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Abstract

High temperature (> 700°C) measurements with wavelength-multiplexed Low Order Fiber Bragg Gratings (LO-FBGs) written using femtosecond lasers generally require the determination of transducer-specific calibration law in order to achieve sufficient accuracy. In this work, we propose to use High Order FBGs (HO-FBGs) to calibrate the waveguide response with respect to temperature (i.e. its thermal sensitivity). We show that the obtained unified calibration law can be subsequently applied to usual wavelength-multiplexed FBGs, in our case type III fs-FBGs, yielding measurement accuracies comparable to the reference thermocouple used for calibration between 25°C and 900°C.

LO-FBGs & HO-FBGs

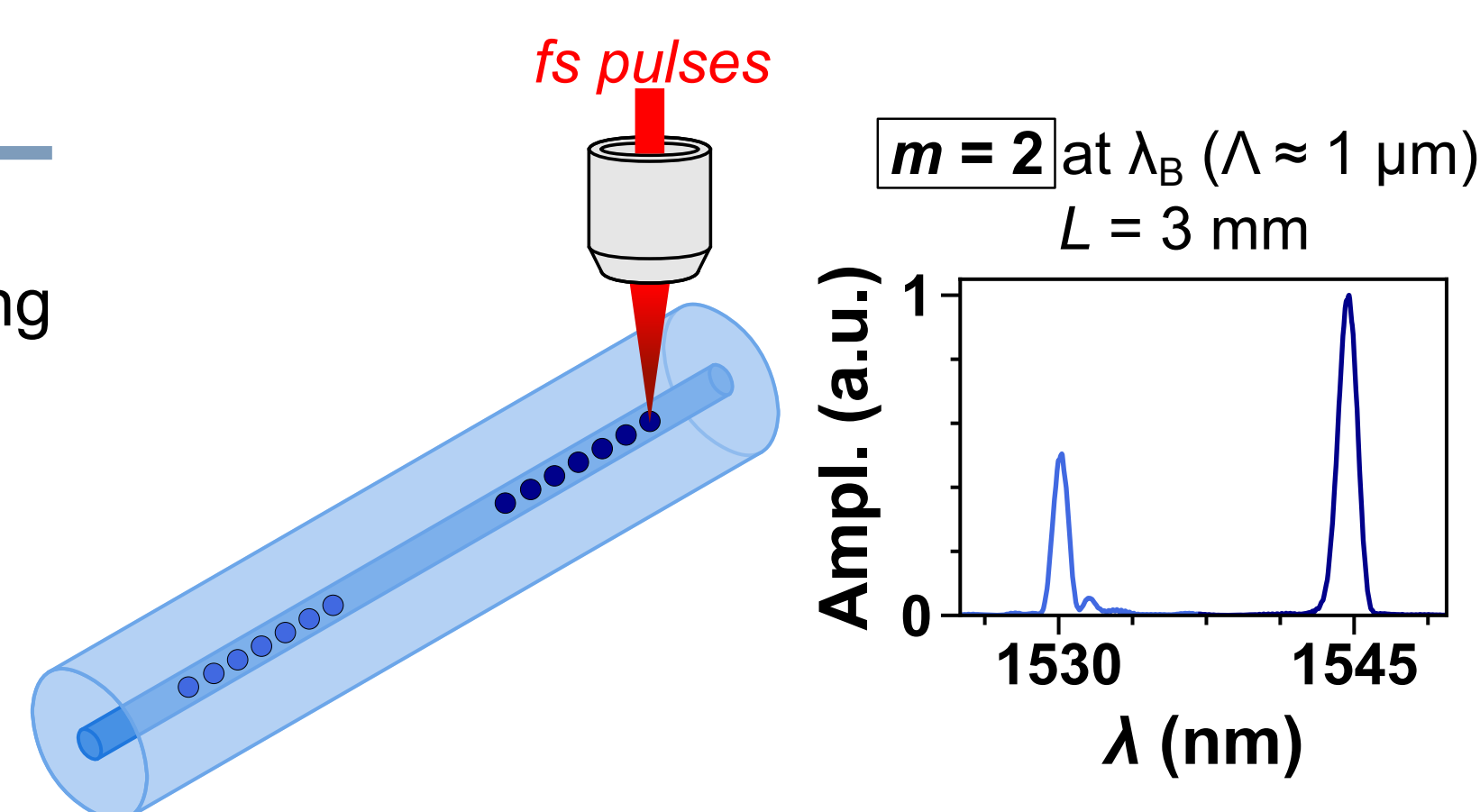
- ▶ Point-by-point written gratings using focused femtosecond laser pulses
- ▶ Writing of void microbubble arrays with high refractive index contrast
- ▶ High temperature resistant (> 1000°C)

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

Labels: Bragg peak wavelength, Harmonic order, Effective refractive index, Period

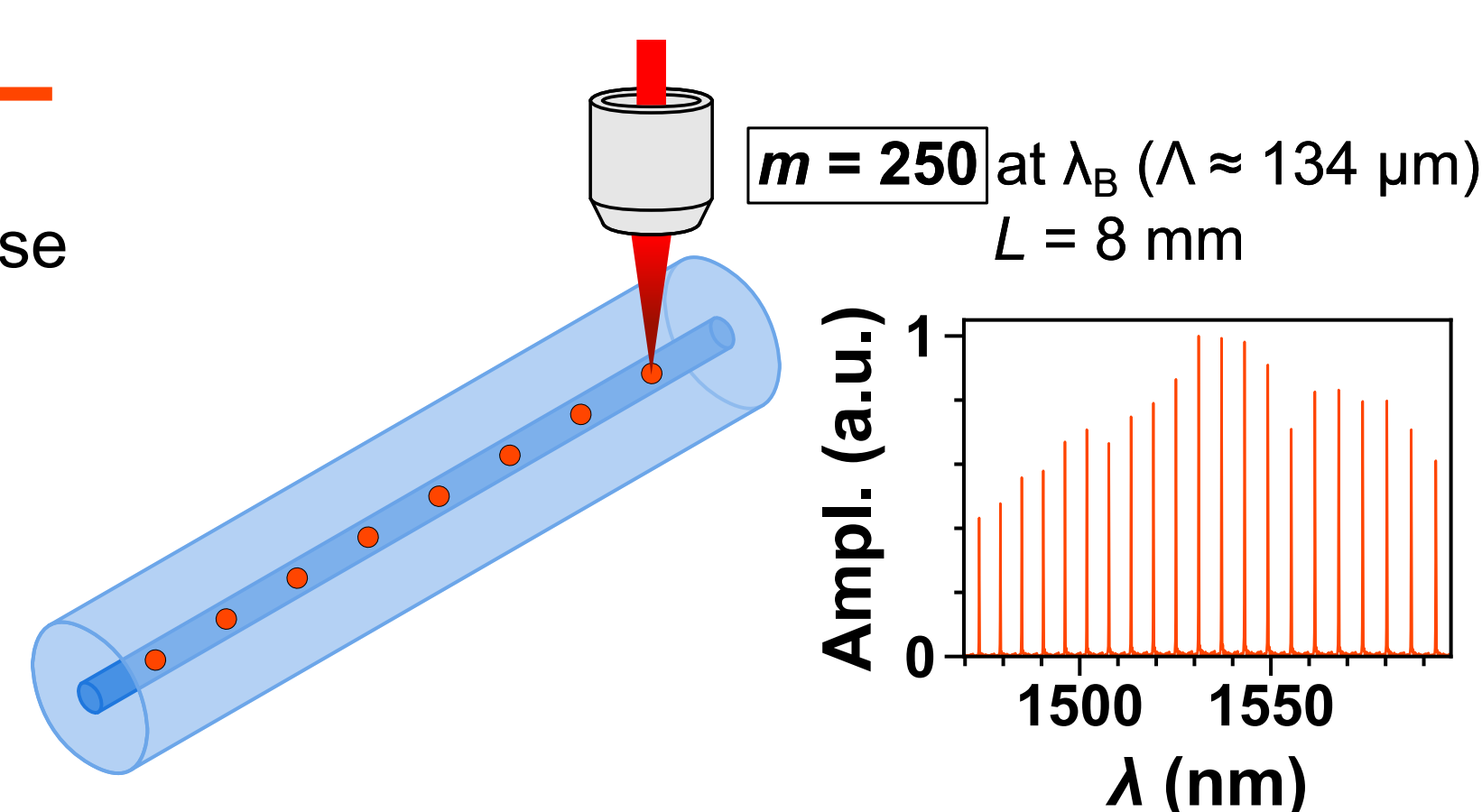
λ -multiplexed LO-FBGs

- ▶ Low-order ($m < 5$) resonances used for multipoint (quasi-distributed) sensing
- ▶ $dT/d\lambda_B = f(\lambda_B) \rightarrow$ generally requires transducer-specific calibration for accuracy at high temperatures



HO-FBGs

- ▶ Broadband response : Wavelength comb-like spectral response
- ▶ Allow for broadband calibration of FBG resonances with respect to temperature



Thermal sensitivity determination

- ▶ Derivation of the Bragg wavelength relationship vs. temperature
- ▶ Assuming constant chromatic dispersion, the thermal sensitivity $\beta(T)$ is obtained :

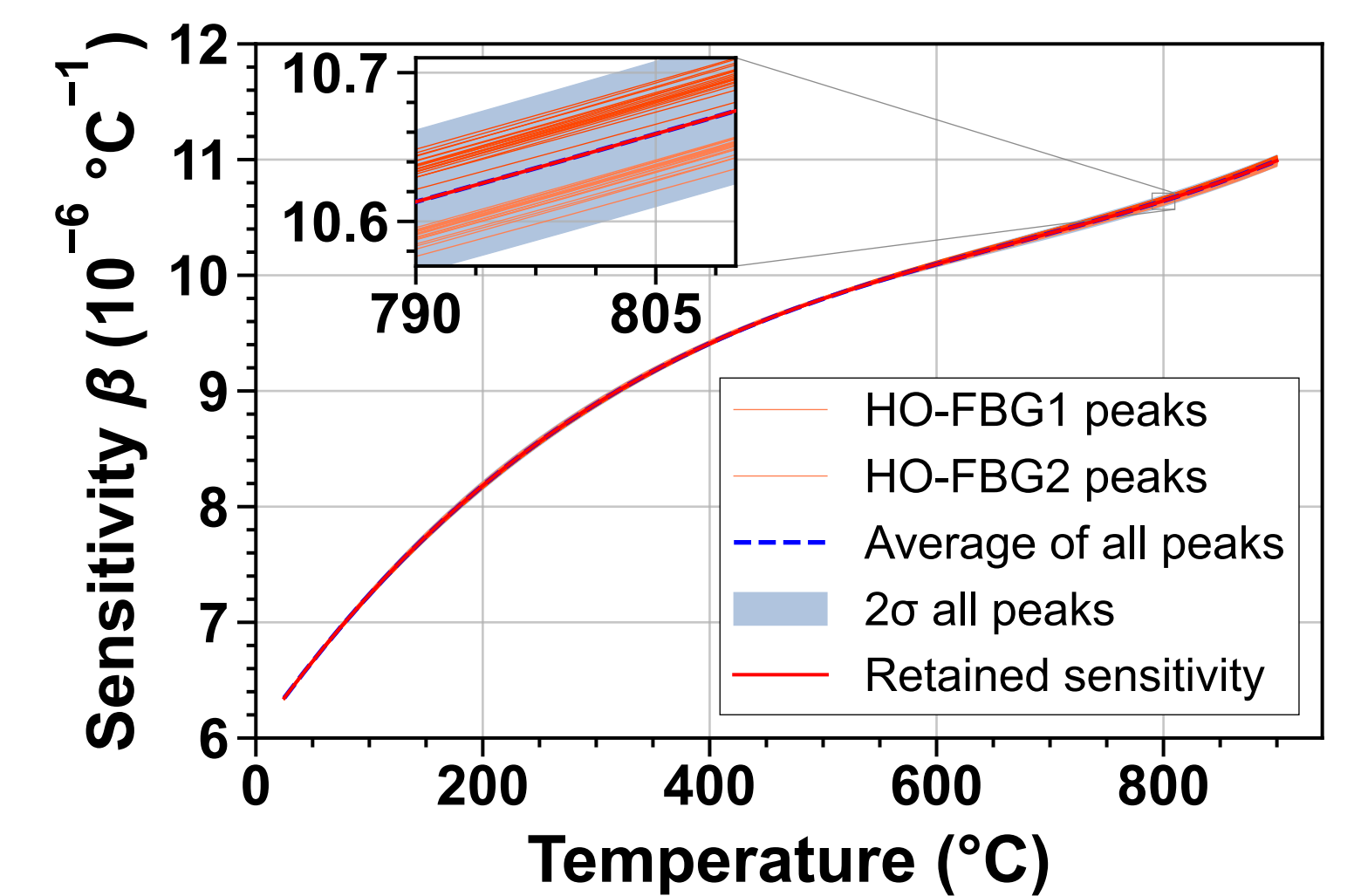
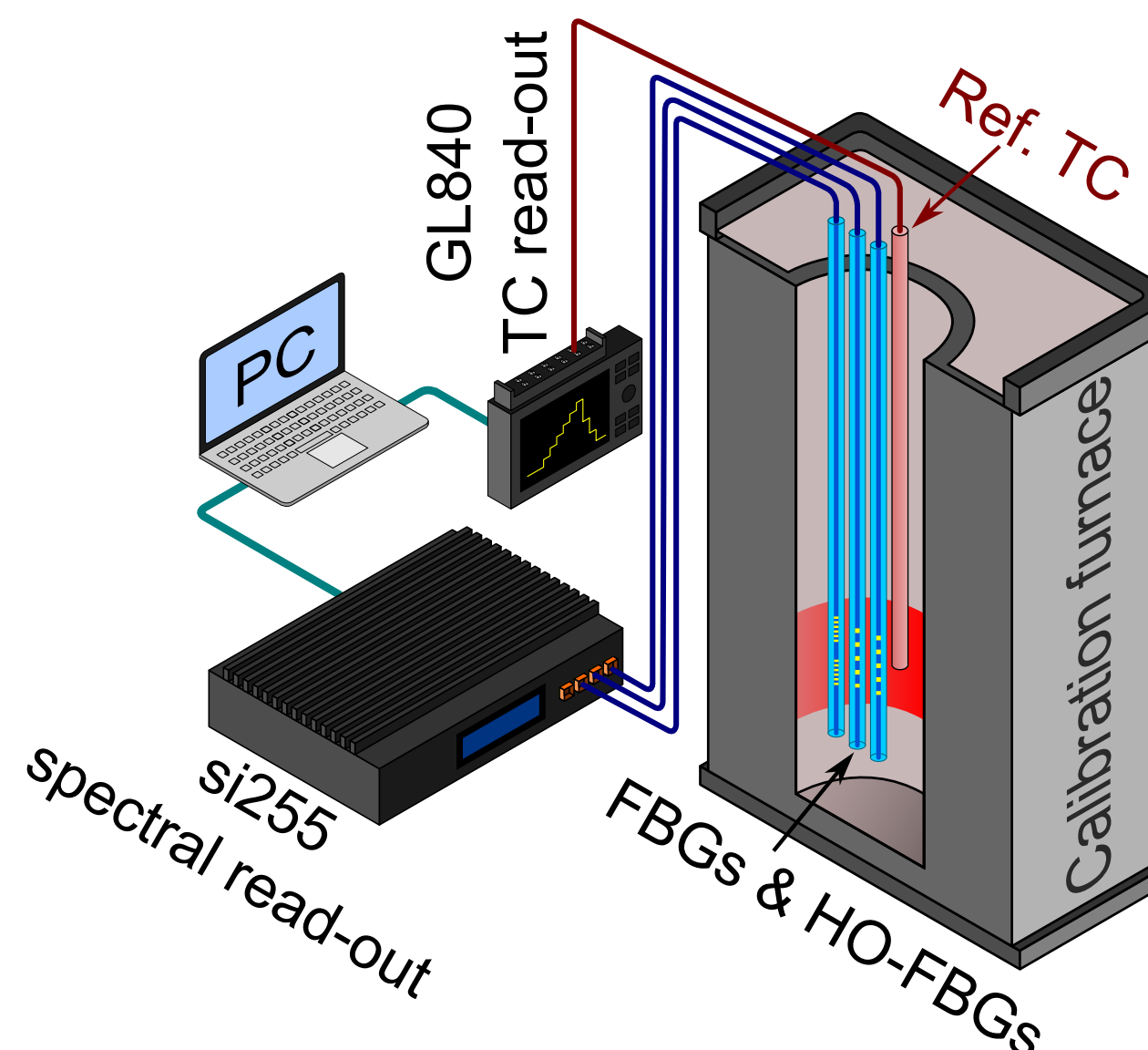
$$\frac{1}{\lambda_B(T)} \frac{d\lambda_B(T)}{dT} = \frac{1}{n_{\text{eff}}(T)} \frac{dn_{\text{eff}}(T)}{dT} + \frac{1}{\Lambda(T)} \frac{d\Lambda(T)}{dT} = \alpha(T) + \xi(T) = \beta(T)$$

intrinsic thermal sensitivity

Considering large temperature variation, its integration yields:

$$\int_{\lambda(T_0)}^{\lambda(T_1)} \frac{d\lambda_B}{\lambda_B(T)} = \ln \left(\frac{\lambda(T_1)}{\lambda(T_0)} \right) = \int_{T_0}^{T_1} \beta(T) dT$$

- ▶ Assuming $\beta(T)$ a polynomial function, it can be determined by deriving the integrated wavelength ratio $\ln[\lambda(T_1)/\lambda(T_0)]$ with respect to temperature.
- ▶ Calibration procedure with 2 HO-FBGs ($m = 250$ at 1550 nm):
 - 7 temperature steps (25°C → 900°C)
 - Derivation of $\beta(T)$ for each HO-FBG peak
 - Determination of global $\beta(T)$ law by averaging the polynomial coefficients



Temperature measurement accuracy using λ -mux FBGs and the intrinsic thermal sensitivity

- ▶ 3 thermal cycles ranging 25°C → 900°C
- ▶ Same thermal history as HO-FBGs used for calibration
- ▶ Reference point for temperature estimation kept constant

Inputs

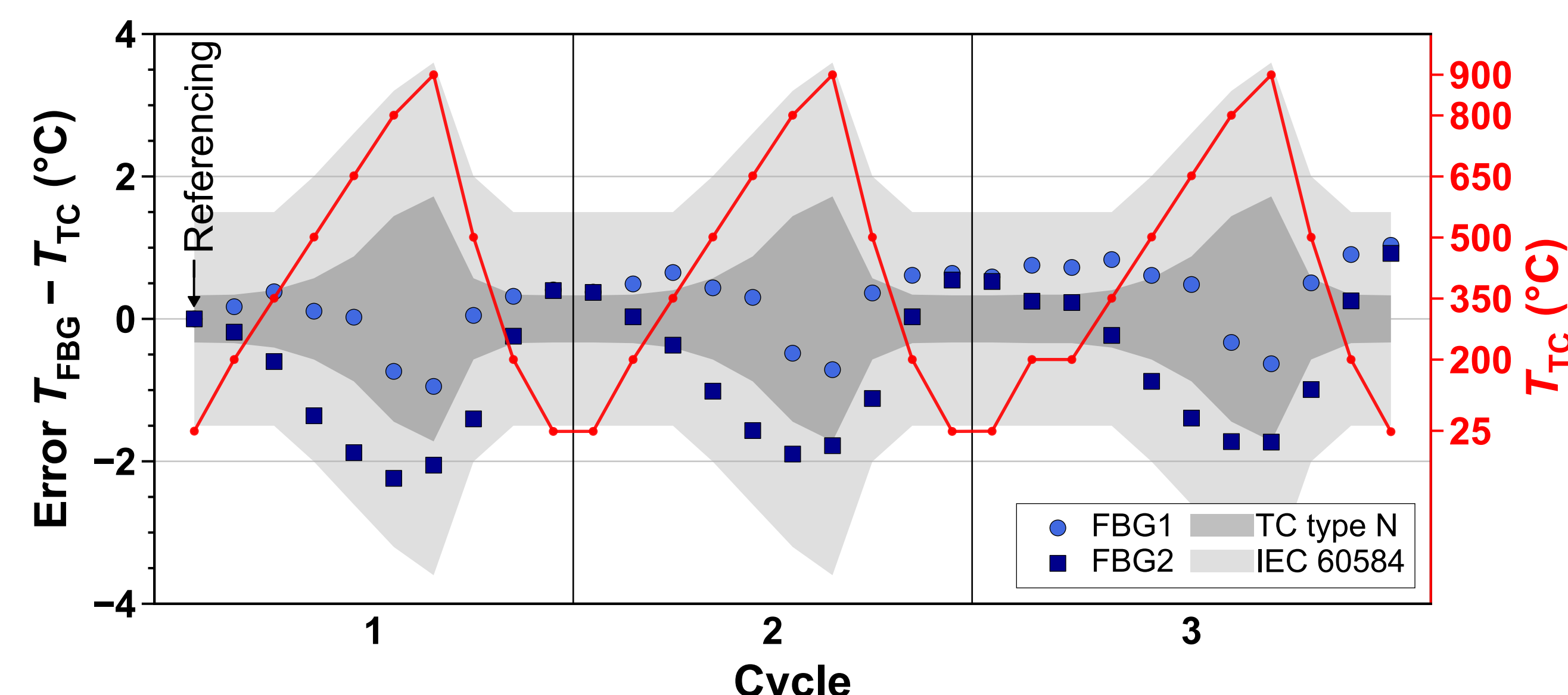
$$\text{Calib. } \beta(T) = \sum_{i=0}^{N=3} b_i T^i$$

$$\text{Ref. point } (T_0, \lambda_B(T_0))$$

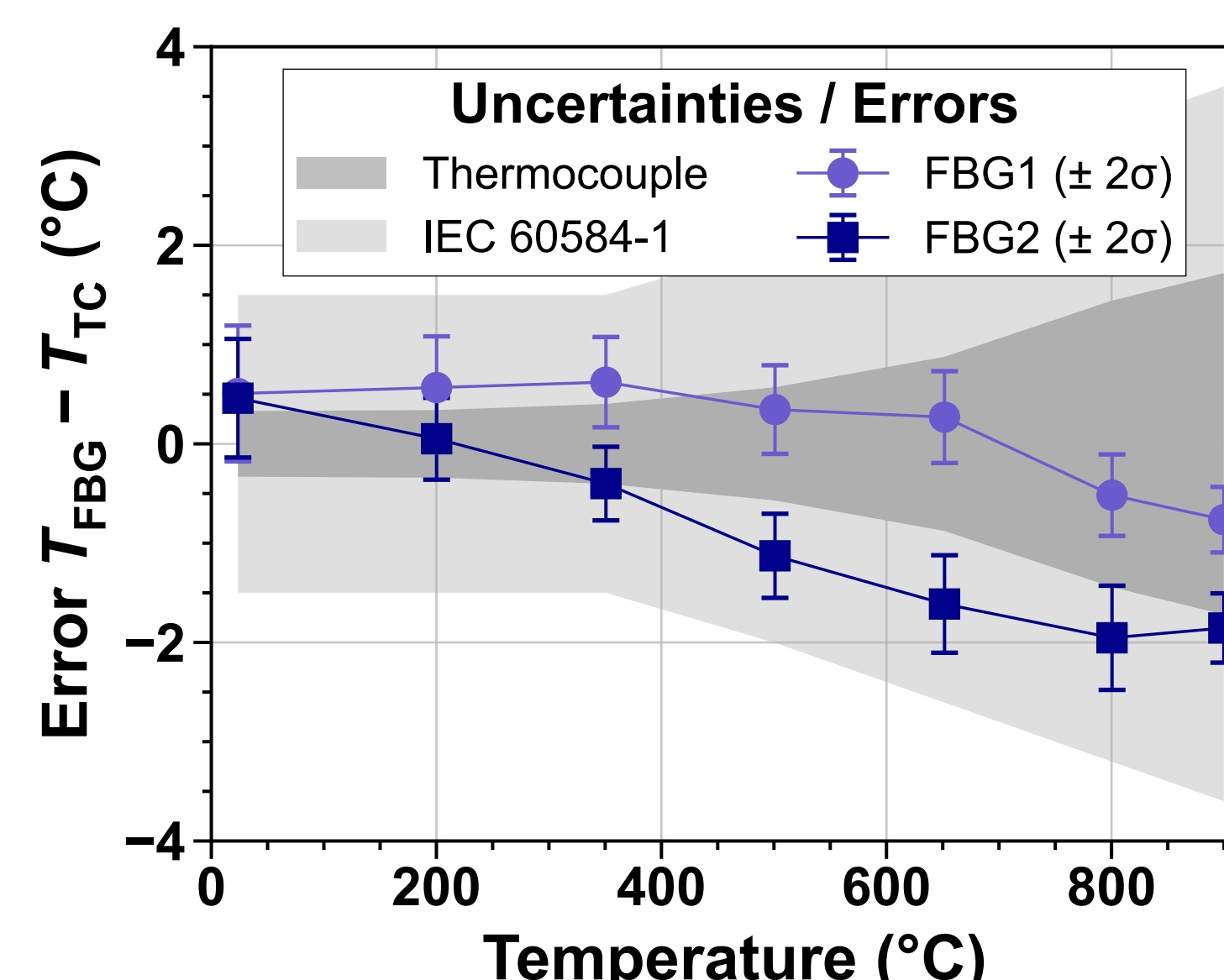
$$\text{Read-out } \lambda_B(T_1)$$

T_1 can be determined by solving:

$$\sum_{i=0}^N \frac{b_i}{i+1} (T_1^{i+1} - T_0^{i+1}) = \ln \left(\frac{\lambda_B(T_1)}{\lambda_B(T_0)} \right)$$



Temperature error evolution on three consecutive cycles (same reference point, same sensitivity law)



Temperature error averaged for each step temperature

- ▶ T_{error} slightly differs for FBG1 & FBG2 → Manufacturing variability
- ▶ Accuracy preserved for 3 cycles without re-referencing transducers
- ▶ Accuracy compliant with standard for a type N class 1 TC (comparable to ref. TC)

Conclusions

- ▶ The proposed approach allow to calibrate the thermal response of point-by-point written fs-FBGs using a component with a broadband comb-like spectral response – the HO-FBG – which presents the same behavior as wavelength-multiplexed LO-FBGs used for long range multipoint sensing.
- ▶ We show that the temperature determination through the integration of the sensitivity function allows to reach measurement accuracies comparable to a type N thermocouple.
- ▶ This method is applicable to multiplexed LO-FBGs, and the used of the HO-FBGs allowed to highlight the existence of a material-dependent calibration law, which is dependent of the material composition, manufacturing parameters and annealing strategy.

More about this approach and measurement performance:

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