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Exploiting complex light transmission in multimode optical fibre for distributed sensing

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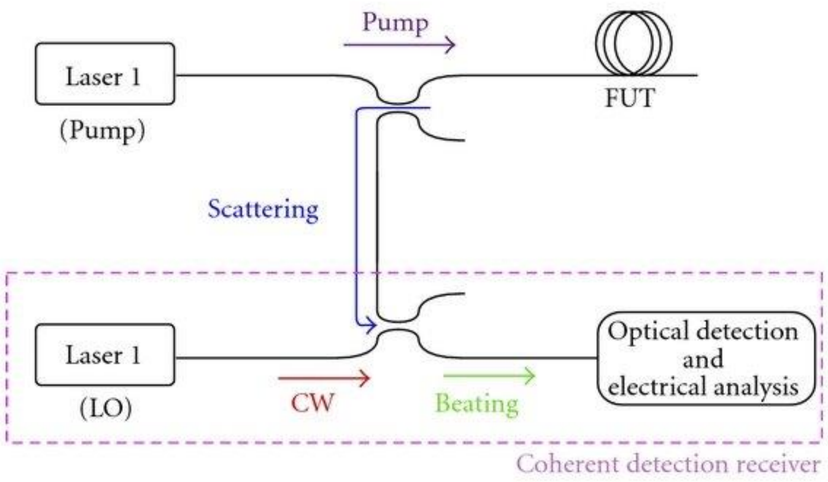
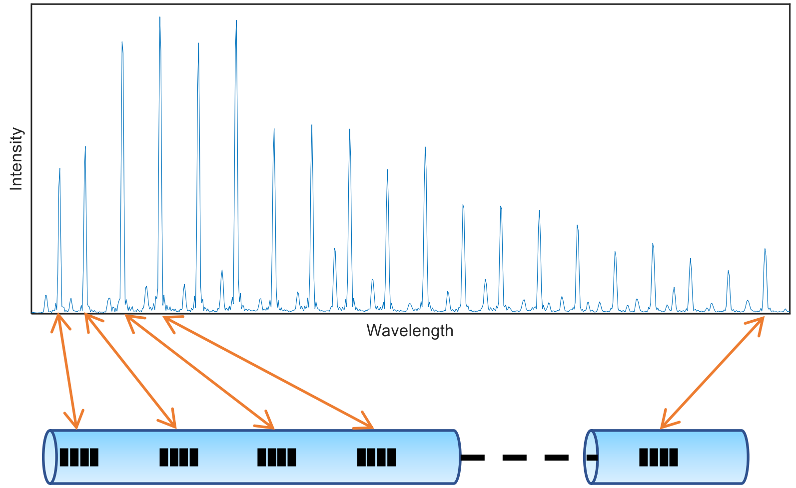
Distributed optical fibre sensing

Scattering-based sensing



Resonance-based sensing



- Interrogate light scattered from Brillouin, Raman and Rayleight scattering
- Scattered wavelength intensity spectrum is sensitive to environment
- Truly distributed – spatial information decoded in time domain

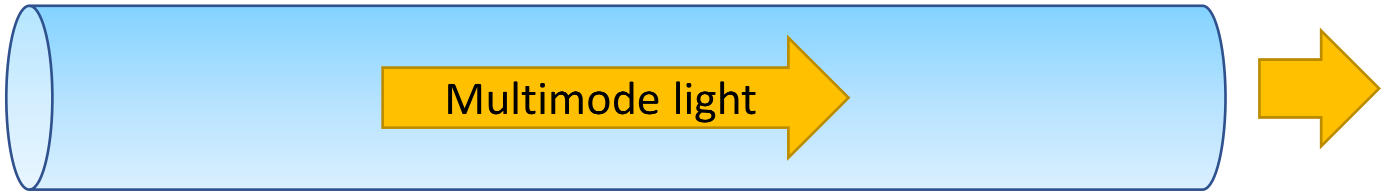
- Interrogate light reflected from resonant structures such as Bragg gratings or Fabry-Perot interferometers
- Resonant wavelength is sensitive to environment
- Distributed sensing achieved through multiplexing of single-point sensors, spatial information decoded in wavelength domain

Issues with standard distributed fibre sensing methods

- Scattering-based sensing
  - Spatial resolution limited by time resolution of interrogation equipment
  - Often limited to a spatial resolution of metres
- Resonance-based sensing
  - Not truly distributed – can only sense discrete points spatially
  - Limited by bandwidth of interrogator
  - Useful information about the complex multimode light transmission process is lost
  - Expensive and time-consuming fabrication process

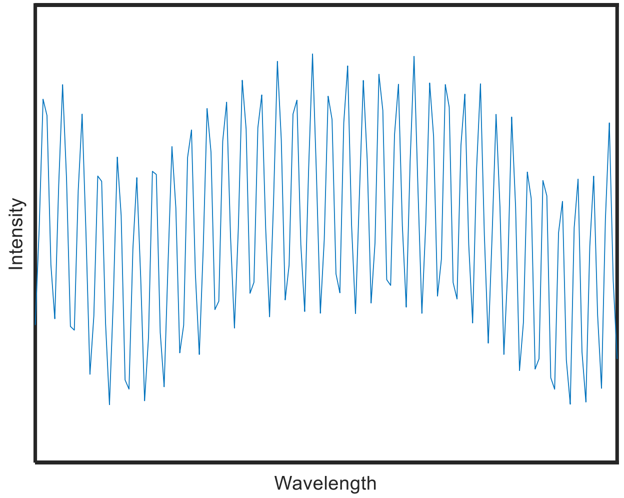
How to overcome these limitations?

Sensing with the raw spectrum from an unaltered multimode fibre



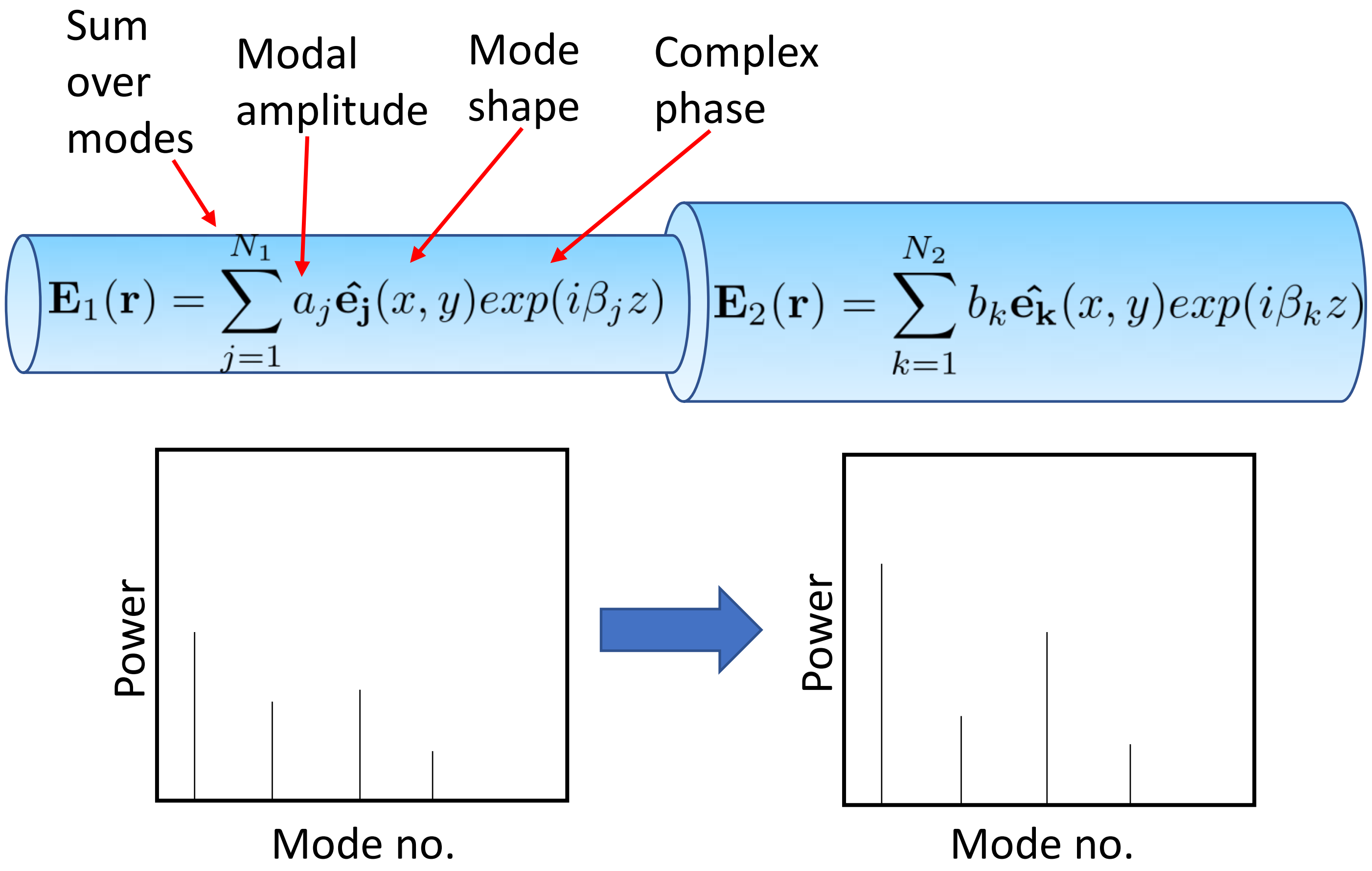
No resonance-producing structures – **Use the full wavelength spectrum and capture the entire MMF transmission process. No need for FBG fabrication.**

Sense using a wavelength intensity spectrum – **No longer limited in the time domain**



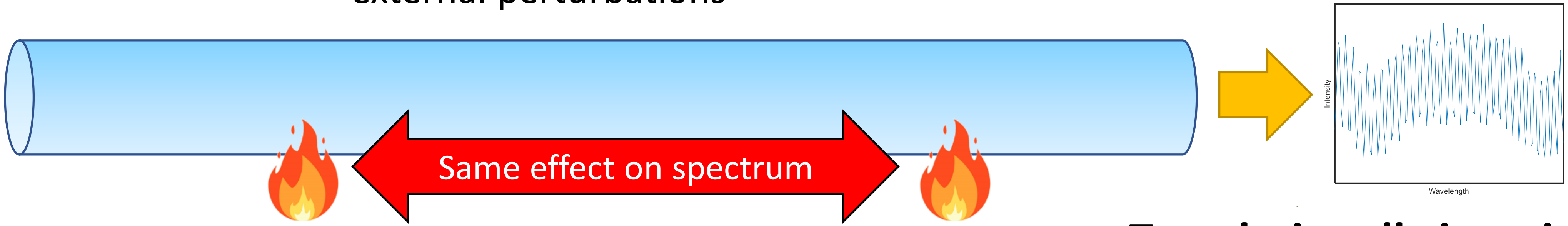
MMF light transmission and mode mixing

- Given fibre has an associated set of modal solutions
- Electric field depends on the modal power distribution and relative phases between modes
- Mode mixing – power redistributed between different sets of modal solutions
- **OPLs and hence relative phases are highly sensitive to fibre perturbations**



Decoding distributed sensing information in a wavelength spectrum

- **Perfectly translationally invariant fibre**
- No mode mixing in the absence of any external perturbations

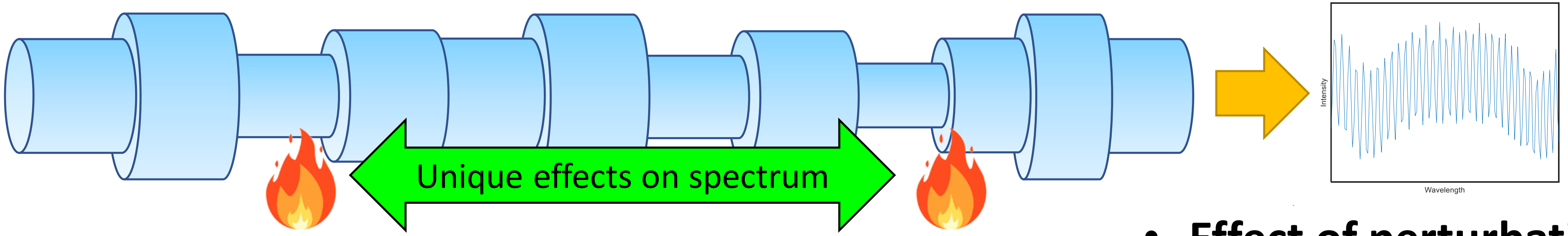


- External perturbation - Δn
- Modal power redistribution and ΔOPL

Translationally invariant fibre => spatially independent effect on spectrum

Decoding distributed sensing information in a wavelength spectrum

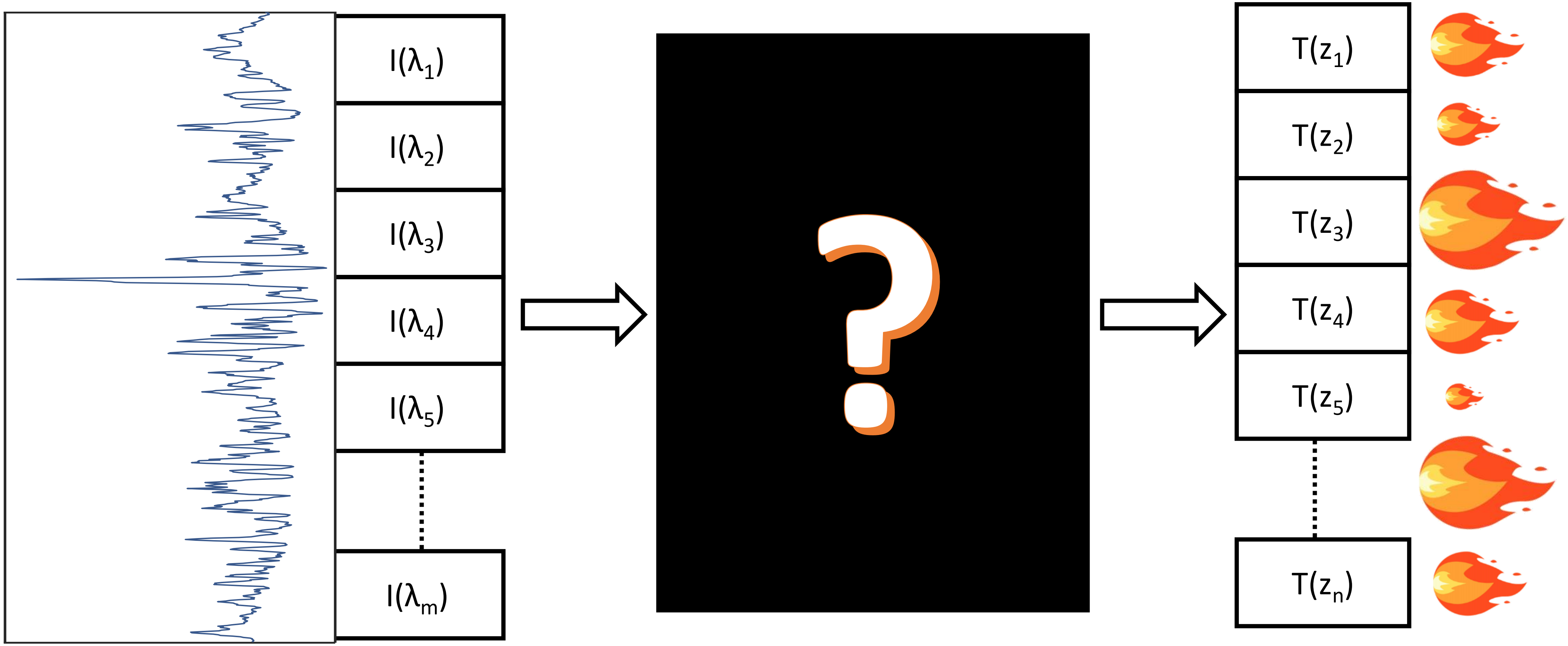
- **Fibre with translational variance**
- Inherent mode mixing along its length



- External perturbation - Δn
- Modal power redistribution and ΔOPL

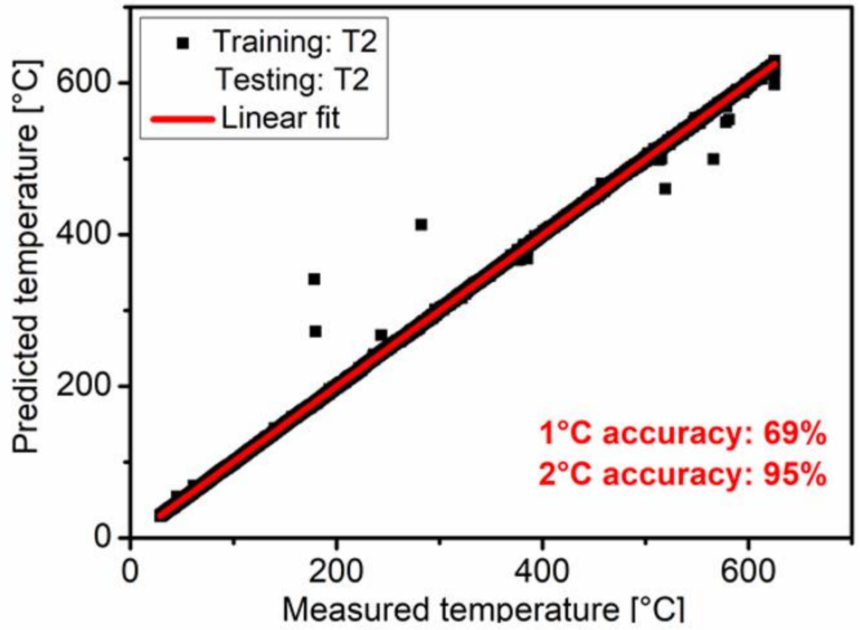
- **Effect of perturbation on wavelength spectrum now spatially dependent**

Map between wavelength spectrum and distributed sensing information

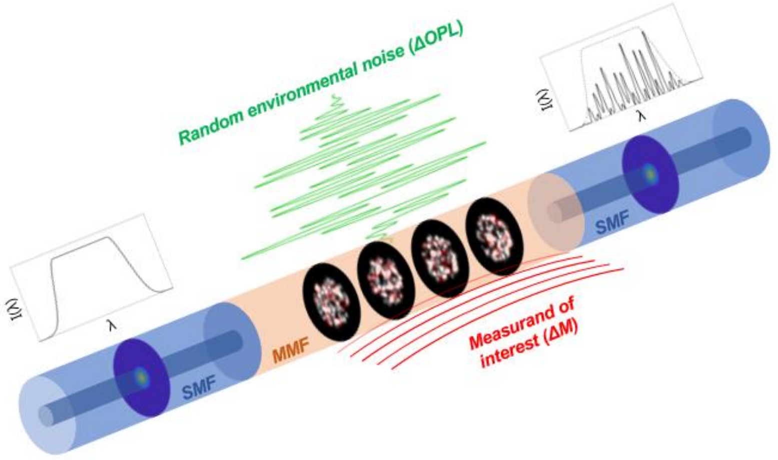


Deep learning for single-point regression sensing

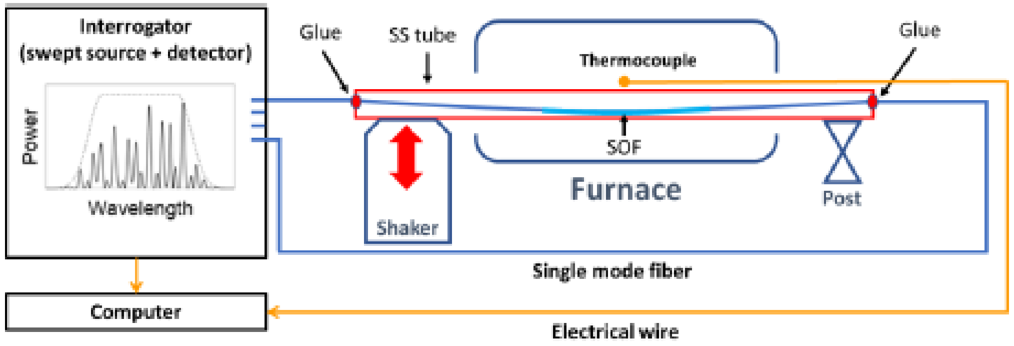
Nguyen, L.V. et al., “Sensing in the presence of strong noise by deep learning of dynamic multimode fiber interference”, 2021



Temperature predictions from the deep neural network

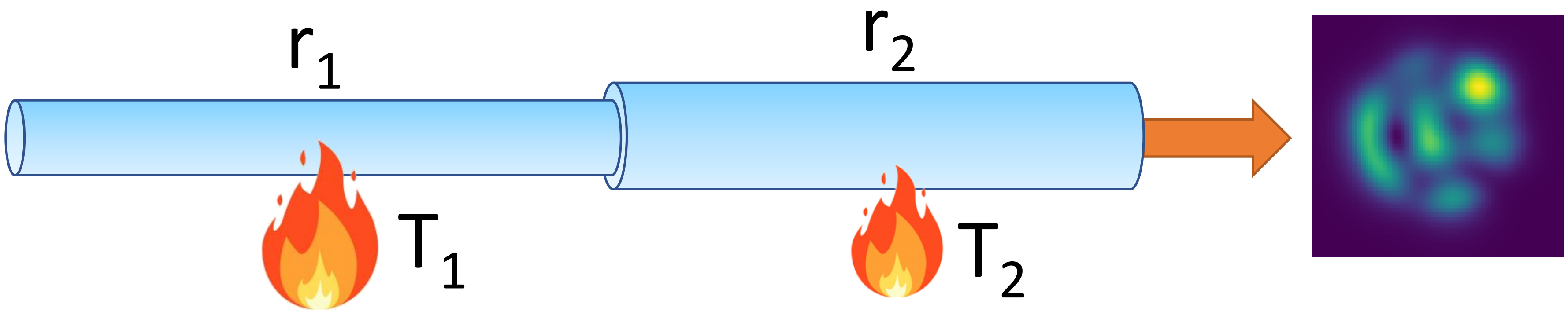


Multimode fibre wavelength spectrum concept



Experimental setup and data collection

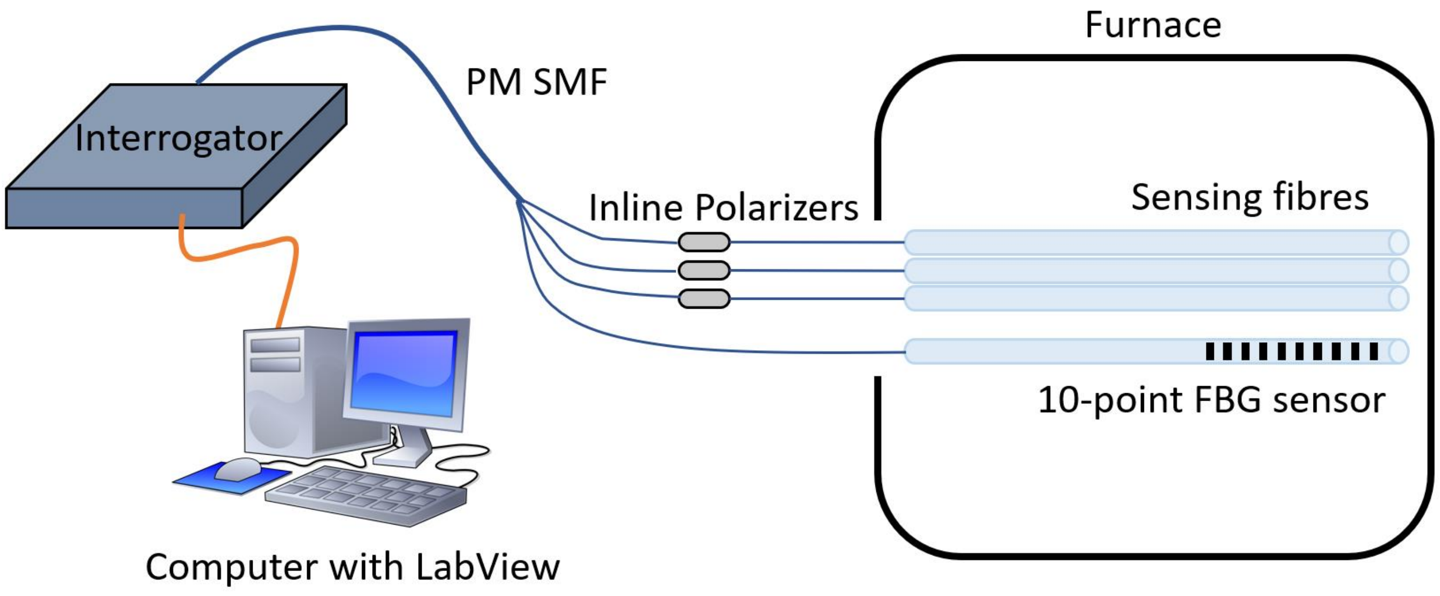
Mode mixing and distributed fibre sensing

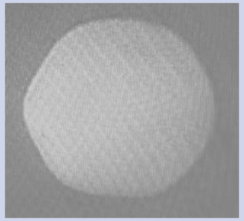
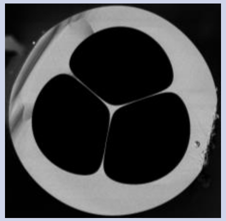
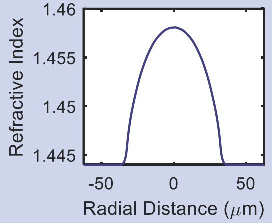


Lowest training loss after 250 epochs (MSE)	$r_2 = 4\mu m$	$r_2 = 6\mu m$
$r_1 = 4\mu m$	2991.44	13.16
$r_1 = 6\mu m$	34.65	942.08

Experiment

- Collect large amount of wavelength spectra and associated temperature distributions
- Train deep neural network to predict temperature distributions from spectra



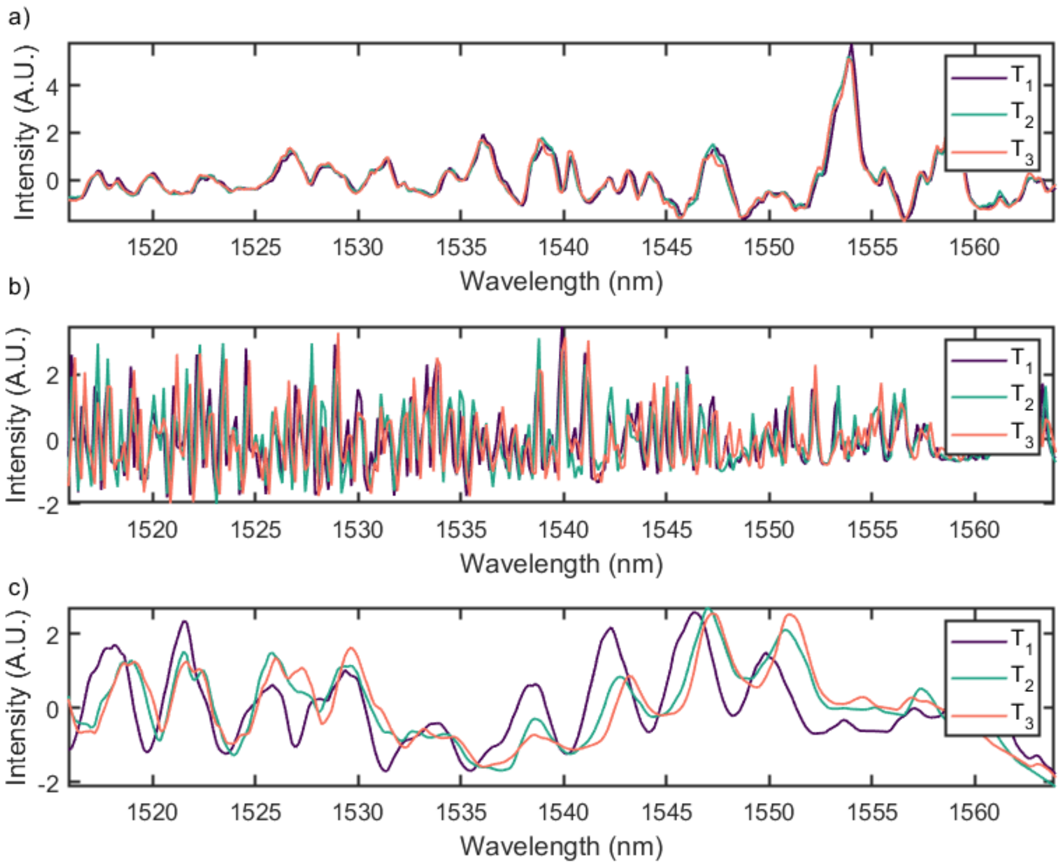
Fibre	Sapphire optical fibre	Suspended-core fibre	Graded-index fibre
Cross-section/refractive index profile			
NA	1.46	0.2	0.2
Core diameter	70 µm	7 µm	50 µm
Est. no. of modes	20,000	200	200
Translational invariance	Poor	Good	Good

Example spectra – room temperature repeatability

Sapphire

SCF

GRIN

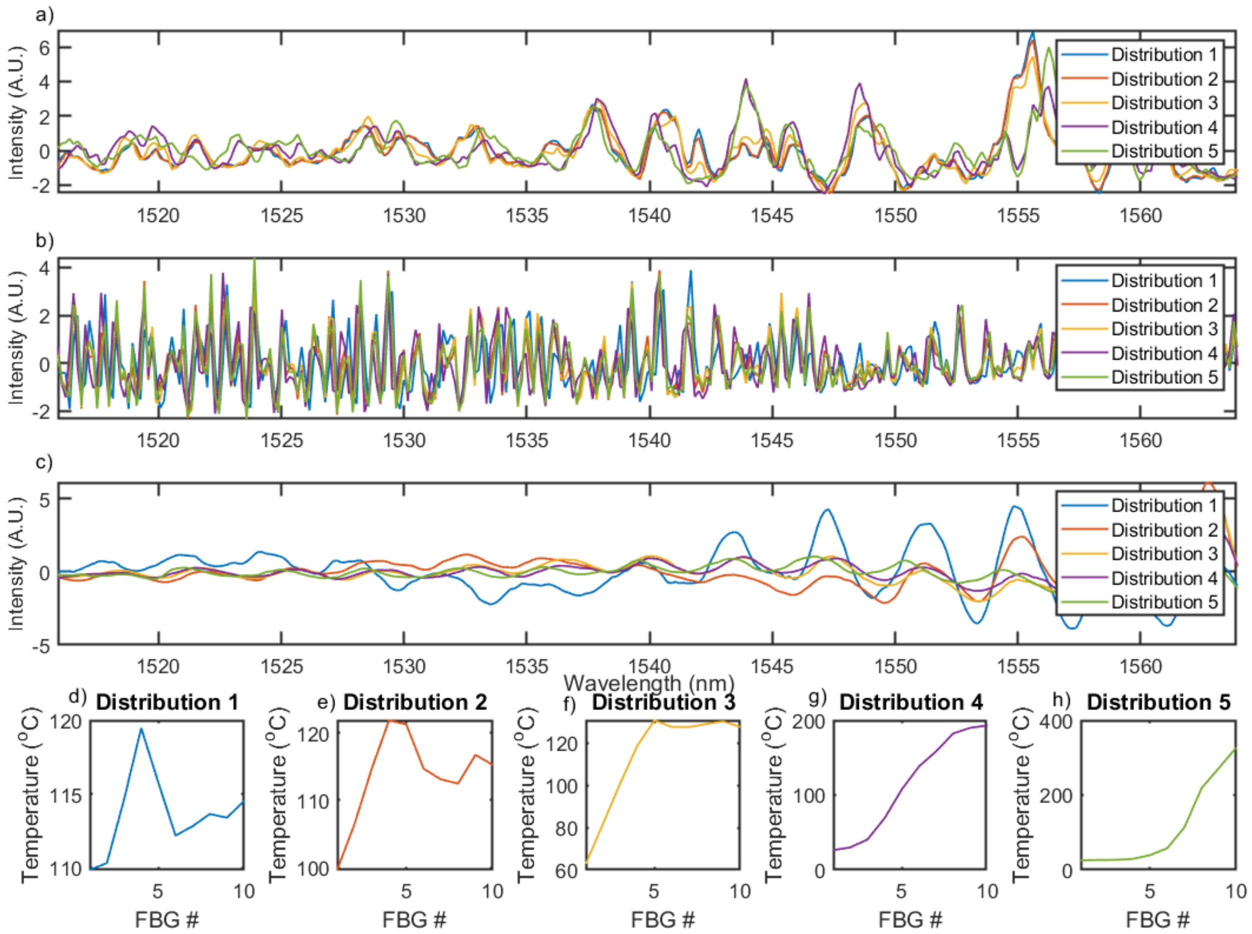


Example spectra – response to various temperature distributions

Sapphire

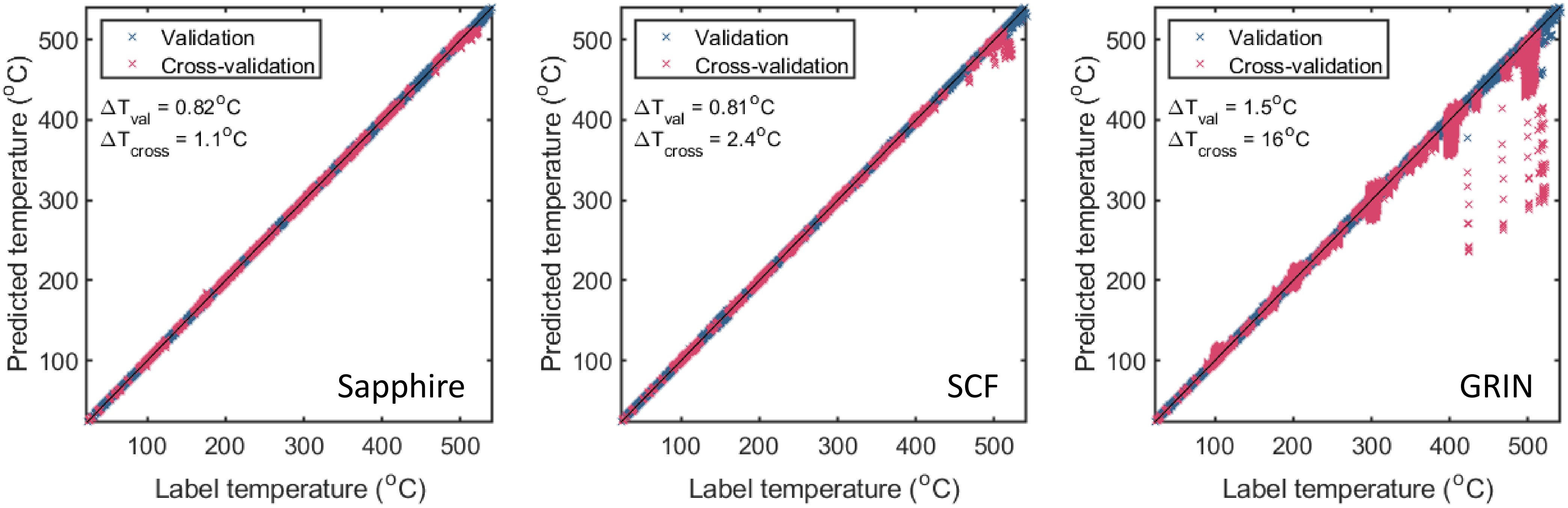
SCF

GRIN



Deep neural network predictions

- Dataset:
  - 59,364 spectra used for training, 4,165 for testing and 4,117 for cross-validation
- Cross-validation: temperature ranges removed from dataset completely prior to shuffling and training – to test generalisation capabilities of models



Conclusion/future work

- First example of a regression deep neural network trained for distributed fibre sensing
- Fibre sensing in the wavelength domain with plain, unaltered fibre
- Theoretical and numerical evidence relating fibre properties to DNN performance
- Next: experiment involving more refined, localised heating of sensing fibres
- End goal question: **is it possible to take a regular fibre, and increase its distributed sensing capabilities by inducing mode mixing along its length?**