Brillouin gain curve measurements in fibres at cryogenic temperatures

A. Fellay, S. Le Floch*, M. Facchini, L. Thévenaz, W. Scandale**, P. Robert

Swiss Federal Institute of Technology, Metrology Laboratory, CH-1015 Lausanne, Switzerland
**Institut Supérieur d'Electronique de Bretagne, 20 rue Cuirassé Bretagne, 29604 Brest, France*
***LHC/MMS, CERN, 1211 Geneva 23, Switzerland*

Corresponding author : alexandre.fellay@epfl.ch

Brillouin gain curves of a standard optical fibre have been measured down to 3 K. In comparison with their well-documented characteristics at room temperature, they show original and interesting features, namely non-monotonous variations of the central frequency shift and of the linewidth. These preliminary measurements indicate that Brillouin-based temperature sensors can advantageously be used in cryogenics with some adaptations.

Introduction

Brillouin spectrum analysis has long been considered as a powerful tool to get structural information about non-crystalline solids, among other physical systems. The Brillouin effect is essentially a scattering of an incident lightwave by the phonons of the medium, and the spectrum of the scattered light contains key information about the vibrational properties of this 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-unidimensional 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.

The dependence of this peak on various factors (temperature, strain, type or concentration of dopant…) has been intensively investigated over the past 12 years. The main motivation for these investigations is the possibility to build sensors using these dependencies. Some operational – and even commercially available – experimental configurations have been reported, that rely on spontaneous or stimulated Brillouin scattering to make distributed measurements of strain or temperature along the fibre for cable check and monitoring. In a fairly wide temperature range (-25°C - 80°C), the Brillouin shift, that is the frequency difference between the incident and the scattered lightwaves, increases linearly, with a slope coefficient around 1.36 MHz/°C at 1319 nm [2]. Over the same temperature range the resonance linewidth steadily decreases.

Surprisingly the low temperature domain has been much less studied, at least as far as the fibre optics community is concerned. But solid state physicists have shown, partly by Brillouin spectroscopy on bulk samples, that glasses under 200 K, far from simply extrapolating their room temperature properties, exhibit new and interesting features [3]. These give an invaluable insight into the physical, atomic-scale structure of the glass. However to the best of our knowledge, nobody ever installed optical fibres in a cryostat down to liquid Helium temperatures (4.2 K) to study their Brillouin spectrum for sensing purpose. In this paper we report the first measurements of Brillouin scattering properties at ultra-low temperatures and discuss the possibilities for cryogenic temperature sensing.

Experimental setup

300 m of standard single-mode fibre have been installed over a circular copper plate (diameter 50 cm) and put into a large cryogenic vessel designed for long term experiments at liquid He temperatures. It was not clear in advance whether the fibre would mechanically overcome the thermal cycle, so that we chose the maximum possible radius of curvature and we took care to avoid any strain along the fibre. It turned out that the attenuation loss at 4 K was only marginally higher than at room temperature. The copper plate was equipped with thermometers and heating resistances, and a PI regulation loop made possible temperature stabilization with 0.2 K accuracy. The accessible temperatures ranged from 140 K down to 1.4 K. Nevertheless the lowest temperatures were attained through partial evaporation of Helium; this made their stability questionable and the corresponding measurements do not show the same accuracy and were consequently discarded.

The Brillouin analyser instrument we used is based on the pump and probe method, both lightwaves being created from one single laser source (here a DFB laser at 1550 nm) thanks to an $LiNbO_3$ electro-optic modulator. This setup is fully described elsewhere [2]. It must be pointed out that it relies on the stimulated flavour of Brillouin scattering. Spontaneous Brillouin or Raman measurements, that can be valid alternatives at room temperatures, are here totally ineffective as a result of the negligible triggering thermal noise.

Results

Keeping in mind the typical values of the parameters of the Lorentzian Brillouin gain curve at 1550 nm and room temperature – 10.8 GHz for the frequency shift and 25 MHz for the linewidth – and their gentle variation over the usual temperature range, the results obtained at cryogenic temperatures show drastic variations, as illustrated by the curves in Fig. 1. Neither the frequency shift nor the linewidth longer depends in a simple way on the temperature.

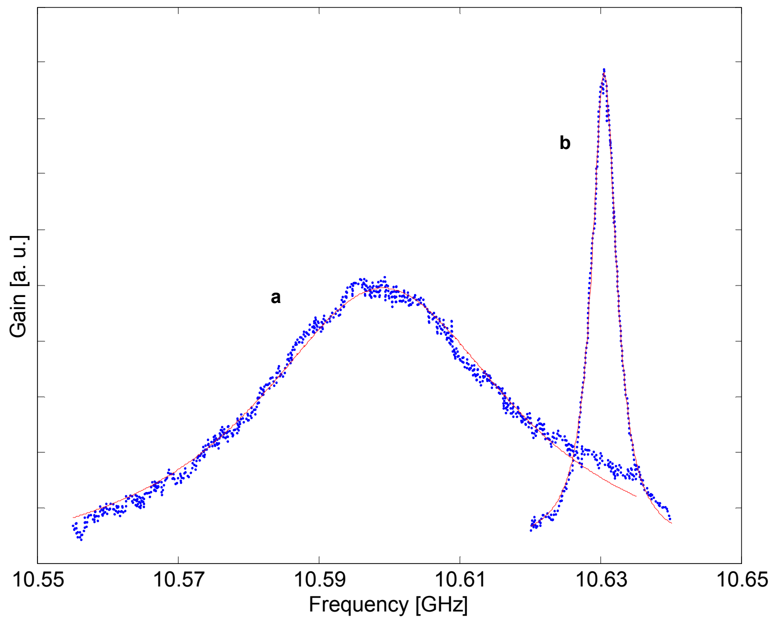

Fig.1 *Typical Brillouin gain curves at 1550 nm for two cryogenic temperatures, showing the large observed changes of the resonance characteristics.*

a) $T = 61$ K, $\nu_B = 10.56$ GHz, $\Delta\nu = 44.6$ MHz

b) $T = 5$ K, $\nu_B = 10.63$ GHz, $\Delta\nu = 4.2$ MHz

Fig.2 shows the variation of the Brillouin shift as a function of temperature *T*. The most striking features on this curve are a broad minimum around 50 K, a subsequent increase with decreasing temperature, and a maximum at 5 K followed by a new decrease. As far as the linewidth is concerned, it can be seen in Fig. 3 that it monotonically depends on temperature over the whole span of measurements with a rapid decrease towards 0 K. At the lowest temperatures the measured FWHM of the gain curve reaches 3 or 4 MHz. With such small values, the lightwaves spectral width, estimated to be 1 MHz for our DFB lasers, is no longer negligible. Actually, according to experiments on bulk silica samples [4], the intrinsic width of the Brillouin gain should be 1 MHz or less. New measurements with a more coherent laser are planned to confirm this behaviour.

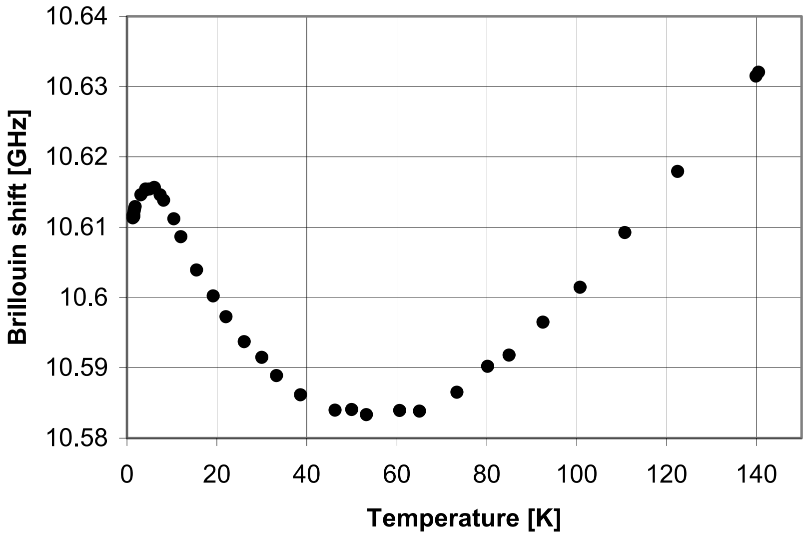

Fig.2 *Brillouin frequency shift at 1550 nm for a standard SMF at low temperatures*

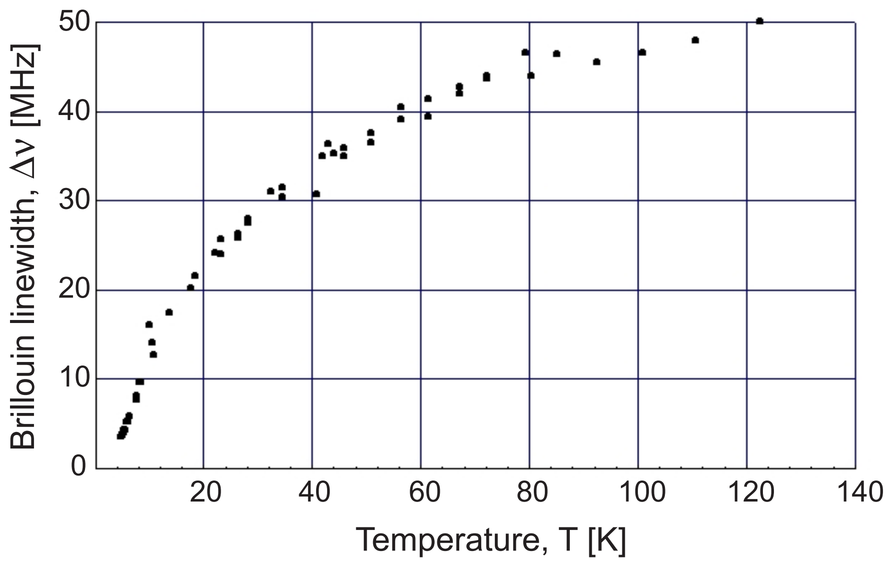

Fig.3 *Brillouin linewidth at 1550 nm for a standard SMF at low temperatures*

Discussion

The acoustic velocity V_a is simply related to the Brillouin frequency shift ν_B by the equation $\nu_B = \frac{2nV_a}{\lambda}$, where λ is the vacuum wavelength of the incident lightwave and n the refractive index of the fibre [5]. Il should be pointed out that the refractive index of the silica also depends on the temperature (see p. 86 in [3]), but this steady decrease with decreasing temperature cannot significantly account for the non-monotonous variation of the Brillouin shift.

A second value derived from the measurements, the ratio $Q^{-1} = \frac{\Delta\nu}{\nu_B}$ has an important physical meaning. It gives the so-called internal friction, a parameter that can also be measured by purely mechanical experiments involving the damping of macroscopic oscillations of the solid.

As mentioned before, the sound velocities and internal frictions corresponding to the results reported in Fig. 2 and Fig. 3 have long been known for bulk glass samples [3, 4, 6, 7]. They have triggered numerous theoretical works about the various processes that could explain them and the very structure of amorphous solids; most of the characteristics of these curves are now partially understood. For the ultra-cold glasses, below 4 K, there are the so-called tunneling states models that give quantitative agreement with experiments. In this temperature range, the damping of acoustical vibrations results from one-phonon absorption by discrete energy states in double-well potentials. Between a few K and 50 K, thermally activated absorption processes become dominant. Here again, models closely related to those describing crystalline solids can account for the observed effects. Paradoxically the room temperature behaviour, with the linear increase of the sound velocity, is the most challenging part. Indeed, in our brief survey of the available literature, we did not find any satisfying explanation of this increase.

And now a practical question arises: is it possible to expand the operational range of Brillouin-based sensors down to cryogenic temperature? The answer is definitely positive: the fibre keeps all its guiding and low attenuation properties and stimulated Brillouin scattering remains efficient. The only problem is the very low temperature sensitivity around the extrema of Fig.2, especially in the prominent 4-6 K region. A combined measurement of linewidth and central frequency shift is probably necessary.

References

[1] G. P. Agrawal, *Nonlinear fibre optics* 2nd ed., Academic Press, San Diego, (1995).

[2] M. Niklès, L. Thévenaz, P. Robert, *Brillouin gain spectrum characterization in single-mode optical fibres*, J. Lightwave Technol. **15**, p. 1842-1851 (1997).

[3] W. A. Phillips (ed.), *Amorphous solids: low-temperature properties*, Springer, Berlin, (1981).

[4] R. Vacher, H. Sussner, S. Hunklinger, *Brillouin scattering in vitreous silica below 1 K*, Phys. Rev. B **21**, p. 5850-5853, (1980).

[5] D. Cotter, *Stimulated Brillouin scattering in monomode optical fibre*, J. Opt. Commun. **4**, p. 10-19 (1983).

[6] D. Tielbürger et al., *Thermally activated relaxation processes in vitreous silica : an investigation by Brillouin scattering at high pressures*, Phys. Rev. **B** 45, p. 2750-2760 (1992)

[7] A. S. Pine, *Brillouin scattering study of acoustic attenuation in fused quartz*, Phys. Rev. **185**, p.1187-1193 (1969).