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Modification of optical fibers using femtosecond laser irradiation

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- Co-workers
  - Florian Dürr (PhD)
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  - M. Douay, F. Hindle, Univ. Lille, France
  - D. Nikogosyan, S. Slattery, Univ. Cork, Ireland

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Content

- fs-laser induced changes in transparent materials: effects
- Laser induced changes in optical fibers
- Fabrication of wavelength selective filters in waveguides
  - LPG
  - FBG
- Characterization of fs-induced glass changes
  - Spectral features of fiber gratings
  - Two-dimensional birefringence / stress distribution changes

Timescale of physical phenomena

REVIEW ARTICLE

Femtosecond laser micromachining in transparent materials

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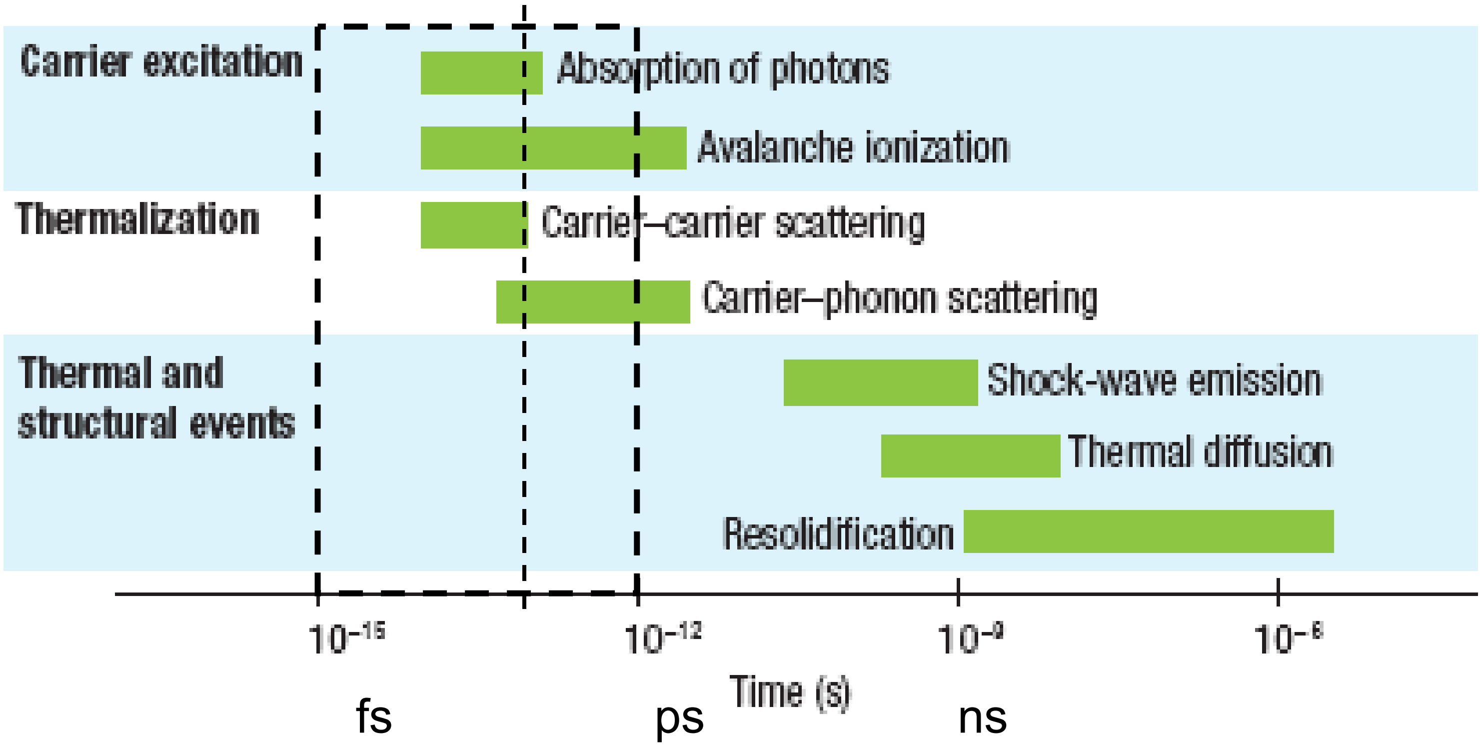
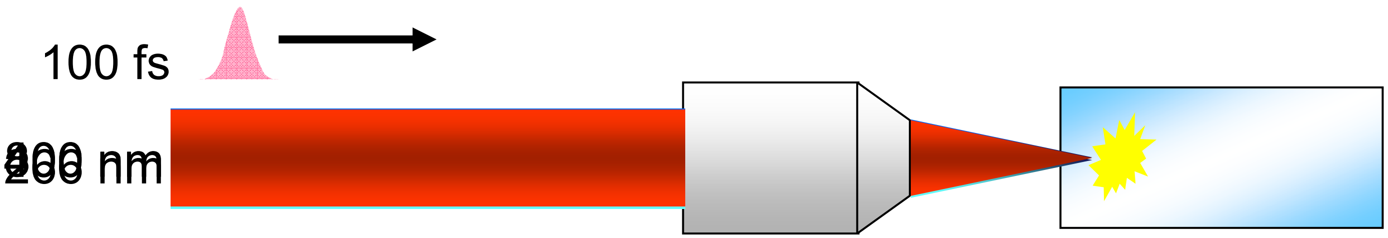


Nonlinear absorption in SiO2



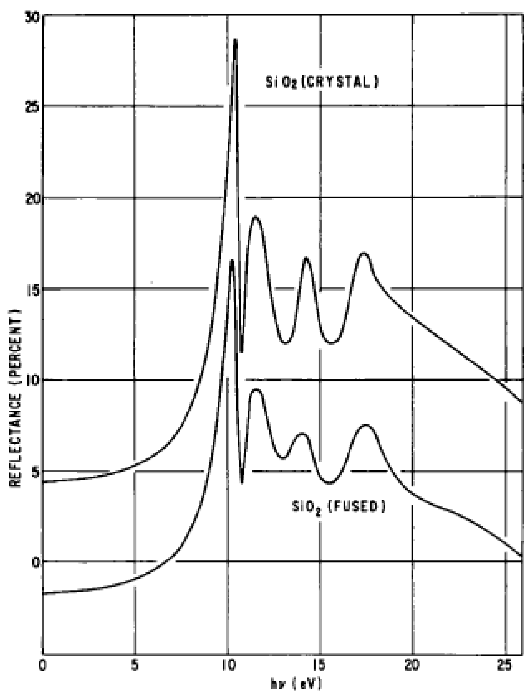
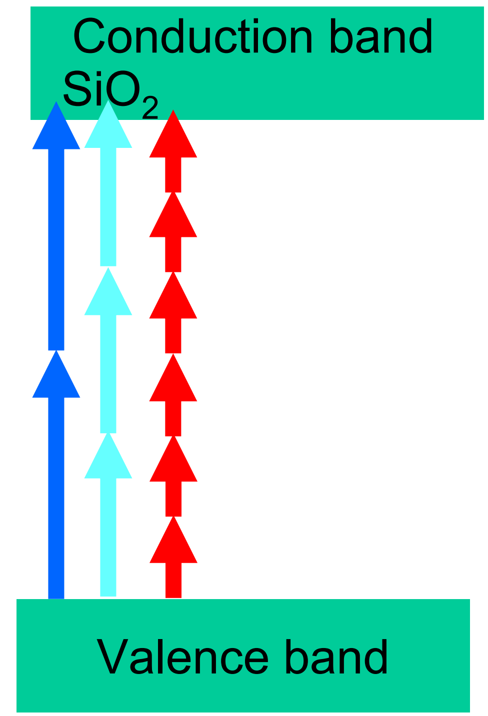


Fig. 1. The spectral dependence of the reflectance of crystalline and fused quartz. For clarity, the values for fused quartz have been lowered by 5 per cent.

6 red photons

3 blue photons

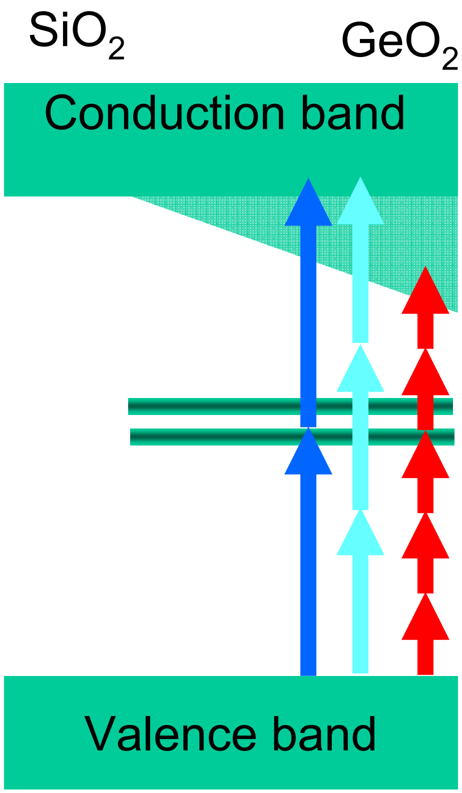
2 UV photons



SiO2 band gap 8.3 - 9.3 eV

JPCS_32_1935_1971_Philipp_SiO2-bandgap

Nonlinear absorption in Ge-SiO_2



5 red photons

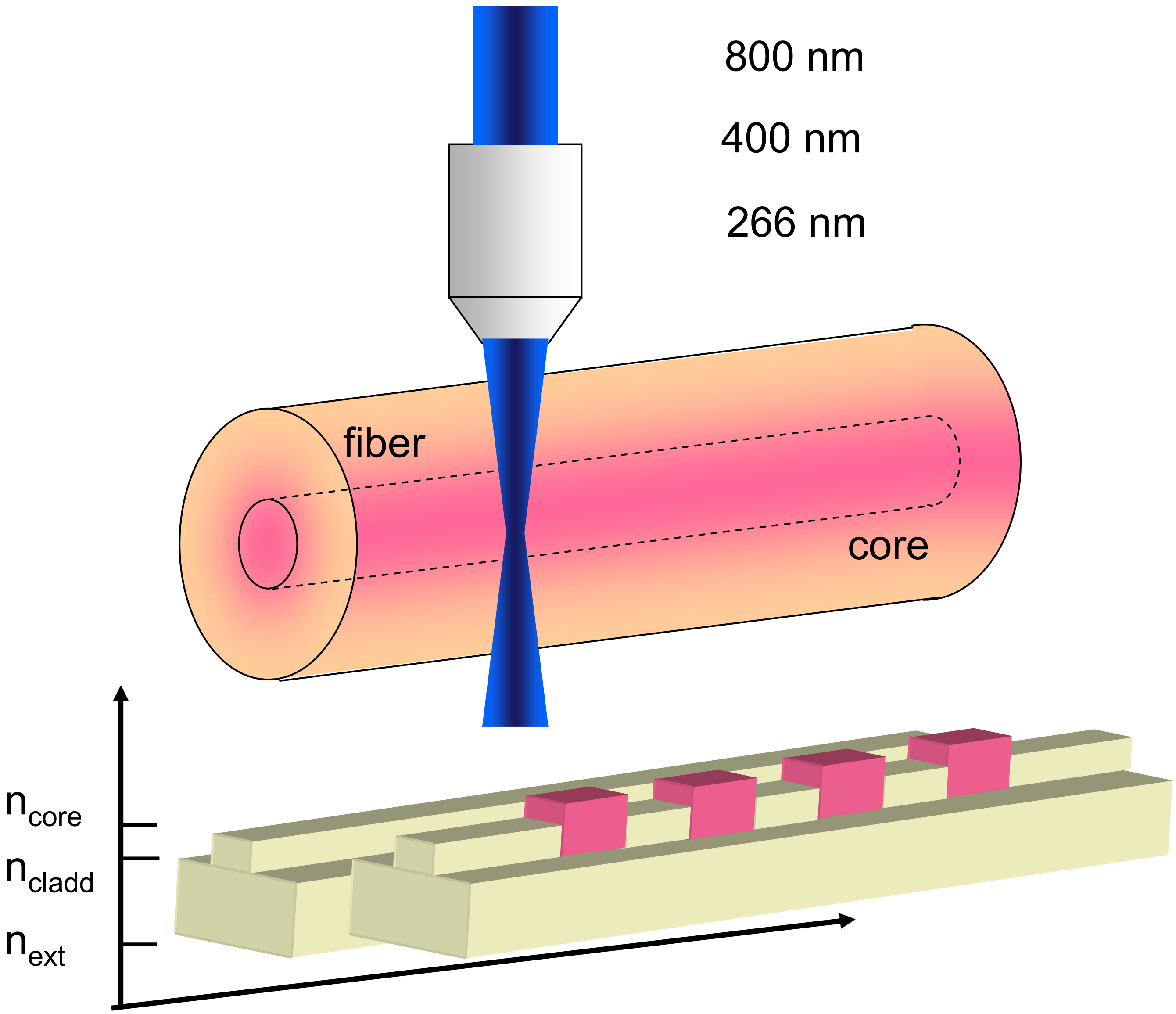
3 blue photons

2 UV photons

Resonant enhanced transition

GeO2 (5mol%) -SiO2 band gap 7.1 eV
GeO2: band gap 5.6 eV

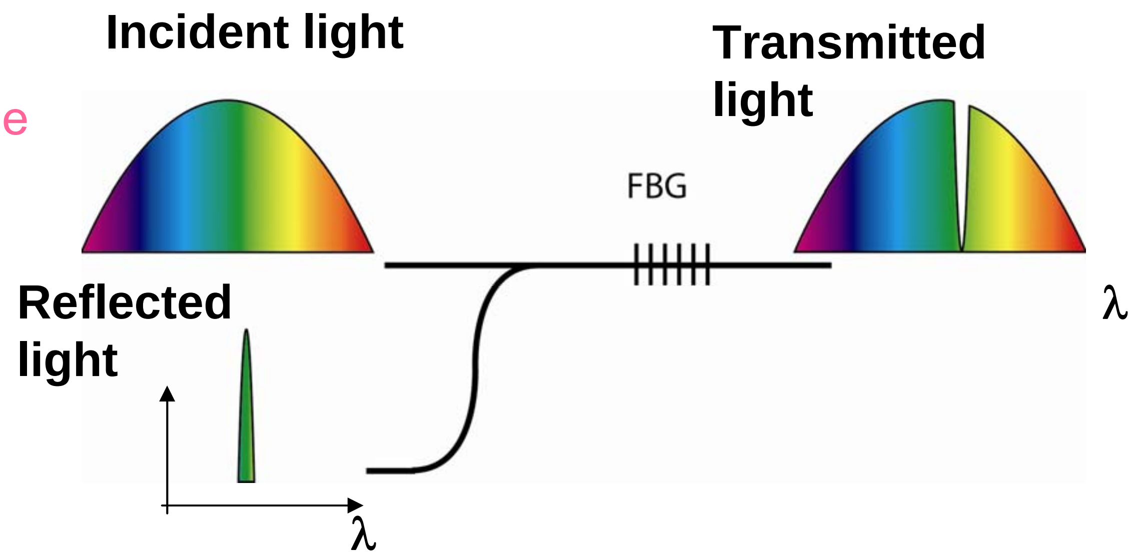
Fs-LPG fabrication



Bragg grating principle

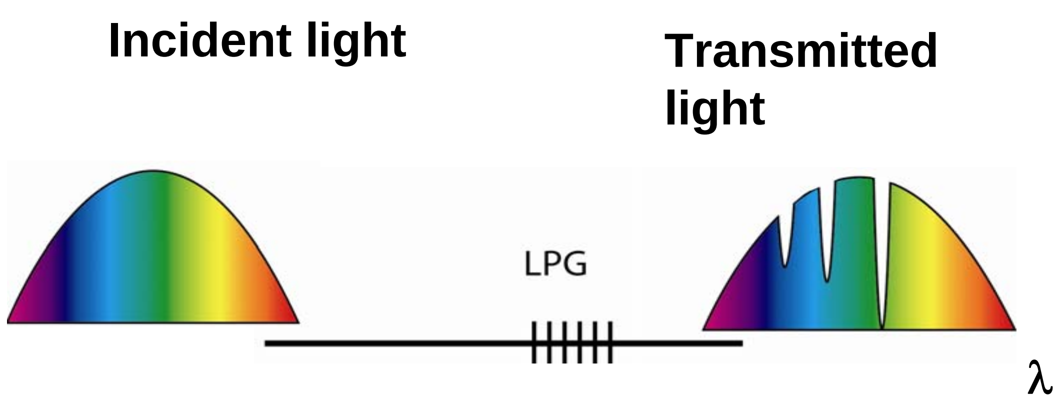
- **Fiber Bragg grating**

  forward to backward propagating mode coupling:
  - **Bragg grating**: core modes
  - **Tilted grating**: core to cladding and continuum



- **Long period grating**

  forward propagating mode coupling:
  - **LPG**: core and cladding mode
  - **Rocking filter**: polarization core modes
  - **Mode converter**: core modes



Bragg grating applications

Temperature and/or strain sensing

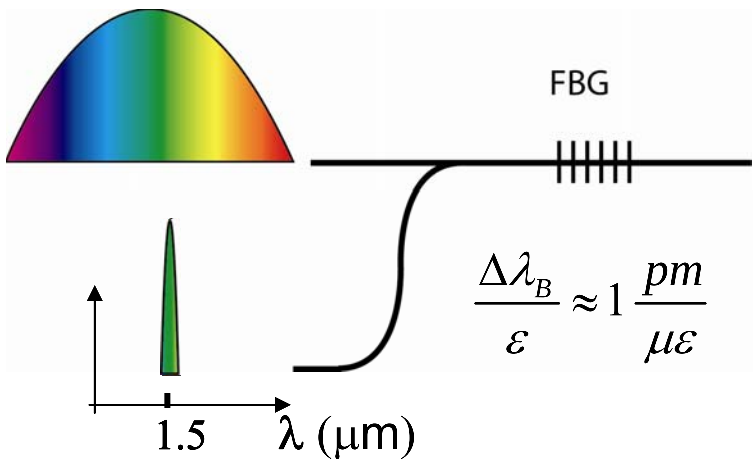
$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg}} = (1 - p_e)\cdot\varepsilon_z + (\alpha + \xi)\cdot\Delta T; \qquad \varepsilon_z = \frac{\Delta L}{L};$$

thermo-optic: $\xi = \frac{1}{n}\frac{\partial n}{\partial T}$; thermal exp.: $\alpha = \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial T}$

effect. photoel. p_e

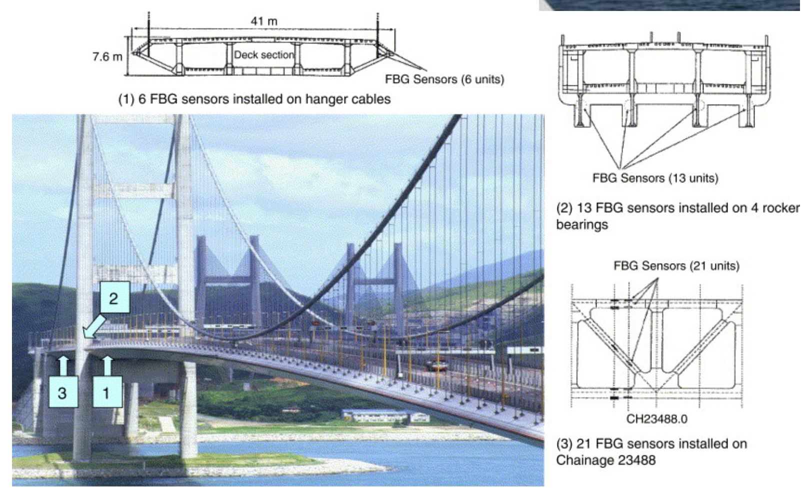
Optical-fibre sensors can be packaged for skin-temperature monitoring, for example during MRI procedures.

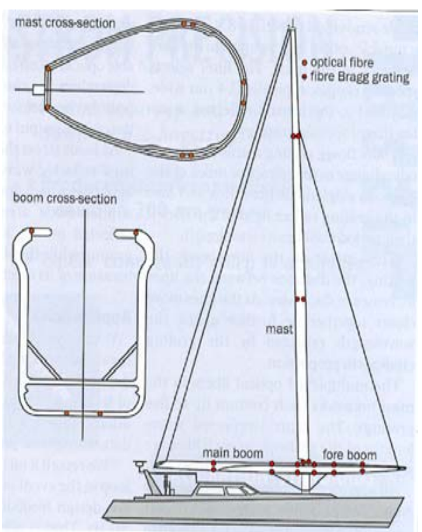
nphoton-techfocus: 3, 2008

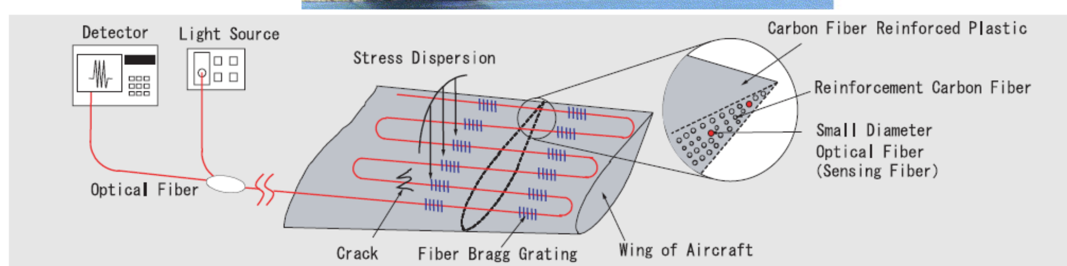


$$\frac{\Delta\lambda_B}{\varepsilon} \approx 1\,\frac{pm}{\mu\varepsilon}$$

$$\frac{\Delta\lambda_B}{\Delta T} \approx 10\,\frac{pm}{K}$$







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Material characterization

- Laser irradiation of glass fibers leads to permanent refractive index changes
  - Stress relief (proposed: Sceats et al., ‘93, ruled out (Limberger et al. ‘95)
  - Color center changes (Hand and Russell, 1990)
    - Local rearrangement of defects ➔ absorption changes. Kramers-Kronig
  - Volume changes, i.e. compaction, (Bernardin, Lawandy, 1990)
    ➔ Densification of the core glass ➔ results in core stress change
- Spectral characterization (online)
  - Mean index change (photosensitivity)
  - Index amplitude (fringe visibility, stability, ..)
- Stress changes (after)
  - Volume changes
  - Photoelastic index changes

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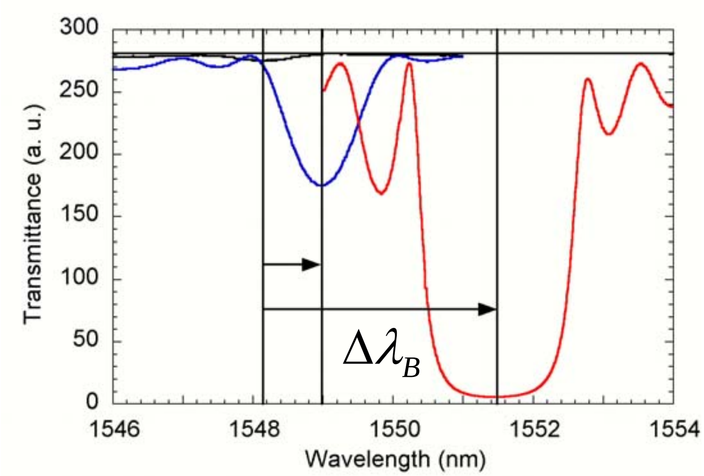
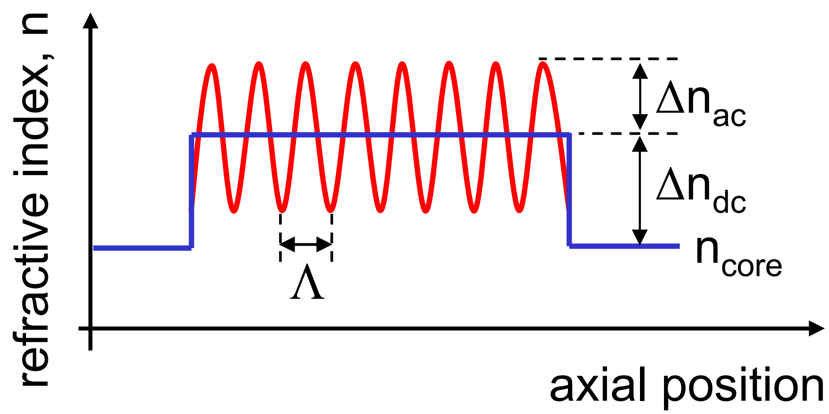
Bragg grating principle & spectra

Bragg gratings: periodic and axial refractive index structure written in the core of the fiber that reflects selectively a wavelength band

Wavelength spectrum



Core index distribution along fiber axis



Bragg wavelength resonance: $\lambda_B = 2n_{eff}\Lambda$

Maximal reflectivity: (top-hat profile) $R = \tanh^2(\kappa L)$

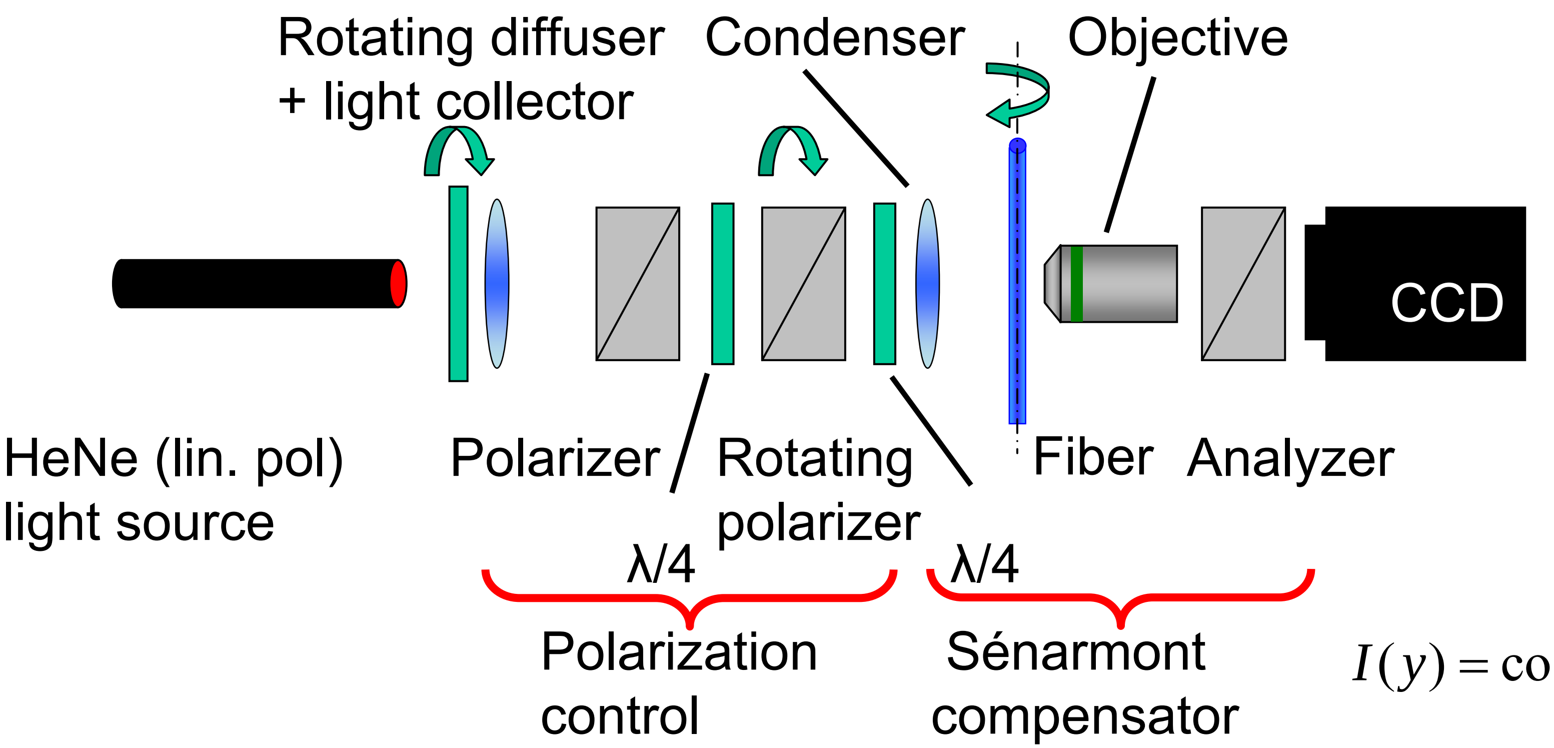
Wavelength shift during grating growth $\Delta\lambda_B$

AC component: $\Delta n_{ac} = \frac{\kappa\lambda_B}{\eta\pi}$

DC component: $\Delta n_{dc} = \frac{n_{eff}}{\eta}\frac{\Delta\lambda_B}{\lambda_B}$

Overlap integral: η

Polarscope



$$I(y) = \cos^2(\theta - \frac{\delta}{2} - \frac{\pi}{4})$$

The intensity captured by the CCD is a cosine squared function of the polarizer's rotation angle and the phase retardation is directly linked to the refractive index.

Retardation:

$$\Re^{tot}(y) = \frac{\lambda}{2\pi}\delta(y) \quad [nm]$$

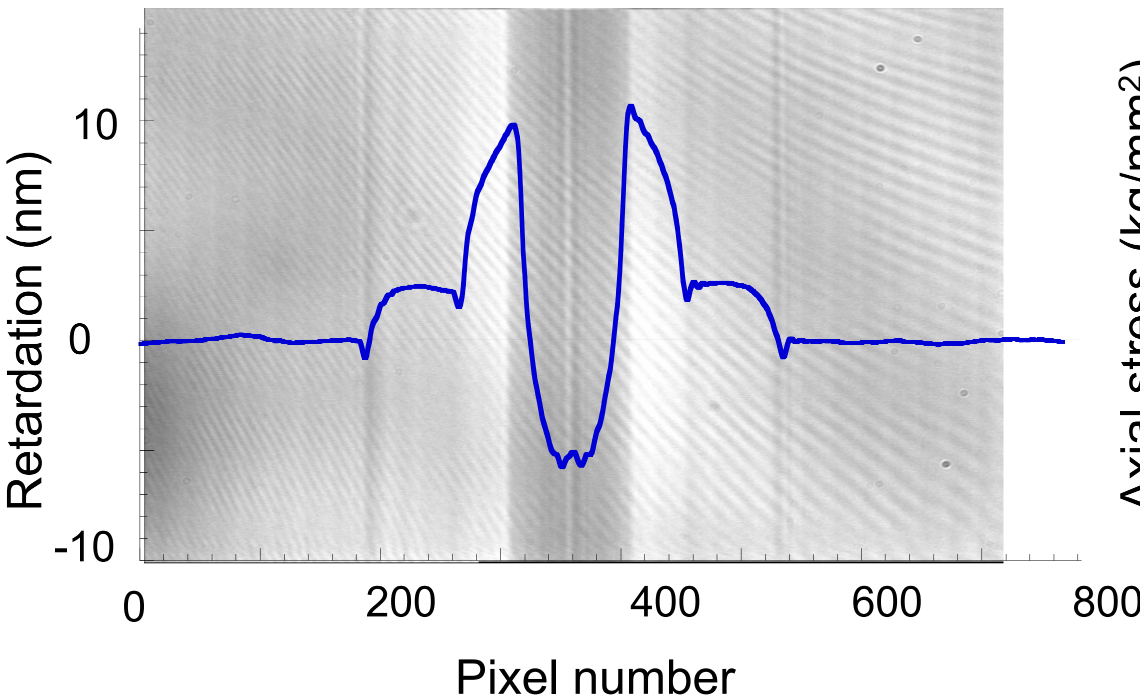
θ: polarizer rotation angle
δ: fiber induced retardation

F. Dürr, PhD 2005

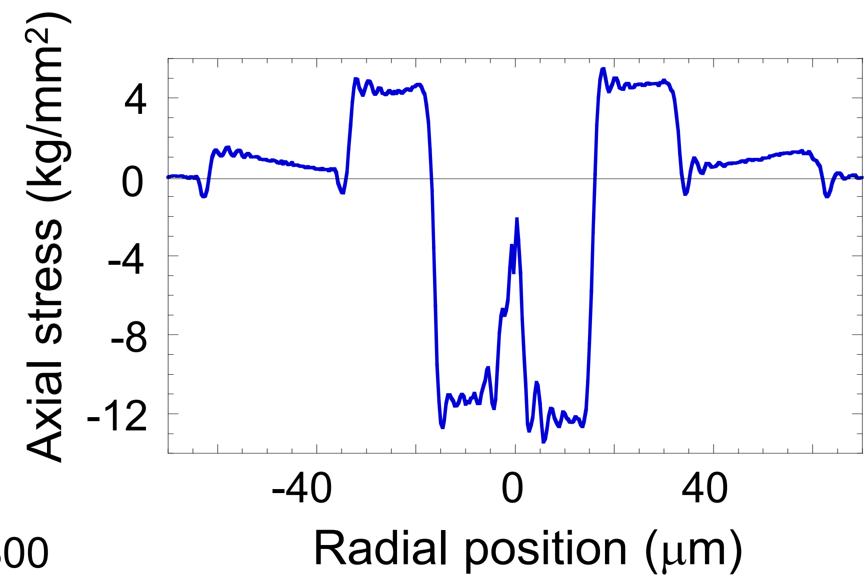
Fiber CCD projection data and stress

- Axial symmetric stress profile (Fiber: 9% GeO_2/SiO_2):

One single capture of projection data



Stress calculated using Abel inversion

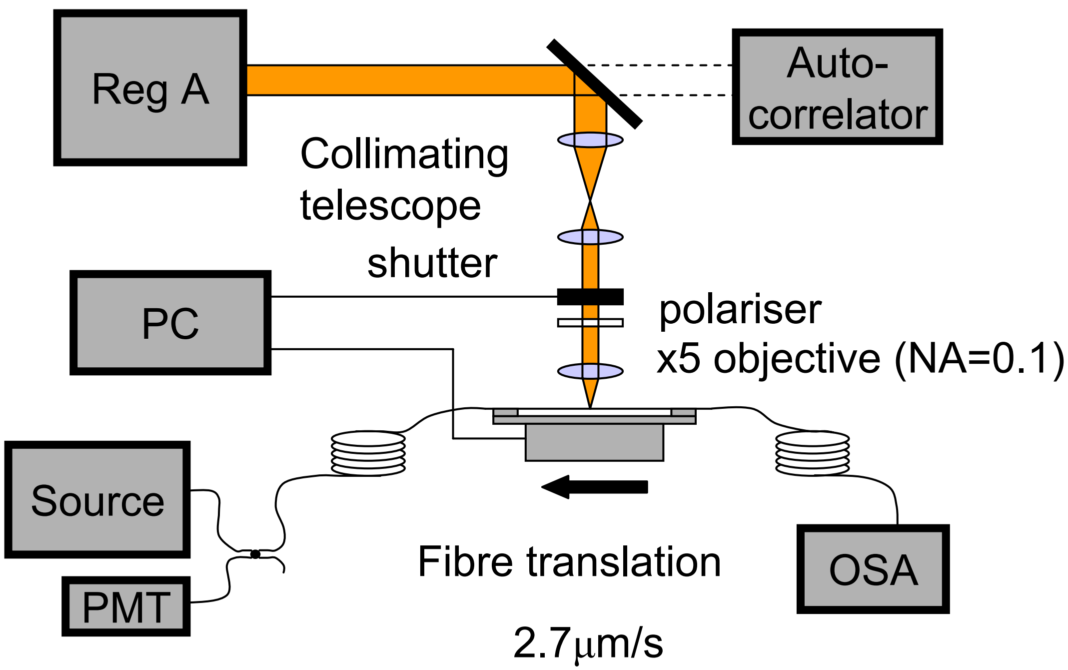


$$1\,\frac{kg}{mm^2} \approx 10\ MPa$$

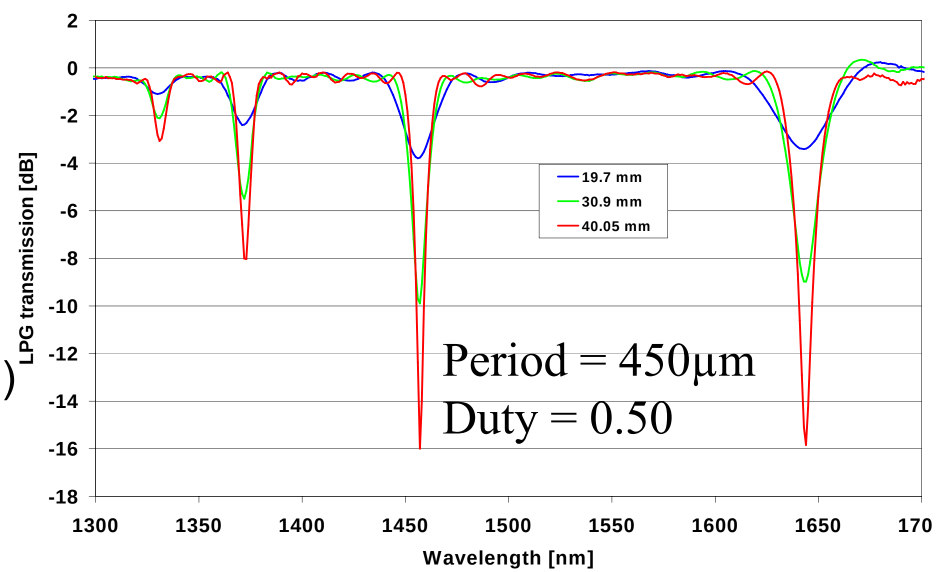
800 nm fs-laser written LPG in SMF-28

- Inscription set-up

F. Hindle, M. Douay et al . PTL. 2004



- Grating transmission during inscription



laser parameters:

λ = 800 nm

τ_P = 160 fs

E_P = 0.27 µJ

f = 200 kHz

beam parameters:

I_{max} = 6×10^{12} W/cm^2

Δx_{FWHM} = 47 µm

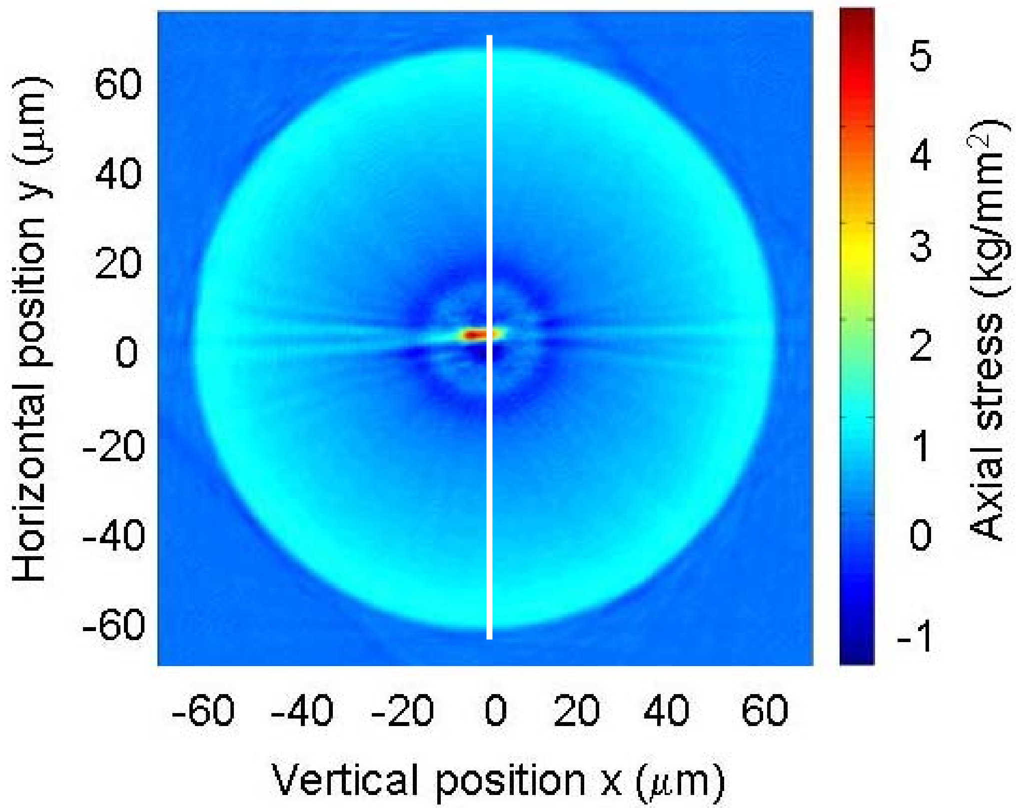
Δy_{FWHM} = 4.2 µm

Index increase (simulation of spectrum): $\Delta n = 4 \times 10^{-4}$

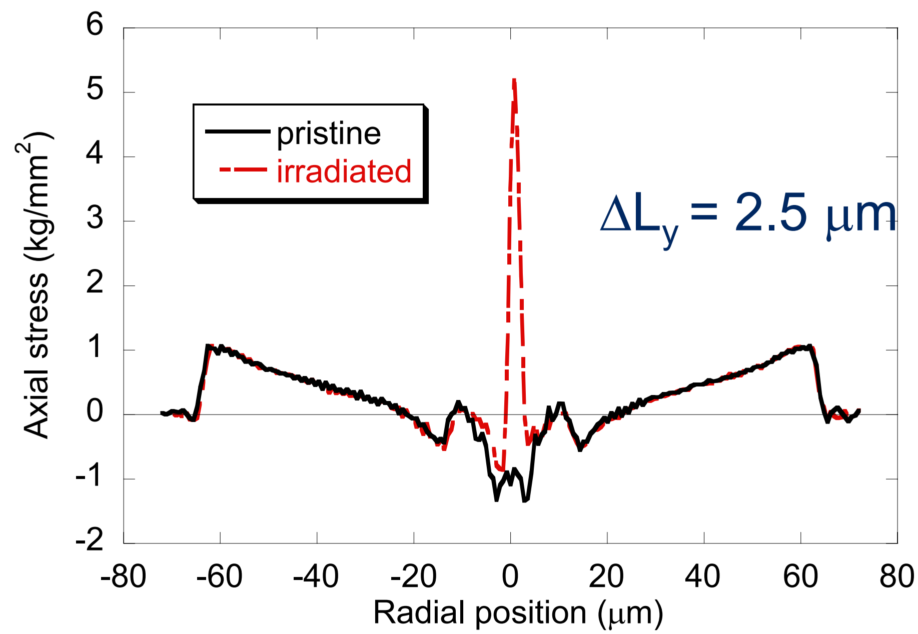
800 nm fs-laser written LPG in SMF-28

Fs-laser: λ=800 nm, τ_P = 160 fs, I_{max} = 6 x 10^{12} W/cm^2

(M.Douay, F. Hindle, Univ. Lille, F)



Vertical



ΔL_y = 2.5 µm

$\Delta\sigma_{max}$ = 6.2 kg/mm^2

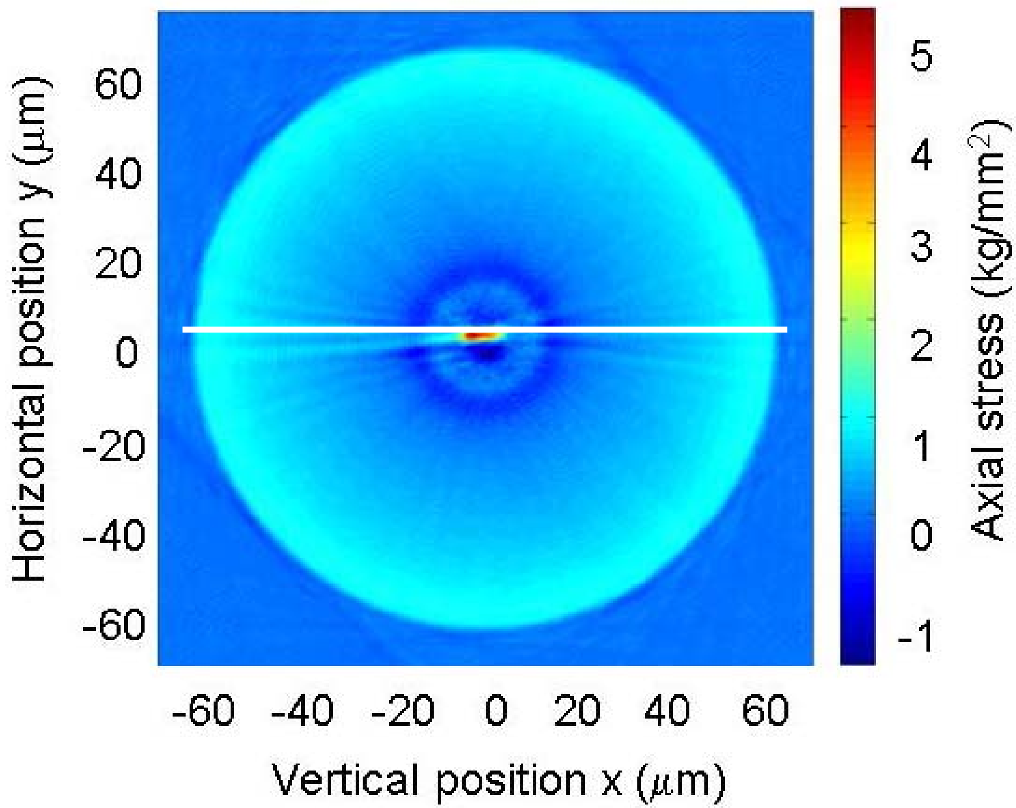
- Modification of stress only occurs in the Ge-doped core

Dürr, Limberger et al. APL 84, 4983, 2004

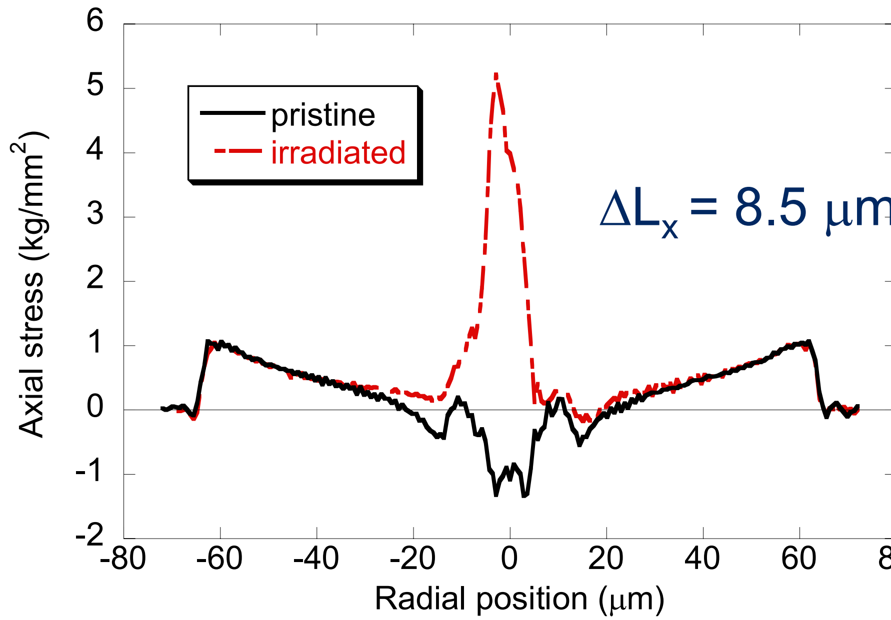
800 nm fs-laser written LPG in SMF-28

Fs-laser: λ=800 nm, τ_P = 160 fs, I_{max} = 6 x 10^{12} W/cm^2

(M.Douay, F. Hindle, Univ. Lille, F)



horizontal



ΔL_x = 8.5 µm

$\Delta\sigma_z / \Delta n$ = 1.55 $\approx 10^{-4}$ kg/mm^2

$\geq$ 69% of index change due to compaction

Dürr, Limberger et al. APL 84, 4983, 2004

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400 nm fs-laser written LPG in SMF-28

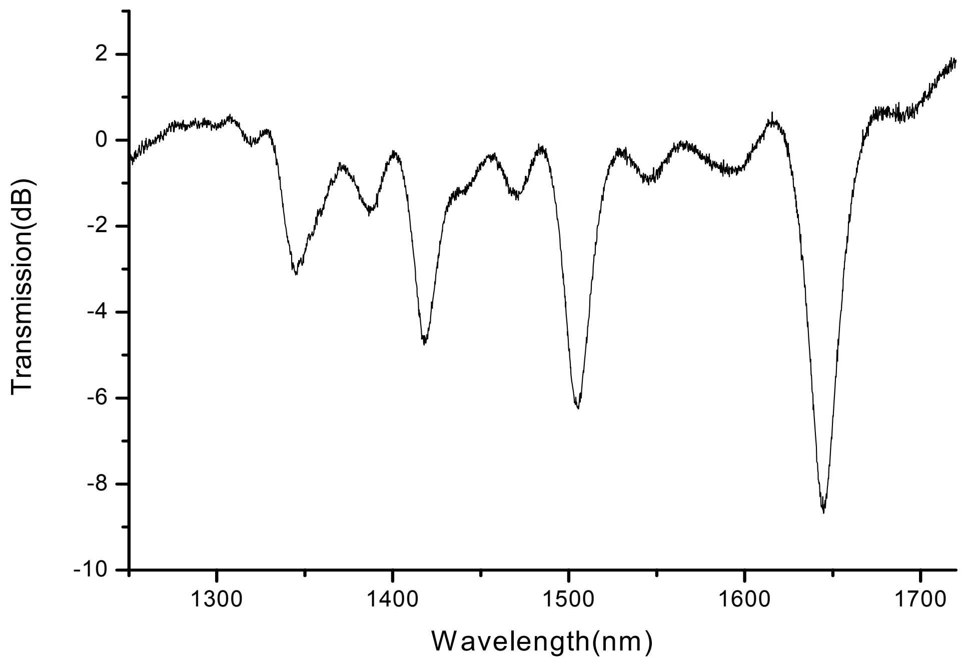
Laser parameters:

Av. power, P: ~140 mW
Repetition rate, f: 248.4 kHz
Pulse width, δt: ~250 fs
Pulse energy, E_p: 0.5 μJ

Focusing and irradiation:

Objective: 20×	N.A.= 0.4 (f=8.55 mm)
Beam diameter:	~6 μm (area, A: ~28 μm)
Pulse fluence, $F_p=E_p/A$:	1.7 J/cm^2
Peak intensity, $P_p=E_p/\delta t$:	2 MW
Intensity, $I=F_p/\delta t$	6.9 x 10^{12} W/cm^2
Stage velocity, v:	0.18 mm/min
Dose, $F=N\ F_p=P/(v\Delta y)$	1.02 MJ/cm^2

LPG Transmission spectrum

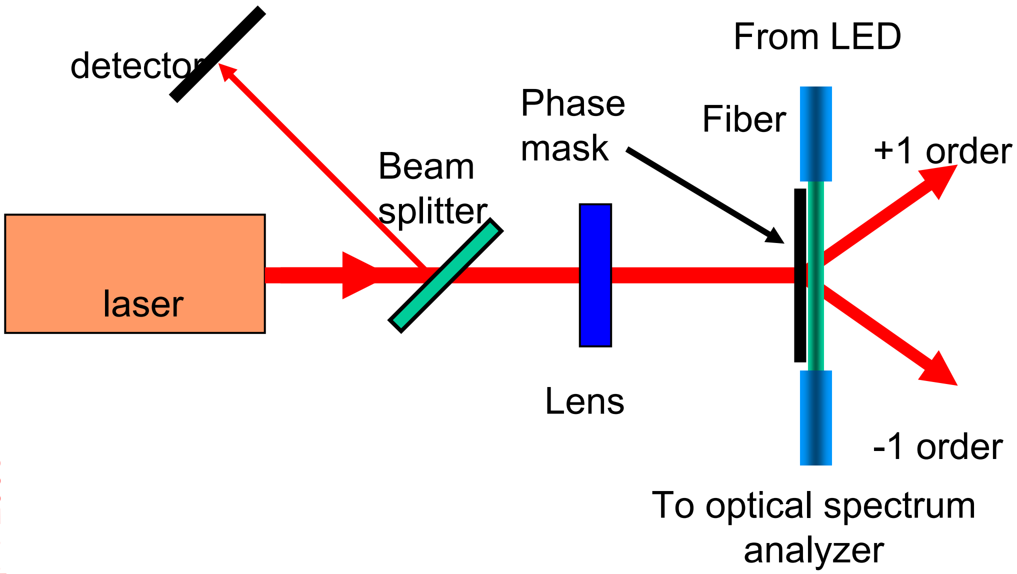


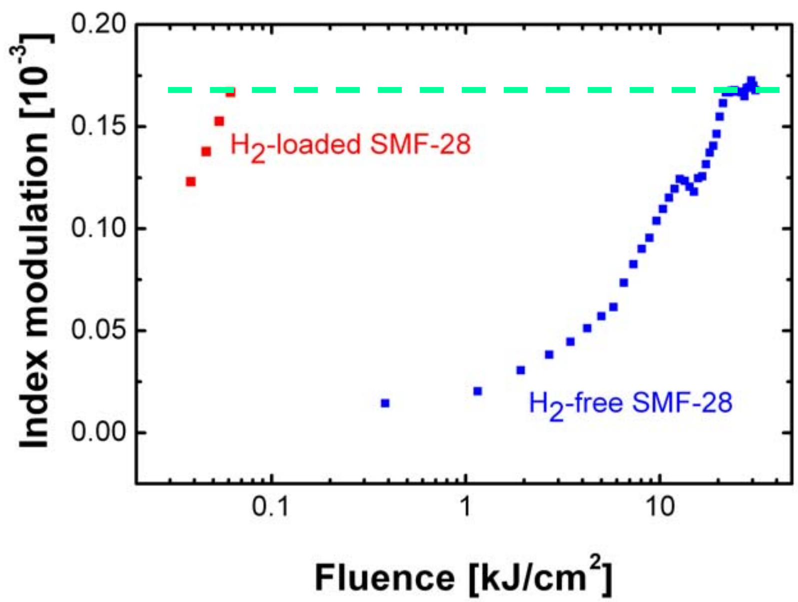
Grating parameters:

SMF-28, Corning
H2 loaded
Period: 450 μm
Duty cycle ratio: 0.5
Length: 18.675 mm

264 fs-laser written FBG in SMF-28

Fs-Nd:glass laser system (Nikogosyan, S. Slattery, Univ. Cork):





264 nm Nd-glass femtosecond laser
pulse duration: 220 fs (FWHM),
beam diameter: 0.3 cm (FWHM),
repetition rate: 27 Hz,
pulse energy: up to 300 μJ.
irradiation intensity: 300-340 GW/cm2.

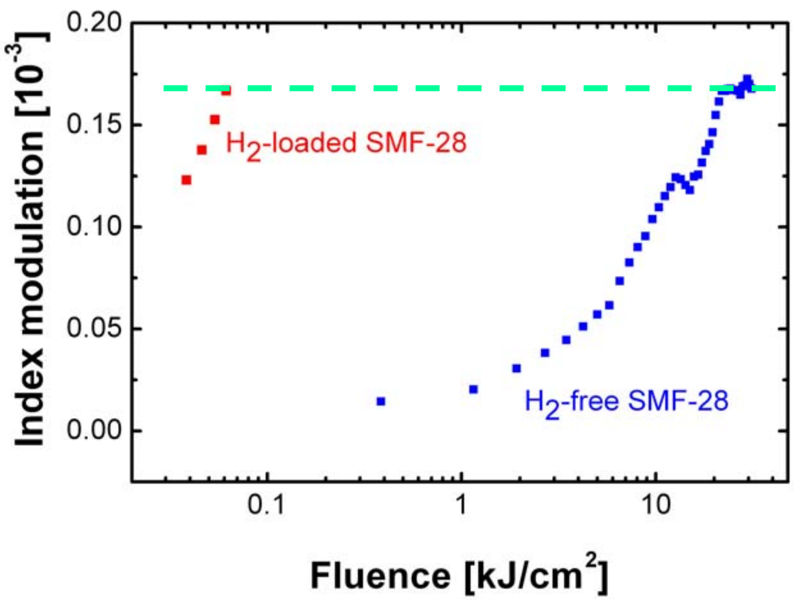
FBG length: 3 mm (FWHM).
neither self-focusing nor type II damage

- 520 times smaller dose for H2 loaded fibers

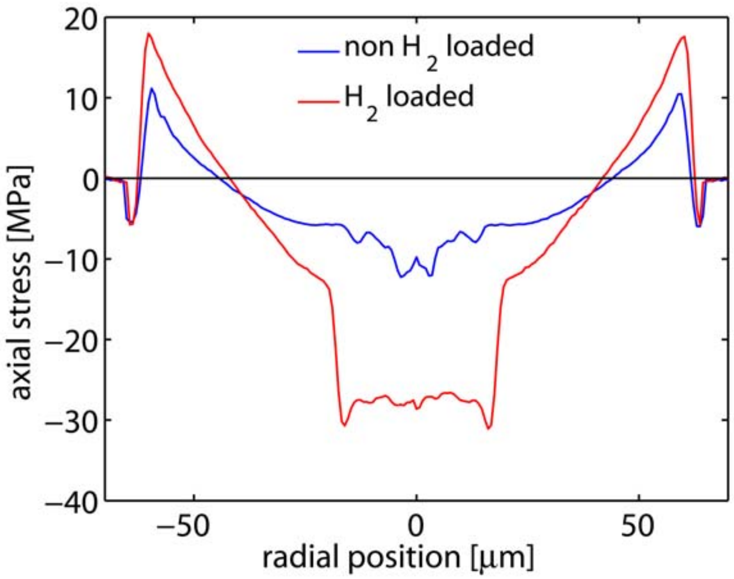
Limberger, Ban et al.
OpEx 15, 5610, 2007

264 fs-laser written FBG in SMF-28

- Fs-Nd:glass laser system:
  - (Nikogosyan, S. Slattery, Univ. Cork)



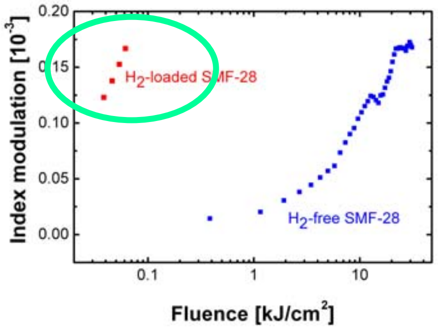
H_2-loaded/pristine fiber



- 520 times smaller dose for H2 loaded fibers
- H_2 loading changes the core stress

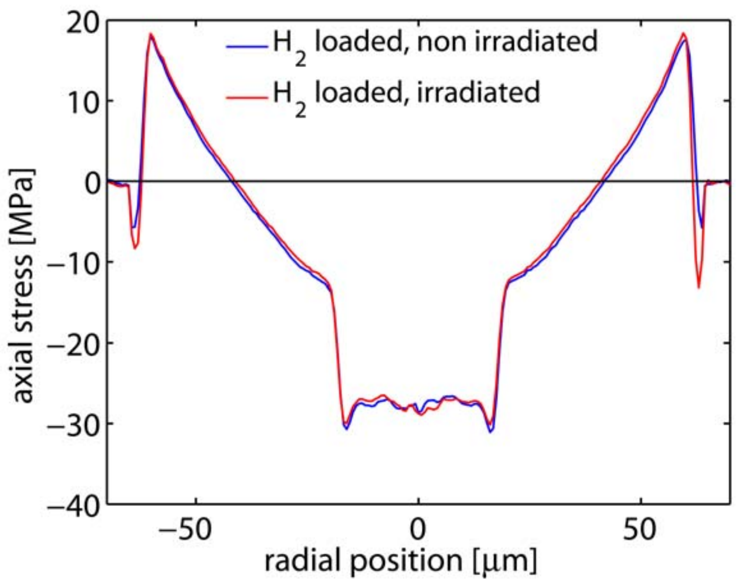
Limberger, Ban et al.
OpEx 15, 5610, 2007

264 fs-laser written FBG in SMF-28 H2



- Fs-Nd:glass laser system:
  - (Nikogosyan, S. Slattery, Univ. Cork)

H_2-loaded, irradiated fiber

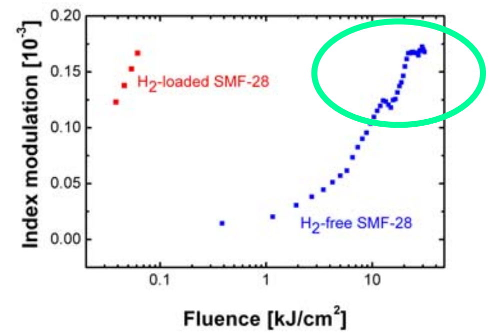


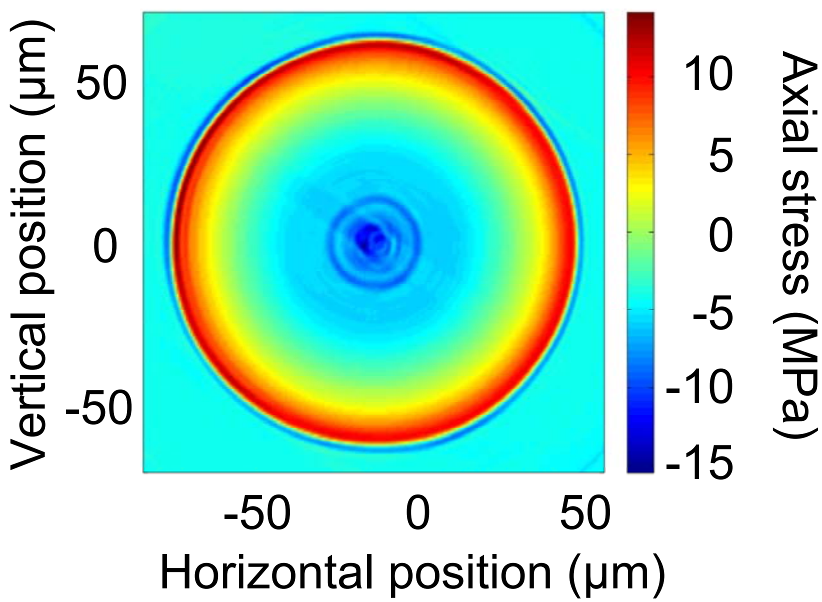
- Index changes without stress changes
- $\Delta\sigma_z / \Delta n = 0$ kg/mm^2.
  ➔ Color center only!

Limberger, Ban et al.
OpEx 15, 5610, 2007

264 fs-laser written FBG in SMF-28

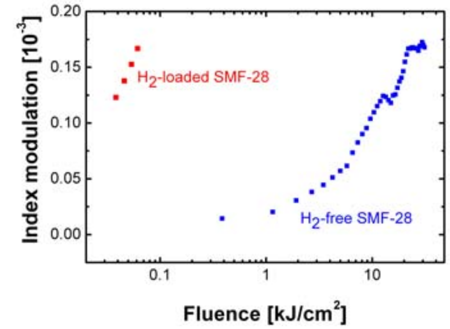
- Fs-Nd:glass laser system:
  - (Nikogosyan, S. Slattery, Univ. Cork)





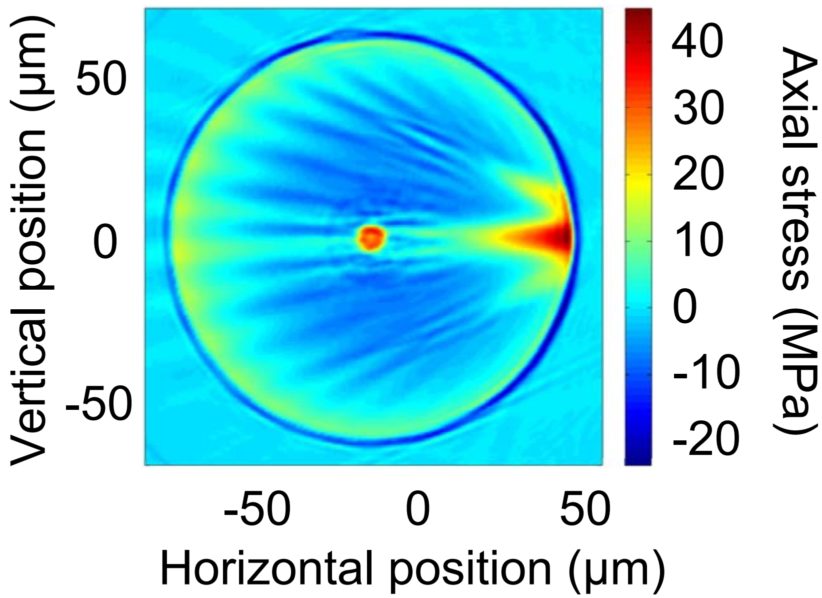
Limberger, Ban et al.
OpEx 15, 5610, 2007

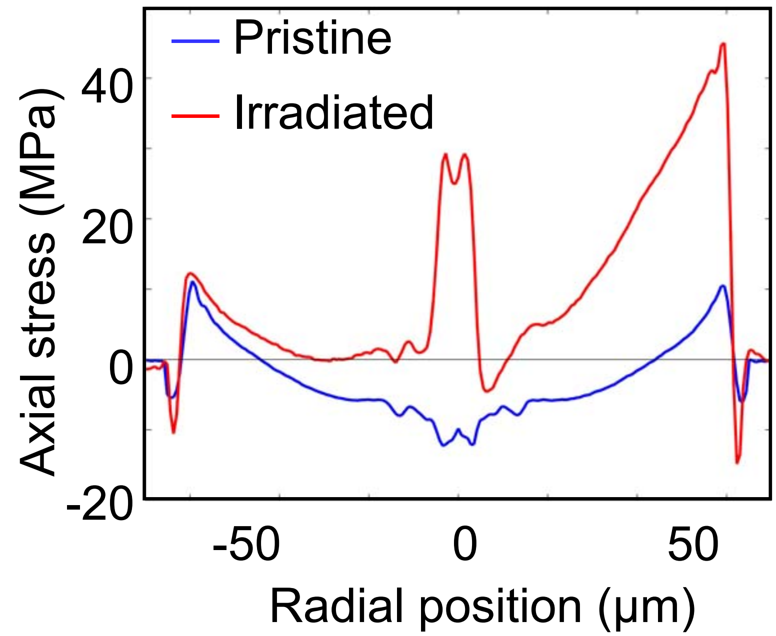
264 fs-laser written FBG in SMF-28



- Fs-Nd:glass laser system:

  (Nikogosyan, S. Slattery, Univ. Cork)





- Local compaction of the silica cladding at fiber exit
- Strong tensile stress change in the fiber core
- $\Delta\sigma_z / \Delta n = 1.55 \times 10^{-4}$ kg/mm^2

  ➔ 69% of core index change due to compaction

Limberger, Ban et al.
OpEx 15, 5610, 2007

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Summary and conclusion

- Fs-laser at different wavelength (800, 400, 266 nm) used to fabricate gratings in GeO2-SiO2 and plastic optical fibers.
- Window of irradiation parameters given by measurable index changes (lower bound) and self-focusing or damage (upper bound)
- Total index change measured using spectral features of gratings
- Birefringence (stress) measurements are used to determine the presence and amount of photoelastic and volume changes (compaction changes) that lead to refractive index changes
- Using fs lasers
  - the percentage of compaction, i.e. structural changes is highest
  - High index changes can be achieved in hydrogen loaded fibers without compaction (color centers only)


Thank you !