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Novel low-temperature fiber sensing technique using Brillouin scattering in gas

Yuting Yang[1]*, Marcelo A. Soto[2] and Luc Thévenaz[1]
[1]*EPFL Ecole Polytechnique Fédérale de Lausanne, Group for Fibre Optics, Station 11, 1015 Lausanne, Switzerland*
[2]*Department of Electronics Engineering, Universidad Técnica Federico Santa María, Chile*
yuting.yang@epfl.ch

Abstract: Brillouin scattering in gases shows the unique property to offer an enhanced temperature sensitivity at very low temperatures. This attractive solution for cryogenic systems is justified theoretically and validated experimentally.

1. Introduction

Obtaining an accurate temperature measurement using optical fiber sensing in the cryogenic range remains an open challenge since the physical effects supporting the thermal dependence of the optical response show a drastically reduced sensitivity or accuracy in the low temperature range. All commonly used effects show a similar trend in silica: Raman [1], Brillouin [2] and refractive index dependence [3]. This could be partially alleviated by conditioning the sensing fiber using special coatings [4,5] for Bragg gratings and coherent Rayleigh systems.

We here propose a totally novel and promising approach that has been yet unexploited, validated by very early experimental results proving the relevance of the concept. It is based on a classical Brillouin sensing configuration retrieving the acoustic velocity in the medium from the Brillouin frequency shift, though not in silica, but in a gaseous medium filling a hollow core fiber. It has been recently demonstrated that Brillouin scattering can be very efficient in gases under the condition that the pressure is raised to tens of bars [6] – even significantly outperforming the gain in silica – and shows a temperature sensitivity fully comparable to silica in ambient conditions [7], while keeping totally insensitive to strain.

Gases being simpler media than condensed solids such as silica, their response can be more straightforwardly and explicitly established using the standard equations of state given by thermodynamic models. This leads to the very unanticipated behavior that the variation of the acoustic velocity with temperature is significantly increased at lower temperatures, primarily scaling as $\sqrt{1/T}$ and leading to an enhanced temperature sensitivity for Brillouin-based measurements.

While this unprecedented response is here proved in an intermediate temperature range between ambient and cryogenic conditions, it is discussed how it can be extended to the fully cryogenic range in a next incremental step.

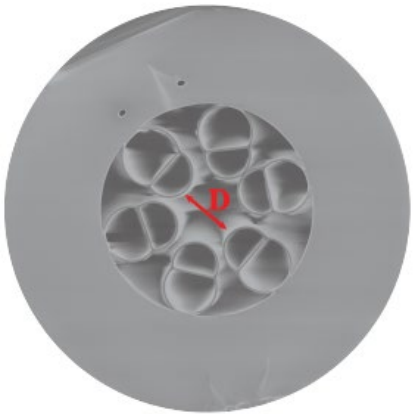

Figure 1. SEM picture of the conjoined-tube anti-resonant fiber (ARF) cross-section (D=22 μm) [7].

2. Principle

The sensing principle is in full analogy with a standard Brillouin optical fiber sensor, in which the solid silica sensing fiber is replaced by a hollow core fiber – in our implementation a novel conjoined-tube anti-resonant fiber (ARF) as

shown in Figure 1 - to secure a light propagation and a Brillouin interaction taking place predominantly in the gaseous medium. Light coupling and gas filling into such a fiber is extensively described in [7] and is reused here.

Brillouin Frequency Shift in Gaseous Medium from the Equations of State

The Brillouin interaction is the result of an inelastic scattering process, in which the light interacts with acoustic phonons and transfers energy between 2 counterpropagating optical waves showing a small and well-defined frequency difference. Under the phase-matching condition maximizing the coupling between the lightwaves, their frequency difference called Brillouin frequency shift ν_B - which represents the frequency of the mediating sound wave - is proportional to the acoustic velocity V_a given by the well-known following expression:

$$\nu_B = 2n_{eff}\frac{V_a}{\lambda_0}. \tag{1}$$

where $n_{eff} = 1.0064$ is the effective refractive index of the mode in the hollow ARF, $\lambda_0 = 1550\ nm$ is the vacuum wavelength of the interacting light. The acoustic velocity V_a is an inherent property of the medium and, in general for fluids, can be calculated using the Newton–Laplace equation:

$$V_a = \sqrt{\frac{\kappa_S}{\rho}}. \tag{2}$$

where ρ is the medium density and κ_s is the bulk modulus. Under the approximation that the acoustic wave propagation is much faster than the heat conduction, the process can be treated as adiabatic and reversible. In this case, $\kappa_S = -V\left(\frac{\partial P}{\partial V}\right)_S$, where P is the pressure, V the volume and the derivative taken at constant entropy S.

When the gas medium is under neither too high pressure nor too low temperature, the interparticle interactions between gas molecules (or atoms) are negligible and the medium follows with a good approximation the ideal gas law:

$$PV = mRT \tag{3}$$

where m is the amount of substance of the gas (number of moles), $R = 8.3145\ \mathrm{J \cdot K^{-1} \cdot mol^{-1}}$ is the gas constant and T is the absolute temperature. For an adiabatic process, $PV^\gamma = \text{constant}$, where γ is the heat capacity ratio.

Combining all above expressions, the BFS in an ideal gas as a function of temperature is expressed as follows:

$$\nu_{B\_ideal} = 2n_{eff}\frac{1}{\lambda_0}\sqrt{\frac{\gamma RT}{M_m}}. \qquad M_m\text{: molar mass of the gas molecules} \tag{4}$$

The derivative of the BFS with temperature T represents the temperature sensitivity of the system and turns out to get larger while the temperature decreases or using lighter gas molecules:

$$\frac{d\nu_{B\_ideal}}{dT} = n_{eff}\frac{1}{\lambda_0}\sqrt{\frac{\gamma R}{M_m T}} \tag{5}$$

All other quantities being constant, this shows the singular and exceptional feature that *the Brillouin sensitivity to temperature T steadily increases for decreasing temperatures in a gaseous medium*, with no apparent limit when approaching cryogenic temperatures. Normally, at high pressure and/or low temperature, the ideal gas model no longer strictly holds and corrective equations of state must be considered. When the interparticle interactions between the gas molecules are no longer negligible, the gas turns nonideal and can be modelled by the van der Waals equation:

$$\left(P + \frac{m^2 a}{V^2}\right)(V - mb) = mRT \tag{6}$$

where a and b are gas-dependent parameters called van der Waals constants. For an adiabatic process, $\left(P + \frac{m^2 a}{V^2}\right)(V - mb)^\gamma = \text{constant}$. Using the Van der Waals equation, the BFS in a non-ideal gas can be more simply written when expressed as a function of the density ρ:

$$\nu_{B\_nonideal} = 2n_{eff}\frac{1}{\lambda_0}\sqrt{\frac{\gamma}{\rho}\frac{M_m}{M_m - b\rho}\left(P + \frac{a\rho^2}{{M_m}^2}\right) - \frac{2a\rho}{{M_m}^2}}. \tag{7}$$

In our experimental conditions, the system is under a constant gas pressure at 28 Bar, so that ρ only depends on the temperature and an empirical dependence on T found in [8] can be used. At the end, the BFS ν_B turns solely function of temperature T, too. In our pioneering initial experiment, we used nitrogen as the gaseous medium in the ARF and the relevant parameters are shown in Table 1. Unexpectedly, within the limits of the van der Waals model, the non-ideality of the gas turns out to further enhance the temperature sensitivity.

Table 1. Values used for the theoretical calculations of the thermal Brillouin response of N_2 gas

Parameter	Symbol	Value
Heat capacity ratio	γ	1.4011
Molar mass	M_m	2.8014×10^{-2} kg/mol
Van der Waals constants	a	1.370×10^{-1} m^{6}Pa/mol^2
	b	3.87×10^{-5} m^3/mol

3. Experimental Demonstration

3.1. Measurement Set Up

A coherent detection, where two signals beat at the photo-detector, is used to measure the frequency shift of the amplified spontaneous Brillouin signal generated by an intense CW very coherent pump. This sensitive configuration offers the additional advantage to require a single end access to the sensing fiber, facilitating the gas filling and flushing. In this case, a frequency tunable local oscillator, synthesized by modulating a fraction of the pump wave, beats with the back reflected spontaneous Brillouin signal and delivers an electric spectral signature from which the the Brillouin frequency shift (BFS) can be conveniently extracted. It has to be mentioned that the acoustic velocity in gases is ~10-100 times slower than in silica and the BFS therefore lies in the 100 MHz-1 GHz range, precluding efficient and simple optical filtering between pump, Stokes and anti-Stokes signals.

The experimental setup is sketched in Figure 2. A RIO 1550 nm external cavity diode laser (ECDL) with a 23 kHz linewidth is used as the laser source. The light is divided into two branches using a 90/10 coupler: the 90% branch is used to synthesize the local oscillator for the coherent detection, while the 10% branch is amplified to work as a pump generating the Brillouin signal.

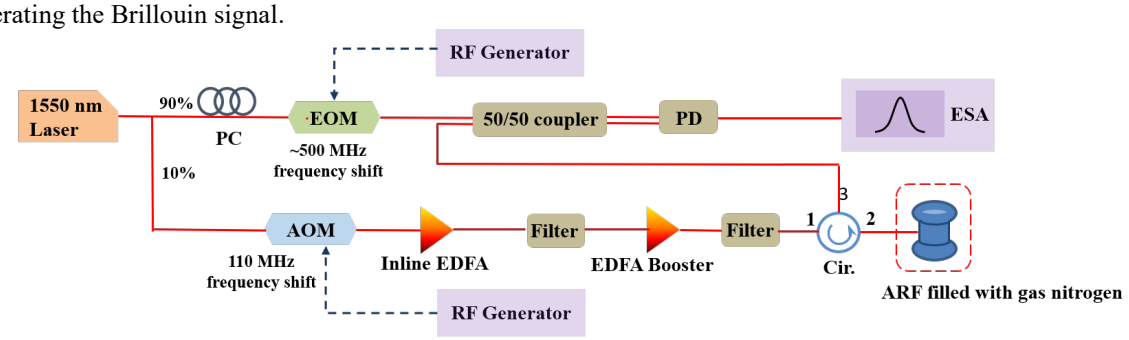

Figure 2. Experimental validation setup. Both ends of the ARF are connected to a tube loaded with N_2 at a constant gas pressure of 28 bar. The temperature of the ARF is controlled by placing the fiber coil at different vertical positions in the Dewar half-filled with liquid N_2.

The 90% branch passes through an electro-optic modulator (EOM), connected to a radio frequency (RF) generator. The carrier is suppressed by a proper DC biasing and two tunable sidebands are symmetrically generated and shifted from the carrier at plus or minus the modulation frequency (~500 MHz).

The 10% branch first goes through an acoustic-optic modulator (AOM) causing a unilateral fixed frequency shift of the light by 110 MHz, making the beating due to the Brillouin Stokes and anti-Stokes signals spectrally separated. The modulated light is then amplified by two successive Erbium-doped fiber amplifiers (EDFAs), each followed by a broadband filter to reduce the EDFAs amplified spontaneous emission noise. The sensing ARF is priorly vacuumed and then filled with gaseous N_2 at a constant pressure of 28 bar. The ARF total length is approximately 16 meters, with a 14-meter portion of the fiber coiled and subjected to different uniform temperatures.

The backscattered light from the ARF combines with the local oscillator using a 50/50 coupler. A photo-detector (PD) used in balanced-detection mode is connected to an electrical spectrum analyzer (ESA), enabling the visualization of the Brillouin scattering spectrum in the electrical domain.

3.2. BFS Measurements as a Function of Temperature

Measurements are performed from room temperature down to 132.5 K, just above the gas-to-liquid phase change temperature of 123.2 K at the N_2 pressure of 28 bar. For this purpose the fiber coil is placed at different vertical positions above the liquid N_2 surface in a half-filled Dewar and is enclosed in a metallic box to secure a good temperature uniformity. As shown in Figure 3, the measurements cover the full range between ambient conditions and the N_2 liquid phase transition temperature.

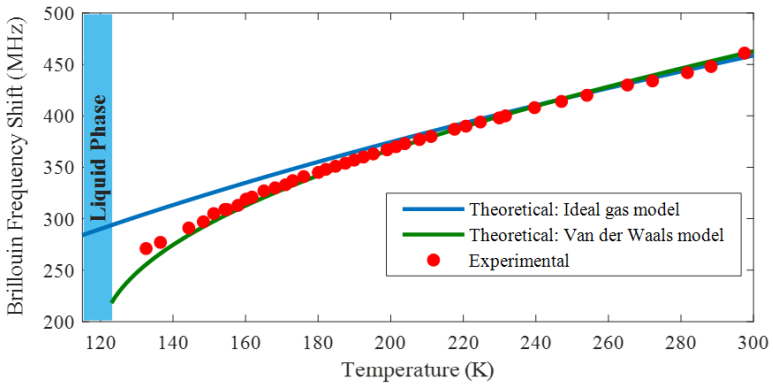

Figure 3. BFS experimental data compared with theoretical curves. At a pressure of 28 bar the validity range of the ideal gas model is for temperatures over 200 K, while the van der Waals model remains a good approximation down to liquefaction temperature. The light blue area shows where N_2 is liquid.

When the temperature is above 200 K, the response tends to follow the anticipated ideal gas behavior, as both experimental data and theoretical ideal gas predictions show strong agreement. In contrast, as expected at temperatures below 200 K, interparticle interactions can no longer be neglected, leading to deviations from the ideal gas behavior. However, the measurements are fully consistent with the theoretical predictions based on the van der Waals model.

4. Discussion and Conclusions

Preliminary experimental data collected using nitrogen as sensing medium demonstrate the relevance of the prediction that Brillouin temperature sensing in a gaseous medium shows an enhanced sensitivity as temperature decreases, in full agreement with the predictions of the ideal gas and the van der Waals models when applicable. The matching between the experimental response and the value obtained directly from models is absolutely remarkable, moreover proving the absence of effects from the fiber conditioning and structure and a response solely due to gas properties.

Nevertheless, the pioneering investigation reported here does not enable to reach the cryogenic temperature range yet, since nitrogen liquefies at a too high temperature when pressure is raised, and raising pressure is required to obtain a significant Brillouin gain in gases. Actually, a simple survey shows that the best gas to implement this sensing scheme is helium (He), since it combines the advantages of a very light molecule for a higher sensitivity, as shown in Equ. 5, and the lowest liquefaction temperature, moreover fairly independent of pressure.

However, helium suffers from a stringent issue: it permeates quickly through glass, in a matter of tens of minutes, so that it is vain to reach a high pressure over several meters of hollow core fibers, as we could conclude from our first attempts. Fiber must be conditioned to prevent this permeation and our efforts are now focused on implementing a solution suitable for helium. This is our preferred avenue to realize distributed fiber temperature sensing at cryogenic temperatures with unmatched performance.

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