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Femtosecond Laser Micromachining of Fabry-Perot Interferometers in SMF-28 fiber for pressure sensing

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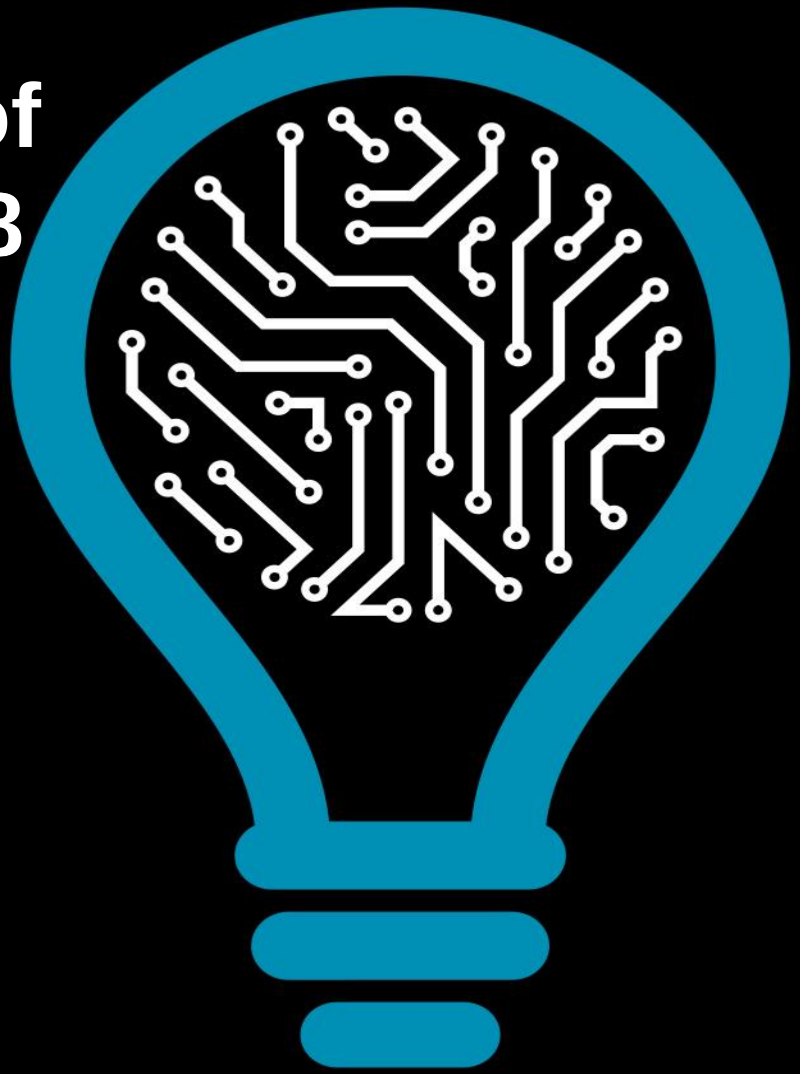

Contents

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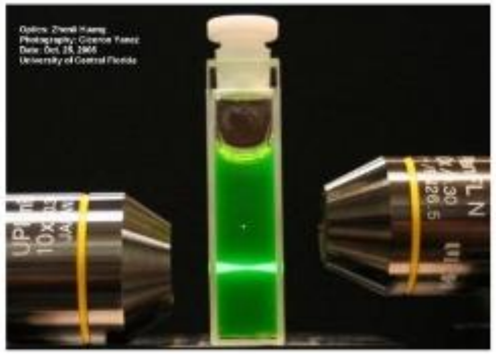
Introduction: why Femtosecond Laser Micromachining?

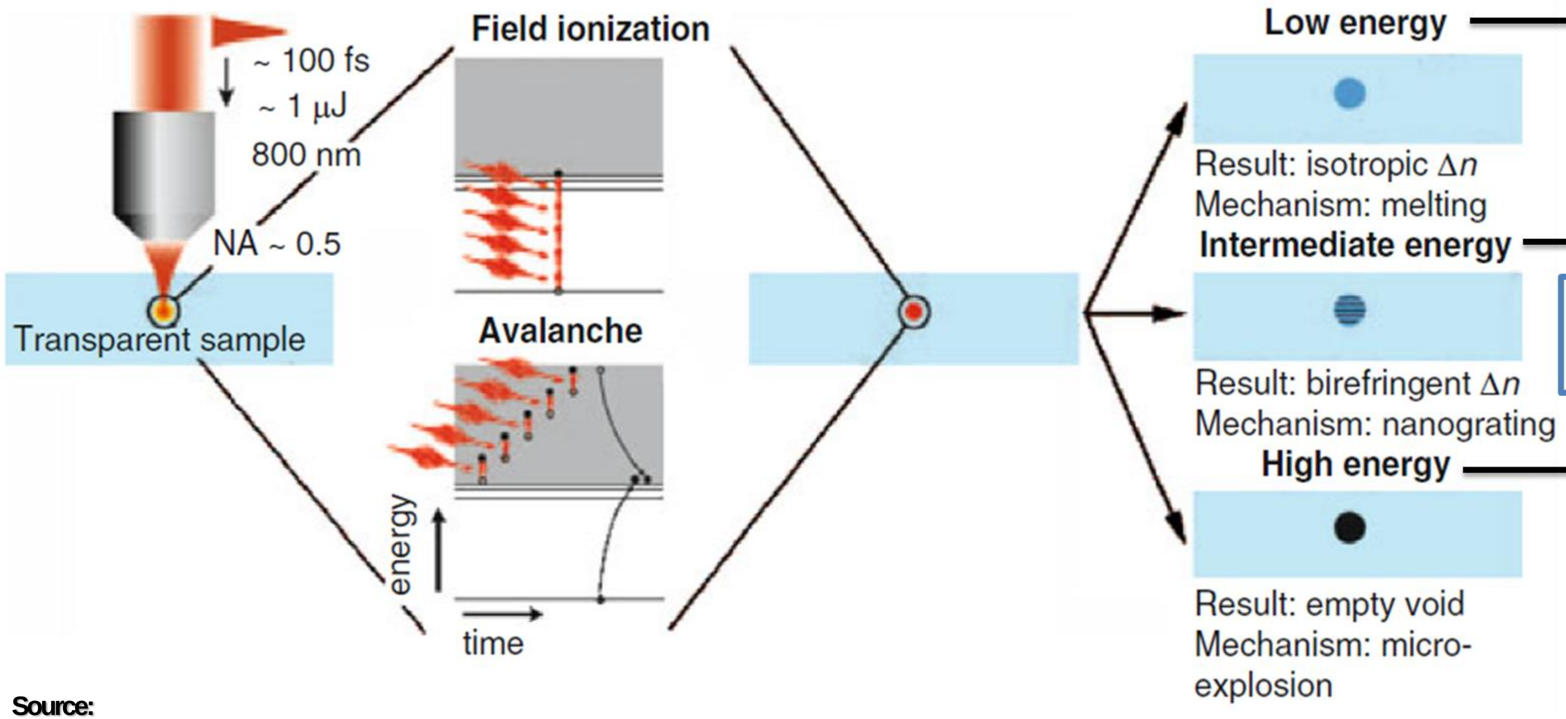
- Truly 3D microfabrication
- High spatial resolution

Nonlinear Absorption: depends on (Intensity)^N



Femtosecond Laser–Material Interaction

High laser intensity in focal volume | **Nonlinear absorption of laser energy** | **Hot electron-ion plasma transfers energy to lattice** | **Permanent material change**



Refractive index modification: waveguides

Induced wet etching anisotropy: glass machining

Ablation: cutting, drilling, micro-holes

Very weak selectivity to etching

Source:

L. Cerami, E. Mazur, S. Nolte, and C. B. Schaffer, “Fundamentals of Femtosecond Laser Modification of Bulk Dielectrics,” in Femtosecond Laser Micromachining: Photonic and Microfluidic Devices in Transparent Materials, Springer Science & Business Media, Ed. 2013, pp. 287–321.

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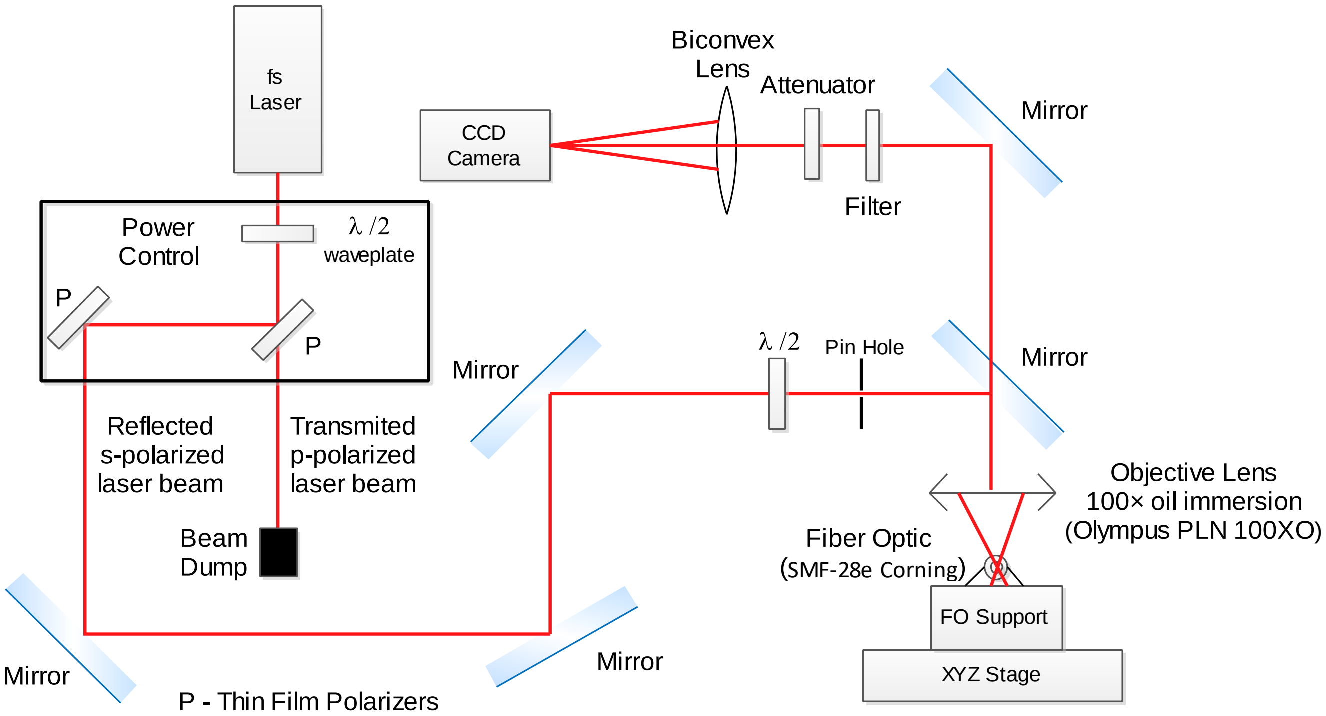
Femtosecond laser micromachining

Basic mechanisms & Fabrication set-up



In this work we choose the following settings:

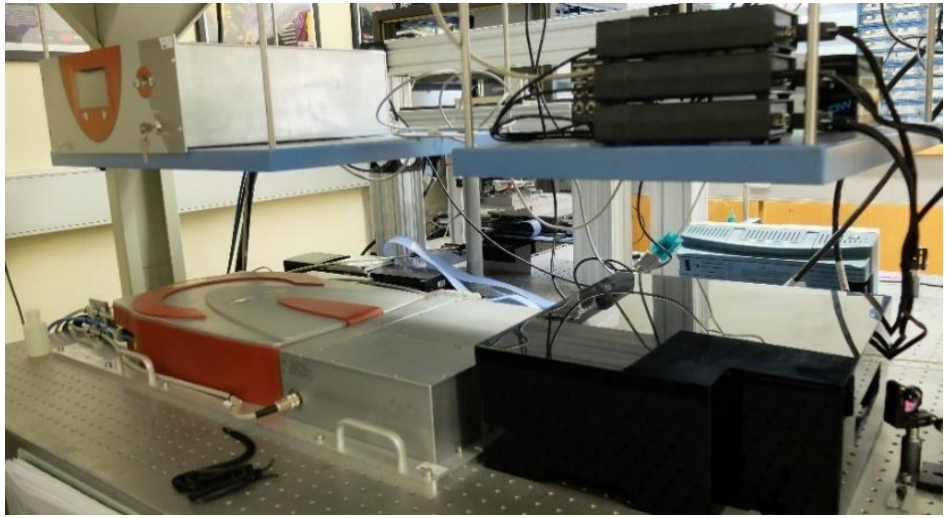
- Second harmonic: 515 nm;
- Maximum Pulse Energy: 11 µJ;
- Maximum Average power: 5.5 W;
- Repetition rate: 500 kHz.

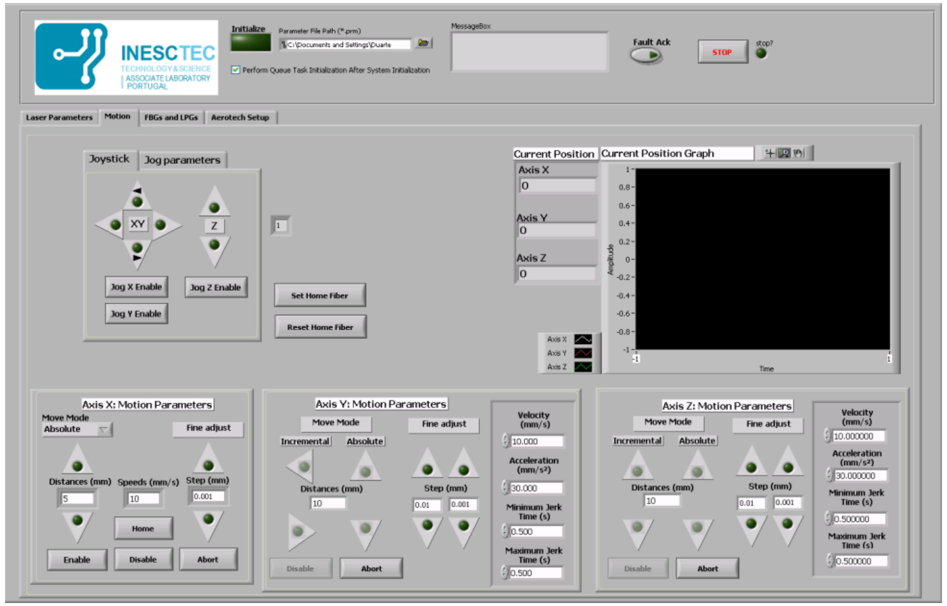
Source:

Femtosecond laser specifications given by Amplitude Systems for Satsuma fiber laser

Femtosecond fiber amplified laser (Satsuma HP, from Amplitude Systèmes):

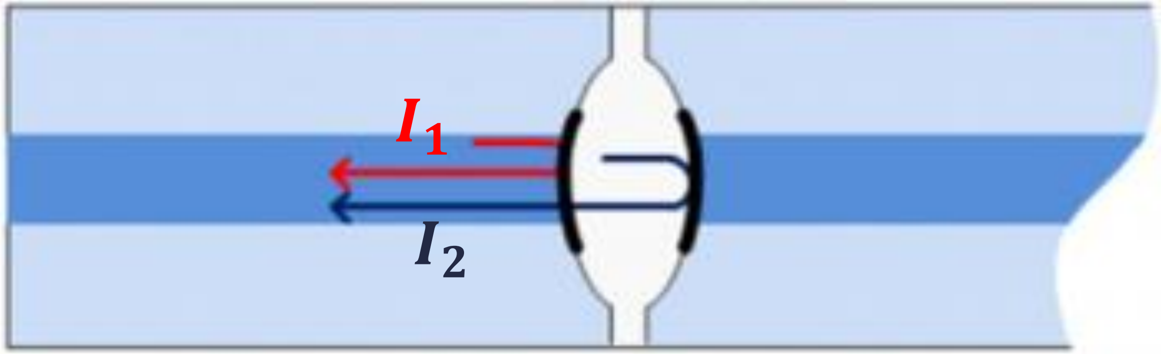
- Pulse Duration: ~ 250 fs;





Fabry-Perot interferometers (FPIs)

Schematic of typical extrinsic cavities in Fabry–Perot (FP) fiber-based sensors



The interference signal intensity can be written as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{4\pi nL}{\lambda} + \varphi_0\right)$$

The spectral spacing between adjacent interference peaks is known as the free spectral range (FSR):

$$FSR = \Delta\lambda = \frac{\lambda^2}{2nL}$$

Fringe Visibility (V):

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Fringe contrast: $I_{max} - I_{min}$

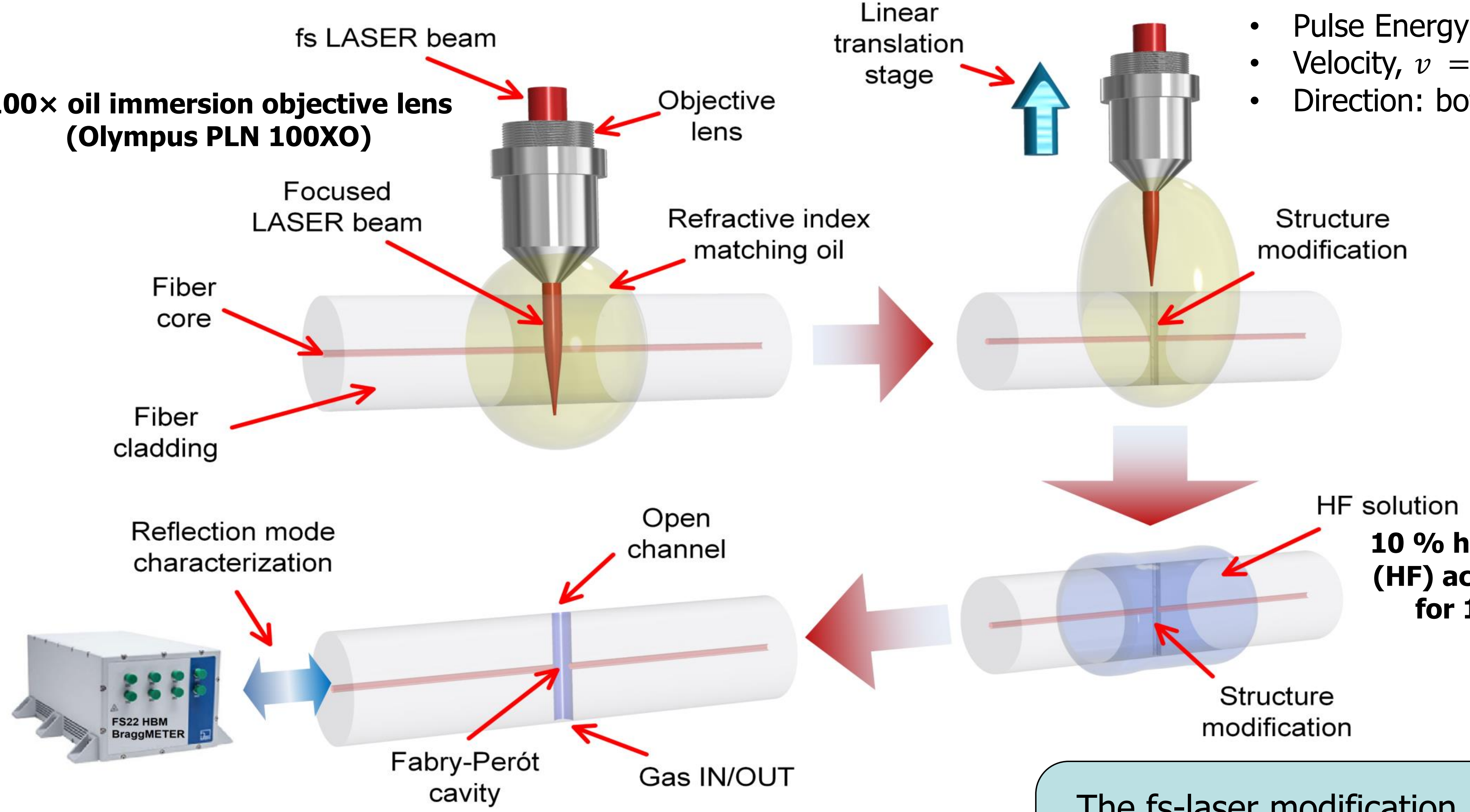
Source:

Liu, Ye, D. N. Wang, and W. P. Chen. "Crescent shaped Fabry-Perot fiber cavity for ultra-sensitive strain measurement." Scientific reports 6 (2016): 38390.

Fabrication: Fs-laser FPIs

Writing Parameters:
- Power: 80 mW
- Pulse Energy: 160 nJ
- Velocity, $v = 10\ \mu m/s$
- Direction: bottom to top

100× oil immersion objective lens (Olympus PLN 100XO)



10 % hydrofluoric (HF) acid solution for 105 min

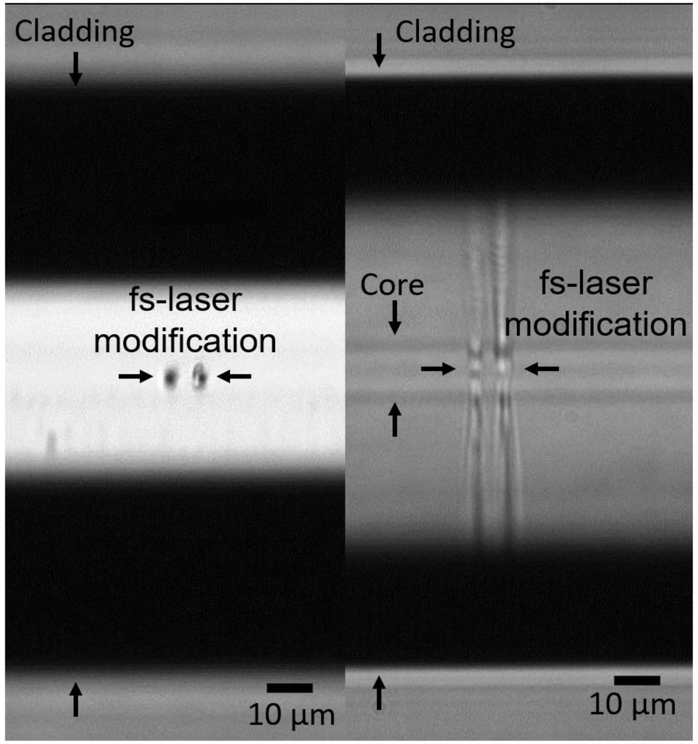
Moderate fluence leads to nanogratings production:

Much higher selectivity in etching of the irradiated regions.

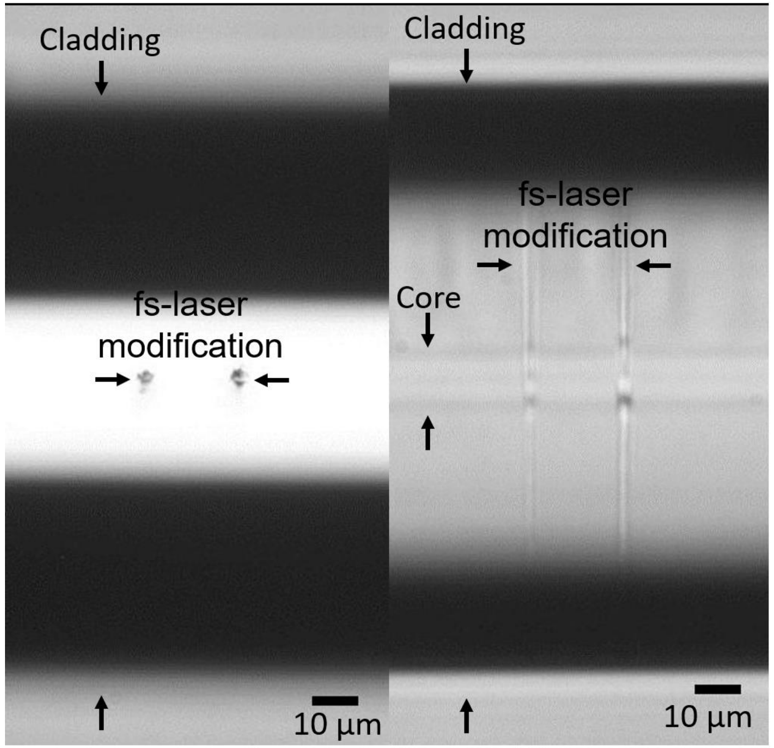
The fs-laser modification is formed as a result of the nonlinear fs-laser pulse absorption

Fabrication: Fs-laser FPIs

Fs-laser modifications in the SMF-28 fiber, Optical microscope views:



6 µm Separation

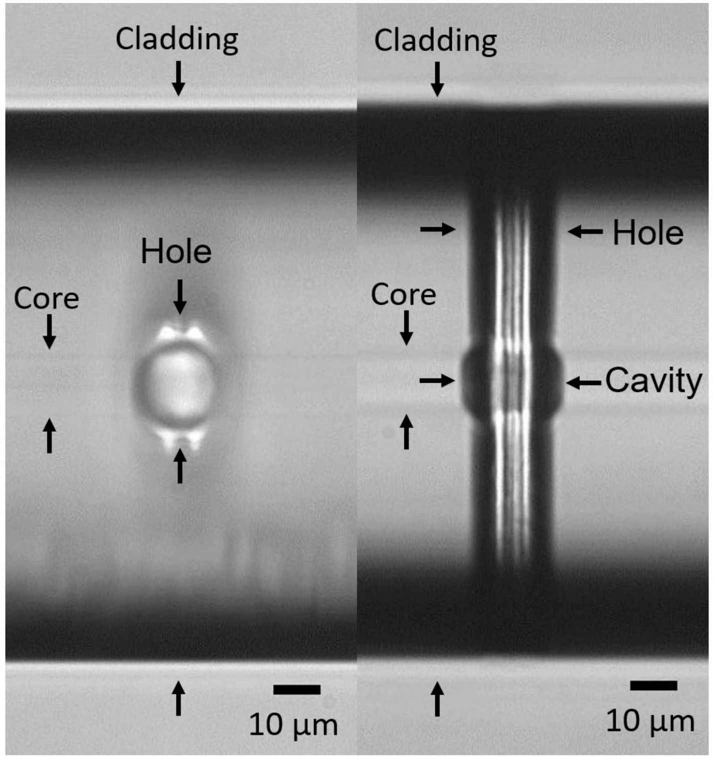


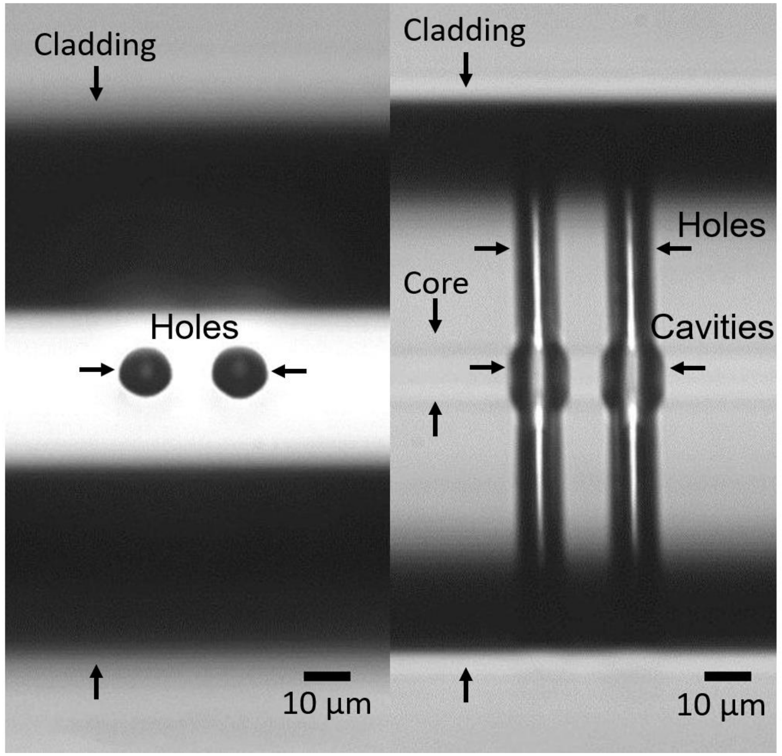
20 µm Separation

Fabrication: Fs-laser FPIs

The etching rate in the germanium-doped core of the SMF is much faster than that in the fiber cladding.

Fs-laser modifications in the SMF-28 fiber, Optical microscope views:





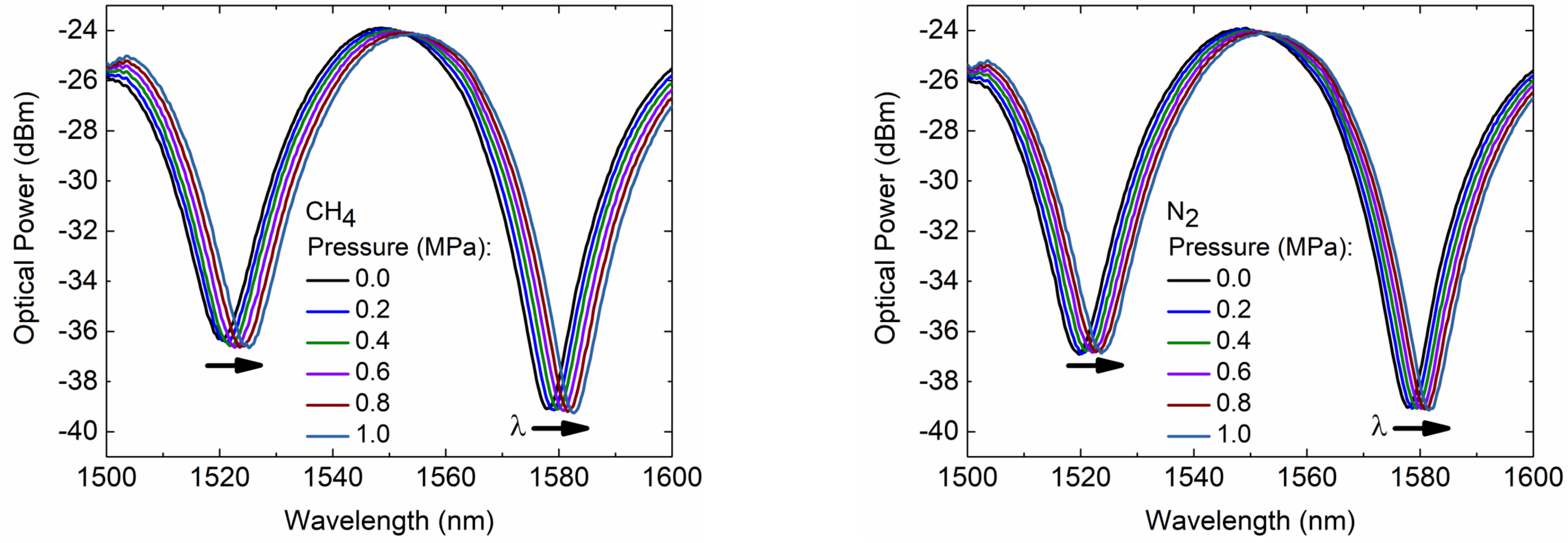
- **~ 23 µm** wide single FPI cavity
- **~ 23 µm** wide single FPI cavity followed by an **~ 800 µm** fibre optic cleaved facet

- **~ 12 µm** wide inline dual FPIs cavities, separated by **~ 8 µm** length of unmodified fibre core

Fs-laser FPIs: Gas Pressure Results

~ **23 µm** wide single FPI cavity

50 % of CH_4/N_2 **100% of N_2**



FSR ≈ 53 nm

Fringe contrast: 15.16 dB

Fringe Visibility: 0.24

As the pressure increases from 0 to 1.0 MPa:

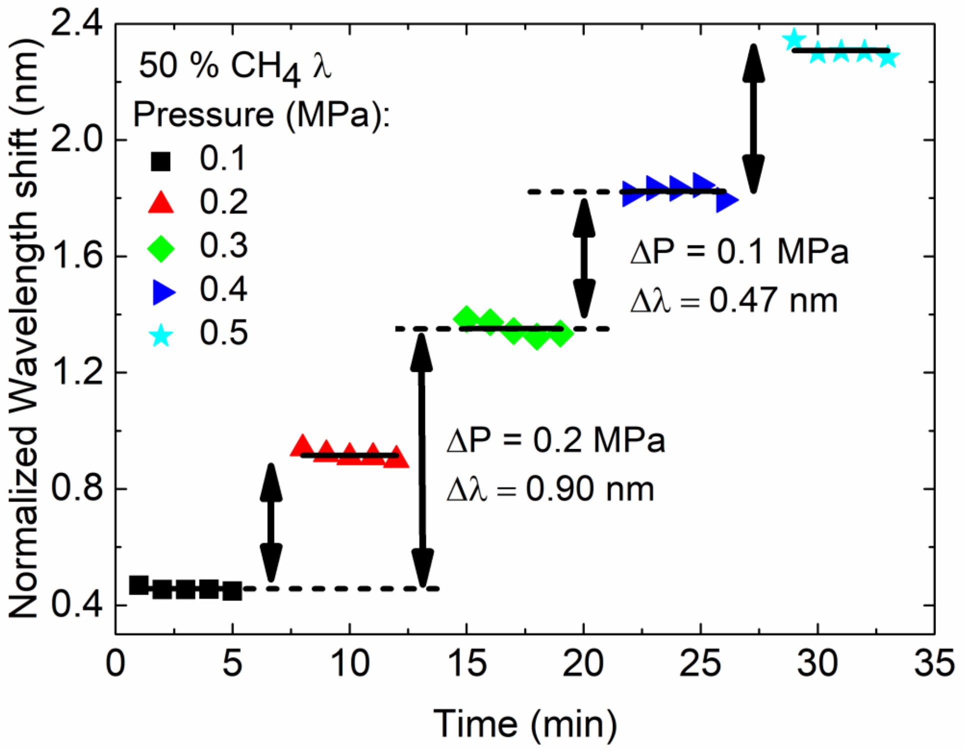
- λ shifts toward the longer wavelength

Fs-laser FPIs: Gas Pressure Results

Resolution: $R_P = \left(\frac{\Delta P}{\Delta \lambda}\right) \sigma_{Max}$

~ 23 µm wide single FPI cavity

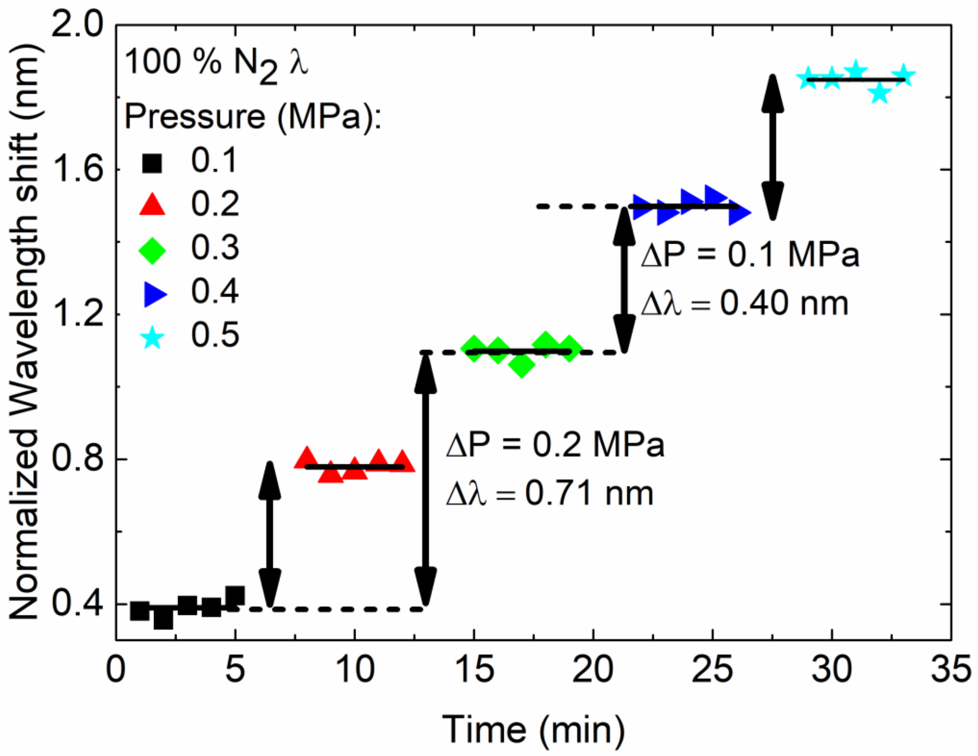
50 % of CH_4/N_2



Resolutions:

- 5.22×10^{-3} MPa
- 4.89×10^{-3} MPa

100% of N_2



Resolutions:

- 5.92×10^{-3} MPa
- 5.00×10^{-3} MPa

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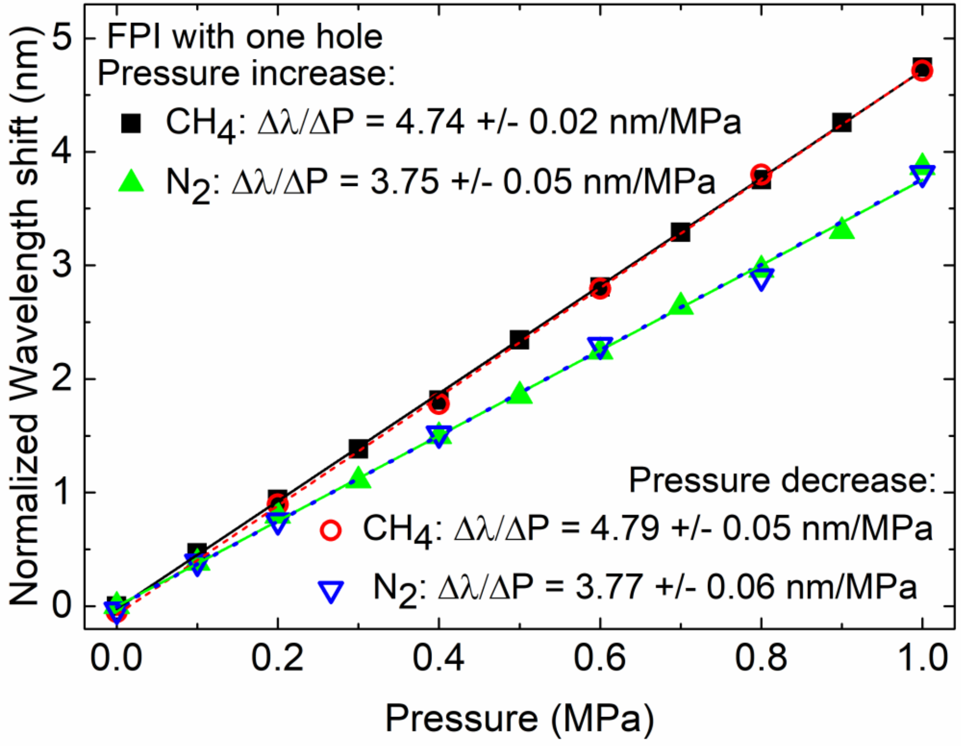
Fs-laser FPIs: Gas Pressure Results

~ 23 µm wide single FPI cavity



Sensitivities:

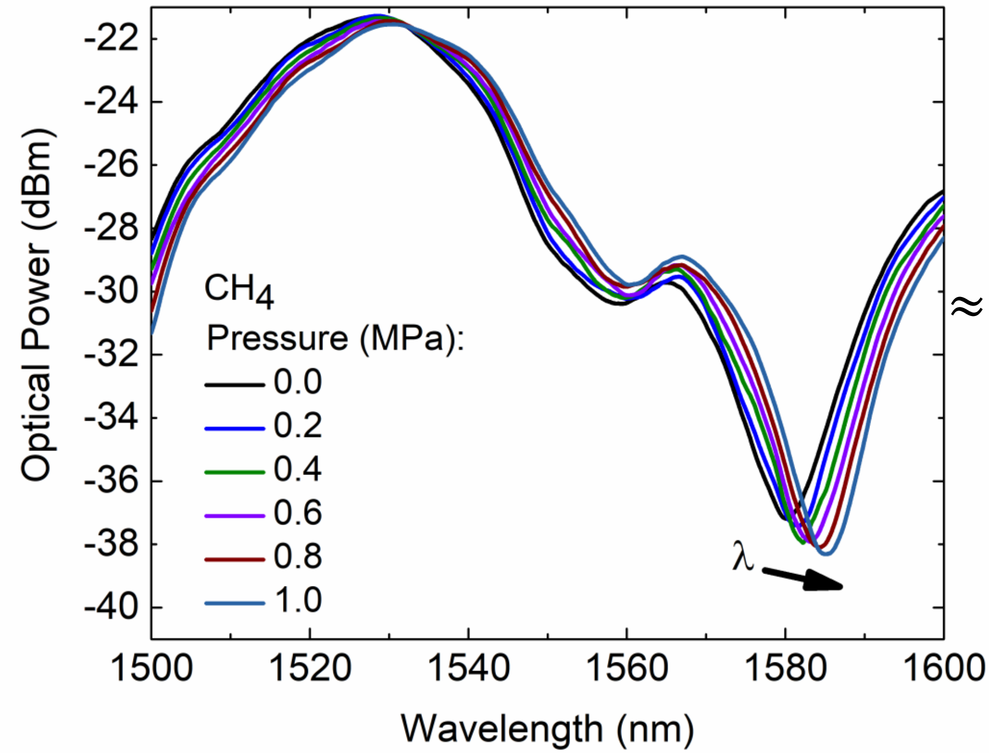
50 % of CH_4/N_2 → 4.74 ± 0.02 nm/MPa

100% of N_2 → 3.75 ± 0.05 nm/MPa

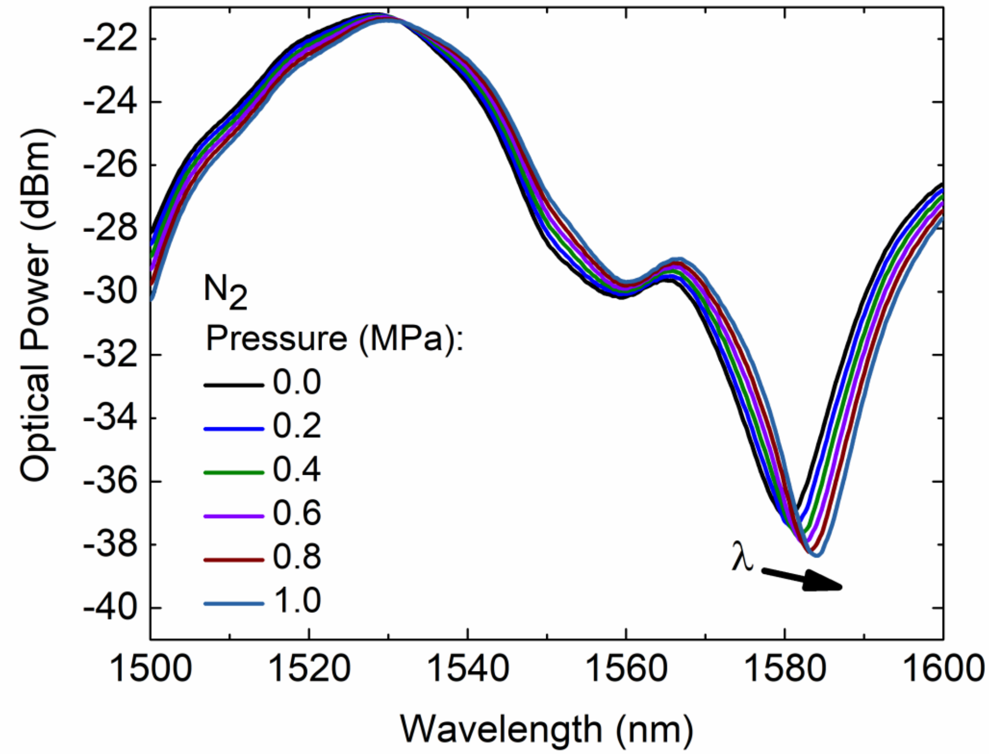
Fs-laser FPIs: Gas Pressure Results

~ 12 µm wide inline dual FPIs cavities, separated by **~ 8 µm** length of unmodified fibre core

50 % of CH_4/N_2



100% of N_2



As the pressure increases from 0 to 1.0 MPa:

- λ shifts toward the longer wavelength and increased fringe contrast.

FSR ≈ 100 nm

Fringe contrast:

P (0.0 MPa): 15.91 dB

P (1.0 Mpa): 16.77 dB

Fringe Visibility:

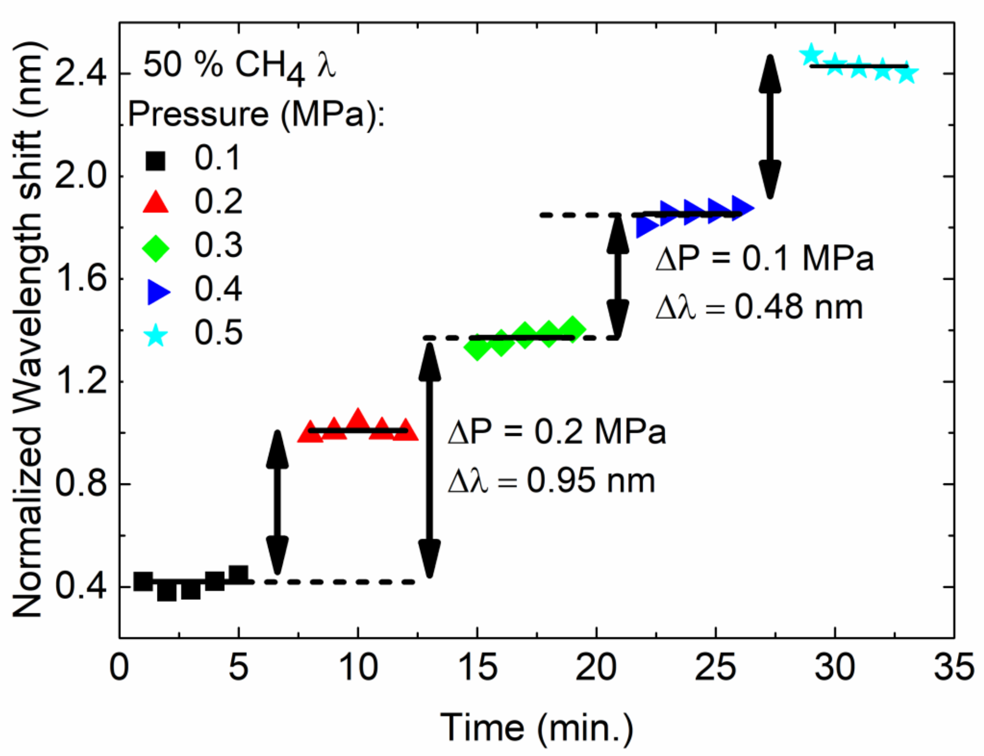
P (0.0 MPa): 0.27

P (1.0 Mpa): 0.28

Fs-laser FPIs: Gas Pressure Results

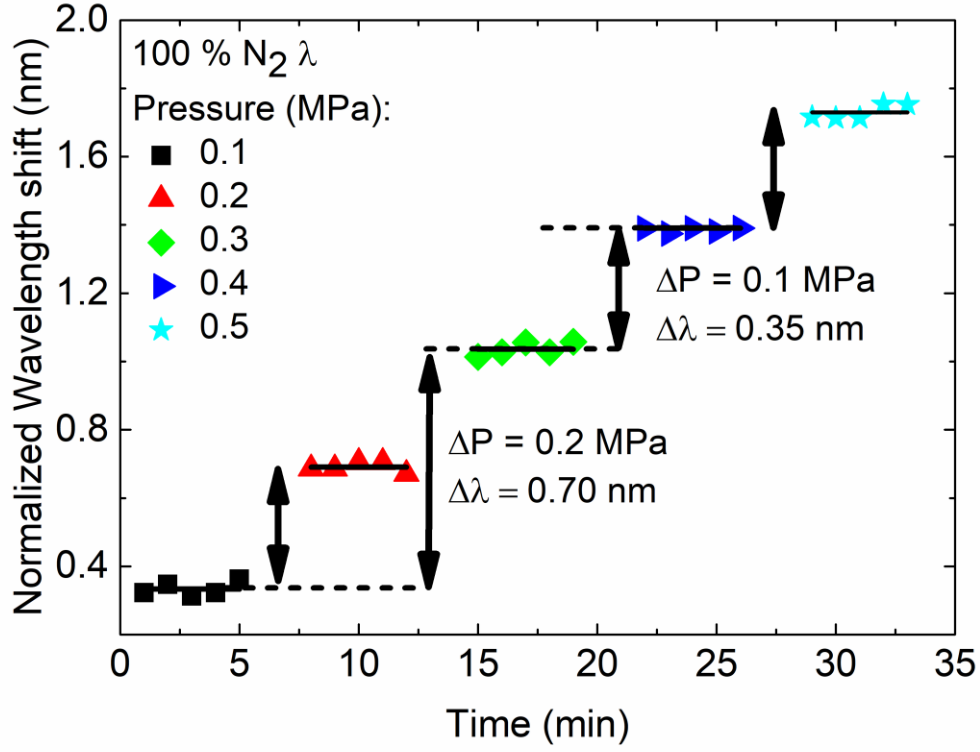
~ 12 µm wide inline dual FPIs cavities, separated by **~ 8 µm** length of unmodified fibre core

50 % of CH_4/N_2



Resolutions:
- 5.26×10^{-3} MPa
- 5.21×10^{-3} MPa

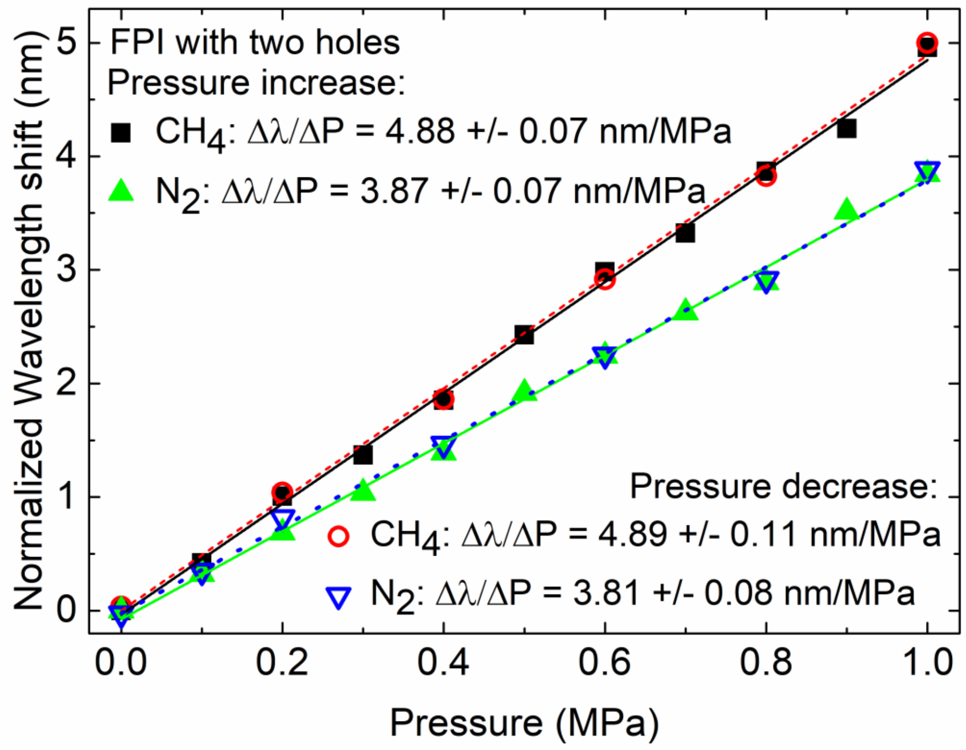
100% of N_2



Resolutions:
- 5.14×10^{-3} MPa
- 4.97×10^{-3} MPa

Fs-laser FPIs: Gas Pressure Results

~ 12 µm wide inline dual FPIs cavities, separated by **~ 8 µm** length of unmodified fibre core



Sensitivities:

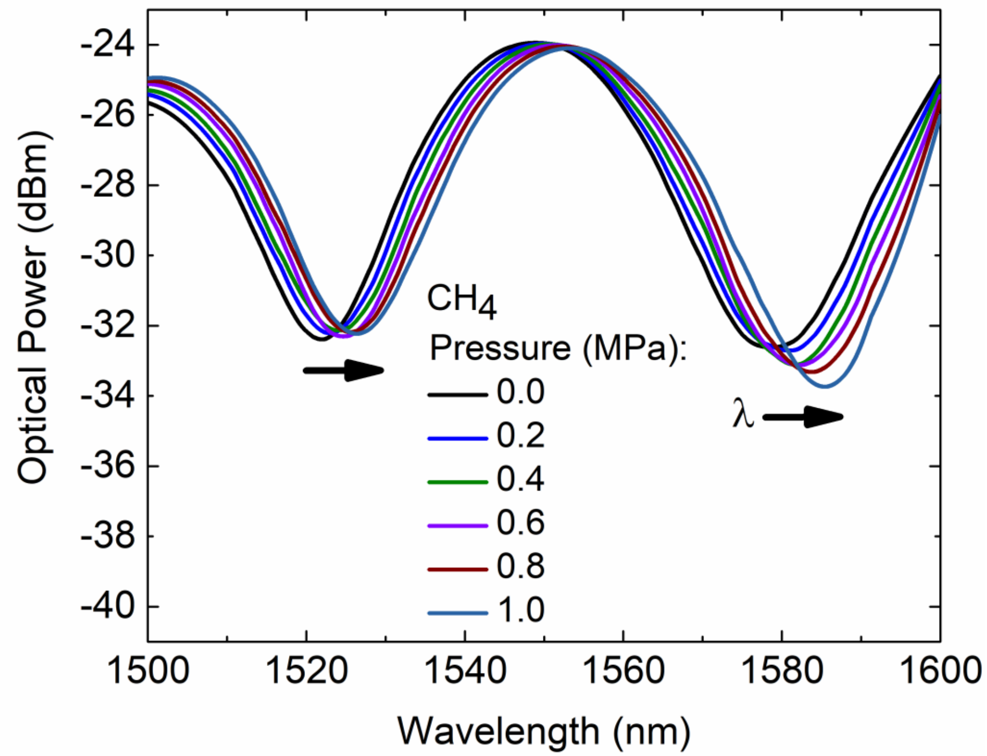
50 % of CH_4/N_2 → 4.88 ± 0.07 nm/MPa

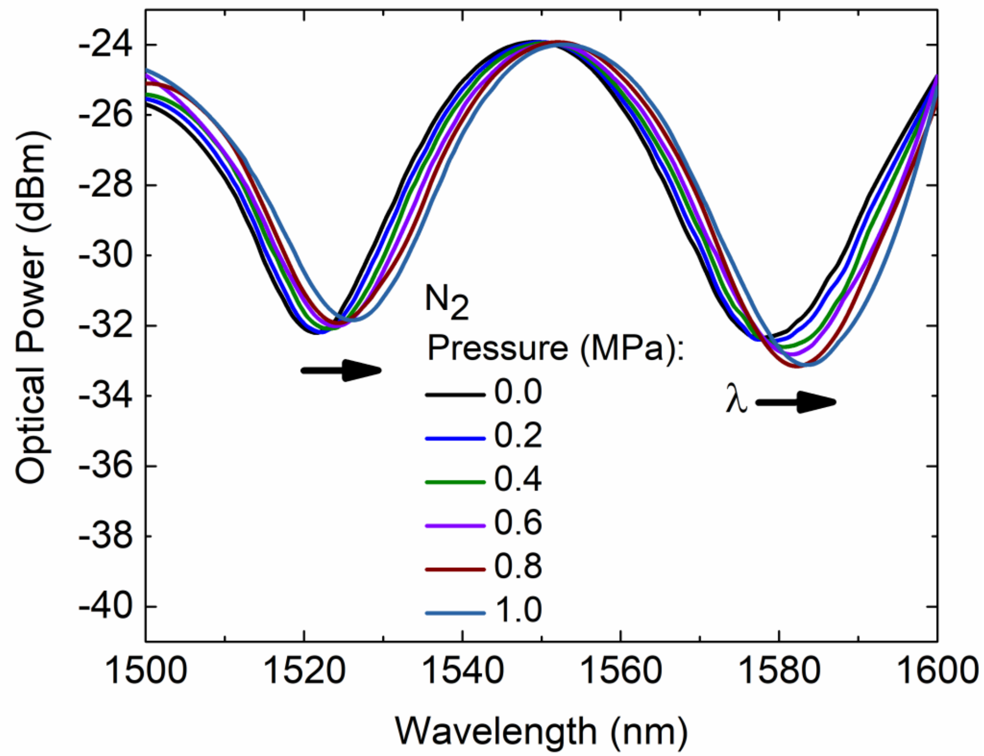
100% of N_2 → 3.87 ± 0.07 nm/MPa

Fs-laser FPIs: Gas Pressure Results

7Hz Low-pass filter

~ 23 µm wide single FPI cavity followed by an **~ 800 µm** fibre optic cleaved facet





FSR ≈ 53 nm

Fringe contrast: 9.65 dB

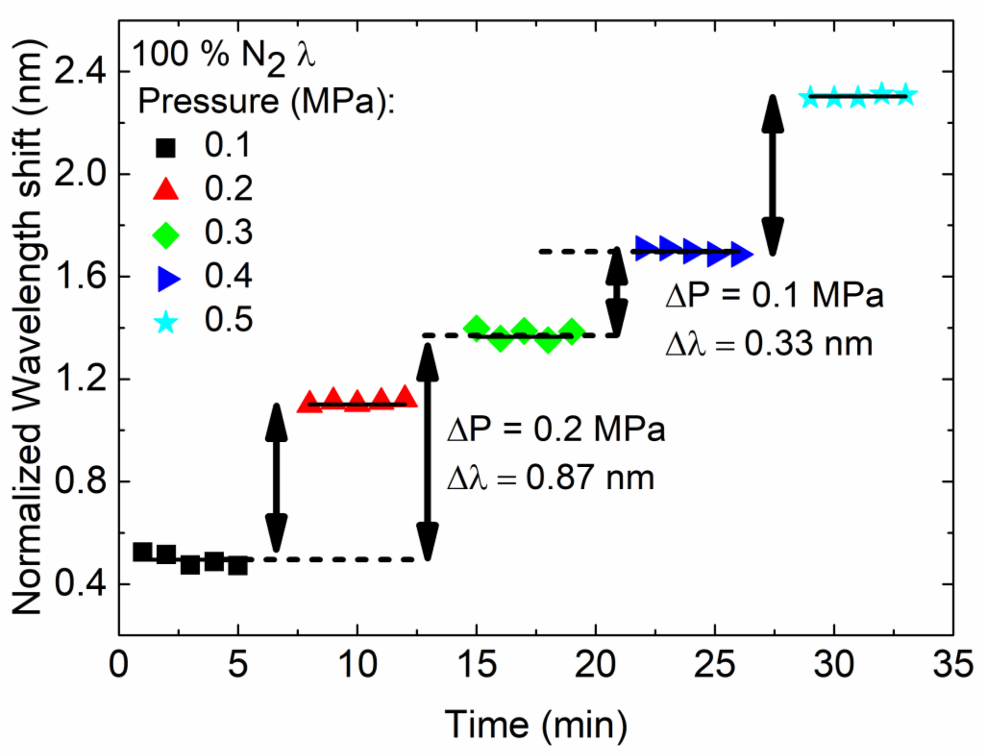
Fringe Visibility: 0.17

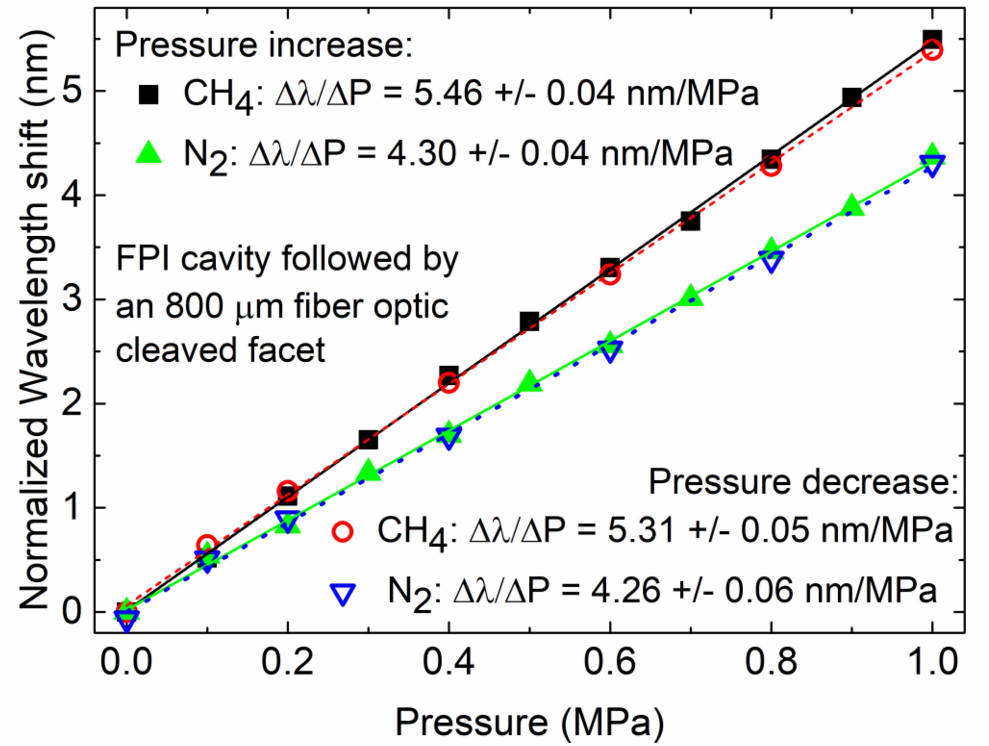
As the pressure increases from 0 to 1.0 MPa:

- λ shifts toward the longer wavelength

Fs-laser FPIs: Gas Pressure Results

~ 23 µm wide single FPI cavity followed by an **~ 800 µm** fibre optic cleaved facet





Resolutions:

- 5.06×10^{-3} MPa
- 5.45×10^{-3} MPa

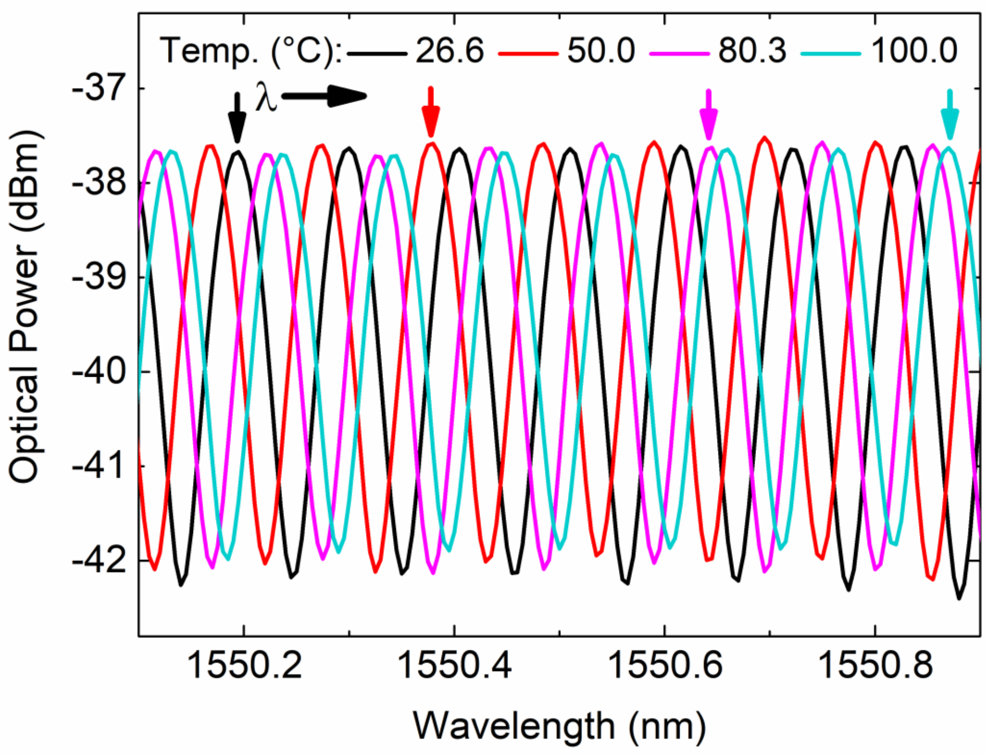
Sensitivities:

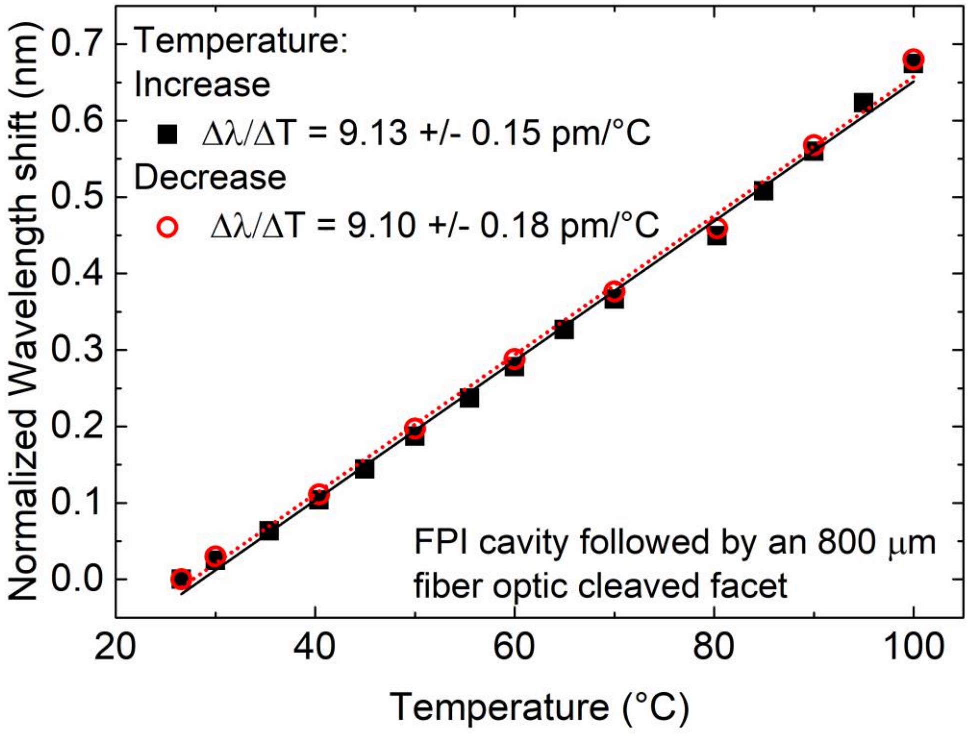
- 50 % of CH_4/N_2 → 5.46 ± 0.04 nm/MPa
- 100% of N_2 → 4.30 ± 0.04 nm/MPa

Fs-laser FPIs: Temperature Characterization Results

~ 23 µm wide single FPI cavity followed by an **~ 800 µm** fibre optic cleaved facet

0.1 Hz High-pass filter





As the temperature increases from 0 to 100 °C:

- λ shifts toward the longer wavelength

Temperature Sensitivity:

9.13 ± 0.15 pm/°C

Fs-laser FPIs: Results Summary

Gas Pressure Sensitivities:

Fs-laser FPIs:	50 % of CH_4/N_2	100% of N_2
~ 23 μm wide single FPI cavity	4.74 ± 0.02 nm/MPa	3.75 ± 0.05 nm/MPa
~ 12 μm wide inline dual FPIs cavities, separated by **~ 8 μm** length of unmodified fibre core	4.88 ± 0.07 nm/MPa	3.87 ± 0.07 nm/MPa
~ 23 μm wide single FPI cavity followed by an **~ 800 μm** fibre optic cleaved facet	**5.46 ± 0.04 nm/MPa**	**4.30 ± 0.04 nm/MPa**

Temperature insensitive

Temperature Sensitivity:

9.13 ± 0.15 pm/°C

Gas Pressure Resolutions around:

50 % of CH_4/N_2

~ 5.15×10^{-3} Mpa

100% of N_2

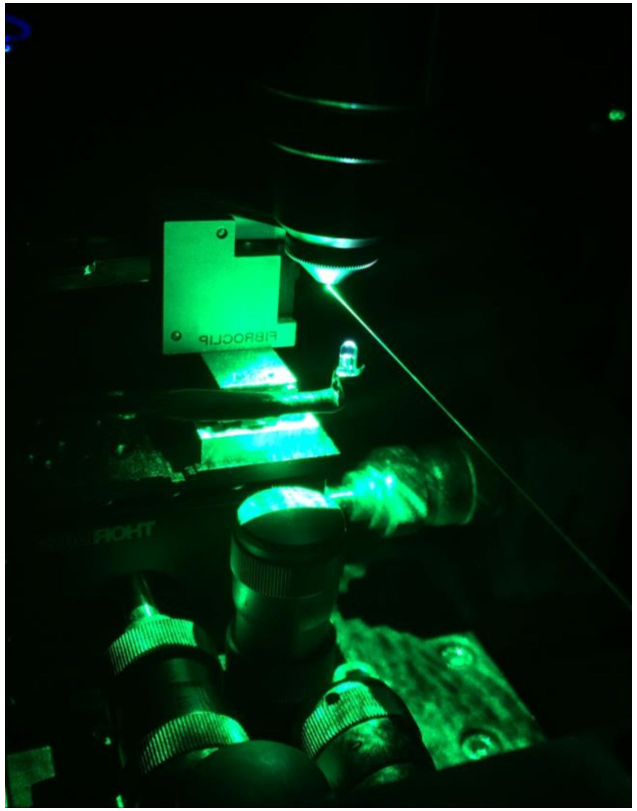
~ 5.26×10^{-3} MPa

Conclusions

- Ultracompact size cavities were fabricated in SMF-28 fibers by using fs-laser micromachining assisted with HF acid
  - Different size cavities can be fabricated due to the high spatial resolution obtained from a non-linear absorption process triggered by the laser exposure;

3D Structures

- The fs-laser modifications fabricated with a separation of 6 μm reduce the consuming of the time for lower concentration of HF etchant, and form cavities with better quality.



- Simultaneous measurement of gas pressure and temperature
  - Single FPI cavity followed by an 800 μm fibre optic cleaved facet

- Ongoing work to improve the performance of such FPIs cavities (optimization of the cavities sizes for achieving refractive index measurements, characterization)

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Acknowledgments

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