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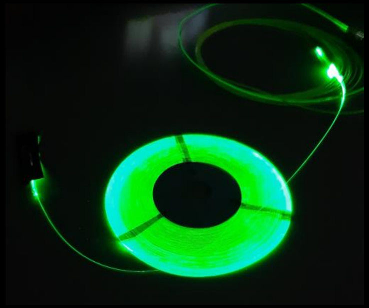

Combined Temperature and Radiation Effects on Silica-based Optical Fibers: Recent Progresses

Sylvain Girard for the MOPERE team & LabH6

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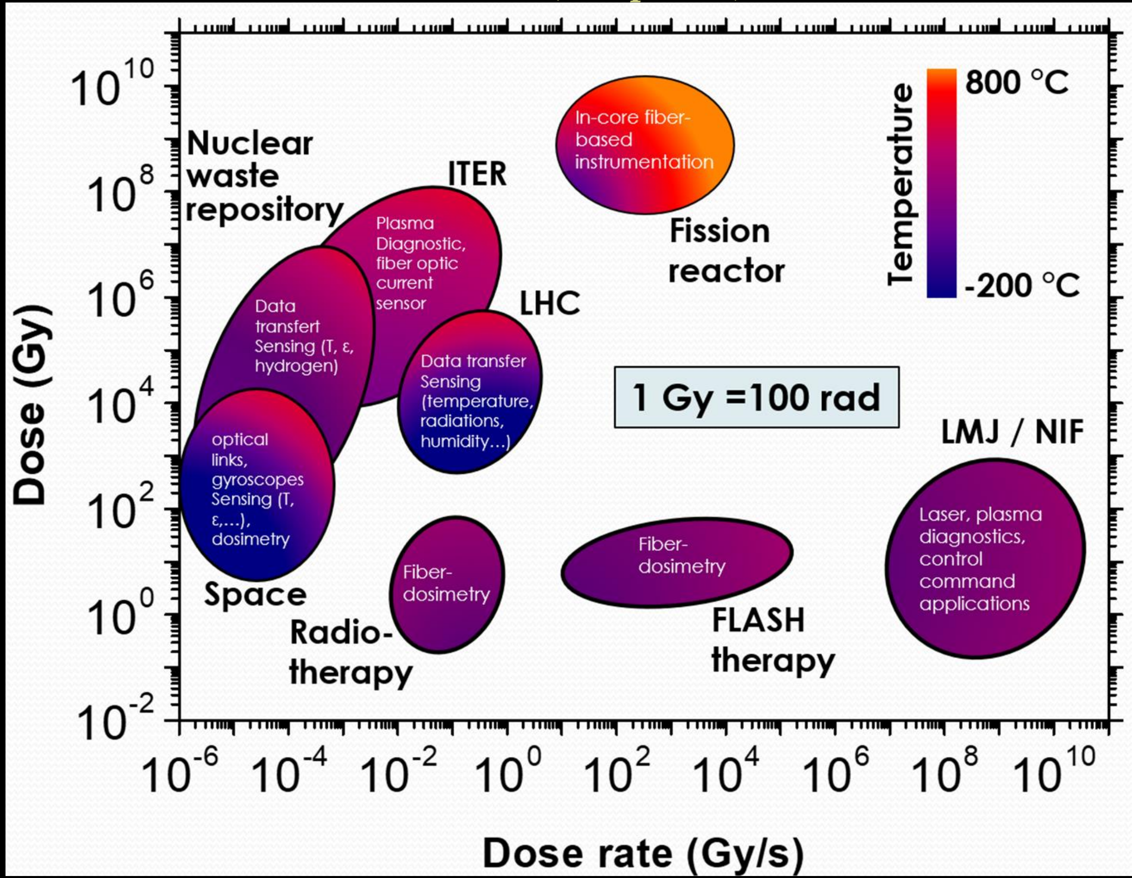
COMET-CNES, June 28th, 2023

Silica-based optical fibers present key advantages for applications in harsh environments

Girard et al., in press, 2023



What's about the radiation effects on optical fibers & fiber sensors?

1. Electromagnetic immunity
2. High bandwidth/ multiplexing capability
3. Low attenuation
4. Low weight and volume
5. High temperature resistance

1. Data Transfer, Communications
2. Laser, Plasma Diagnostics
3. Point or Distributed Sensors
   - ✓ Temperature
   - ✓ Strain
   - ✓ Current sensors
   - ✓ FOGs
   - ✓ Liquid level
   - ✓ Radiations....

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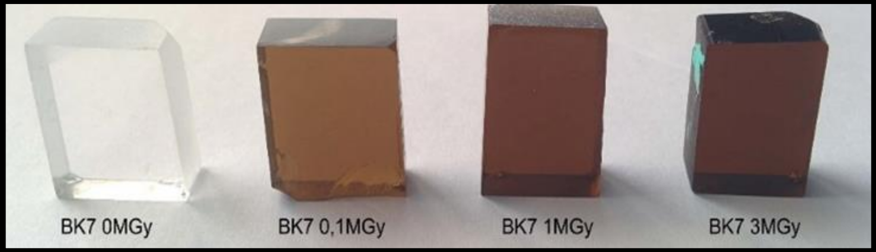
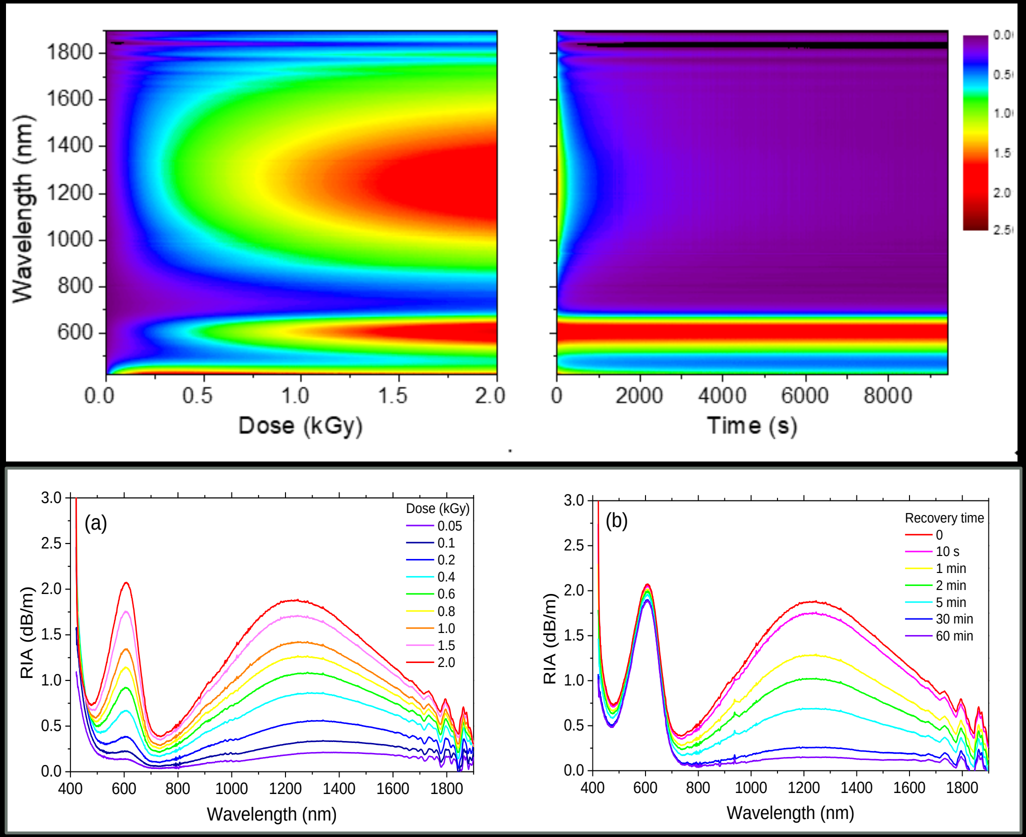
RIA is the main degradation mechanism identified under irradiation for optical fiber



Radiation Induced Attenuation = excess of optical loss induced by radiations



S. Girard. et al. Optical Materials X 2023

- ➢ Understanding the basic mechanisms of radiation effects is mandatory to **control** the RIA levels and kinetics: **radiation hardening / dosimetry**

Point defects created by ionization or displacement damages in pure or doped silica explained the RIA

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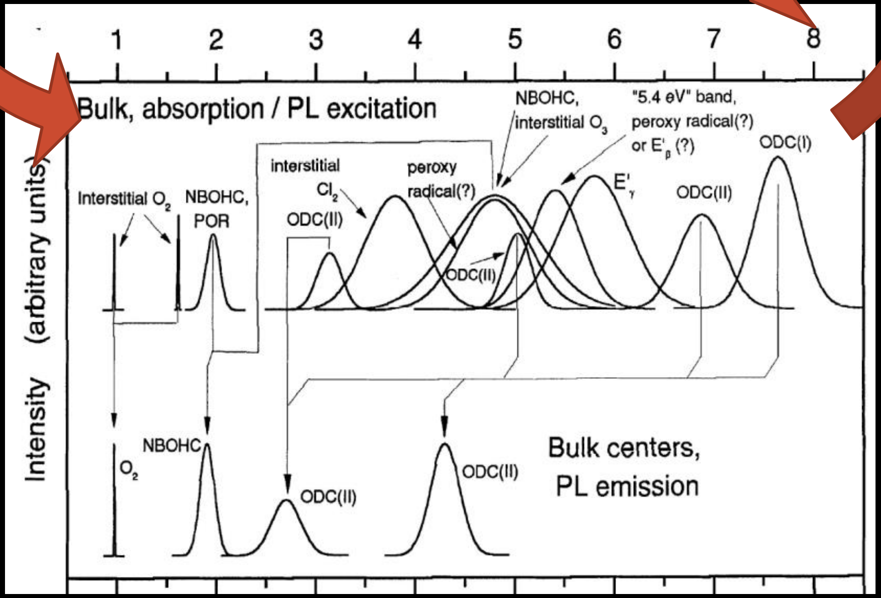
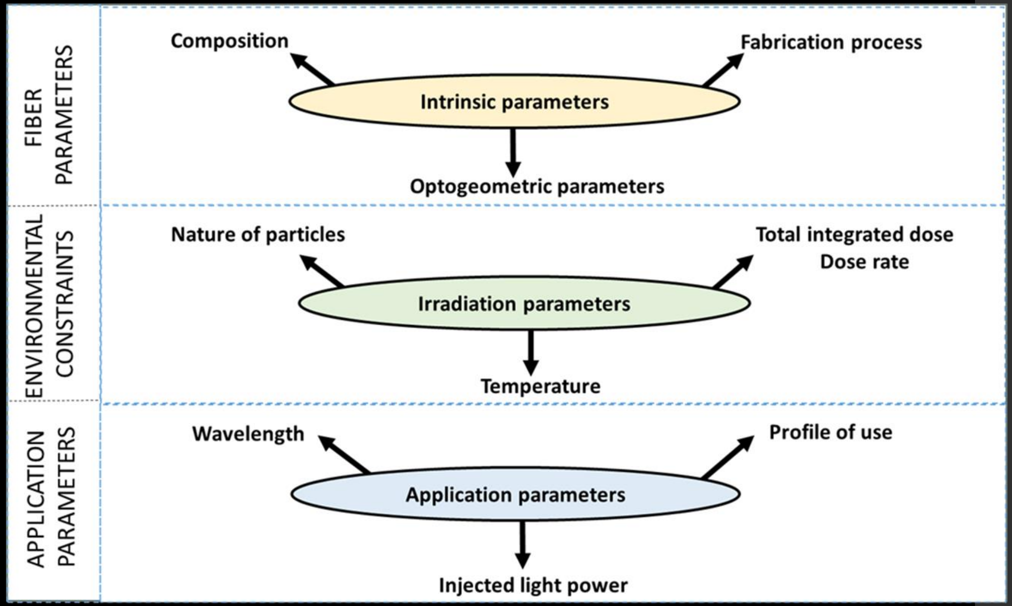
Temperature affects both the creation and recovery efficiencies!

Dopants (Ge, P, Al, N, …)
Impurities (Cl, OH,….)

Interaction between defects

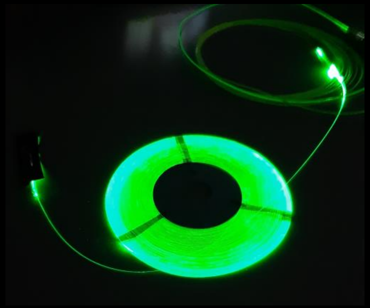


Skuja; NATO Book Chapter, 2000



S. Girard, et al. IEEE TNS, 60 (3) 2015, 2013

- ❖ Each parameter affecting the stability, generation or bleaching efficiencies or optical properties of point defects affects the OF response
- ❖ Combined T and radiation effects are poorly studied in literature (R+T vs R&T)!



2013: First study on combined radiation and temperature effects in the UV-visible domain

S. Girard *et al.*, "Combined High Dose and Temperature Radiation Effects on Multimode Silica-Based Optical Fibers," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 6, pp. 4305-4313, Dec. 2013

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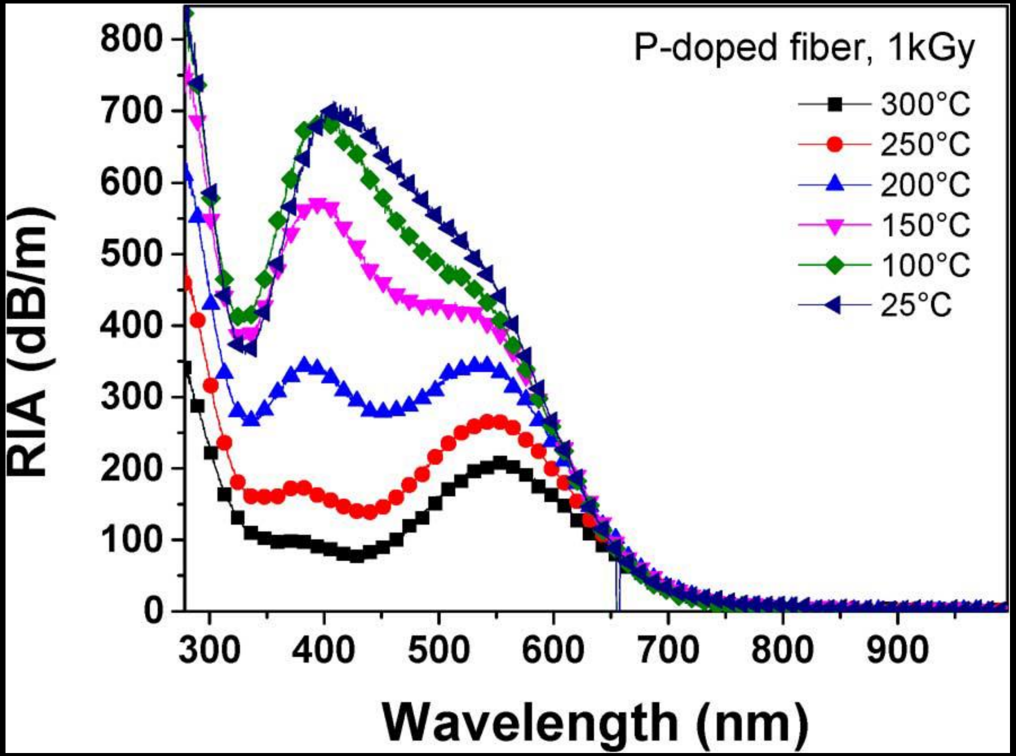
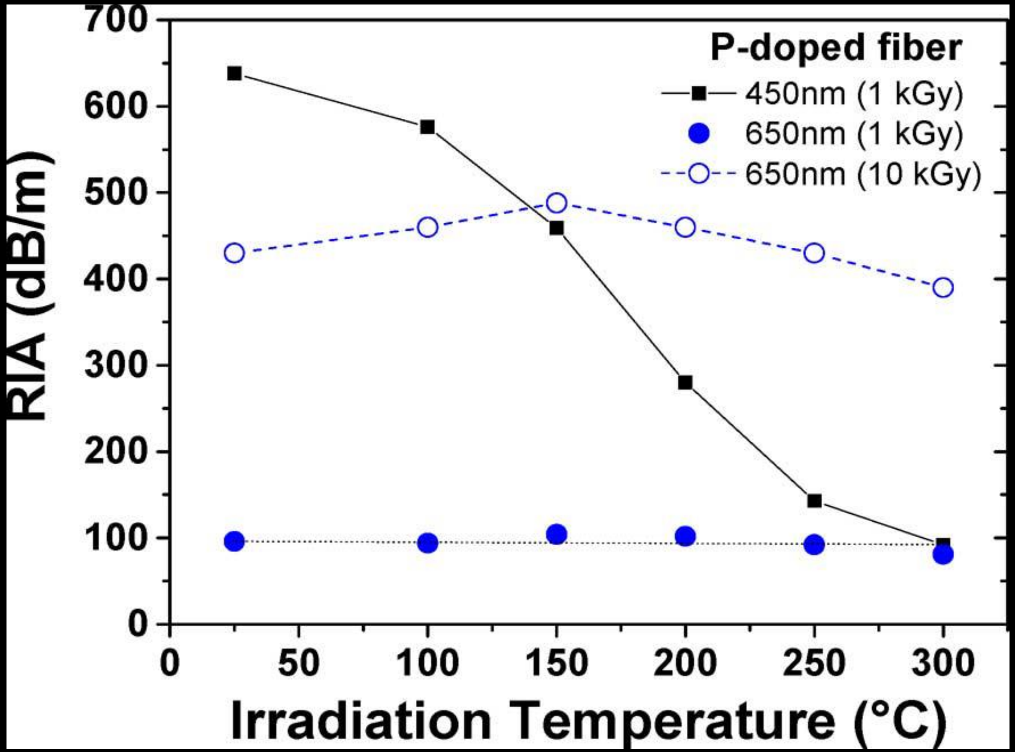
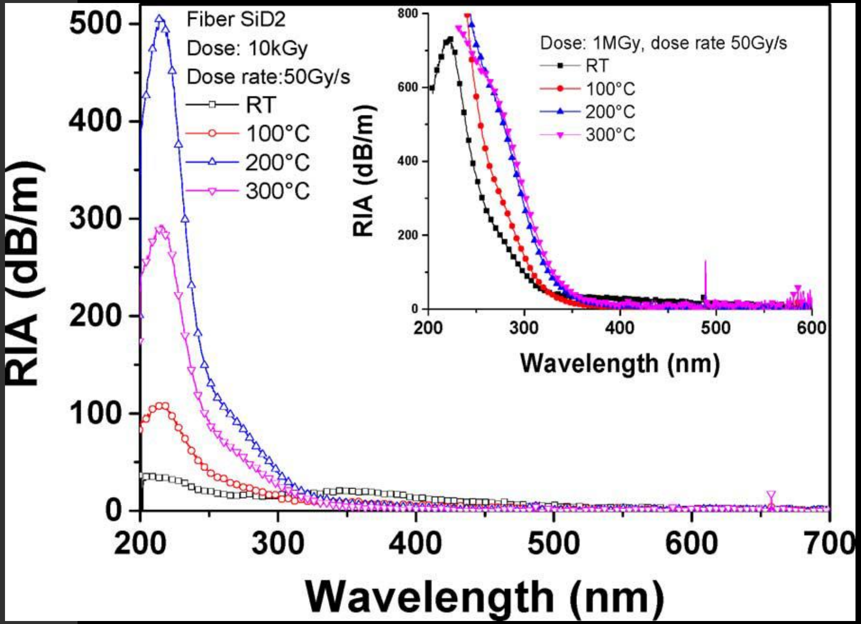
First demonstration of the complex effect of combined temperature and radiation effects in the UV-vis (1/2)

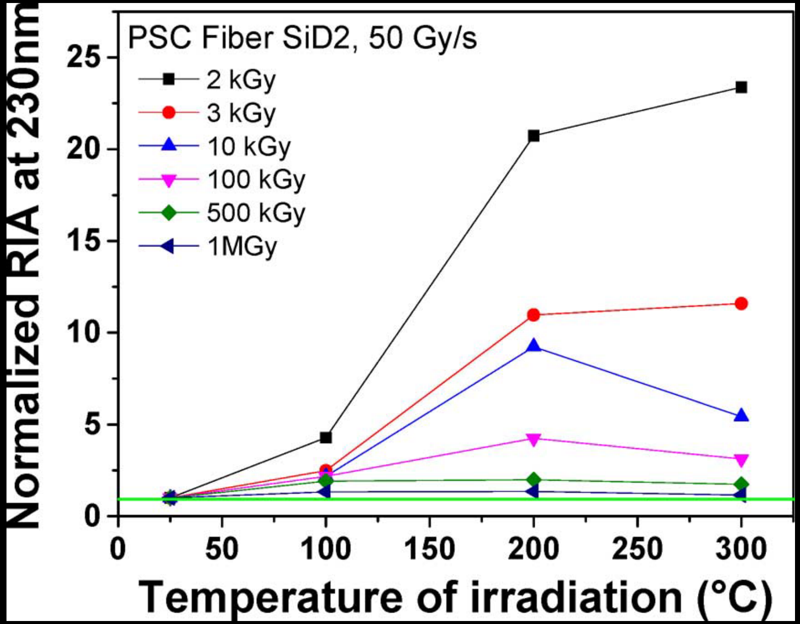


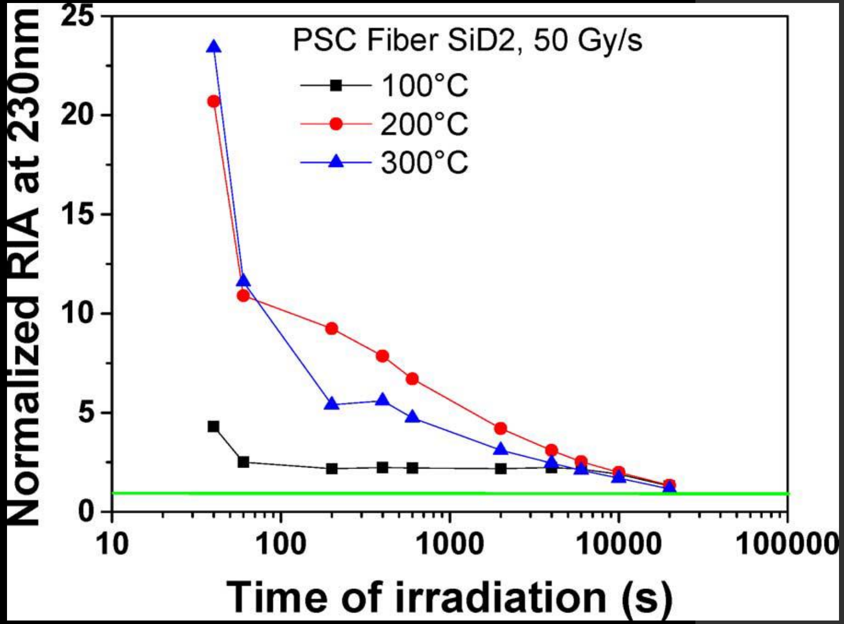


- ❖ Setups have been built at UJM to irradiate with X-rays at -120°C < Tirr <350°C
- ❖ For some optical fibers, such as P-doped fibers, we have the classical response: either the defects are bleached at high-T either they are stable

First demonstration of the complex effect of combined temperature and radiation effects in the UV-vis (2/2)

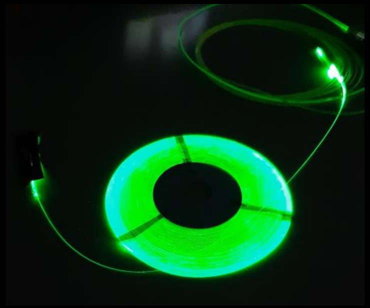






- For pure-silica core fibers, the UV induced losses increase strongly with the temperature of irradiation, RIA can be 25 larger at 300°C than at RT (@2kGy)

- Irradiation temperature effect is strongly dose (time) dependent and then probably dose rate dependent. At longer time, the thermal bleaching overcomes the possible increase of the generation efficiency ➔ main risk is at low doses (beginning of irradiation)

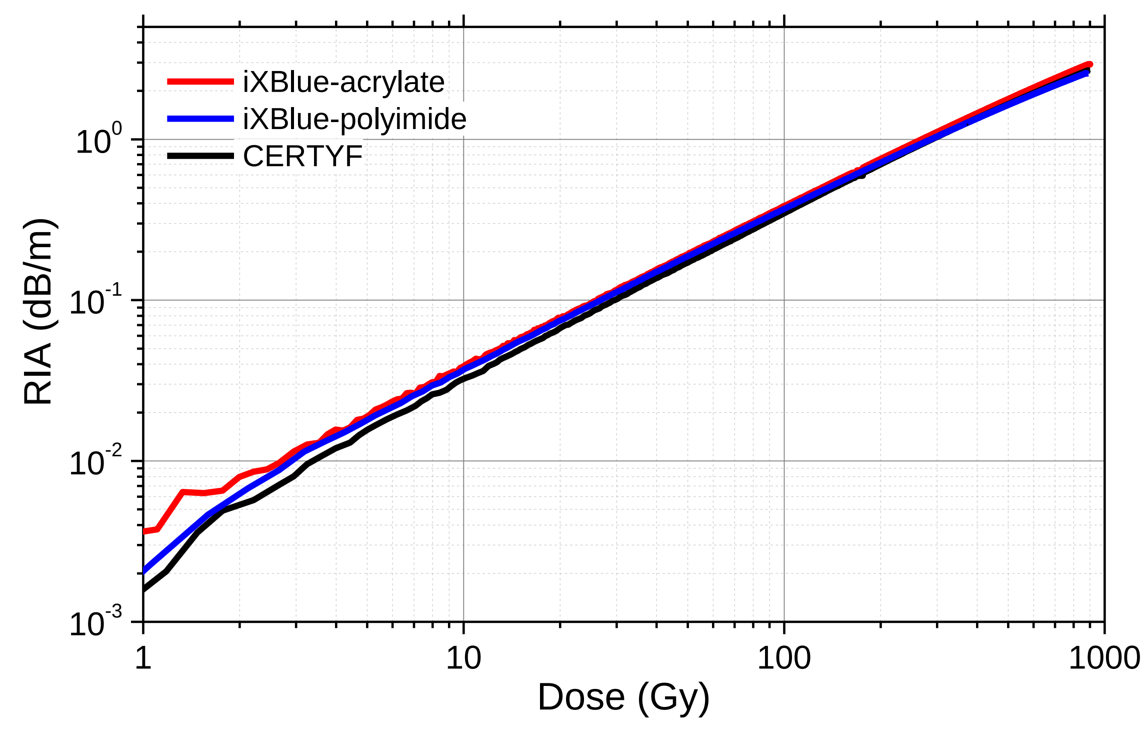


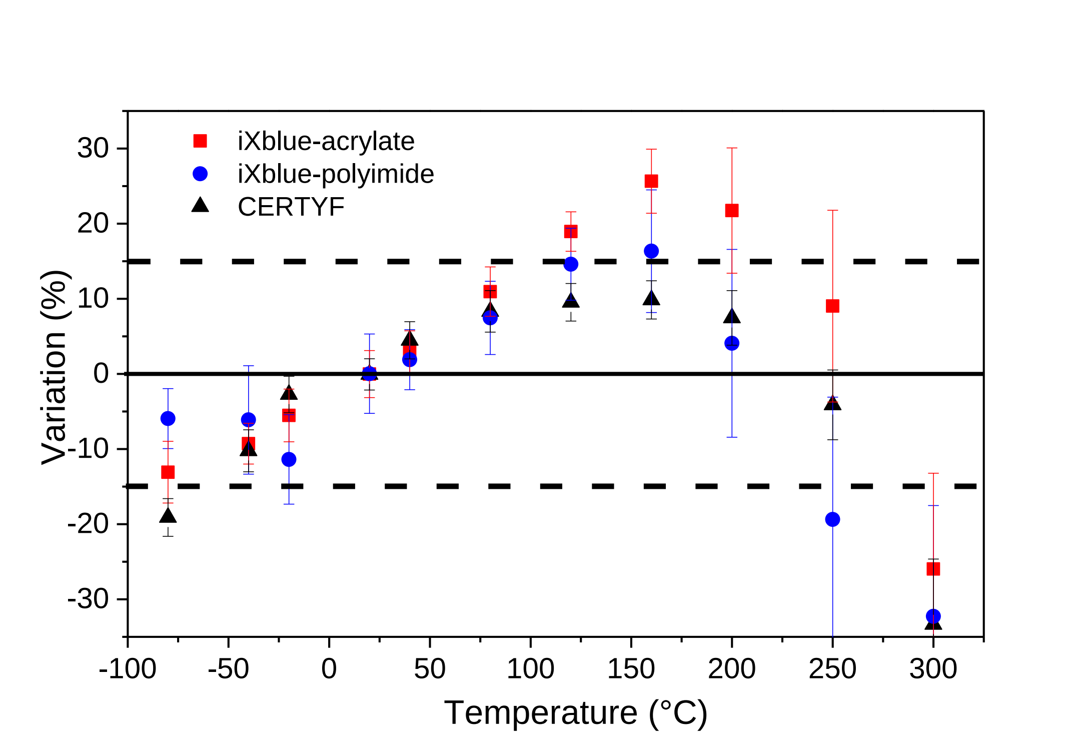
Systematic investigation in the infrared domain

1. P-doped optical fibers (dosimetry)
2. Ge-doped optical fibers
3. Fluorine-doped optical fibers

A. Morana et al., "Operating Temperature Range of Phosphorous-Doped Optical Fiber Dosimeters Exploiting Infrared Radiation-Induced Attenuation," in IEEE Transactions on Nuclear Science, vol. 68, no. 5, pp. 906-912, May 2021

We first investigate the radiation response of P-doped optical fibers at 1550 nm (dosimetry application) in the -100°C – 300°C





- 3 fibers from 2 different manufacturers have the same temperature dependence of RIA
- Temperature effect on P-doped is low in the IR domain (1550nm), less than 10% variation in the -80°C/80°C range. Larger (positive) impact at high T, > 250°C
- For dosimetry application, T calibration sounds feasible (under investigation)

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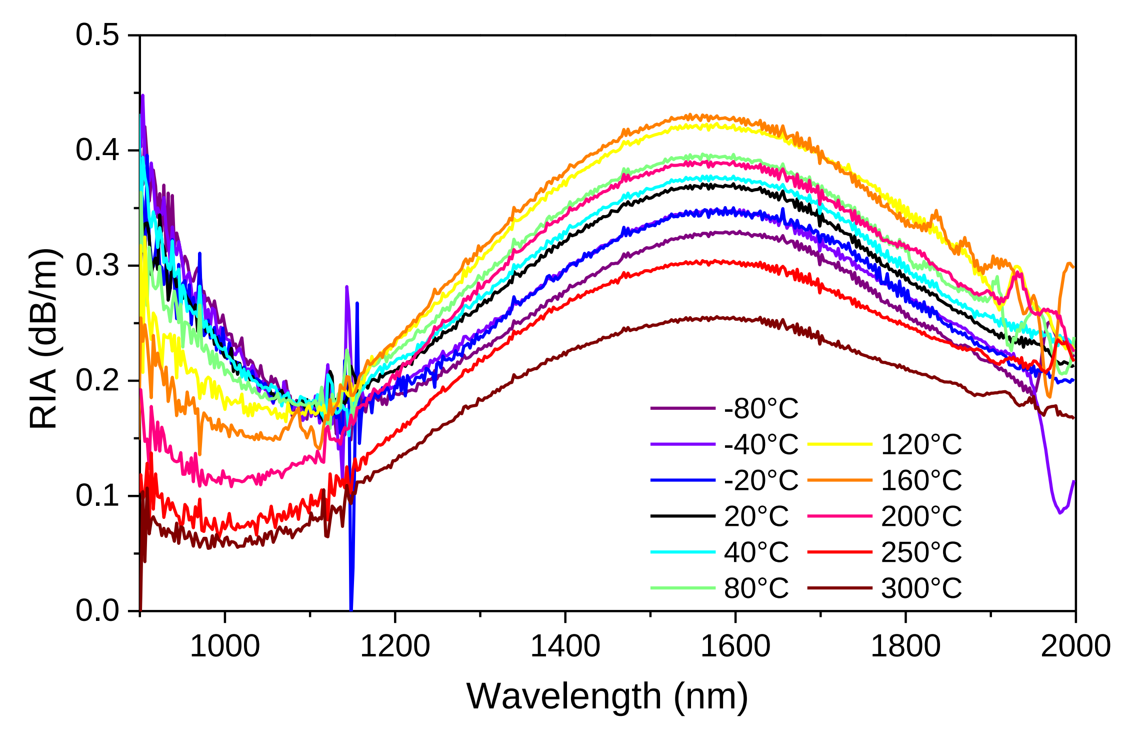
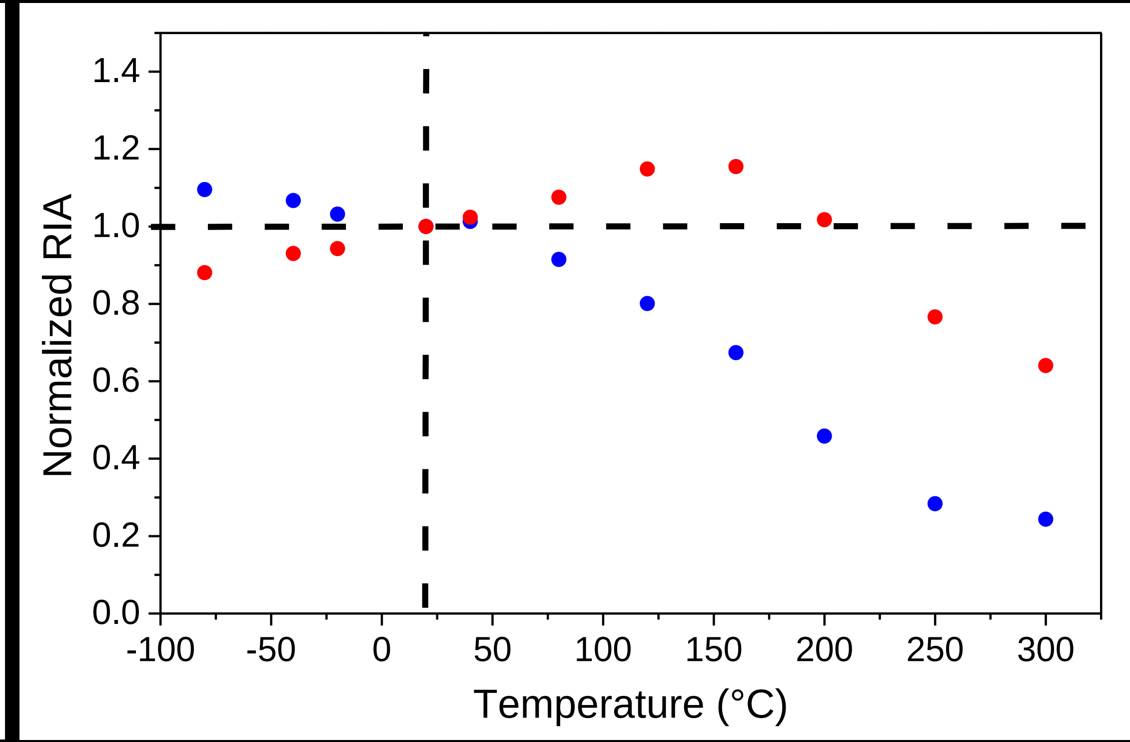
We first investigate the radiation response of P-doped optical fibers at 1550 nm (dosimetry application) in the -100°C – 300°C





❖ Spectral analysis of RIA is very interesting, it reveals the interconversion between the POHC and P1 defects up to 150°C

➔ online T measurements could help in identifying the IR absorbing point defects.

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Conclusions on T effect on P-doped fibers at 1550nm

- IR-RIA linearly increases with the dose up to hundreds of Gy and does not show any recovery after irradiation, dosimeter calibration factor (sensitivity) remains unchanged (+/- 10%) at least for T up to 120°C.

- At temperature higher than 120°C, the thermo-bleaching effect becomes predominant and the calibration factor is affected.

- The calibration factor remains independent on the dose-rate in the 10 mGy/s to 1 Gy/s range at temperatures up to 120°C.

➔ Sounds feasible to do fiber dosimetry in a large temperature range

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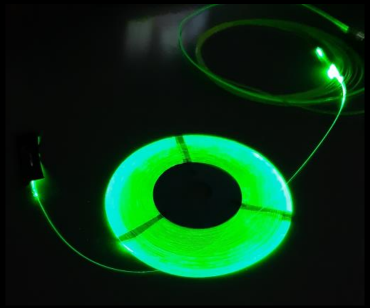

Systematic investigation in the infrared domain

1. P-doped optical fibers (dosimetry)
2. Ge-doped optical fibers
3. Fluorine-doped optical fibers

A. Morana *et al.*, "Temperature Dependence of Low-Dose Radiation-Induced Attenuation of Germanium-Doped Optical Fiber at Infrared Wavelengths," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 3, pp. 512-517, March 2022

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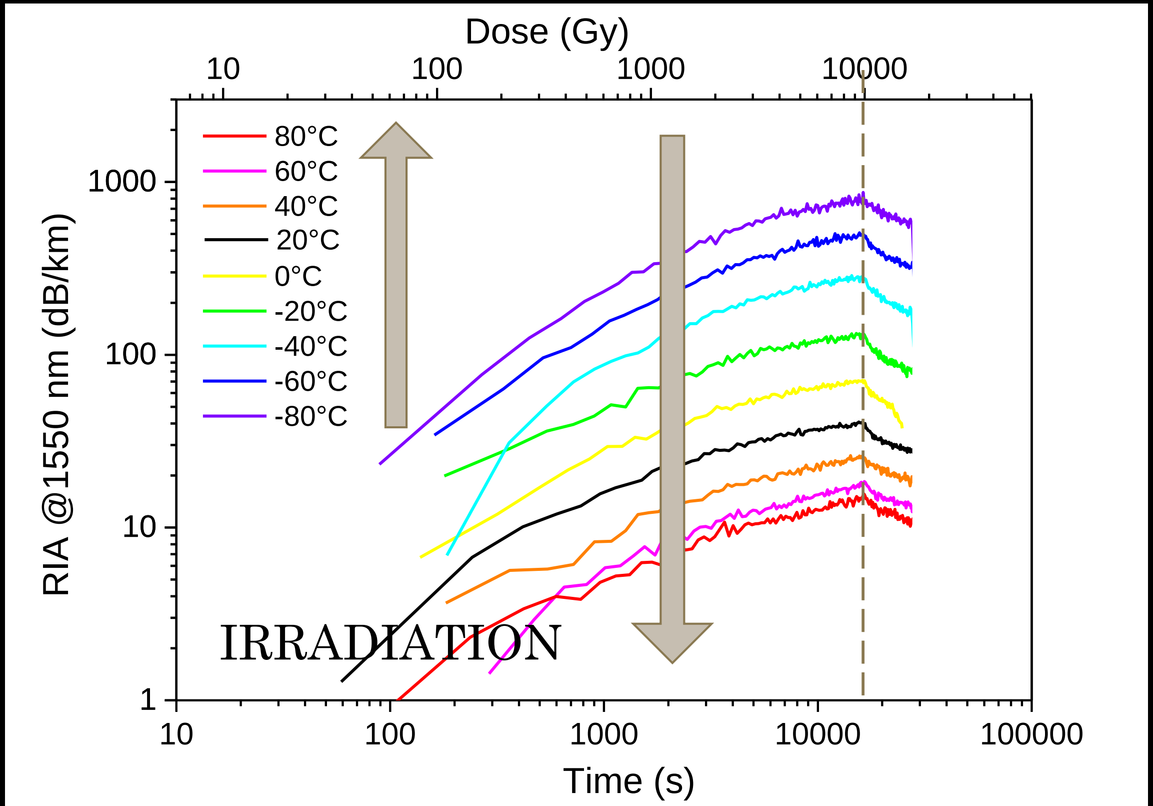
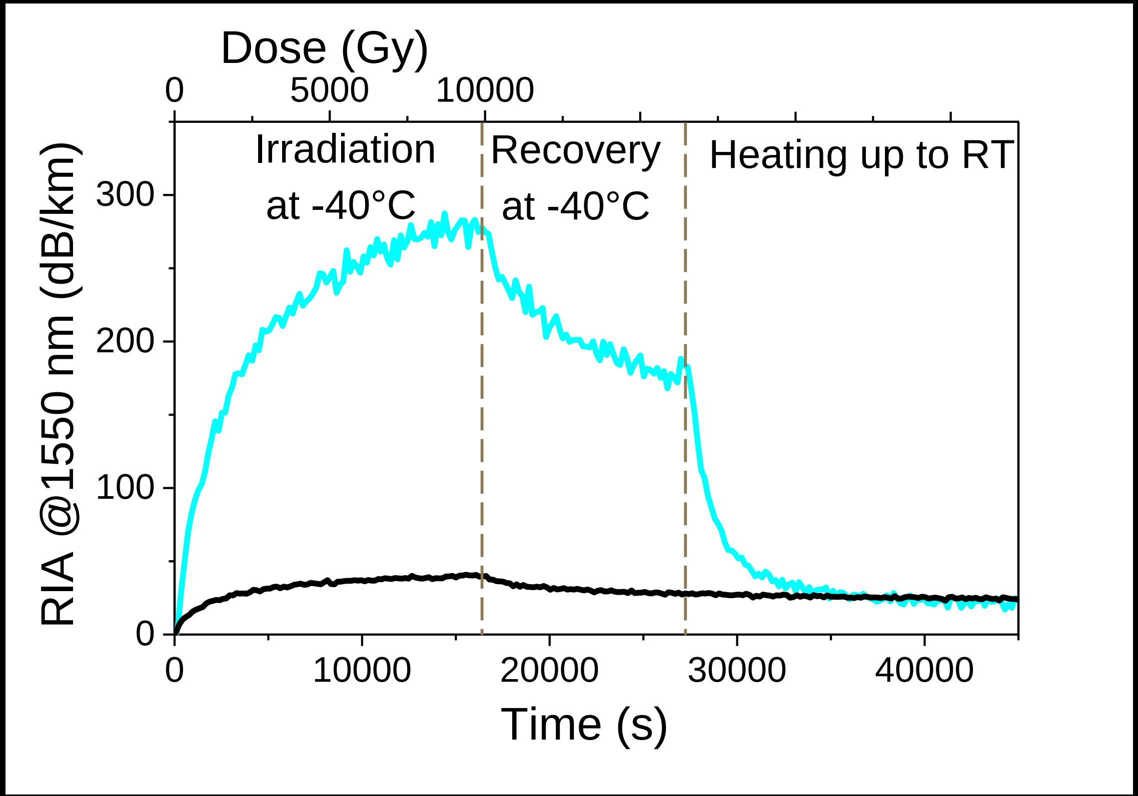
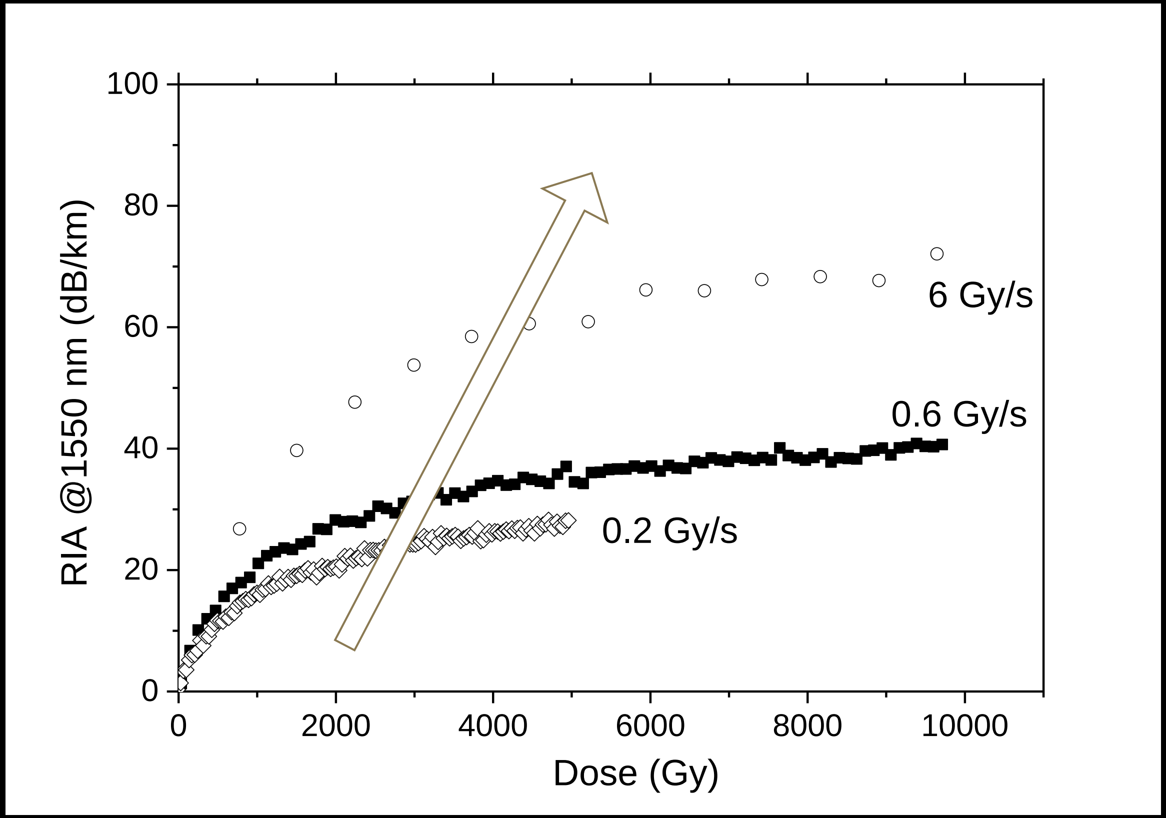
We then investigate the radiation response of Ge-doped optical fibers at 1550 nm (dosimetry application) in the -80°C – 80°C

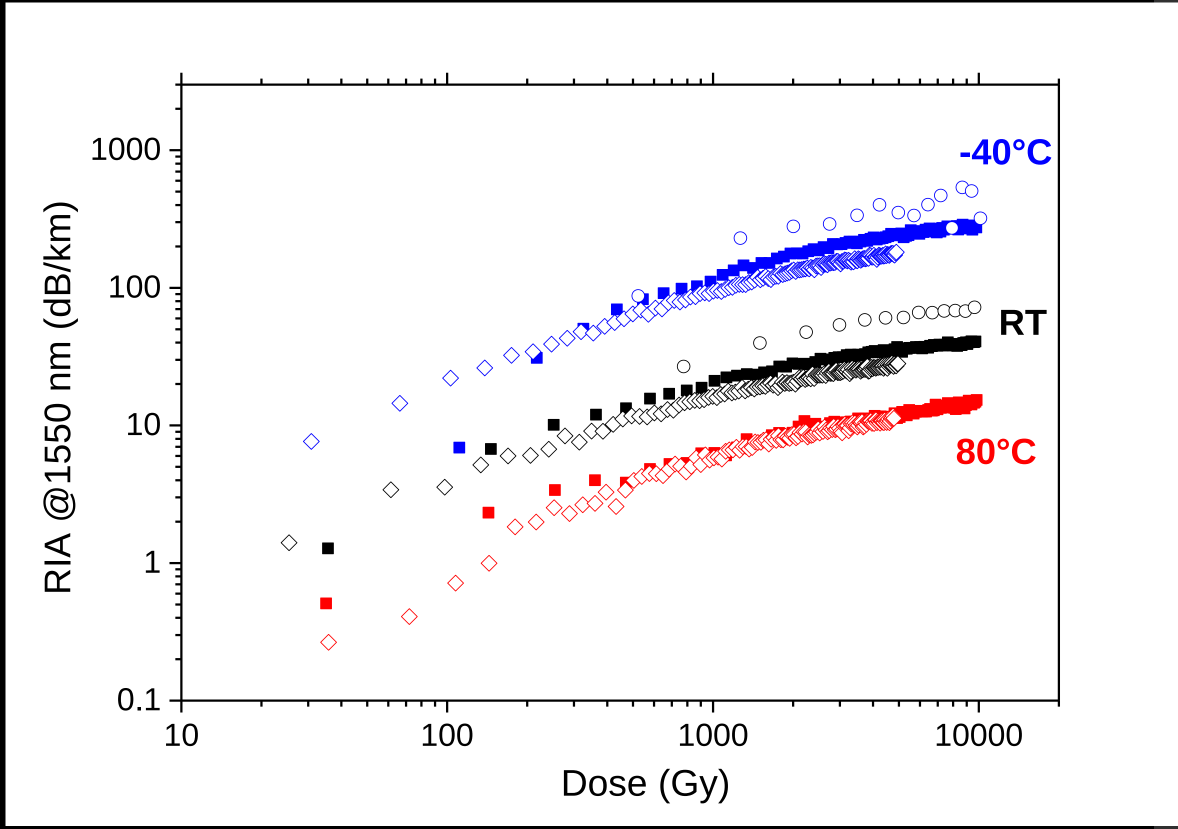




- T_{irr} has a major impact on the RIA of Ge-doped fibers ➔ very high RIA at low T
- RIA growth and decay kinetics seem to be same whatever the irradiation temperature

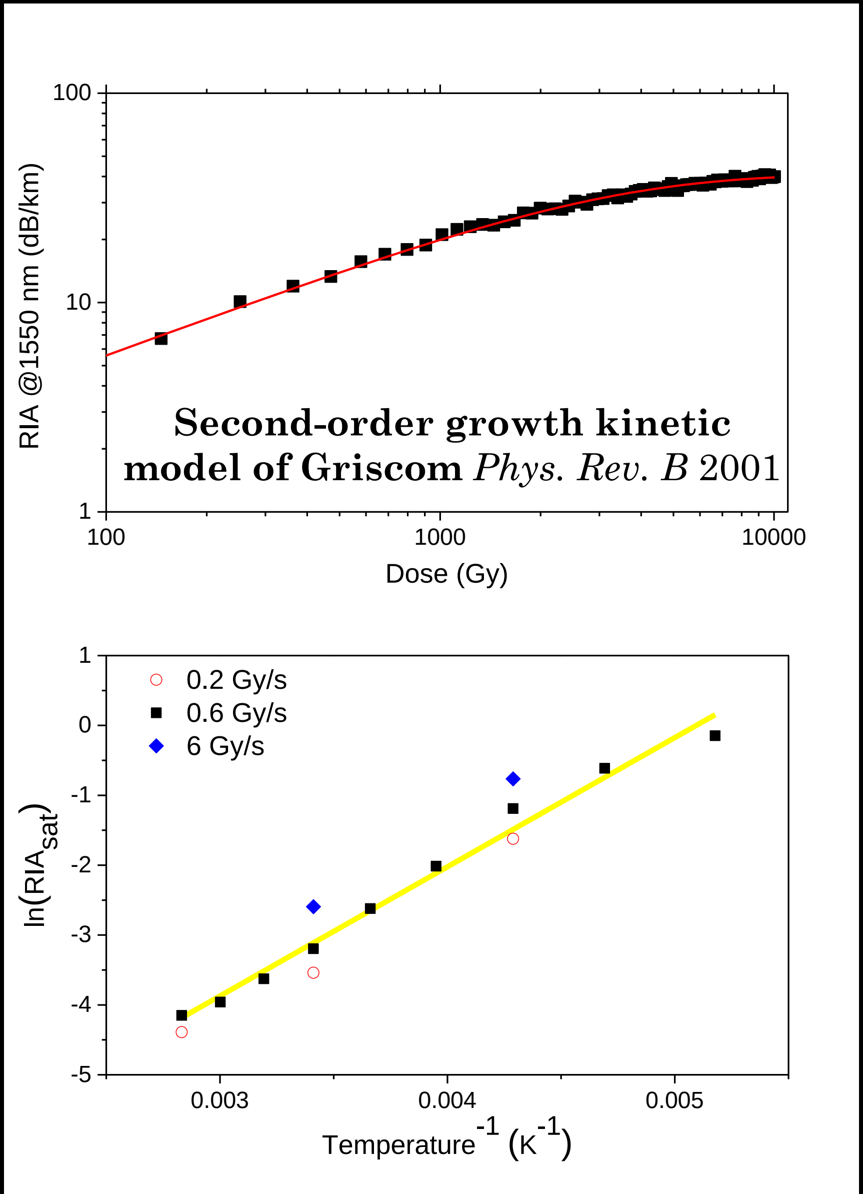
We then investigate the radiation response of Ge-doped optical fibers at 1550 nm (dosimetry application) in the -80°C – 80°C





❖ As expected the higher the dose-rate, the larger is the RIA. BUT, the temperature effect is more important than the one of the dose rate in these ranges

We then investigate the radiation response of Ge-doped optical fibers at 1550 nm (dosimetry application) in the -80°C – 80°C



$$RIA(T,\dot{D},D) = RIA_{sat} \cdot \tanh\left((k\ D)^{\beta}\right)$$

Arrhenius law

$$RIA_{sat}(T,\dot{D}) = C(\dot{D}) \cdot \exp\left(\frac{E_a}{K_B T}\right)$$

Wavelength (nm)	Ea (eV)
1310 nm	0.20
1550 nm	0.16

Same activation energy → same defect involved at the two wavelengths

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Conclusions on T effect on Ge-doped fibers at IR telecom wavelengths

- Low temperatures, combined with radiations, deteriorate the performance of the Ge-doped fibers at low doses (< 10kGy, < 1Mrad) and Telecom wavelengths

- The induced losses in the IR at -80°C increase by a factor 43 (18) at 1310 nm (1550 nm), compared to the ones induced at 20°C.

- The RIA depends on dose, dose-rate and temperature according to the second-order growth kinetic model proposed by David Griscom.

- The value at which the RIA tends to saturate shows a dependence following the Arrhenius law, with an activation energy of ~0.18 eV. At both telecom wavelengths, there is a single defect at the origin of these induced losses.

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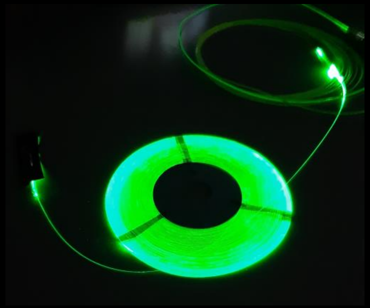
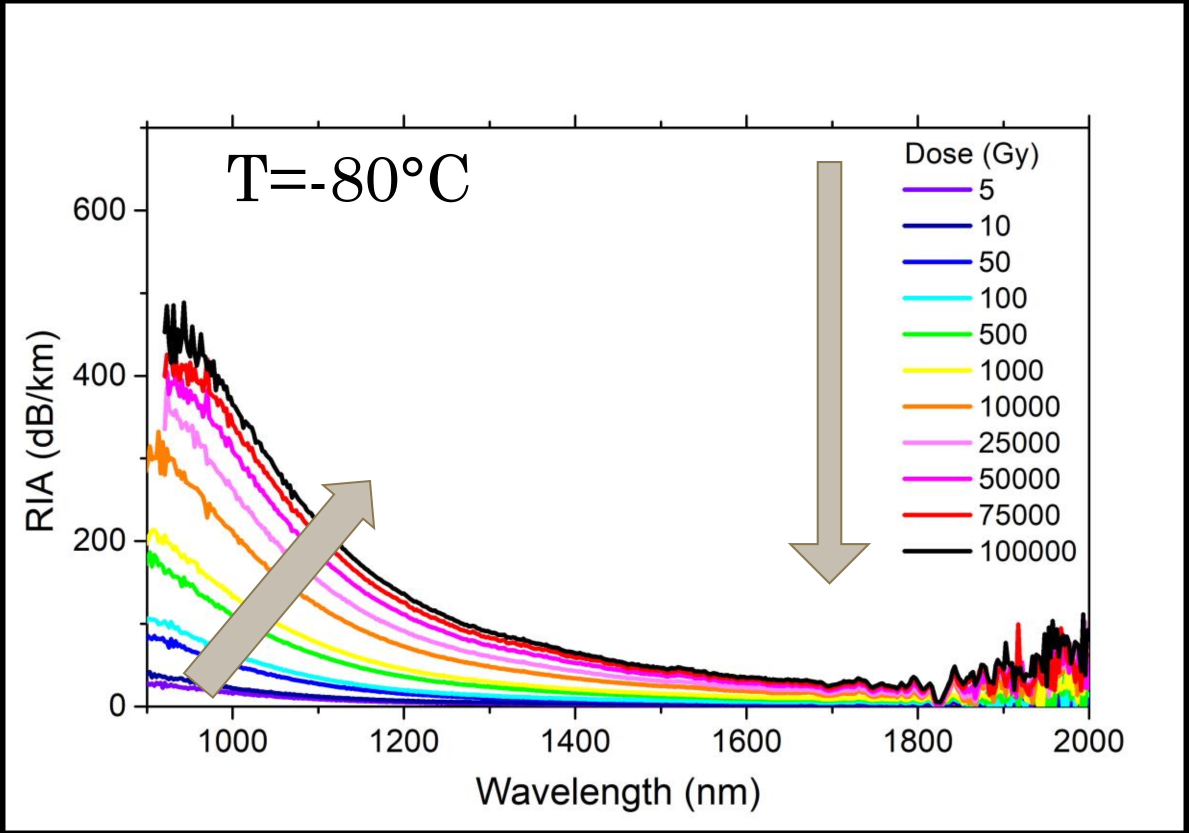


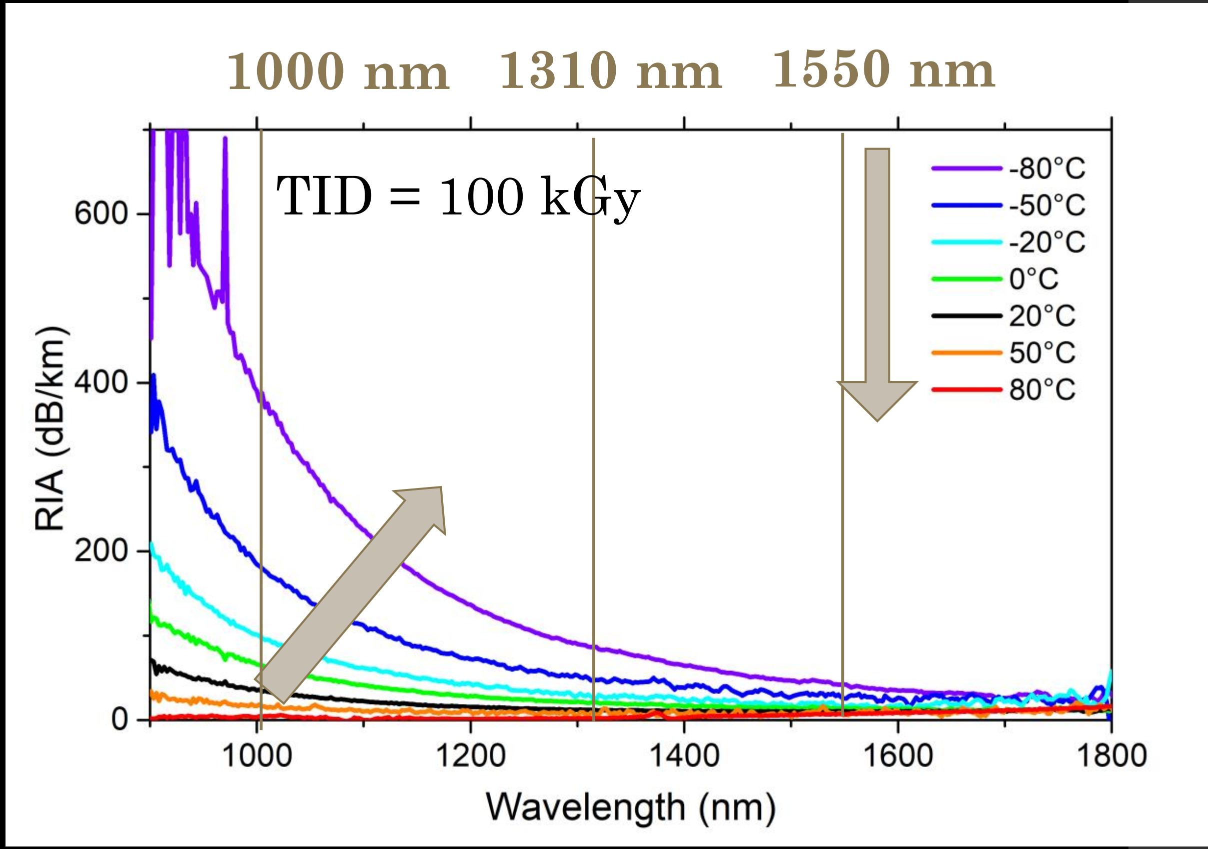
Systematic investigation in the infrared domain

1. P-doped optical fibers (dosimetry)
2. Ge-doped optical fibers
3. Fluorine-doped optical fibers

A. Morana *et al.*, "Temperature Dependence of Radiation-Induced Attenuation of a Fluorine-Doped Single-Mode Optical Fiber at Infrared Wavelengths," in *IEEE Transactions on Nuclear Science*, vol. 70, no. 4, pp. 549-555, April 2023

We then investigate the radiation response of rad-hard F-doped optical fibers in the IR for the -80°C – 80°C





- The RIA decreases by increasing the temperature: an increase up to an order of magnitude can be reached, when the temperature decreases from 80°C to -80°C.

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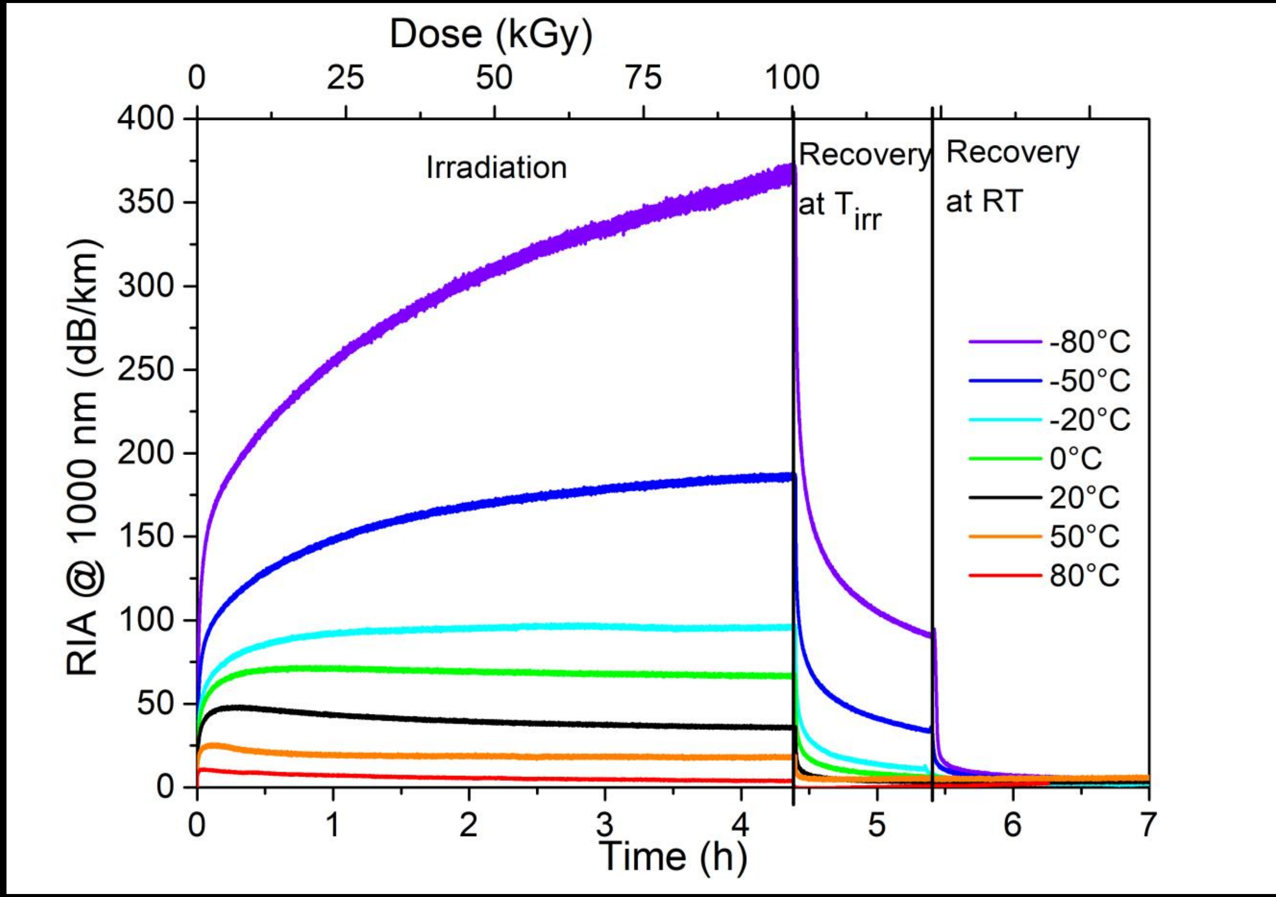
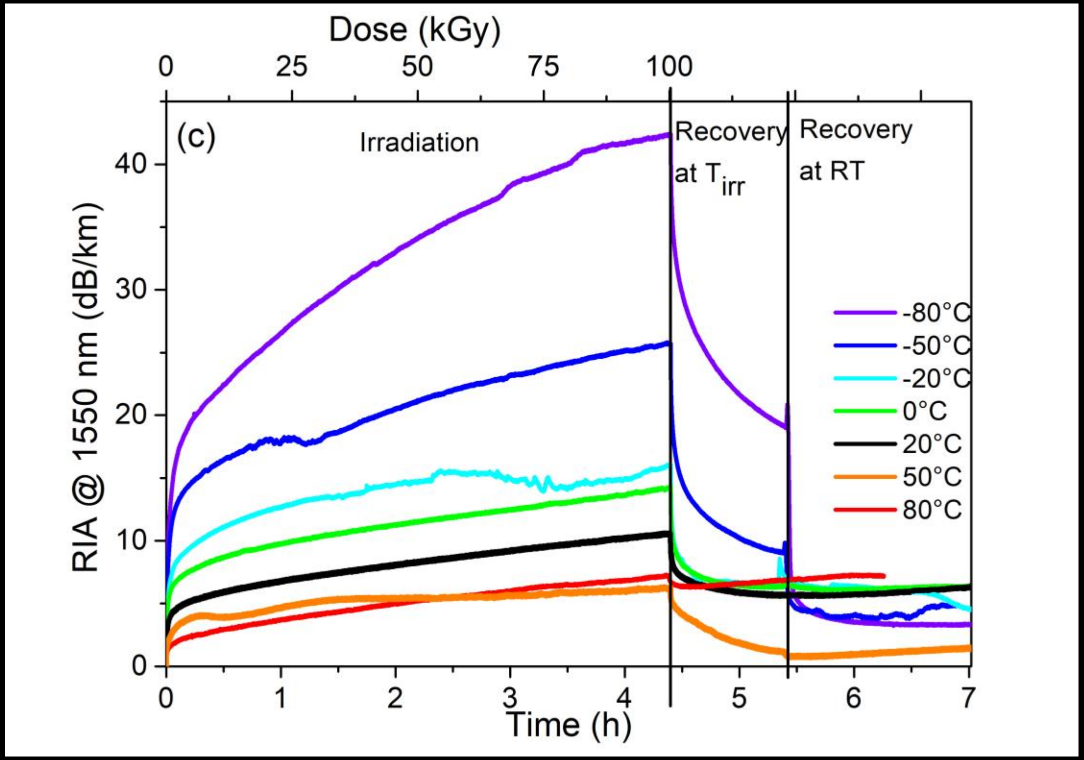
We then investigate the radiation response of rad-hard F-doped optical fibers in the IR for the -80°C – 80°C



- For temperatures higher than RT, the RIA reaches a maximum before starting to decrease.
- At -20°C and 0°C, the RIA saturates.
- At -80°C and -50°C, the kinetics does not saturate up to 100 kGy TID.

The recovery is more important at low temperatures, but faster when the temperature comes back to the RT value.

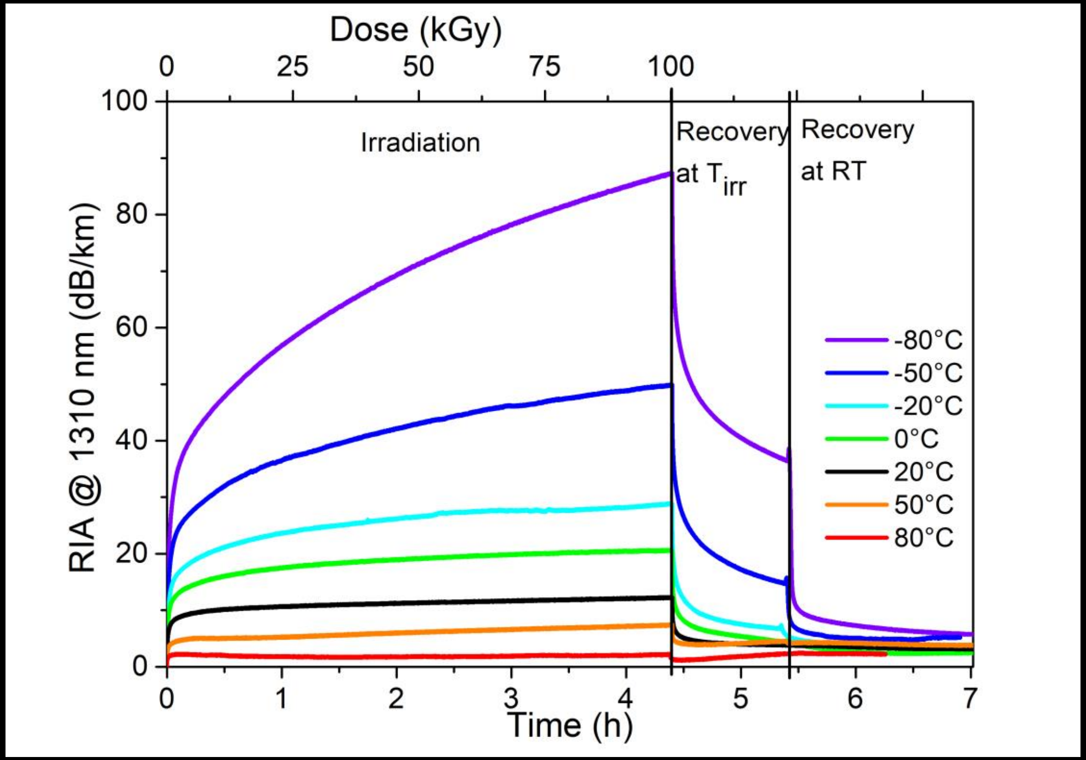
We then investigate the radiation response of rad-hard F-doped optical fibers in the IR for the -80°C – 80°C



1550nm RIA at 100 kGy TID, no saturation tendency:

- at RT 10.6 dB/km
- at -80°C 42 dB/km

→ Increase by a factor ~4



1310 nm RIA at 100 kGy TID, saturation tendency at low T:

- at RT 12 dB/km
- at -80°C 87 dB/km

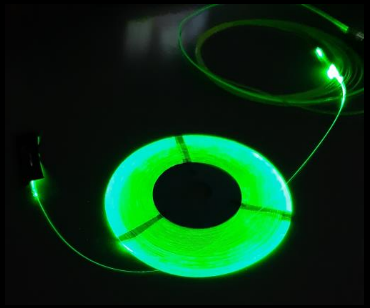
→ Increase by a factor ~7

Conclusions on T effect on F-doped fibers at IR telecom wavelengths

- Combining low temperatures and radiations, the performance of the F-doped fibers deteriorate.

- The induced losses at 100 kGy TID and at -80°C increase by a factor ~4 (7) at 1550 nm (1310 nm), compared to the ones induced at 20°C. → This increase is lower than the one observed on the Ge-doped fiber (a factor 18 at 1550 nm).

- Spectral analysis reveal that at least three different defects contribute to the RIA (both at 1310 nm and 1550 nm):
  - two defects are generated from precursors;
  - one center is created from the matrix.

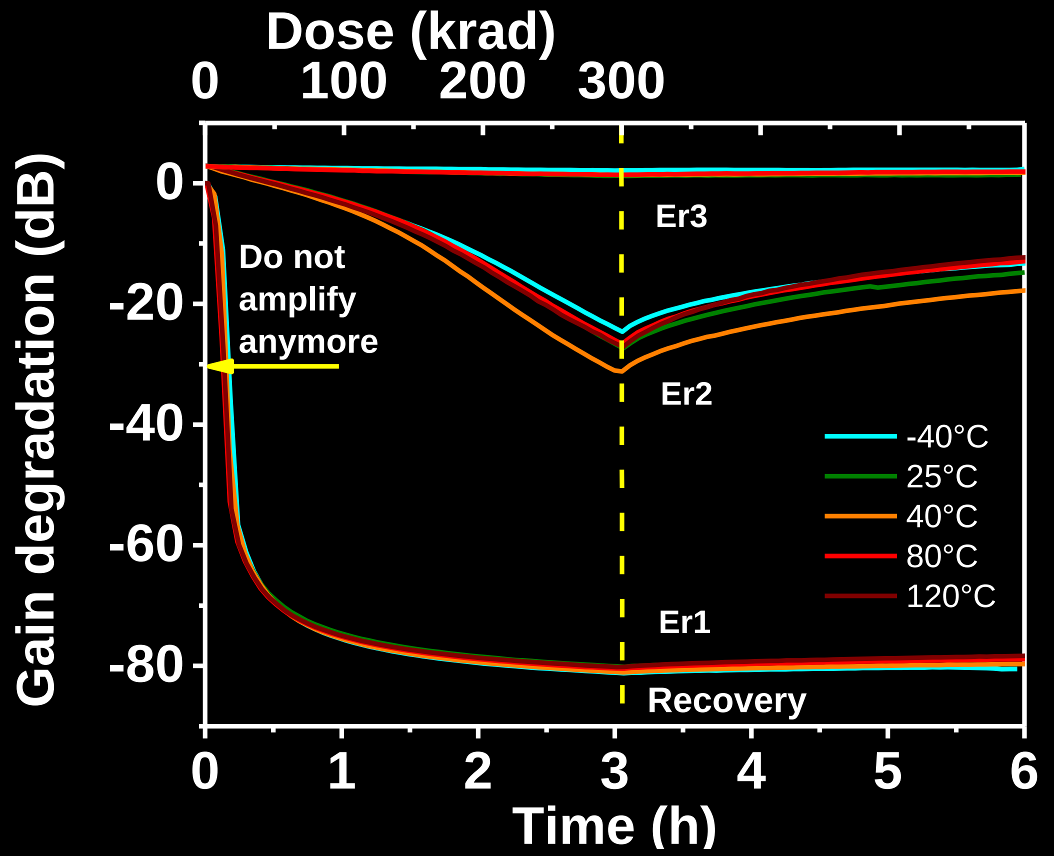


And on Rare-Earth doped Optical Amplifiers?

M. Aubry et al., "Combined Temperature and Radiation Effects on the Gain of Er- and Er–Yb-Doped Fiber Amplifiers," in IEEE Transactions on Nuclear Science, vol. 68, no. 5, pp. 793-800, May 2021

The coupled temperature – irradiation effects have been recently investigated for EDFA and EYDFAs

PhD thesis of Marine Aubry

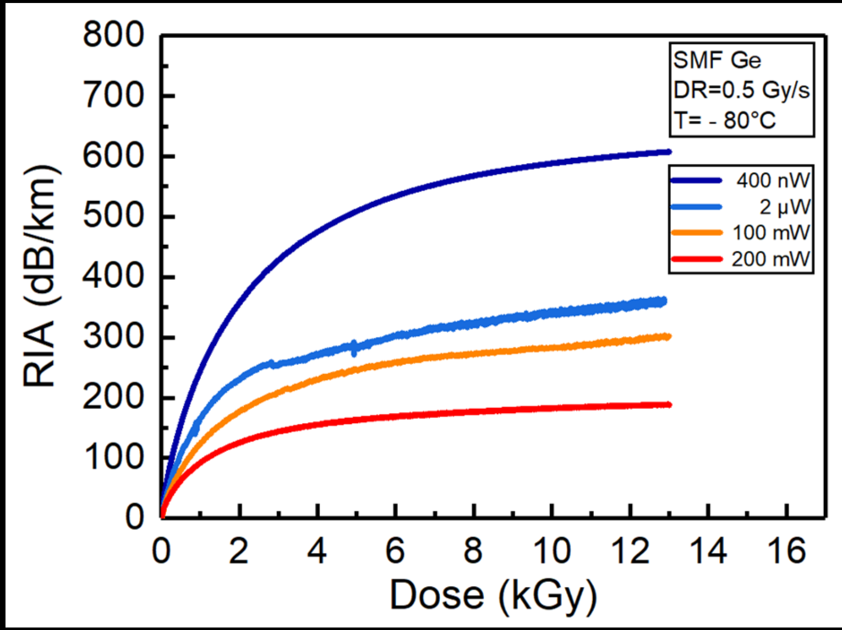


M. Aubry, IEEE TNS, 68(5), 2021

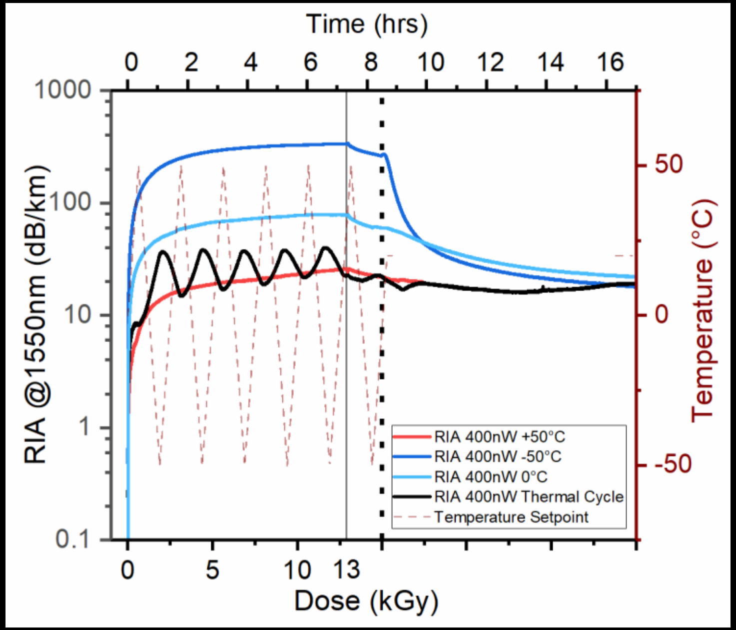
- The temperature impact on ON-EDFA or ON-EDFA gain degradation is minor (in the range of tested dose – dose rate & temperature)
- There is a noticeable impact on RIA at pump and signal wavelength but compensated at device levels
- Implementation of combined temperature and radiation effects in simulation codes in progress

Conclusions & Perspectives

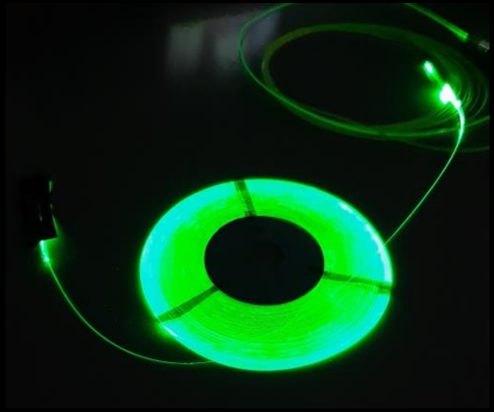
- Tirr has a strong impact on RIA growth and decay kinetics, depending on the fiber parameters and profile of use
- Dedicated irradiation tests are needed to assess the combined effects
- It is possible to consider even more complex profiles of us: temperature cycling or combined temperature, radiation, PB



M. Roche, RADECS 2002, in press IEEE TNS



M. Roche, NSREC 2023 to be presented



Thanks for your attention!

- This work has been done partially in the framework of the LabH6, joint research lab between UJM, CNRS, Exail