Time-resolved fibre optic distributed temperature sensing with CMOS SPAD arrays

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1. Introduction

Time-resolved fibre optic distributed temperature sensing maps out the temperature profile along the length of an optical fibre using time of photon travel to determine location. A benefit of using an optical fibre as a temperature sensor is that the optical fibre can replace multiple individual sensors [1]. Additionally, the flexibility and size of the optical fibre enables access to otherwise inaccessible environments such as mountain snowpacks or under lakes [2].

Here we exploit an array of silicon based single photon detectors, enabling rapid parallel photon counting, to demonstrate fast distributed temperature measurement.

2. Experimental set-up

The temperature profile of the optical fibre is obtained by sending a laser pulse down the fibre. Inside the fibre, Raman (Stokes and anti-Stokes) scattering will occur and backscatter towards the single photon detector. The arrival time of the backscattered photons is used to determine the position of the Raman scattering inside the fibre. At each scattering position the ratio of the Stokes and anti-Stokes is used to map out the temperature profile of the fibre.

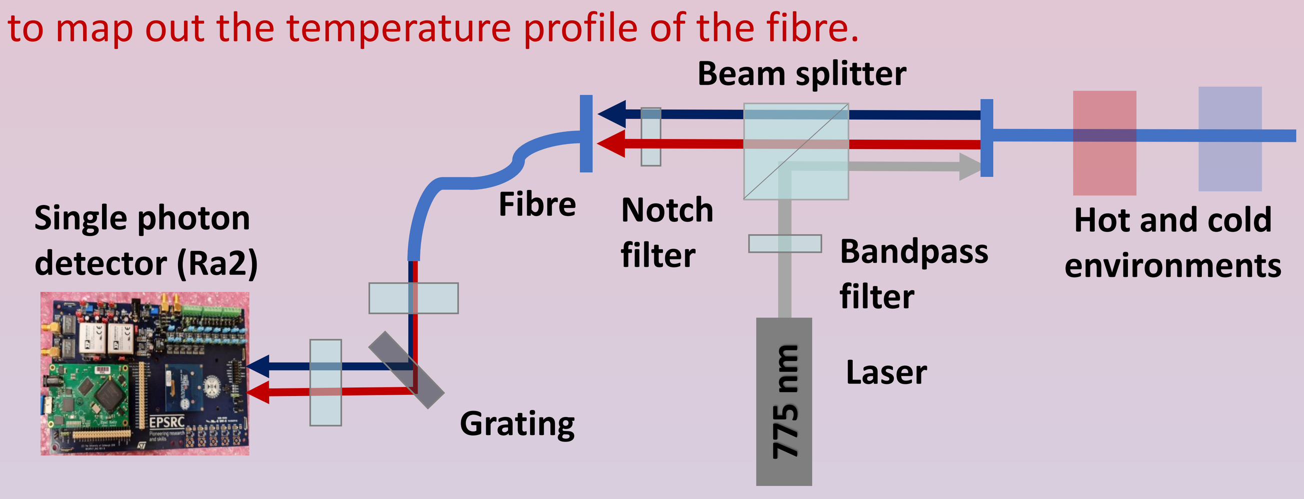

Fig. 1 Time-resolved distributed temperature sensing experimental set-up

3. Time-resolved distributed temperature sensing

The arrival time of the backscattered photons is converted to length along the fibre to obtain the different scattering intensities in different sections. The intensity of Raman scattering is affected by temperature. In these figures time is reversed: scattering at the end of the fibre happens at earlier time bins than scattering at the start of the fibre.

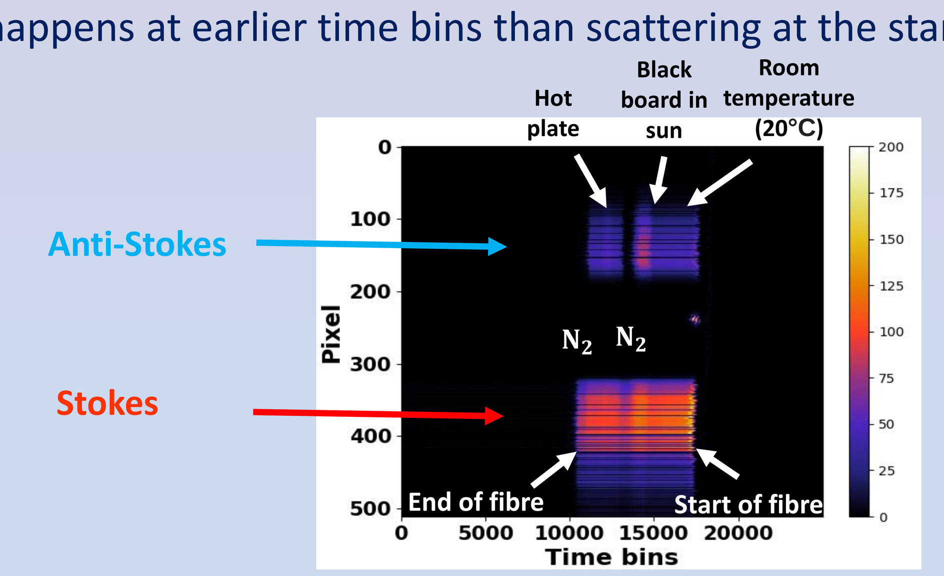

Fig. 2 Time-resolved distributed temperature sensing

4. Raman scattering

Raman scattering is the inelastic scattering of photons in a medium. Stokes scattering occurs when the incident photon excites an atom in the ground state which returns to a vibrational state whilst emitting a red shifted photon. Anti-Stokes scattering occurs when a photon excites a particle in a vibrational state which returns to the ground state by releasing a blue-shifted photon.

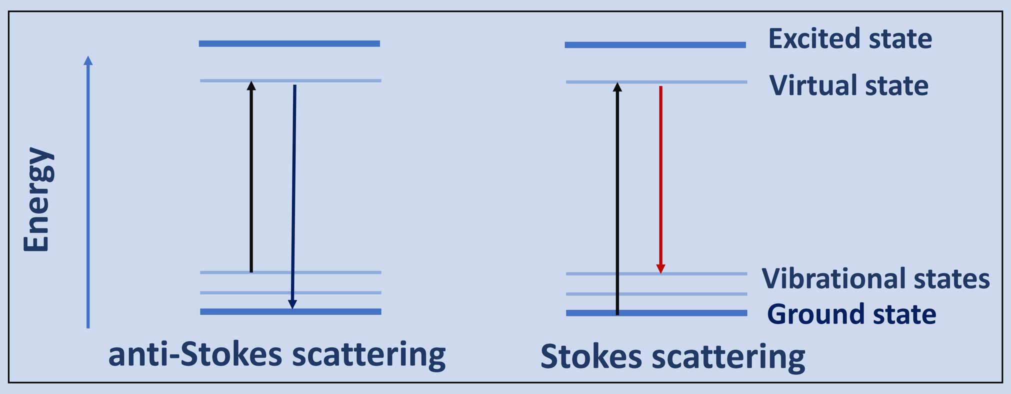

Fig. 3 Stokes and anti-Stokes scattering

The intensity of the Stokes or anti-Stokes scattering depends on the population of the initial states of the surrounding material. The probability of a particle being in a given state is described by the Boltzmann distribution. The Boltzmann distribution is temperature dependant therefore Stokes and anti-Stokes scattering is also temperature dependant.

5. Temperature of surrounding environment

The temperature dependence of Stokes and anti-Stokes scattering can be used to determine the temperature of the surrounding environment using the following equation

$$T = \frac{\hbar\Omega}{k_b} \frac{1}{ln\left(\frac{I_S}{I_{AS}}\right) - ln(C)}$$

Ω = Frequency detuning between laser and Stokes/anti-Stokes

C = Calibration constant

I_S = Intensity Stokes

I_{AS} = Intensity anti-Stokes

6. Calibration constant and frequency detuning

$$T = \frac{\hbar\boldsymbol{\Omega}}{k_b} \frac{1}{ln\left(\frac{I_S}{I_{AS}}\right) - ln(C)}$$

Ω is a range of values, however only Ω=7.8 THz is used in the temperature equation.

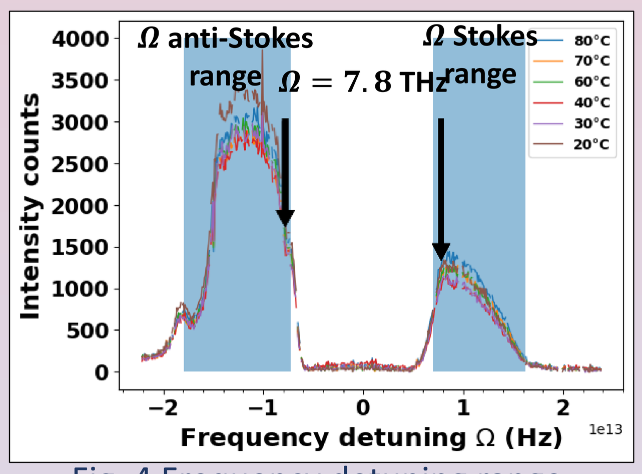

Fig. 4 Frequency detuning range

$$T = \frac{\hbar\Omega}{k_b} \frac{1}{ln\left(\frac{I_S}{I_{AS}}\right) - ln(\boldsymbol{C})}$$

C is obtained from a section of the fibre at a known temperature (e.g. 293K).

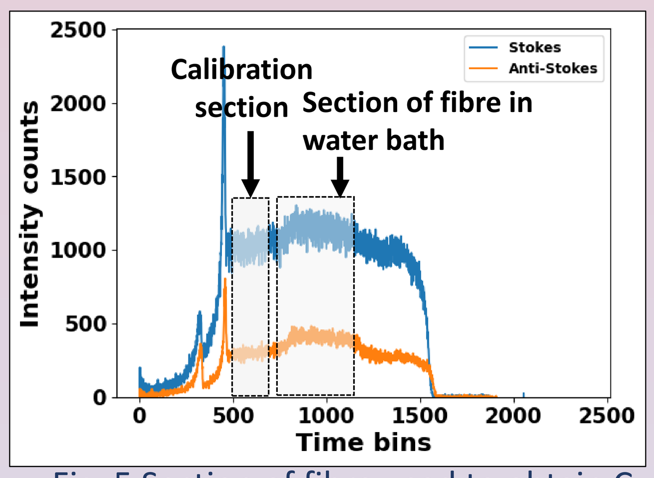

Fig. 5 Section of fibre used to obtain C

7. Results with a 5 m fibre

The optical fibre was placed in a water bath at varying temperatures. A linear trend was found between the measured temperature and water temperature.

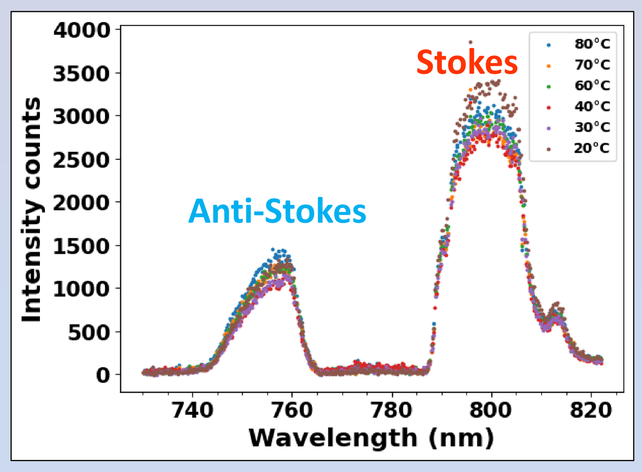

Fig. 6 Intensity of Raman scattering in an optical fibre placed in a water bath

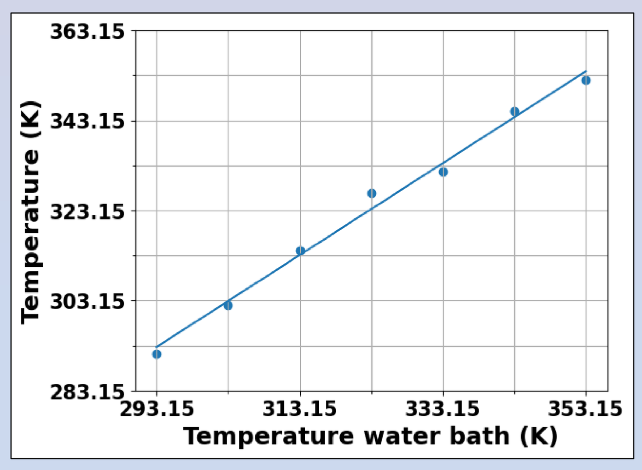

Fig. 7 Measured temperature vs temperature in water bath

8. Results with a 35 m fibre

Four different sections of the fibre were subjected to different conditions at the same time. The first section was placed on a hot plate, the second section was immersed in liquid nitrogen ($\mathbf{N_2}$), the third section was placed on a black board in the sun and the last section was immersed in liquid nitrogen.

The periodic noise in the original signal Fig. 8 was removed using a Fast Fourier Transform (FFT) filter to remove high frequency noise.

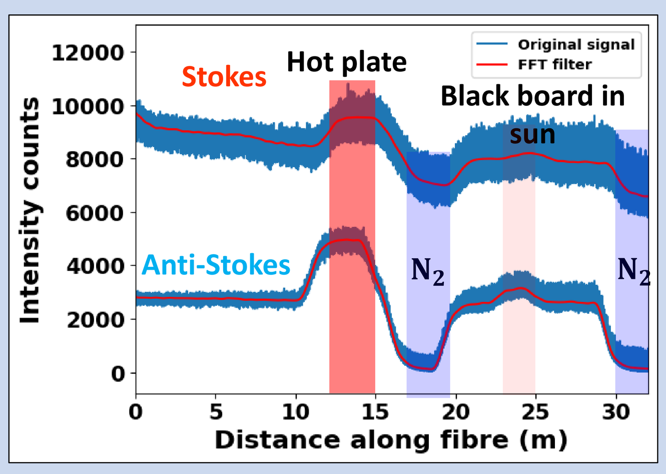

Fig. 8 Stokes and anti-Stokes scattering with and without the FFT filter

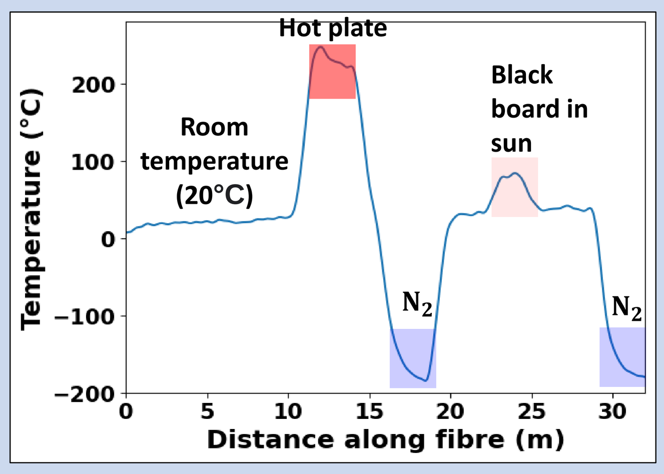

Fig. 9 Temperature versus position in fibre

9. Conclusion

Time-resolved fibre optic distributed temperature sensing uses Raman scattering to determine the temperature profile of an optical fibre. Here, rapid measurement is enabled due to >100 detectors measuring each of the Stokes and anti-Stokes bands in parallel. These detectors are expected to have a spatial resolution on the order of 10 cm and a temporal resolution on the order of seconds for 1°C accuracy. However, these limits are to be further investigated in the future.

Acknowledgments

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