Brillouin gain spectrum characterization in optical fibres from 1 to 1000 K

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The Brillouin frequency shift and linewidth were measured over the full temperature range in which the fibre experiences no structural damage, demonstrating that Brillouin sensing can be actually performed from 1 K to 1000 K.

We present here for the first time the characteristics of the Brillouin gain spectrum in optical fibres measured over the full practical temperature range, i.e. over 3 decades of absolute temperature from 1 K to 1000 K. Temperatures below 1 K are experienced only in very extreme experiments and small volumes making Brillouin distributed sensing mostly irrelevant, while temperatures over 1000 K result in irreversible structural changes within the optical fibre reducing drastically the glass transparency.

The linear increase of the Brillouin shift with temperature was noticed very early at standard temperatures, verified many times and has motivated to a large extent the development of many configurations of distributed temperature sensors, some of them being even commercially available. It turns out that this is not the full picture, as the linearity does not extend up to the physical limits of the optical fibres. The objective of this paper is to look closely at the temperature ranges where the linear behaviour is no longer observed, below and above the ambient temperature and to present the full picture of the Brillouin gain spectrum, with a special attention to thermal variations of the central frequency and of the linewidth.

Basically the Brillouin effect is a scattering of an incident lightwave by the acoustic phonons of a medium, the spectrum of the scattered light containing key information about the vibrational properties of the considered medium. Practically the centre of the Brillouin spectrum is directly proportional to the velocity of a vibration mode, while its linewidth is related to its characteristic damping time. In the quasi-one-dimensional geometry of single-mode optical fibres [1], the Brillouin spectrum of the backscattered light is by far dominated by the resonance peak corresponding to the fundamental longitudinal acoustic mode.

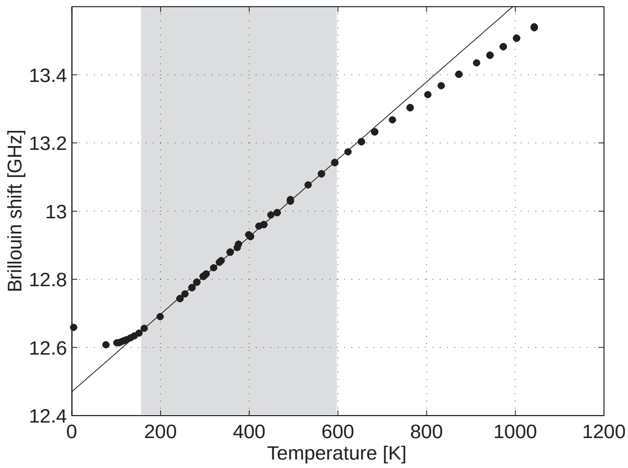

Fig. 1 Brillouin frequency shift measured at a wavelength of 1319nm over the full practical temperature range, in a standard fibre with a polyimide jacket. The shaded area represents the linear region that extends from -100 to 320 degC.

Fig. 1 shows the total picture of the change of the Brillouin frequency shift over the 1-1000K temperature range. The linear region extends over approximately half of the range and the behaviour at high temperature is not fundamentally different, the slope being only slightly reduced. In the low temperature range the dependence of the Brillouin shift on temperature is definitely more complex and it cannot be clearly seen on a linear scale graph. Fig. 2 shows on a logarithmic scale the compound re-scaled data of many measurements of the Brillouin frequency shift as a function of temperature, showing the more complex behaviour at cryogenic temperatures.

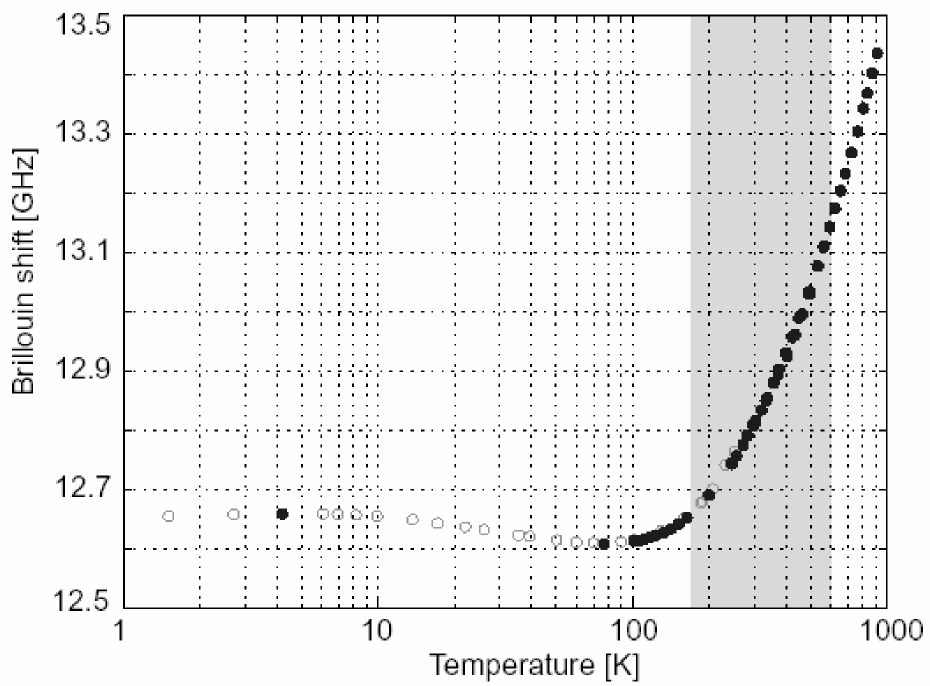

Fig. 2 Brillouin frequency shift over the full practical temperature range shown on a logarithmic temperature scale. The data were obtained from the measurements of 2 different fibres (black and white dots) and re-scaled to make the acoustic velocity match in the 2 fibres. The shaded area represents the linear region.

Experimental installations

The measurements were performed using the technique and devices reported in [2]. It is based on the sideband technique, in which the probe signal is generated using an electro-optic modulator operated at microwave frequencies. With such a technique a single laser source is needed and was in this case a ND:YAG laser operating at a wavelength of 1319nm. Such a source was chosen owing to its reduced linewidth of 1 kHz, making possible an accurate measurement of the Brillouin linewidth without extra-broadening due to the laser intrinsic spectral width. This aspect turned out to be critical at very low temperature where the Brillouin linewidth narrows drastically down to a few MHz. In this case the spectral width of a semiconductor laser would be comparable and bias the measurement, accordingly.

Covering the entire temperature range required many different facilities that are listed in Table 1. Unfortunately, different fibres had been tested in different installations for practical reasons and because the measurement campaign extended over a couple of years, so that a full set of data for a particular fibre over the full 1-1000K range is not available. But measurements were performed with very similar fibres and the curve shown in Fig. 2 could be obtained with a minor re-scaling of the acoustic velocity.

	Temperature range	**Location**
Oven 1	293-1000 K	EPFL
Oven 2	293-550 K	CERN
Refrigerator	243-293 K	EPFL
Liquid N_2 cryostat	77-200 K	CERN
Liquid He cryostat	1-150 K	CERN

Table 1 List of the different thermal facilities used to cover the full temperature range.

Low-temperature range

Most of the results for the cryogenic temperature range have been reported in a former publication [3], so that we present here some latest data obtained recently. Let just remind the main characteristics of the Brillouin frequency shift in this range: an absolute minimum is observed around 60 K, then there is a subsequent increase with decreasing temperature up to a maximum located at 6 K and a new decrease for still lower temperatures, as shown in Fig. 2. As for the linewidth, it exhibits a maximum in the 110 K range and a steady decrease down to an exceedingly low value (< 2 MHz) at a

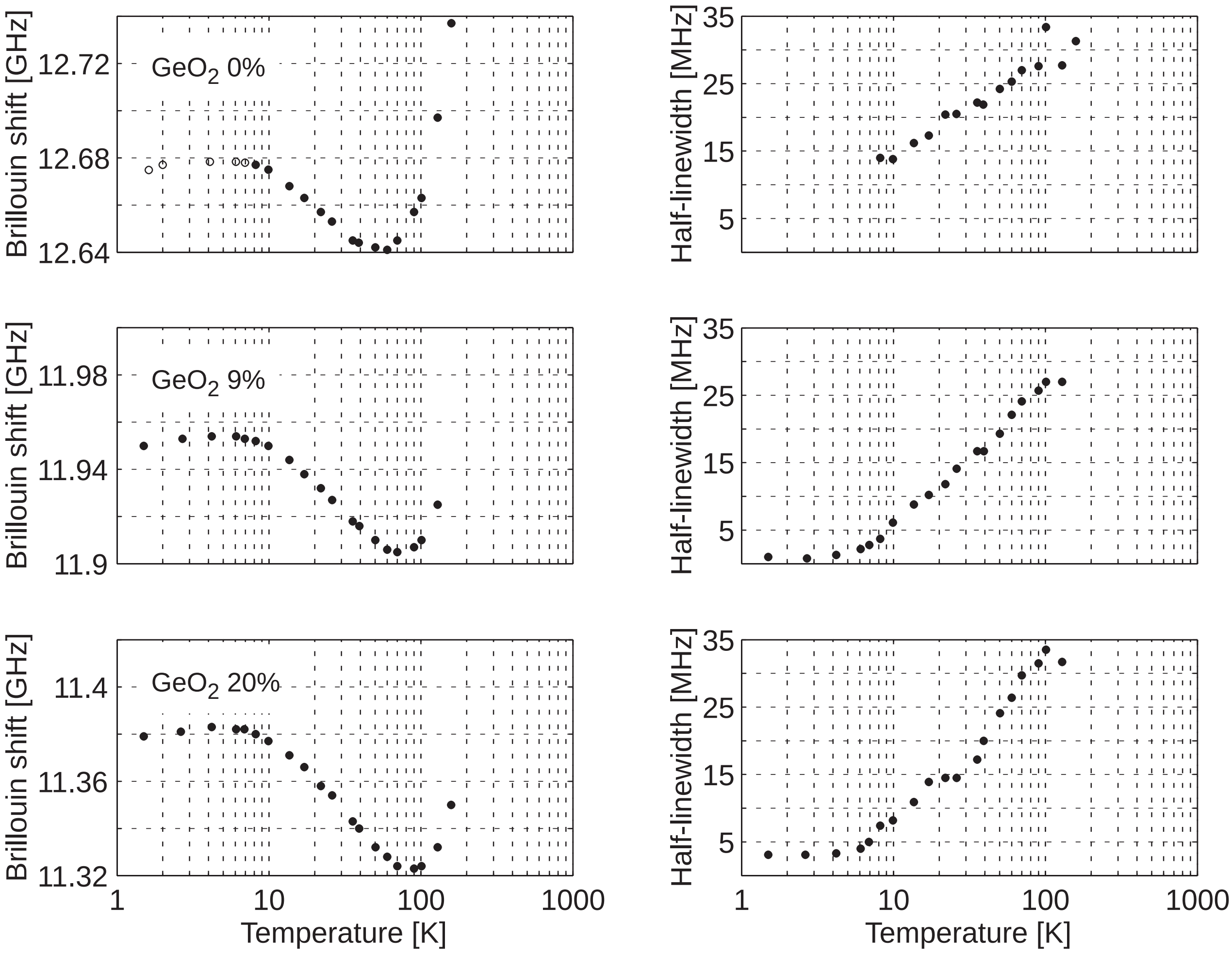

Fig. 3 Brillouin frequency shift and linewidth in the cryogenic temperature range for 3 different fibres, showing important differences in the core doping concentration. The most important variation is related to the absolute minimum position and depth. The linewidth of the pure silica core fibre could not be extracted for temperature below 10K, the Brillouin spectrum containing many peaks for this particular fibre.

few K. The linewidth seems to be fairly constant between 1 and 4-5 K.

Measurements were recently completed by testing 3 different fibres showing very different GeO_2 core doping concentration: 0% (pure silica core), 9% and 20%. The purpose of these measurements was to determine if the observed behaviour at cryogenic temperature is universal or dependent on the fibre guiding properties. Fig. 3 shows the Brillouin shift and linewidth for these 3 fibres.

The most important dependence is observed for the position and depth of the absolute minimum of the Brillouin frequency shift, moving from 60 K for 0% GeO_2 to 90 K for 20% GeO_2. This result agrees with the observation made in bulk materials, for which the minimum was measured to be at 70 K pure SiO_2 and 300 K in pure GeO_2. The shift of the minimum to higher temperature just reflects the increasing importance of GeO_2 in the compound glass material in the core.

High-temperature range

For the first time to our knowledge Brillouin gain spectrum characteristics have been measured in optical fibres up to the fibre structural damage temperature. Results are presented in Fig. 4 and Fig. 5 and show no surprising feature. The Brillouin frequency shift still increases monotonously, with a sudden change in the slope value. This may be simply explained by the combustion of the polyimide jacket that occurs exactly at the temperature of the slope change. It is well-known that the jacket has a non-negligible contribution on this slope value [4].

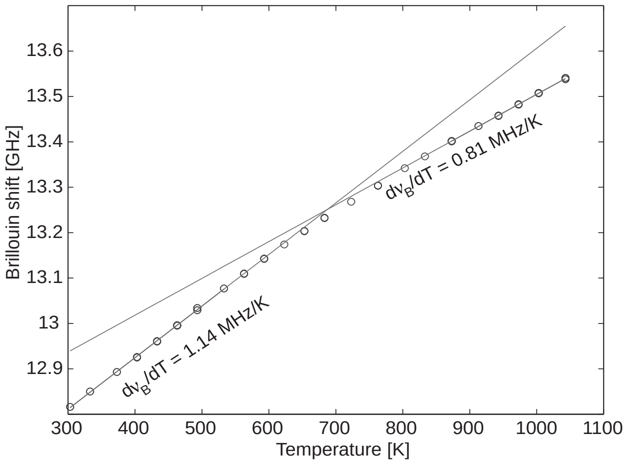

Fig. 4 Brillouin frequency shift for temperature above room temperature for a standard single mode fibre with polyimide primary jacket. The slope change is due to jacket destruction.

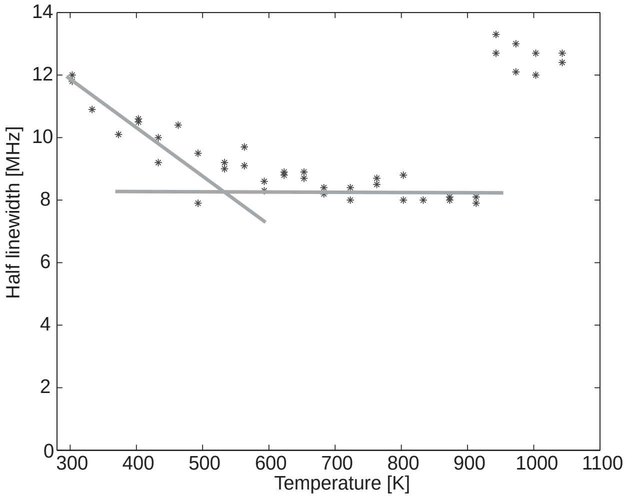

Fig. 5 Brillouin gain HWHM linewidth for temperature above room temperature (same fibre as Fig. 4). The step change above 900K is due to polycrystalline glass transition.

The behaviour of the linewidth brings up more comments. The steady decrease of the Brillouin linewidth observed at ambient temperature stops near 600 K to a value of 8 MHz HWHM. More surprising is the step increase of the linewidth slightly above 900 K: this is certainly due to a major change in the silica structure that moves from an amorphous to a polycrystalline state, resulting in a more lossy acoustic and optical propagation. This assumption is backed up by the observation that the linear loss in the fibre sample showed a significant change simultaneously and by the brittle mechanical behaviour of the fibre that led to its destruction and actually stopped the measurement slightly above 1000 K.

Conclusion

These characterisations demonstrate that stimulated Brillouin scattering is observed over the full temperature range in which a fibre experiences no structural damages, i.e. from 1 to 900 K. Lorentzian spectra are obtained over this full temperature range, except for the pure silica core fibre that shows multiple peaks below 8 K. Brillouin sensing can thus be used at any temperature, provided that the fibre remains structurally safe. Processing of data may be more complex at cryogenic temperature, the dependence in temperature being non monotonous, but ambiguous values may be properly discriminated using an estimation of the linewidth value.

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