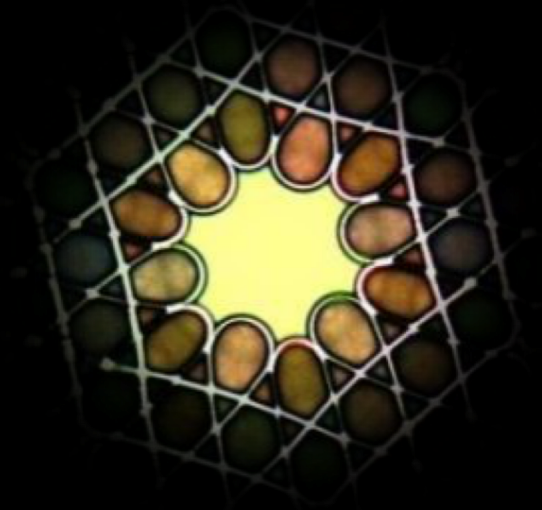


« Iodine vapor Photonic Microcell »



C. Goïcochéa^{1,2}, T. Billotte¹, J. Jouin³, P. Thomas³, D. Naik², F. Gêrôme^{1,2}, B. Debord^{1,2}, F. Benabid^{1,2}

¹ GPPMM group, Xlim Research Institute, CNRS UMR 7252, University of Limoges, Limoges, France

² Glophotonics, 123 avenue Albert Thomas 87060 Limoges, France

³ IRCER UMR CNRS 7315, Centre Européen de la Céramique, 12 rue Atlantis, 87068 Limoges, France

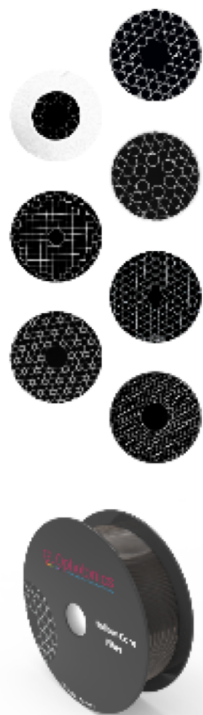
GLOphotonics



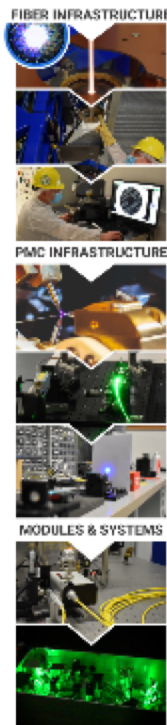
The Hollow-Core PCF & Photonic MicroCell™ company

GPPMM
Gas-Phase Photonic
Microwave Materials **xlim**

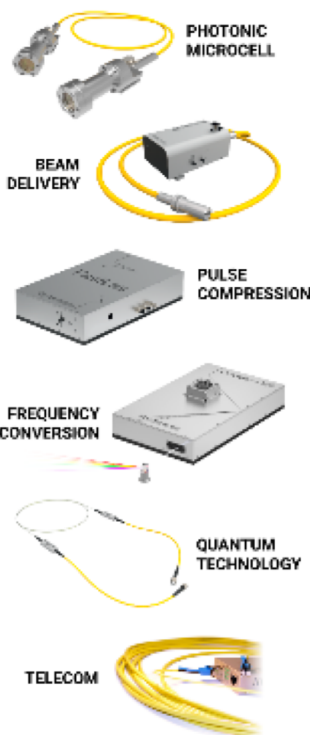
LEADING INDUSTRIAL HOLLOW-CORE PHOTONIC CRYSTAL FIBER



UNIQUE PLATFORM TECHNOLOGY



MULTI-SECTOR PHOTONIC MODULES & SYSTEMS



Fiber photonics

- Design and fabrication of PCF
- Fiber components

Gas nonlinear optics

- Frequency conversion
- Ultra-broad comb generation
- Pulse compression & High field photonics

Atom optics & Laser metrology

- Atomic optical / microwaves clocks
- Coherent

Plasma photonics

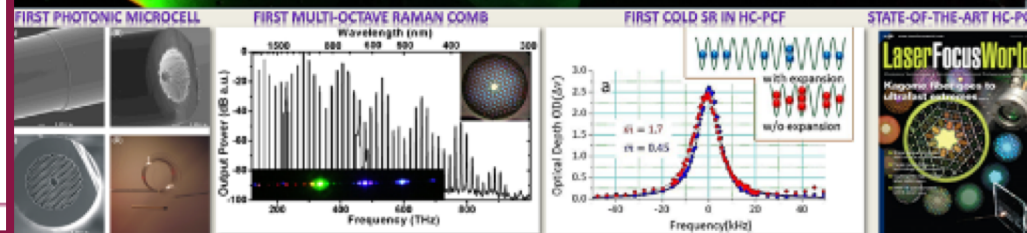
- UV-DUV lasers
- Micro-confined plasma dynamics

Contact: f.benabid@xlim.fr



GPPMM PIONEER AND WORLD-LEADER of
GAS-PHOTONICS & HOLLOW-CORE PCF

GLOphotonics SAS
123 avenue Albert Thomas | 07000 Limoges Cedex | FRANCE
glophotonics.fr | contact@glophotonics.fr

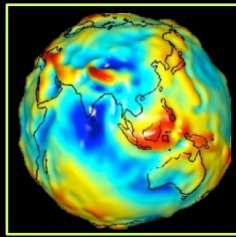


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Frequency standards



Navigation positioning



Geodesy



Stable laser & Microwave source



Atomic clocks & Sensors

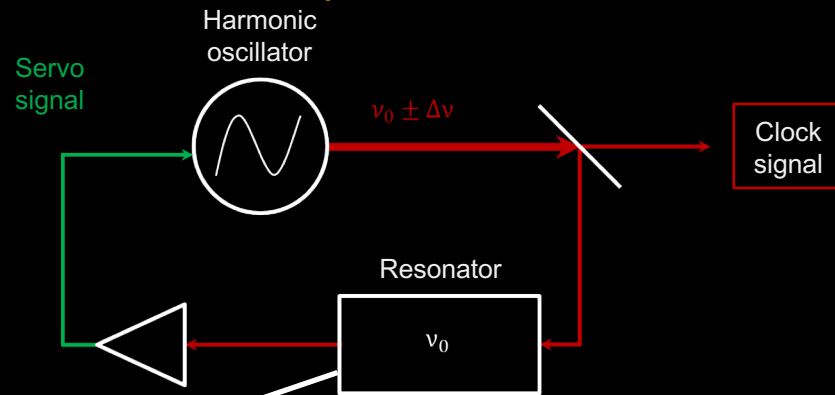


Telecommunication & Data networks



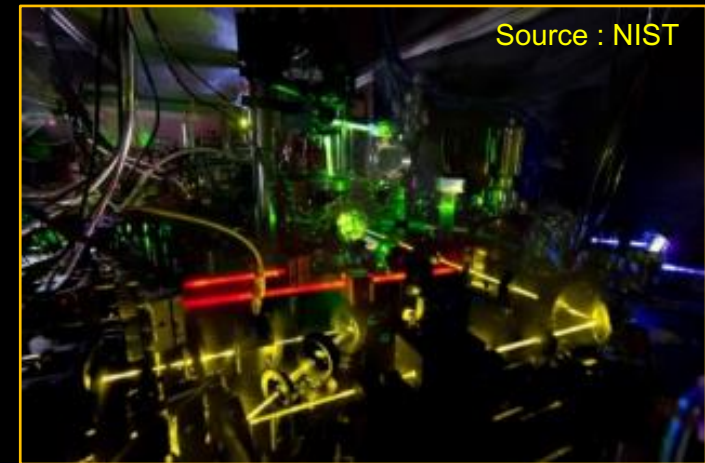
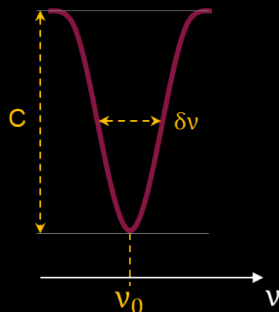
Quantum information & Computing

High performance : Optical clocks !



High quality resonator :

- Great contrast
- Narrow linewidth



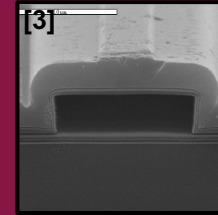
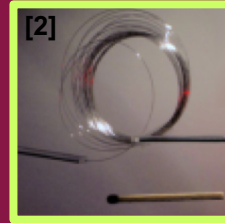
Fractional frequency stability :

$$\frac{\delta\nu}{\nu} = \sim 10^{-19}$$

S. Brewer et al. PRL 123 (2019)

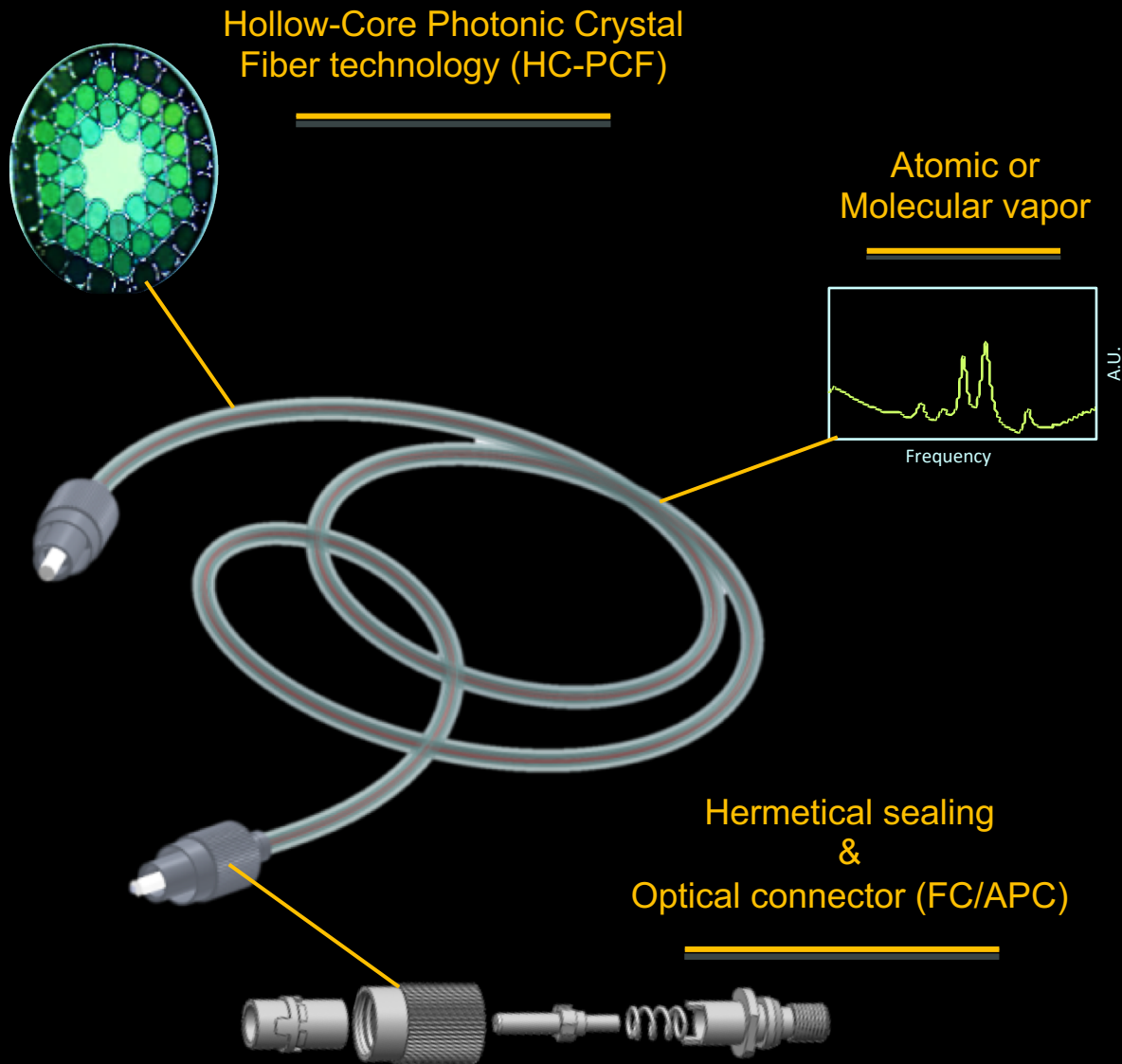
Performance vs Practicality : Miniaturisation trend

- [1] S. Knappe et al. Applied Physics Letters 85 (9) (2004)
 [2] F. Benabid et al. Nature 434 (7032) (2004)
 [3] W Yang, et al. Nature Photonics 1 (6) (2007)
 [4] M.Graf et al., Opt. Lett. 43, (2018)



Cell architecture	Macroscopic glass cell	Silicon cell	HC-PCF	Planar waveguide	Multi-pass cell
Technology	Glass blowing	MEMS	Fiber photonic	CMOS-compatible	Opto-mechanics
Footprint	~100 – 1000 mm de long by ~100mm wide	Millimetric (low end)	Micrometrical	Micrometrical	Millimetric (High end)
Optical integration	Free-space	Free space	Guided scheme	Guided scheme	Free-space
Performances	Low interaction length (poor SNR) Collisional / lifetime limited linewidth	Low interaction length (poor SNR) Collisional / transit-time limited linewidth	Ultra-long interaction length (very high SNR) Transit-time / wall-collisional limited linewidth	Intermediate interaction length (poor SNR) Transit-time / wall-collisional limited linewidth	Intermediate interaction length (high SNR) Collisional / lifetime limited linewidth

What is a PMC ?



Hollow-Core Photonic Crystal
Fiber technology (HC-PCF)

Atomic or
Molecular vapor

Hermetical sealing
&
Optical connector (FC/APC)



Pros :

- ✓ Very high interaction length, high contrast
- ✓ Easily integrated to any optical setup
- ✓ « Plug & Play »
- ✓ Mechanically resistant



Cons :

- Confined medium – High wall-collisions
- Short transit-time



Challenges :

- Extension to all reference species
- Industrial scalability
- Connectibility and insertion loss

Vapor choice : Iodine

- Iodine: state of the art
- Spectroscopic & chemical properties

Fabrication & Characterisation of Iodine PMC

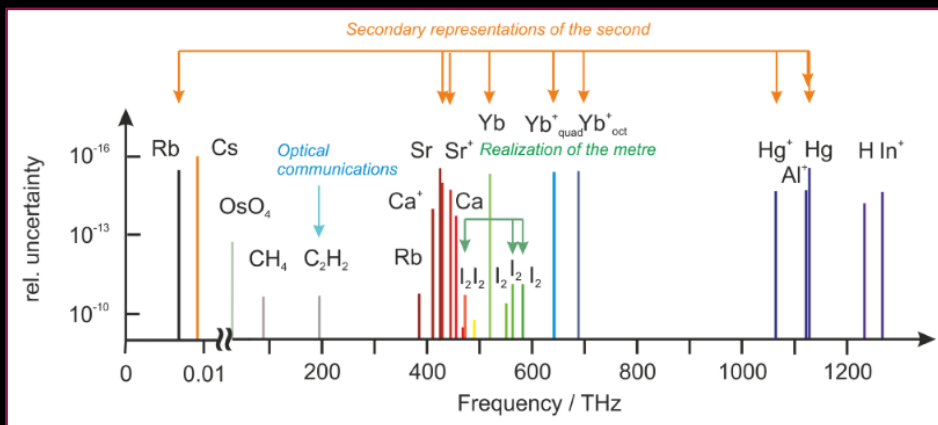
- Assembly platform
- PMC loading process
- Real time spectroscopic monitoring and characterisation
- PMC performances

Iodine hyperfine structure resolution

- Saturable Absorption Spectroscopy (SAS)
- Hyperfine structure of the Iodine B-X spectrum
- Proof of concept : P(33)6-3 hyperfine structure resolution

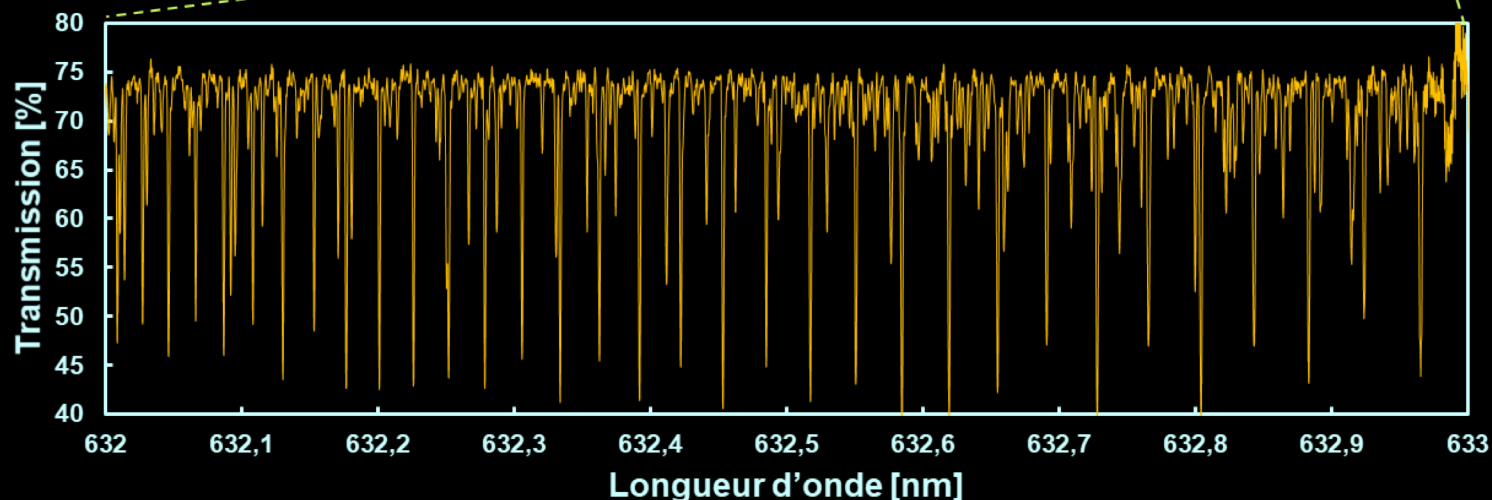
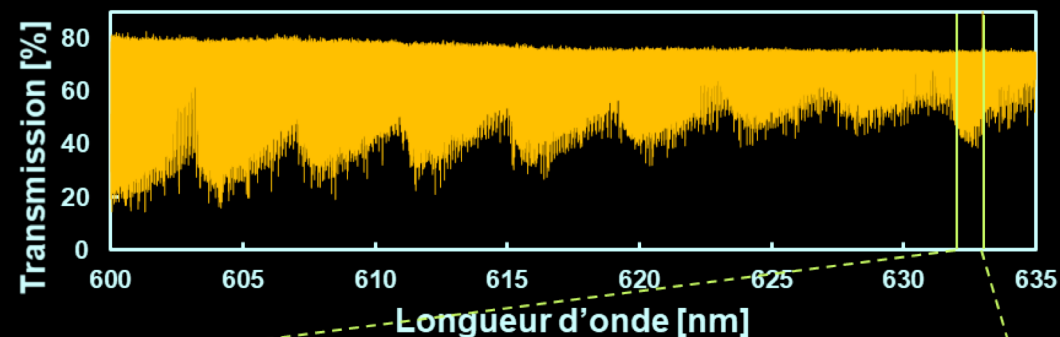
Conclusion & Prospects

Iodine : State of the art & Spectrum properties



F. Riehle *et al.* 2018 *Metrologia* 55 188

- State of the art : Microwaves up to UV
- Iodine : Green-red visible spectrum
- Recommended molecule for the realization of the meter (BIPM)



H. Salami *et al.*
Journal of Molecular Spectroscopy
2005 vol.233, 1, p157-159

Iodine spectroscopy : Applications

« Guiding star »
laser



DB. Calia, et al. *The Messenger* 139 (2010): 12-19.

High spectral resolution
LIDAR



N. Wang, et al. *J. Quant. Spectr. Radi. Transfer* 261 (2021): 107513.

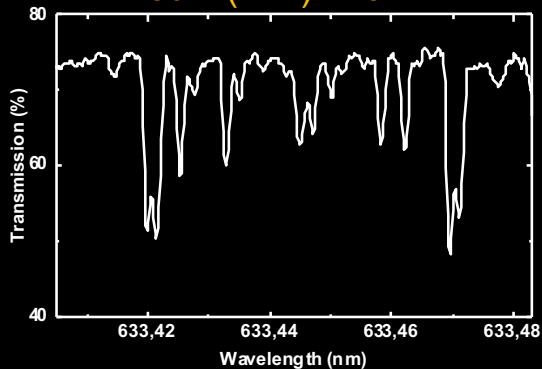
Frequency laser
stabilization



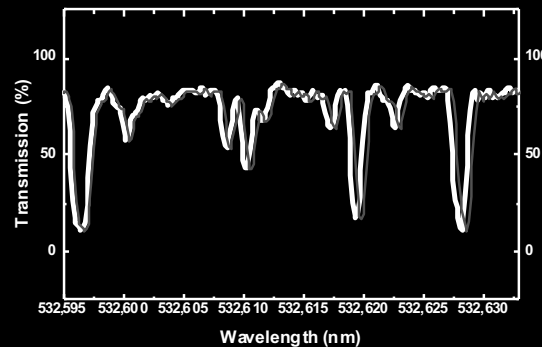
J. Barbarat, et al. *International Conference on Space Optics—ICSO 2018*. Vol. 11180.

Optical frequency references (BIPM/CIPM)

HeNe & laser diode P(33)6-3
ou R(127)11-5



Nd-Yag Laser 2x frequency R(56)32-0



Yb Laser 2x frequency R(73)46-0



Chemical characteristics



Notable chemical properties :

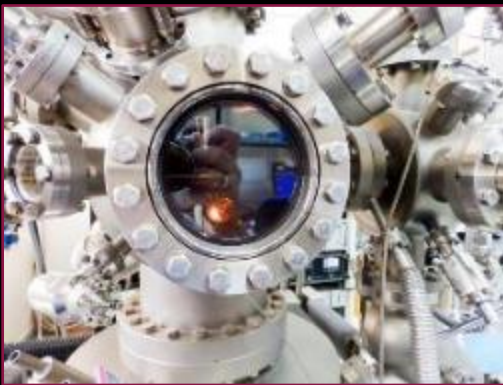
- Highly reactive with Oxygen and Hydrogen atoms
- Highly corrosive to metals (due to the first point)

$I_2 - Al$ reaction



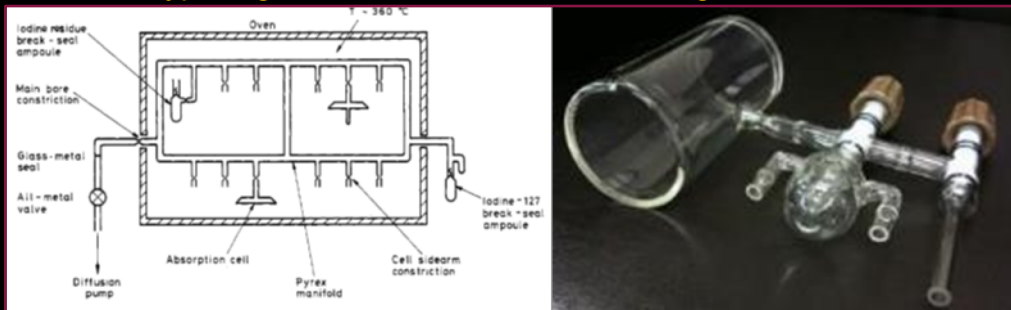
Complete video :
<https://www.youtube.com/watch?v=RcIM2S2YIBg>

Conventional HV system



- Conventional stainless steel / Aluminium vacuum system are not appropriate
- Glass manifold are the common solution for this issue
- Alternative loading process is needed for I₂-PMC production scaling

Typical glass-manifold for I₂ cell-loading



Source: NPL



Vapor choice : Iodine

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- Spectroscopic & chemical properties

Fabrication & Characterisation of Iodine PMC

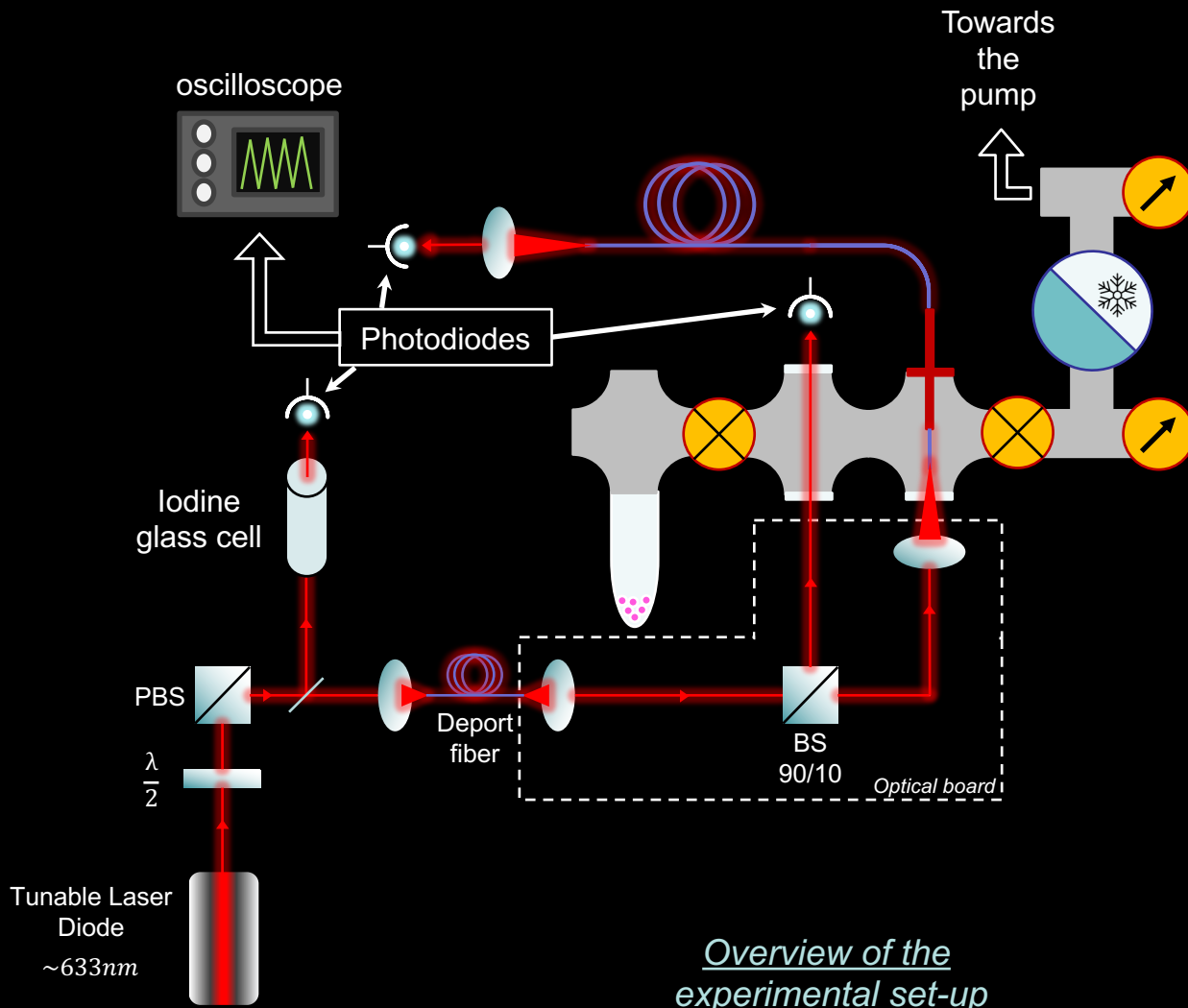
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Conclusion & Prospects

PMC assembly platform



Overview of the experimental set-up

Vacuum system

- ✓ Iodine reactivity & corrosiveness proof
- ✓ Iodine vapor-filling the HC-PCF

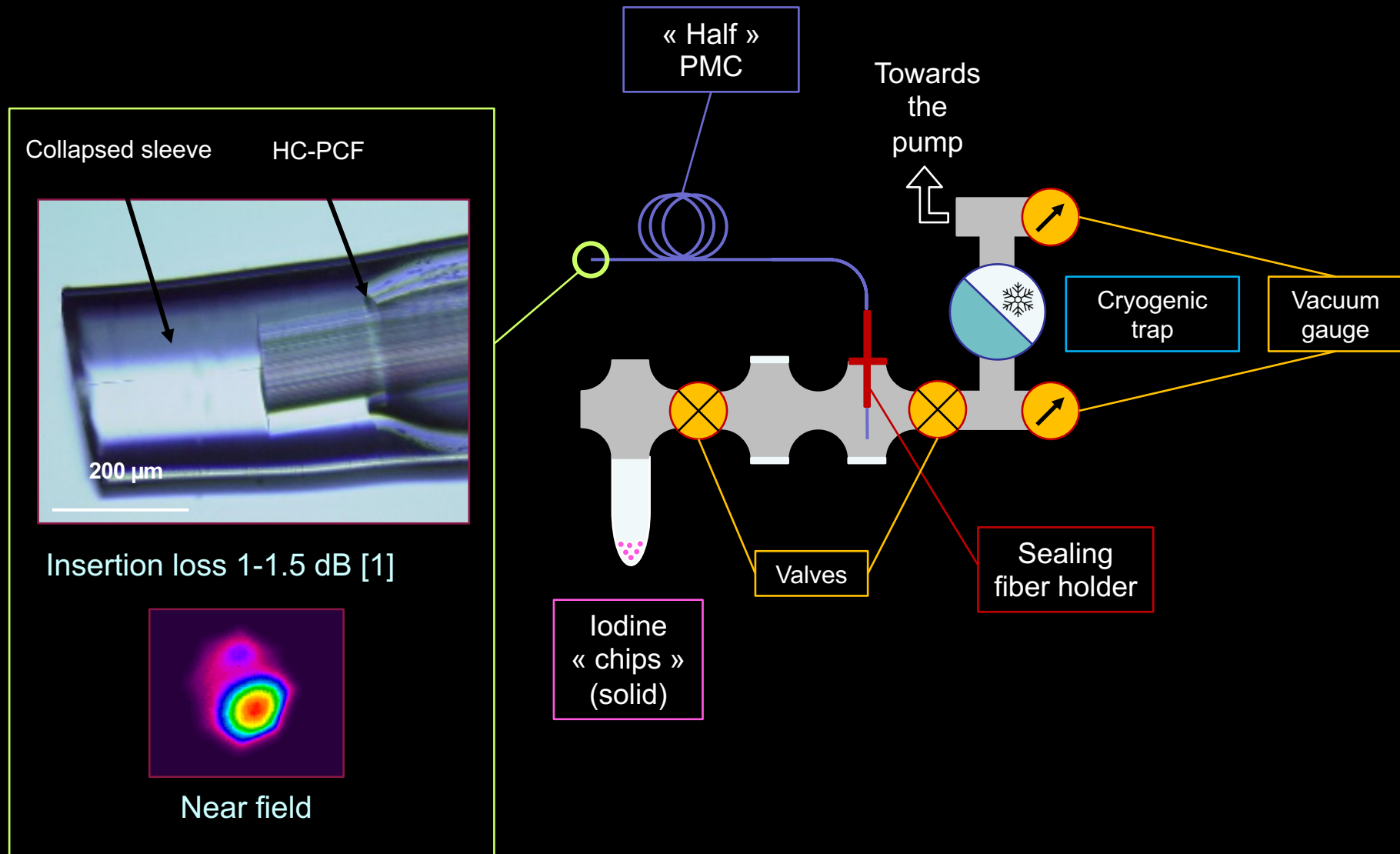
Optical system

- ✓ Spectroscopic monitoring

Splicing machine

- ✓ Contaminant-free encapsulation

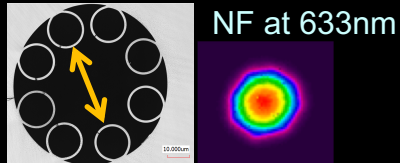
PMC Fabrication – System presentation



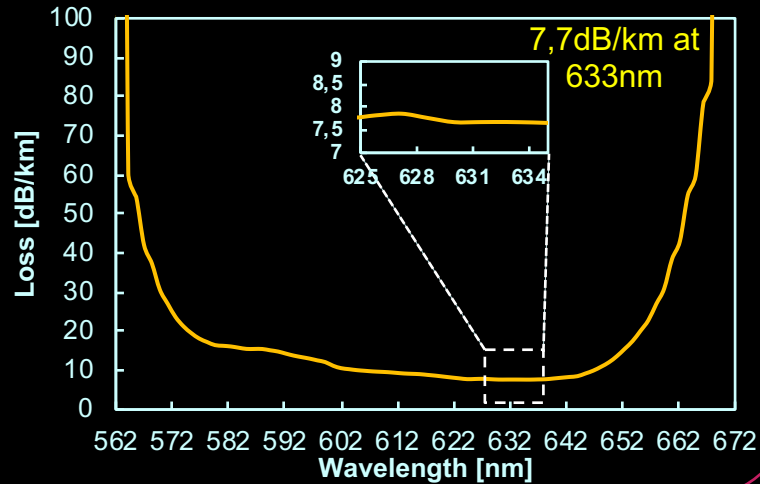
Optimized HC-PCF for Iodine spectral range

All fiber are Inhibited-Coupling HC-PCF

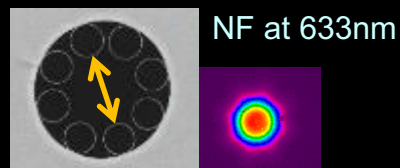
Fiber 1 : Tubular lattice



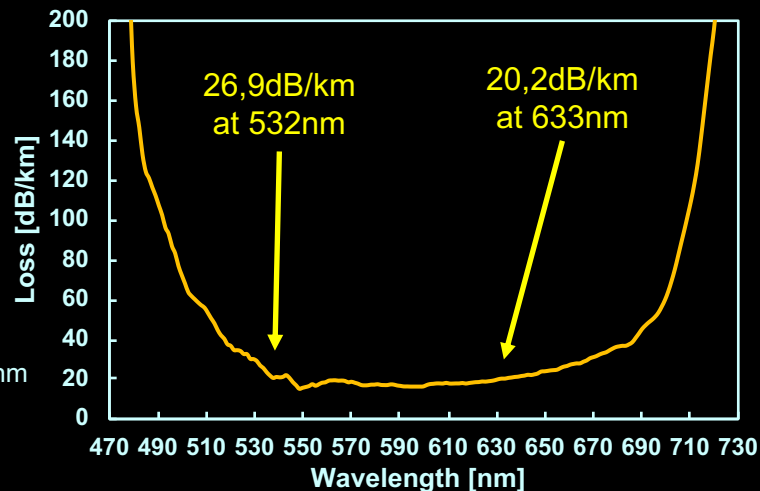
- Large core diameter : $40\mu\text{m}$
- Low-loss & large transmission bandwidth
605nm to 647nm below 10 dB/km
 $7,7\text{ dB/km}$ at operating wavelength 633nm
- Quasi single mode transmission



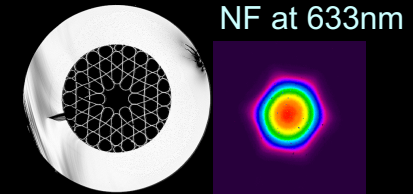
Fiber 2 : Tubular lattice



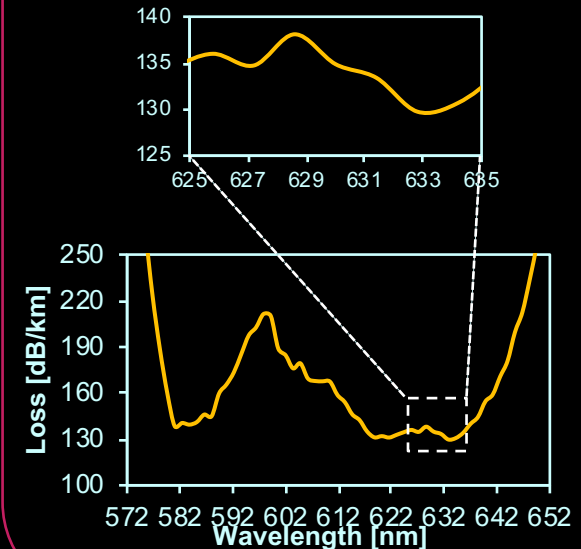
- Large core diameter : $30\mu\text{m}$
- Large transmission bandwidth 530nm to 668nm below 30 dB/km
 $20,2\text{ dB/km}$ at operating wavelength 633nm
- Quasi single mode transmission



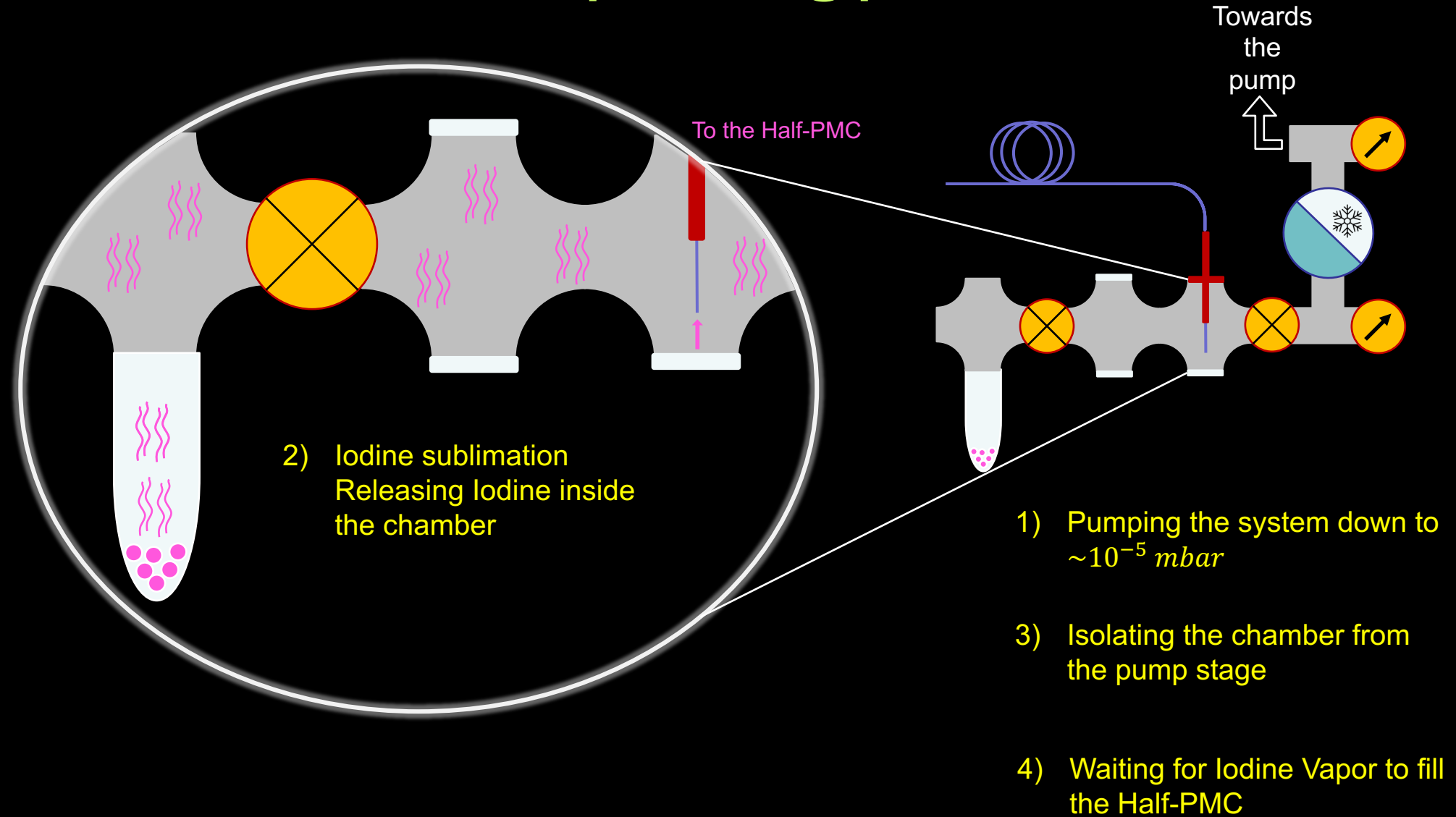
Fibre 3 : Kagomé lattice



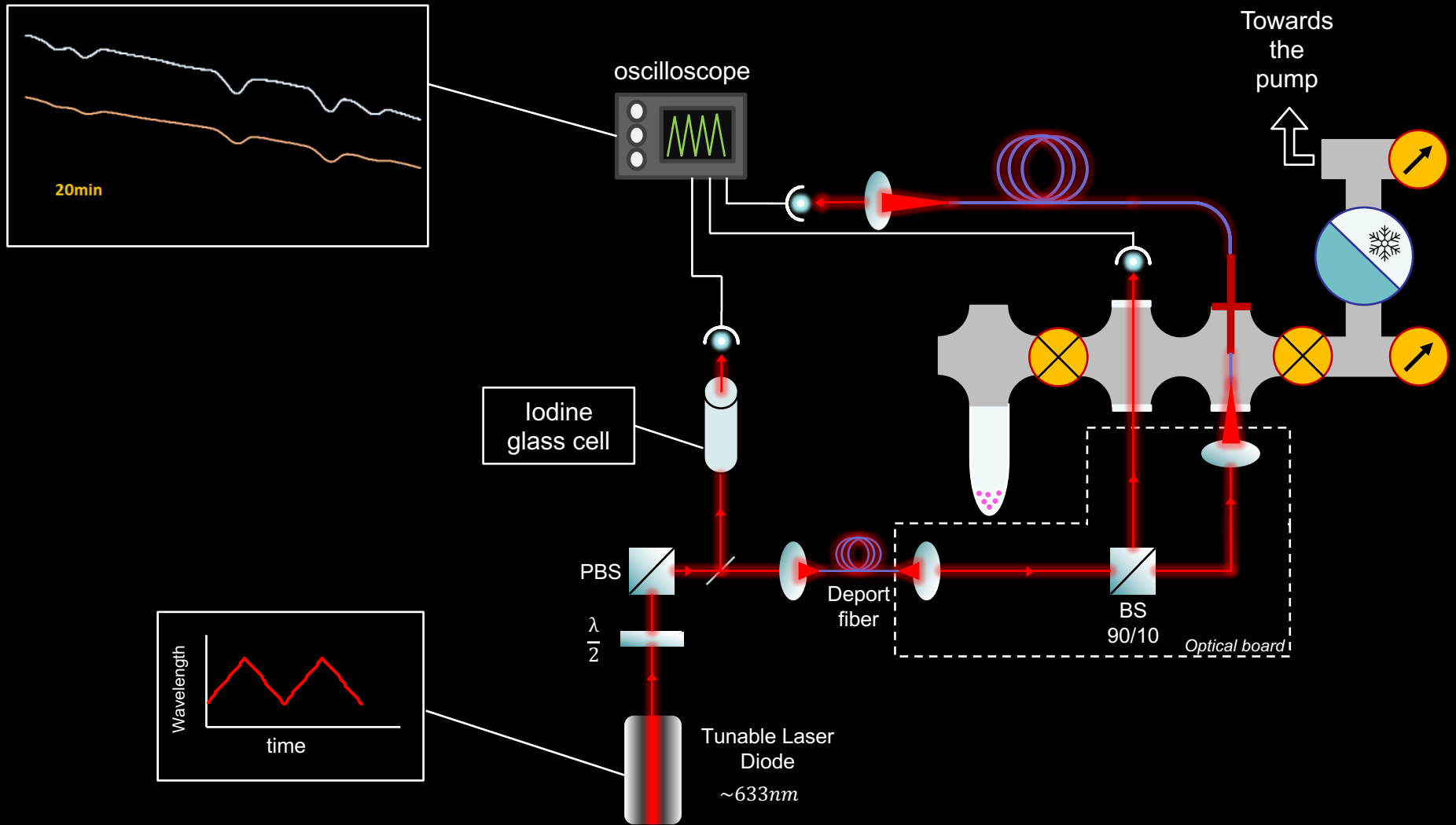
- Large core diameter : $36-40\mu\text{m}$
- 130 dB/km at operating wavelength 633nm
- **Single mode** transmission



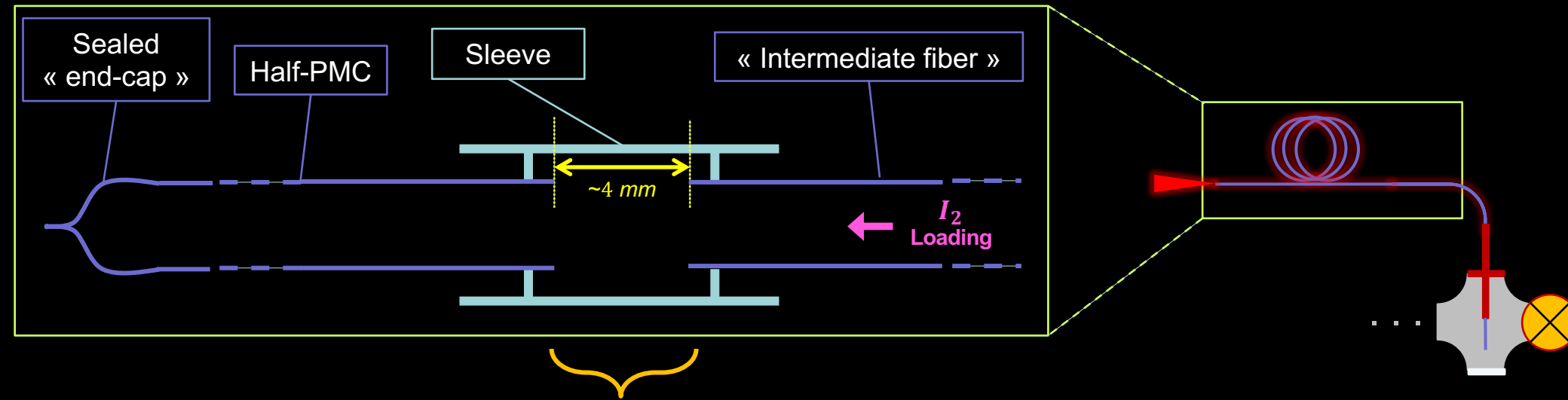
PMC fabrication – Vapor filling process



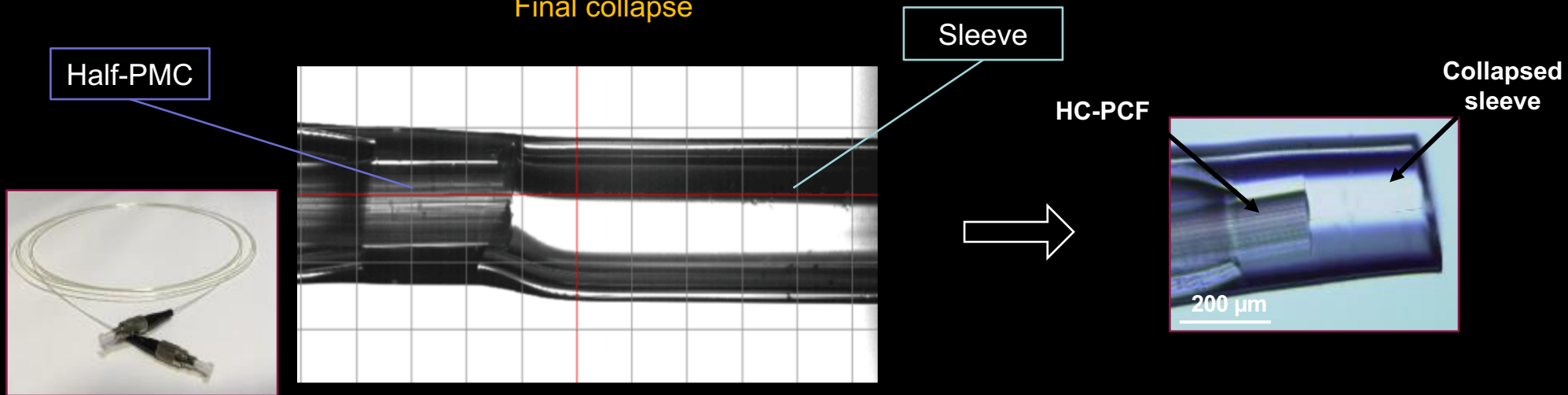
PMC fabrication – Spectroscopic Monitoring



PMC fabrication – Final PMC closing

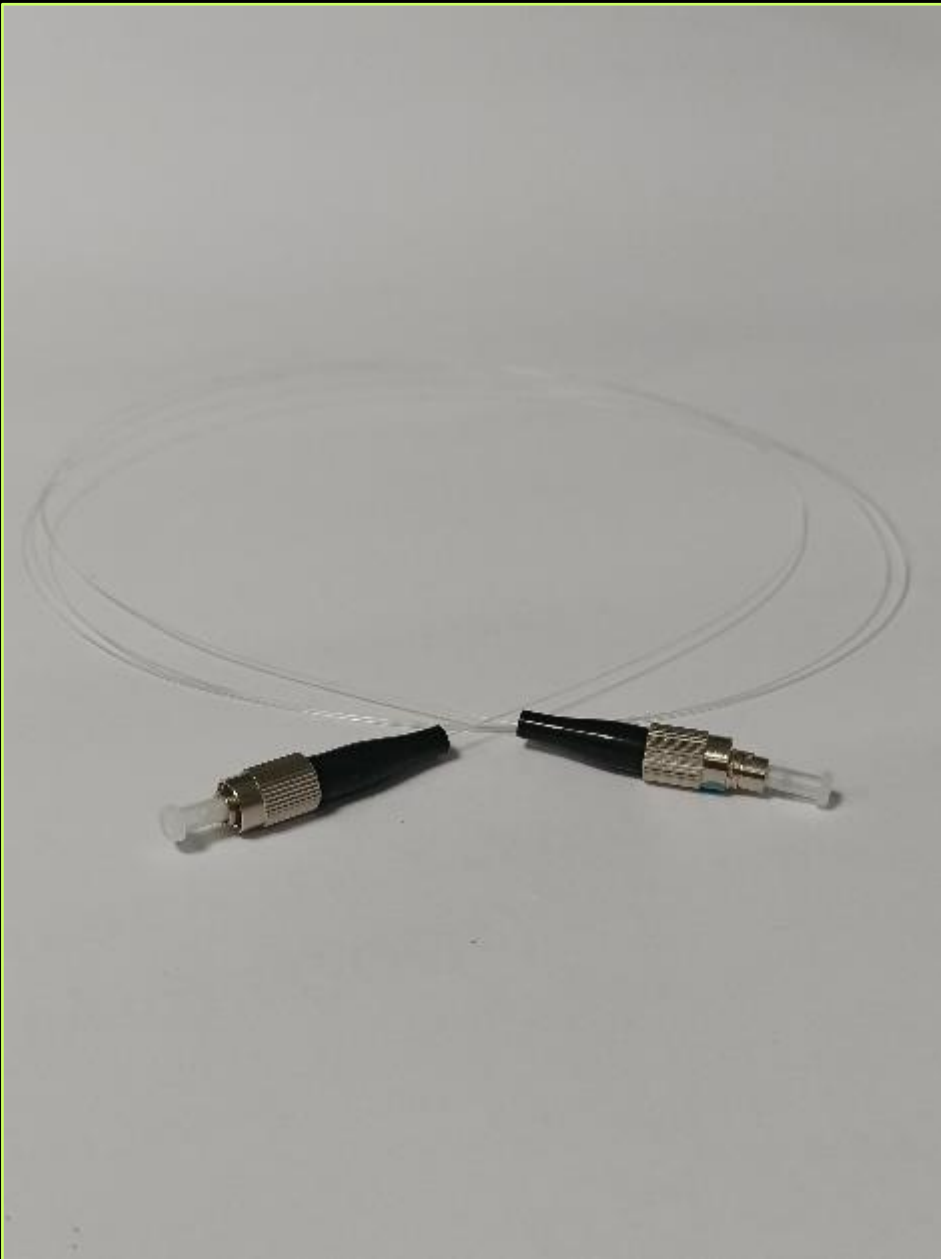


Final collapse



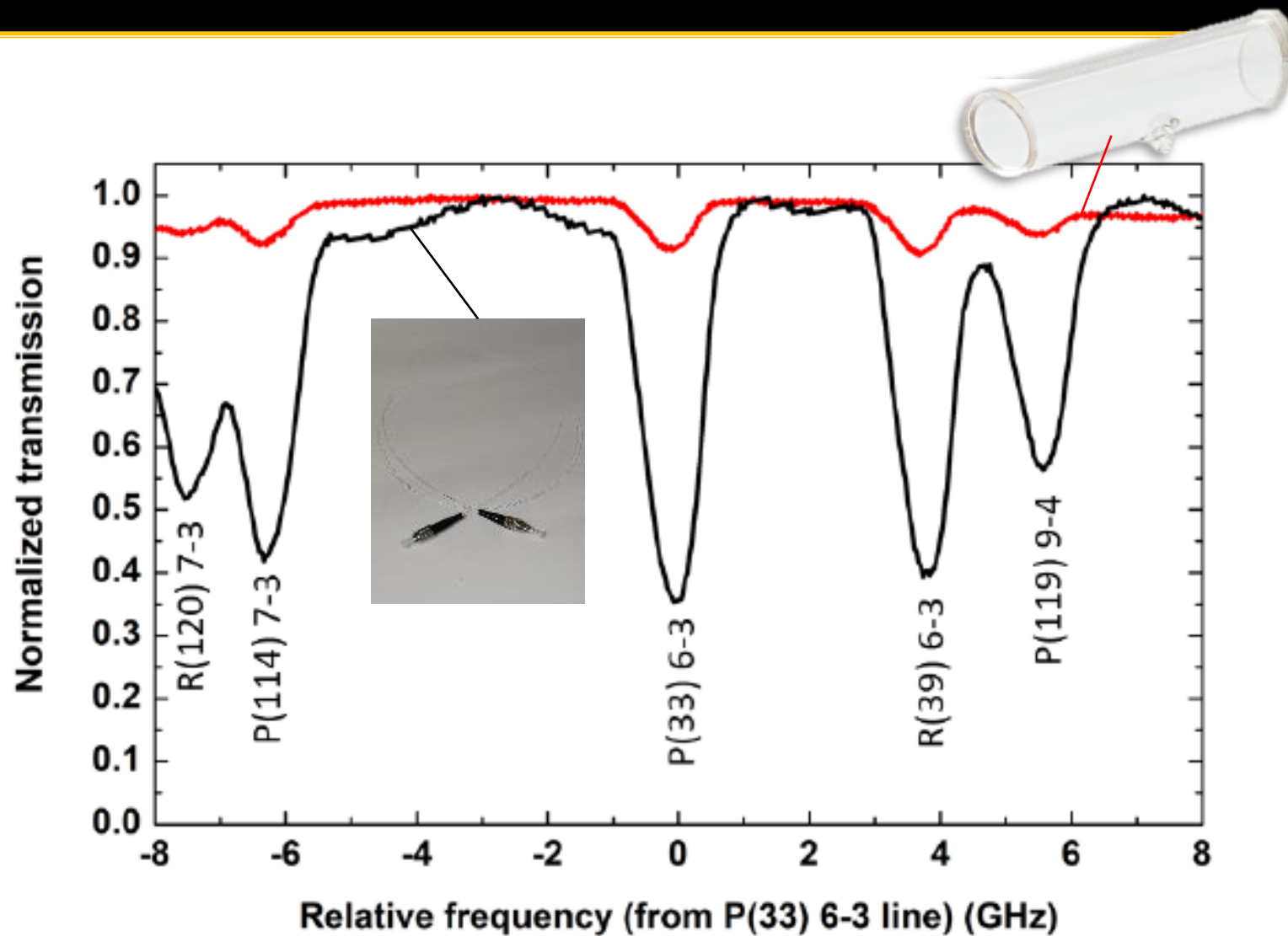
PMC fabrication – PMC terminations

Patchcord-like stand-alone PMC FC/APC connectorized

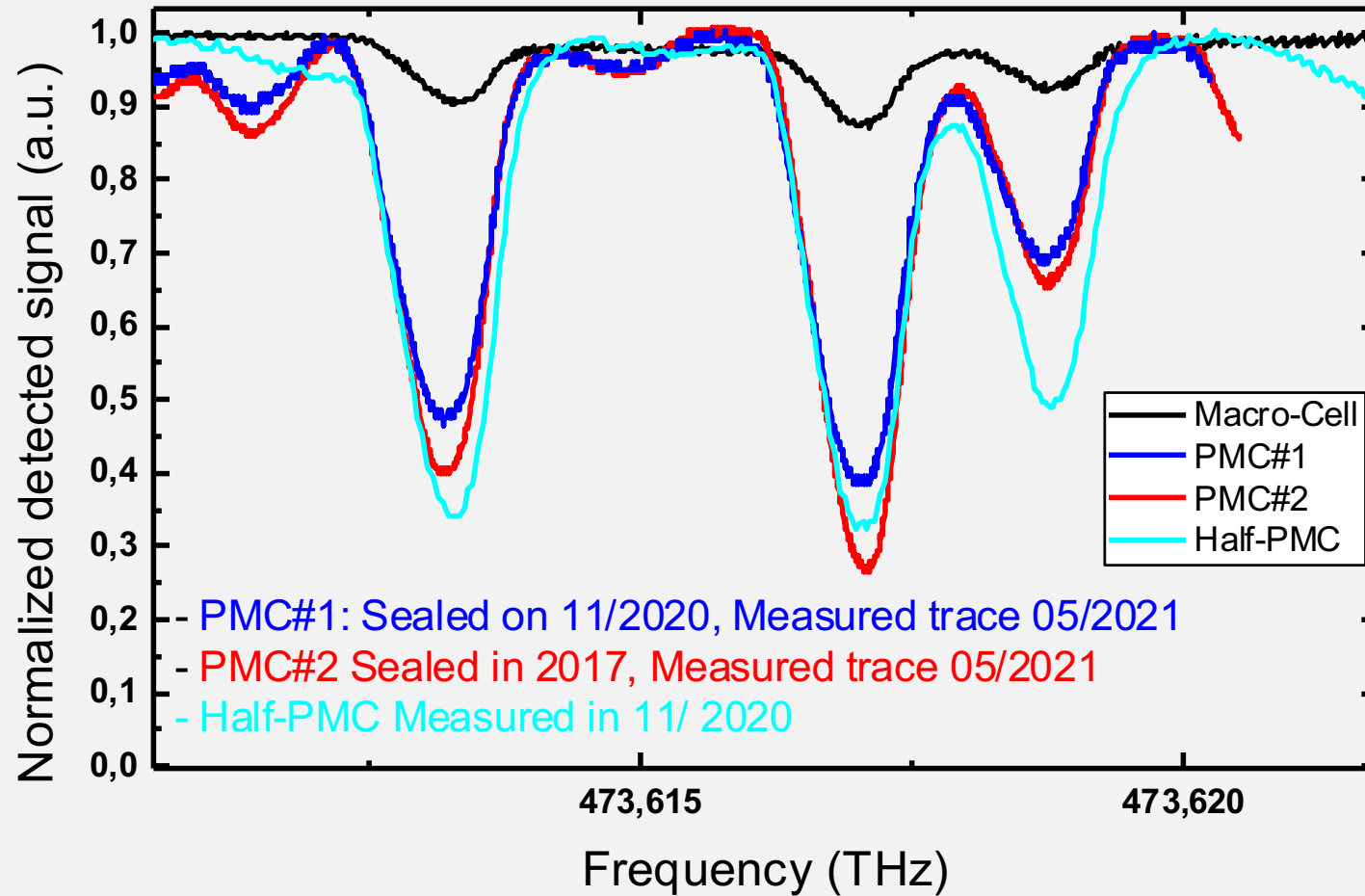


- Contamination free hermetic sealing
- Easily integrable device
- « Plug & Play »
- Mechanically resistant

Iodine PMC - Performances



Iodine PMC - Performances



Contrast

- Contrast in the range of 55-75% (compared to 8% for macroscopic cell)

Life-span / Durability

- No degradation in the signal of PMC#2 since its sealing in 11/2017

Integration

- FC-connector. Insertion loss in the range of 3-4dB

Vapor choice : Iodine

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Fabrication & Characterisation of Iodine PMC

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- PMC loading process
- Real time spectroscopic monitoring and characterisation
- PMC performances

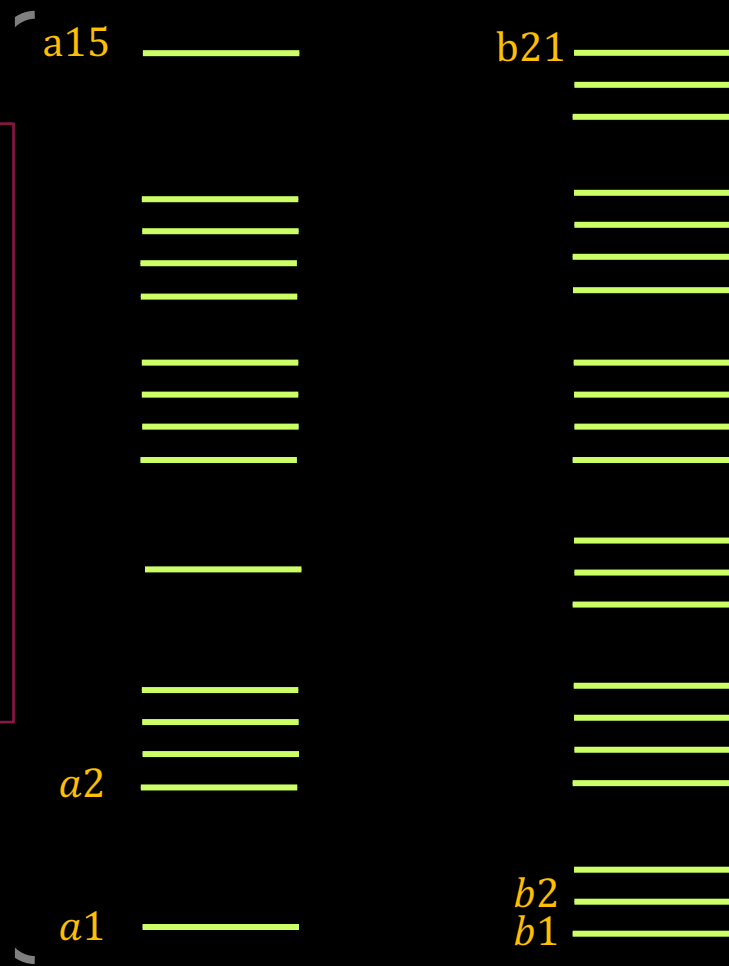
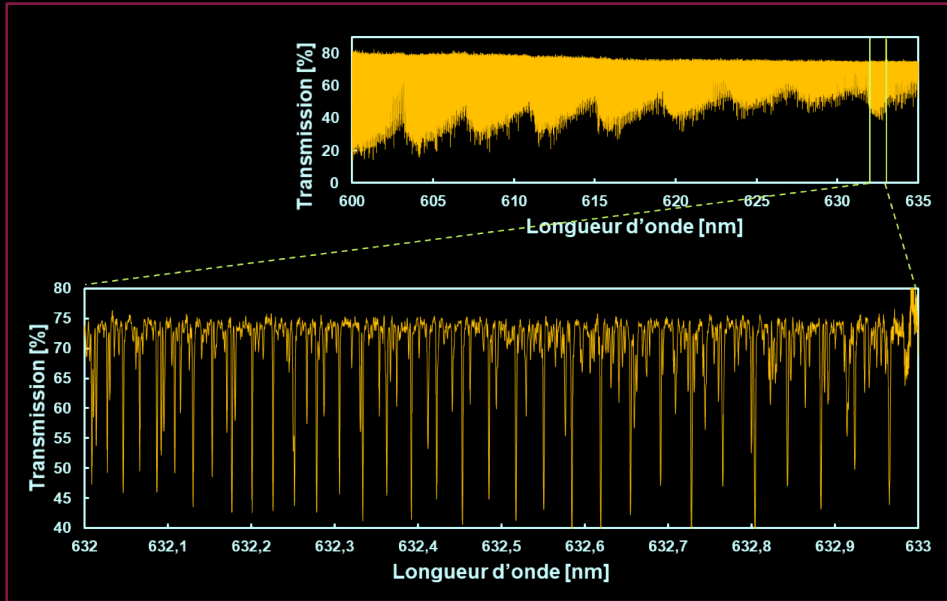
Iodine hyperfine structure resolution

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- Hyperfine structure of the Iodine B-X spectrum
- Proof of concept : P(33)6-3 hyperfine structure resolution

Conclusion & Prospects

Iodine hyperfine structure

15 & 21 hyperfine narrow-linewidth transitions



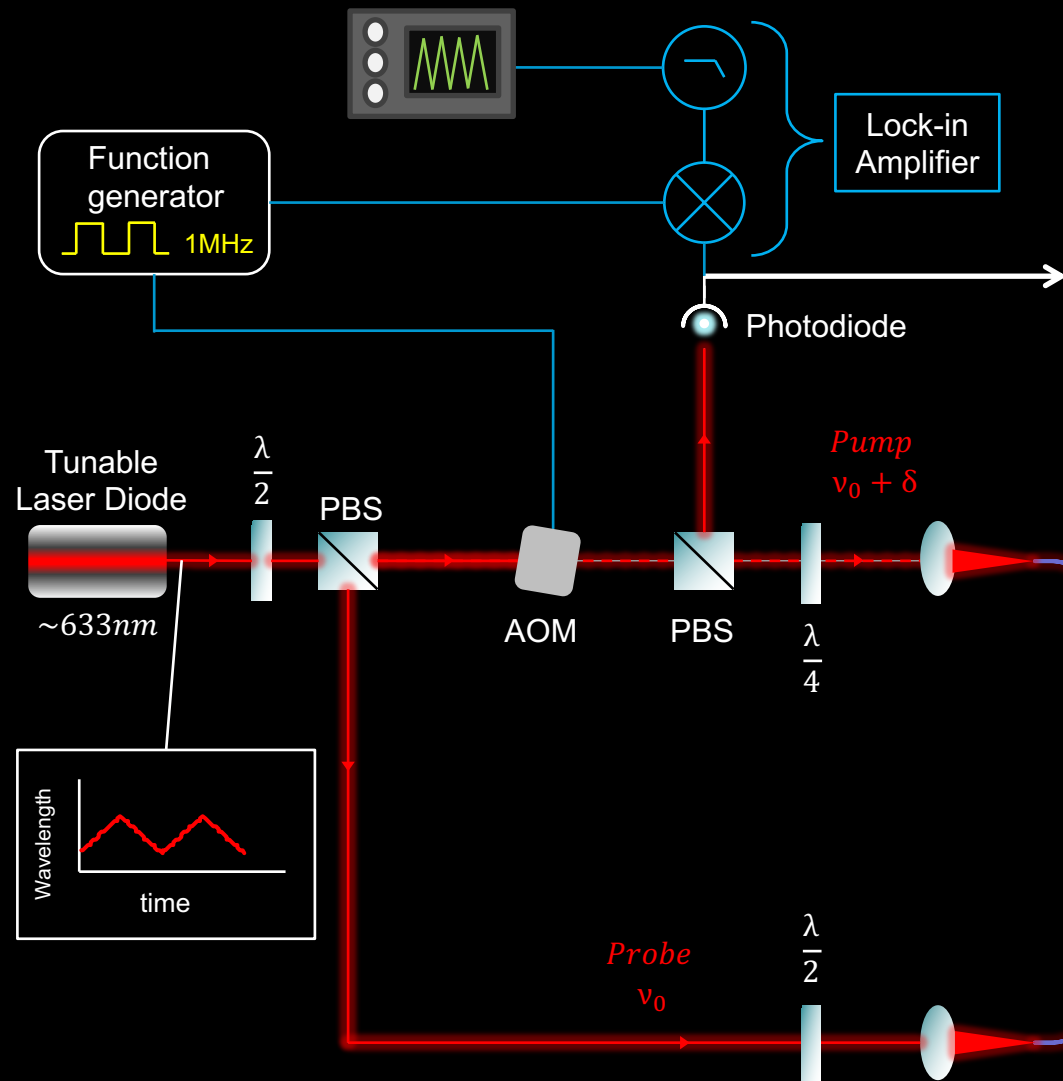
Symmetric spin wavefunction

Antisymmetric spin wavefunction

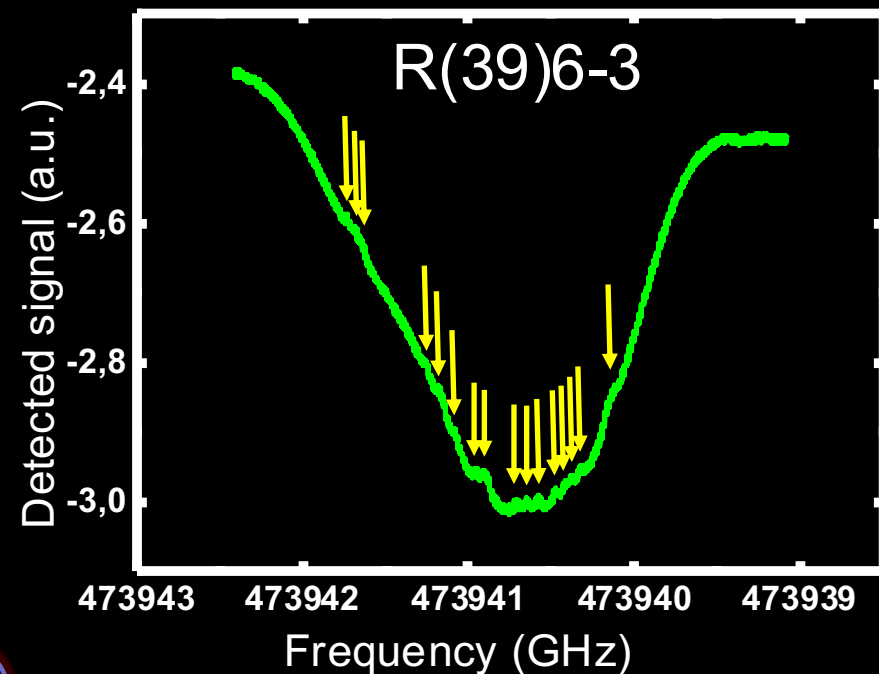
Saturable absorption spectroscopy (SAS)

Saturable absorption spectroscopy

set-up

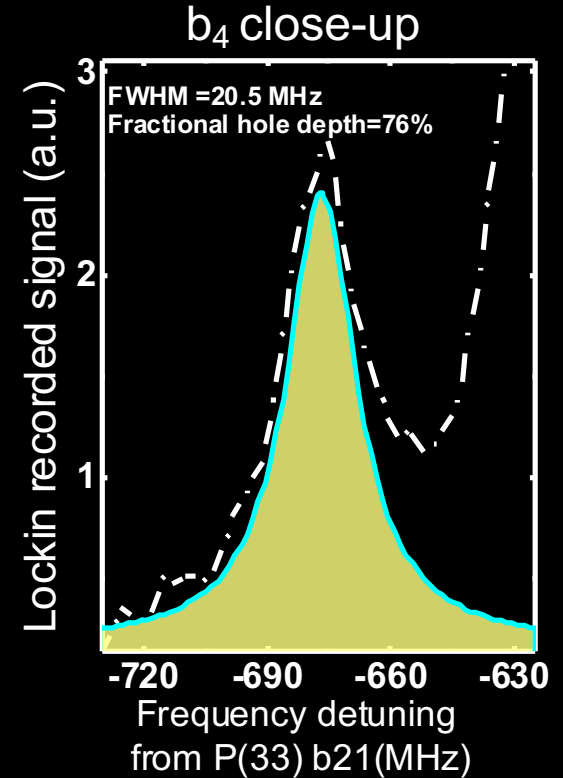
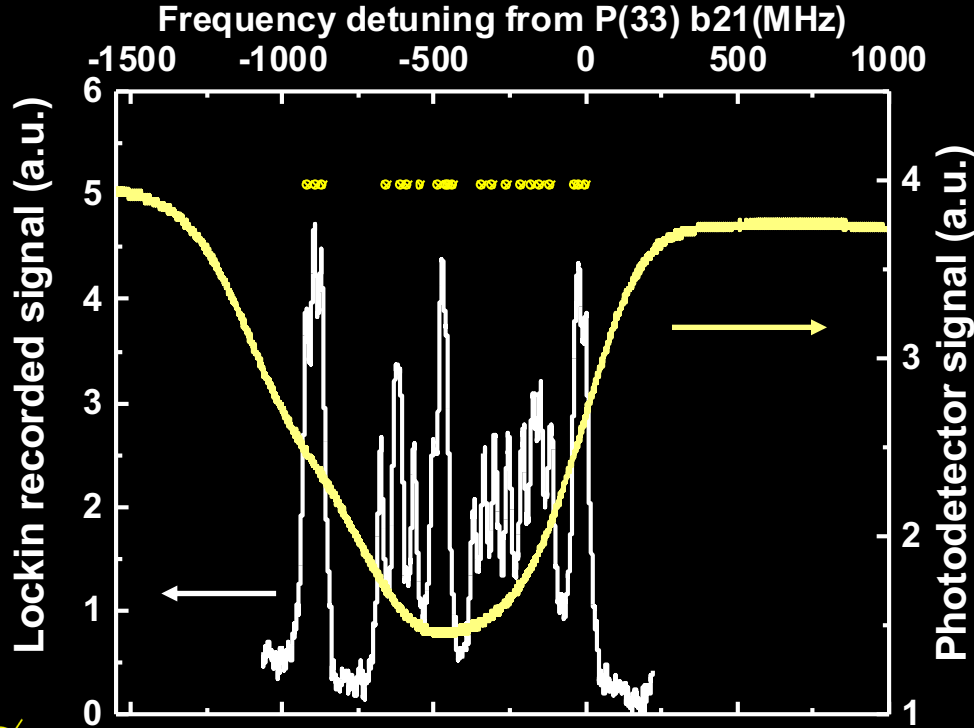


Typical recording of the probe transmission trace

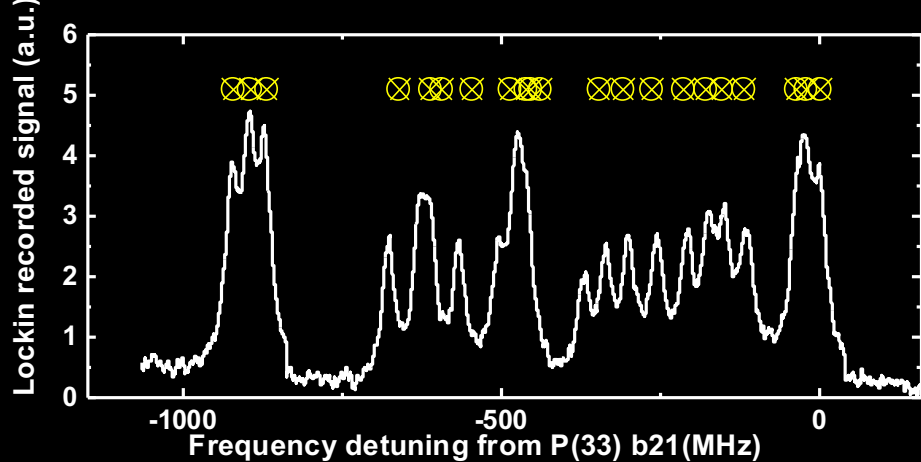


Coupled Pump power ~4mW
Coupled Probe power ~40 μ W
 $\delta = 64$ MHz

Resolution of the P(33)6-3 hyperfine line structure



\otimes b_1 frequencies (from BIPM) — P(33) Doppler line — P(33) Lockin-signal



Estimated broadening sources (MHz)	
Lifetime	0.160
Power broadening	19 - 27
Transit-time ($\Delta\nu = (2/\pi t_{tr})1.51\sqrt{\eta}$)	2.5 - 6
Inter-Molecule collisions	<0.012
Wall-molecule collisions ($T_w \approx (V/A)(2\sqrt{\pi})/v$)	0.6

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Conclusion & Prospects

Conclusion & Prospects

❖ Conclusion :

- New process for Iodine PMC loading and assembly
- Fabricated I2-PMC with demonstrated life-span >4 years
- FC-connector PMC & insertion loss of 3-4dB
- Observation of lockin-free SAS at room temperature
- Resolution of P(33)6-3 (633nm) of the 21 hyperfine lines

❖ Future goals & ideas :

- Improving insertion loss of the final splice process
- Laser Stabilization
- Improving PMC quality :
 - Optimizing excitation for transit-time limited linewidth
 - Optimizing vapor pressure for extending transit-time
- Improving insertion loss : **AR coating**

❖ Extending the technology to alkaline vapors :

Li, Na, K, Rb, Cs, Fr (High reactivity to surfaces)

Thank you for your attention

Acknowledgment

GLO is thankful to Toptica for collaboration and support



GPPMM acknowledges funding support from ANR and RA region



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