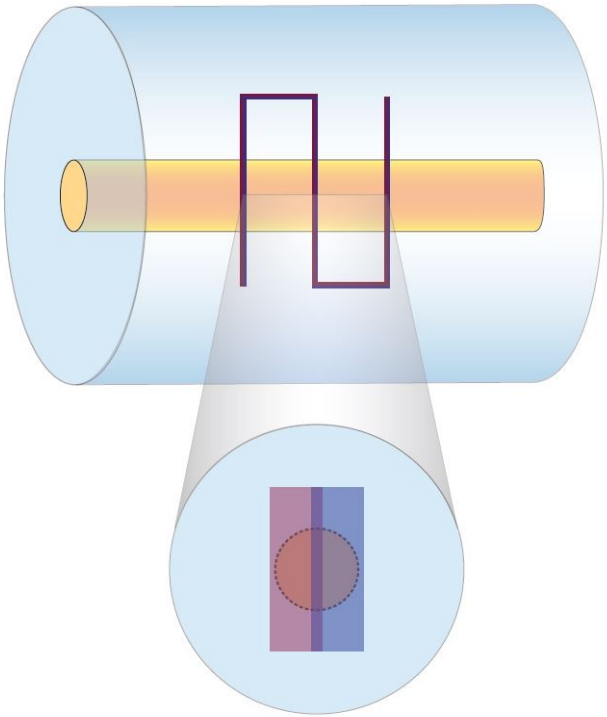
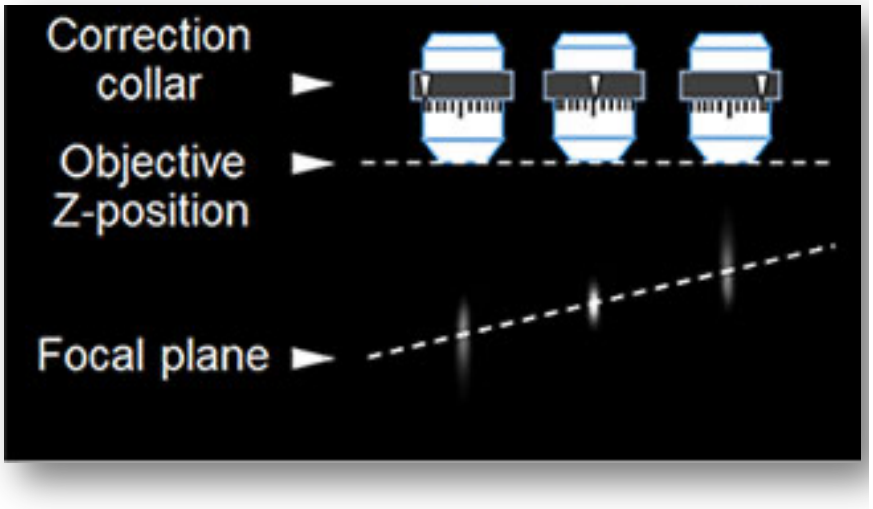
line-by-line



Stacking (plane-by-plane)



Controlled aberrations



Bharathan et al, Opt. Letters **44**, 423 (2019)

Annealing behaviour

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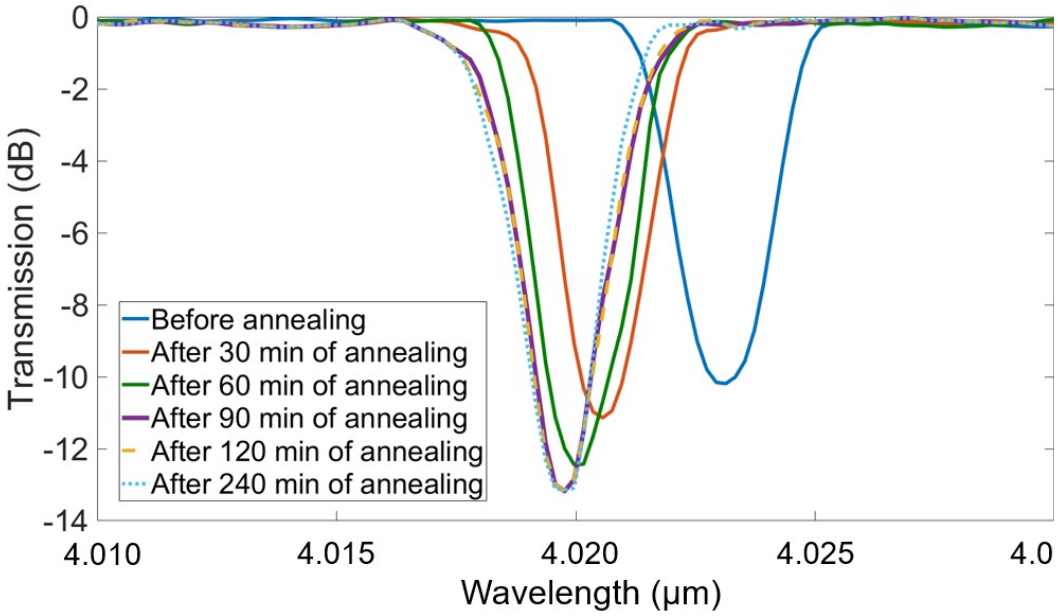
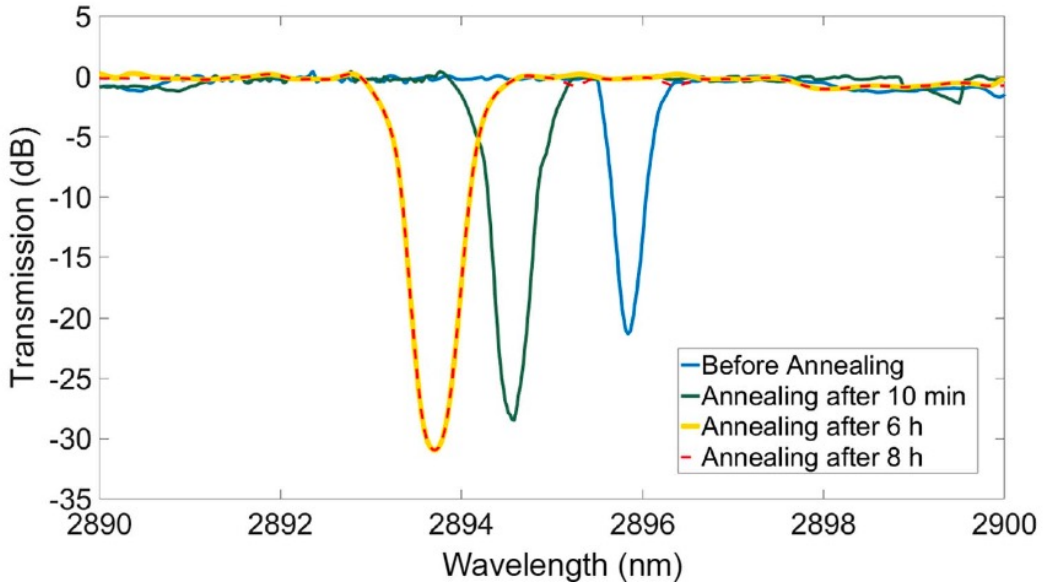
InF_3



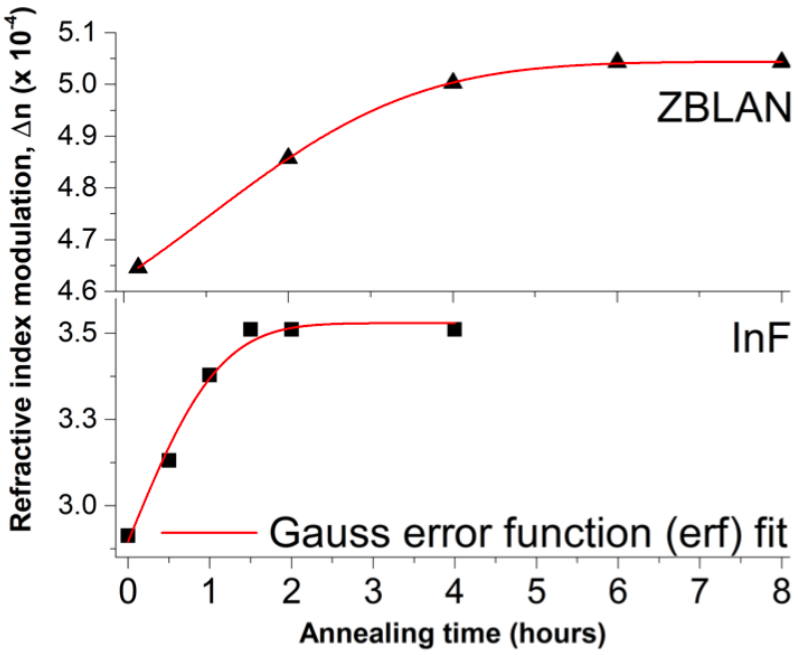
Bharathan et al, Opt. Letters **45**, 4316 (2020)

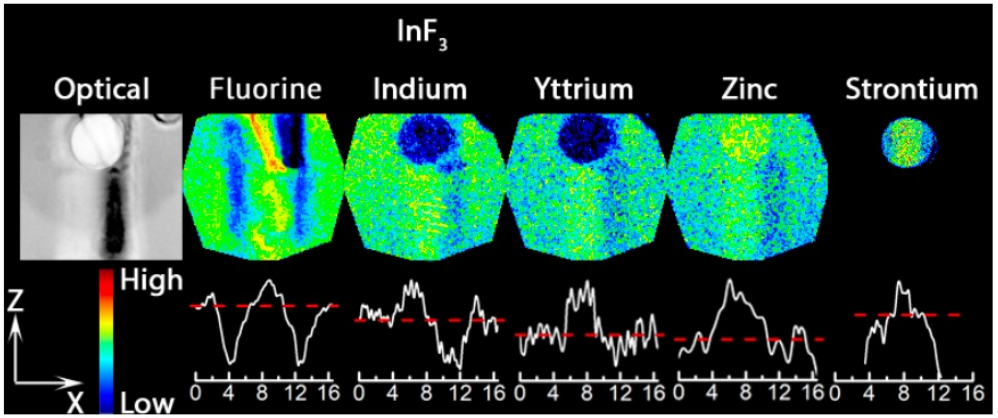
ZBLAN

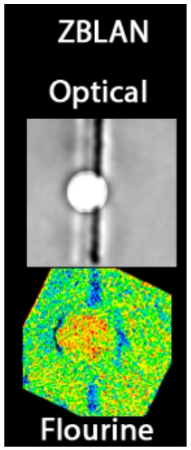


Bharathan et al, Opt. Letters **44**, 423 (2019)

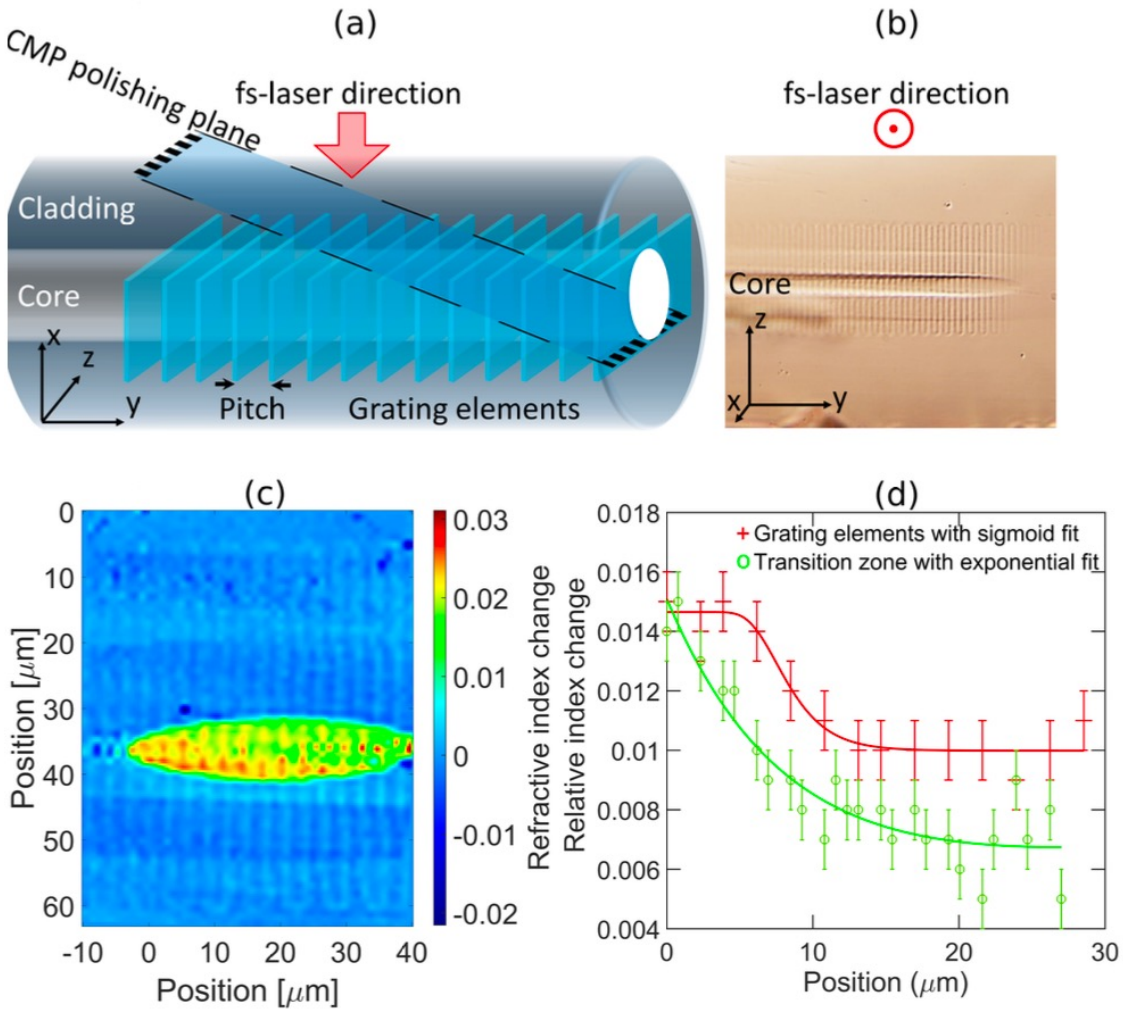
Mass transport behaviour







Side-polishing and Micro-reflectivity



Fernandez et al, APL Photoncis **9**, 110802 (2024)

Acknowledgements