Optical Fiber Sensors (OFS) 2023 © Optica Publishing Group 2023

New avenues in optical fiber sensing using gas

Luc Thévenaz[1], Fan Yang[1], Flavien Gyger[1], Li Zhang[1], Malak Galal[1], Yuting Yang[1], and Marcelo A. Soto[2]
[1]EPFL Ecole Polytechnique Fédérale de Lausanne, Group for Fibre Optics, SCI-STI-LT Station 11, 1015 Lausanne, Switzerland
[2]Department of Electronics Engineering, Universidad Técnica Federico Santa María, Chile
Author e-mail address: Luc.Thevenaz@EPFL.CH

Abstract: Gases turn out to be a very attractive medium for optical fiber sensing, showing highly flexible possibilities though widely unexploited so far. A new era opens for fiber sensing, exploiting the unprecedented potentialities of fluids.

1. Introduction

Thanks to the advent of novel types of fibers, light guided in optical fibers can extensively interact with a gaseous medium, mostly by taking advantage of a holey structure. The most evident structure is the so-called hollow core fibers, which are a rather ideal case since the virtually entire guided light is interacting with the gas. But other simpler structures offer the possibility of a light-gas interaction such as the tapered nano-fibers or the side air-holes fibers, though with a more limited light-gas overlapping.

The concept of using light-gas interactions in such fibers has attracted much attention for several years, mostly for exploiting the light amplification using Raman scattering [1] or the spectral absorption of molecular lines in gas [2]. In the sensing field, hollow core fibers have been extensively studied to detect gas traces through molecular absorption, requiring the creation of lateral holes to let the gas circulate within the fiber [3].

However, little research has been performed so far to exploit the physical changes experienced by a gas for sensing purposes. For instance, unmatched Brillouin gains can be achieved, offering a dreamful platform for high performance sensing with a fully specific response: Brillouin sensing turns strain-insensitive and therefore responds only to temperature with enhanced accuracy. Other perspectives are foreseen through thermodynamic phase transitions using specially designed fibers, opening many new avenues for simple sensing schemes and offering a bright refreshed future to optical fiber sensors. This presentation will address these specific new avenues offered by gases for optical fiber sensing, reporting some latest results demonstrating promising prospects.

2. Generalities

Solids and gases show marked basic differences in their physical response that are summarized in Fig. 1 for the most significant ones related to fiber sensing.

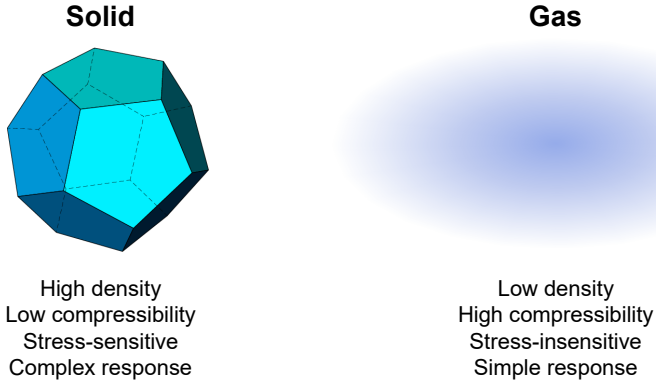

Figure 1. Solids and gases show fundamental differences in their response to external quantities and how this translates into a change in the optical properties of the medium.

A gaseous medium presents crucial advantages: it offers a high flexibility, since the fiber can be prepared by filling it with gases under different conditions. The gas composition can be easily changed and mixed, and its density can be varied through pressure. Moreover, its response can be precisely predicted using simple thermodynamical models,

such as the ideal gas law for an approximative trend, and the van der Waals or virial equations of state for a more precise prediction.

A clear penalty is related to the much lower density of a gas under standard conditions (~1 kg/m^3 for air) when compared to glass (~2500 kg/m^3), resulting in much lower interaction strength. This can be only partially compensated by raising the gas pressure, but it remains unrealistic to reach equivalent material densities. This manifests by a refractive index of the gaseous medium remaining close to unity.

Two very different cases are showcased in this presentation where the gas response offers a clear advantage when compared to its silica counterpart. The first example presents distributed Brillouin sensing along hollow core fibers, showing an unmatched response and sensitivity on top of a total absence of temperature-strain cross-sensitivity. The second example shows very simple distributed configurations to detect cold or hot spots along a fiber.

3. Brillouin distributed sensing in gases

Stimulated Brillouin scattering in gases under ambient conditions shows gain that are much smaller than those observed in silica, mostly as a result of the much lower mass density and in spite of a significant boost in compressibility. The situation changes radically when the gas pressure is raised, since the density increases proportionally and the acoustic loss concurrently decreases linearly, too [4]. The association of these 2 effects result in a peak gain increasing quadratically with pressure, so that a linear gain higher than in silica can be readily obtained with pressure in excess of 1000 kPa (10 bars), as shown in Fig. 2.

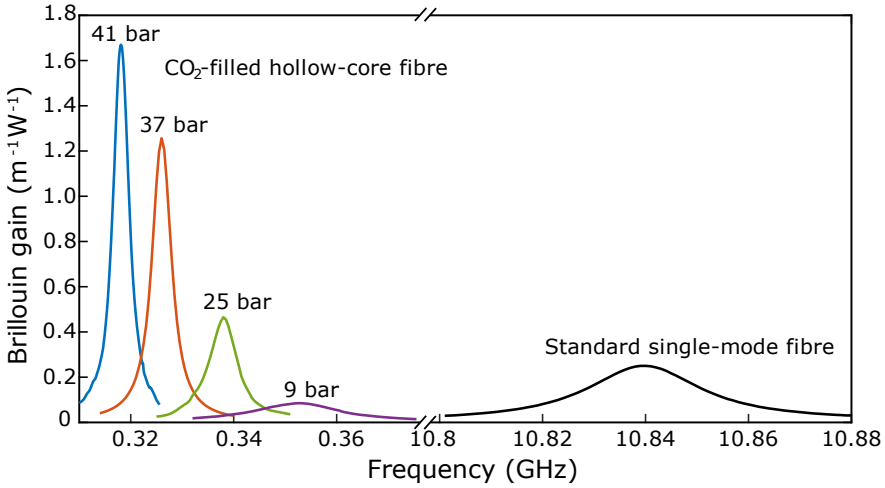

Fig. 2. Gain measured in a hollow-core photonic bandgap fiber filled with CO2 gas at high pressure, as function of the optical frequency detuning between the pump and the counterpropagating amplified probe signal. For comparison the gain measured in a solid core silica fiber is also represented. It demonstrates that a substantially higher gain is achieved in the gas, showing a narrower gain linewidth obtained at a smaller frequency detuning as a result of the slower acoustic velocity. The horizontal scale is broken for a better visualization (from [4]).

The gain shows some variations with the type of gas and a general trend is that gases showing a larger molecular mass gives rise to a stronger gain [4,5]. It must be noted that gases with heavy molecules normally show a liquefaction pressure that is relatively low, cancelling most benefits from the higher molecular mass by setting a maximum possible pressure and thus a saturation value for the gain. A lighter molecule showing no liquid phase at ambient temperature may eventually deliver higher gains by simply rising the pressure. More complex molecules are also more likely to present spectral absorption lines near the wavelength of interest, substantially raising the optical attenuation.

A gas is by essence insensitive to shear stress and thus to elongation applied to the fibre, so it is an elegant way to solve the recurring issue of the temperature-strain cross-sensitivity in most fibre sensors. This has been strikingly demonstrated by simultaneously applying temperature and strain changes on the same fiber segment [4] and no evidence of a strain effect could be detected.

This makes the gas Brillouin sensor essentially sensitive to temperature only and it remains to assess if the temperature sensitivity is large enough to be exploited. This is basically scaled by the change of the acoustic velocity in the gas as a function of temperature and it can be straightforwardly estimated by using the ideal gas model. The change of the

Brillouin shift ν_B per Kelvin turns out to be $d\nu_B/dT=½\,\nu_B/T$ [5], so that the larger the Brillouin shift (and thus the acoustic velocity), the larger the sensitivity. But a larger acoustic velocity is observed for lighter molecules, which in turn show a lower linear gain. In all cases, with the values of acoustic velocities observed in current gases, a sensitivity larger than 1 MHz/K is expected, slightly better than the value observed in silica, as illustrated in Fig. 3.

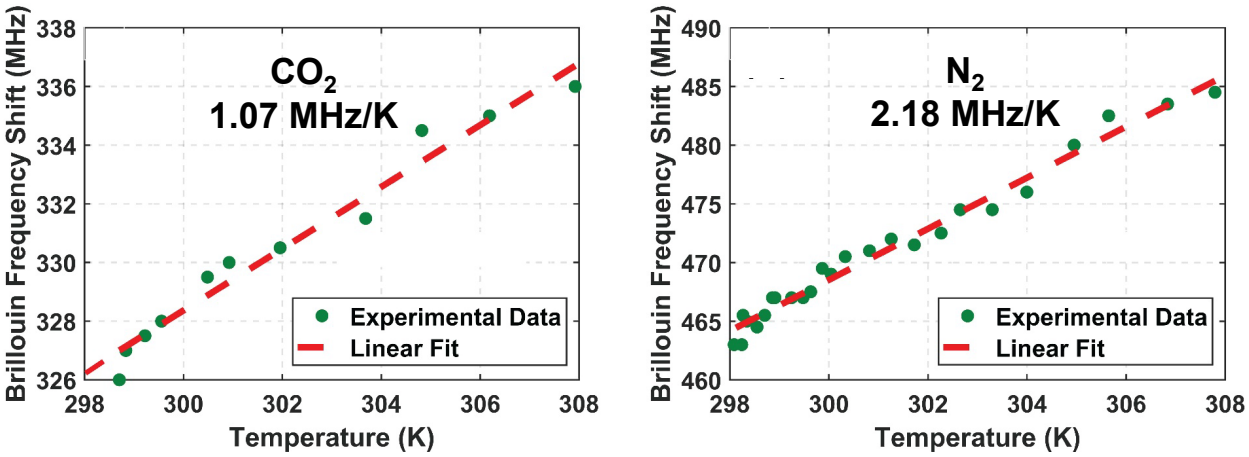

Fig. 3. Temperature dependence of the Brillouin frequency shift measured in carbon dioxide (left) and nitrogen (right). This latter shows a higher sensitivity thanks to its larger acoustic velocity resulting from its lighter molecular mass, resulting in a sensitivity twice larger than carbon dioxide and silica (from [5]).

4. Distributed sensing exploiting gas-liquid phase transition

With the notable exception of gases with simple molecular structures – such as hydrogen, helium, nitrogen and oxygen – most gas species liquefy above a given pressure around room temperature. More precisely, at a given temperature the gas will liquefy above a fixed pressure, very well determined for a given gas species. For instance, CO_2 liquefies over approx. 61 bars at 20°C, but only over ~30 bars at 0°C, as shown in Fig. 4.

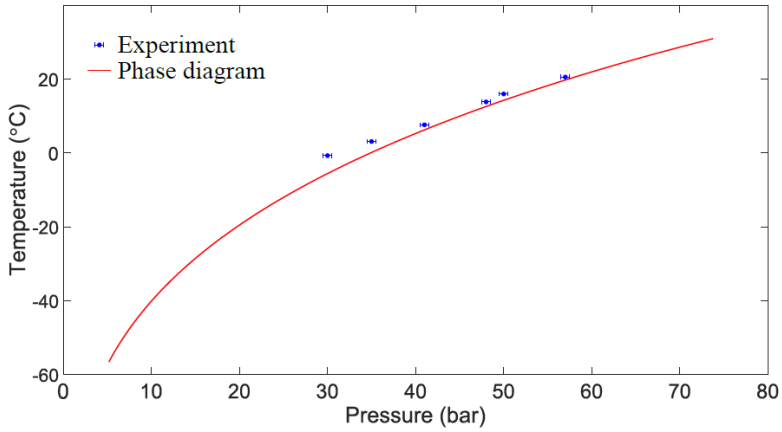

Fig. 4. Measured critical temperature for liquefaction as a function of the CO_2 pressure (blue dots) and corresponding theoretical phase diagram (red curve) (from [6]).

This property can be used to realize a very simple detection scheme to detect a temperature spot along an optical fiber showing a transition above (or below) a given temperature. For this purpose a hollow core fiber is filled with a gas at a given pressure corresponding to liquefaction at the target transition temperature. When locally the temperature goes below the transition temperature, the gas turns liquid and its refractive index is very significantly changed, dramatically changing the guiding conditions in the hollow core fiber. In a photonic bandgap hollow core fiber, in most cases, this disables the guiding by spectrally shifting the photonic bandgap – and thus the transmission window – to another wavelength range, abruptly stopping the light transmission. A simple alarm system could be devised by a point-to-point measurement of the overall transmitted light. It detects precisely and nearly instantaneously the occurrence of the cold spot, though with no possibility to localize the thermal spot [6].

This coarse binary behavior can be actually improved by converting the radical on-off transmission into a change of linear attenuation. This way, multiple liquid and gaseous sections can be discriminated and localized using a basic OTDR interrogator as fiber sections showing a different linear attenuation, visualized as distinct slopes on the backscattered temporal trace. This has been demonstrated in a side air-holes fiber, where the tiny fraction of the evanescent field propagating in CO_2 shows a marked distinct linear attenuation where CO_2 is liquid [7].

5. Conclusion

Gas offers a platform of unmatched flexibility for fiber sensing, regarding its vast potentiality for customization by varying its composition and pressure. A holey fiber can be prepared and customized by filling it with a gas preparation at preset conditions using a relatively simple setup, and then can be permanently sealed by splicing it to standard solid silica fibers. It could lead to the prodigious result that stimulated Brillouin scattering in gases can outperform any existing nonlinear amplification [4], not only in hollow core fibers by simply using the evanescent field of a tapered fiber [8].

The physical response of a gas is actually much simpler and more predictable than silica, facilitating the design of sensors with a specific response. This has enabled to demonstrate a Brillouin distributed sensor totally insensitive to the strain applied to the fiber, but showing a temperature response stronger than that observed in silica [4,5].

Totally unexplored avenues for fiber sensing are offered by a fluidic medium, which in the cases presented here is not the object to be sensed like in many current advanced researches [9], but the transducing medium converting a change in an environmental quantity into a variation of the optical response.

The recent advent of ultra-low-loss hollow core fibers further amplifies the perspectives offered by this novel approach, which may give a new impetus to optical fiber sensing.

Acknowledgements: This research was supported by Swiss National Foundation under grant agreement numbers 178895 and 159897 and by the projects C21-13 of the Swiss Data Science Centre and Innosuisse 38390.1.

5. References

[1] F. Benabid, J. C. Knight, G. Antonopoulos and P. S. T. J. Russell, “Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber.” Science **298**, 399–402 (2002).

[2] M. R. A. Hassan, F. Yu, W.J. Wadsworth and J.C. Knight, “Cavity-based mid-IR fiber gas laser pumped by a diode laser.” Optica **3**, 218–221 (2016).

[3] W. Jin, H.L. Ho, Y.C. Cao, J. Ju and L.F. Qi, “Gas detection with micro- and nano-engineered optical fibers,” Opt. Fiber Technol. **19**, 741–759 (2013).

[4] F. Yang, F. Gyger, and L. Thévenaz, “Intense Brillouin amplification in gas using hollow-core waveguides,” Nat. Photonics **14**, 700–708 (2020).

[5] M. Galal, L. Zhang, S. Gao, Y. Wang, and L. Thévenaz, "Study of backward Brillouin scattering in gas-filled anti-resonant fibers," APL Photonics **8**, 086104 (2023).

[6] L. Zhang, F. Yang, F. Gyger, and L. Thévenaz, "Distributed fiber temperature alarm system based on thermodynamic phase transition," in *Optical Fiber Sensors Conference 2020 Special Edition* (Optica Publishing Group, 2021), paper T2B.3.

[7] Y.Yang, M.A. Soto, and L. Thévenaz, “Distributed alarm system based on OTDR interrogation of side air-hole fibers,” submitted to *28th Optical Fiber Sensors Conference* (2023).

[8] F. Yang, F. Gyger, A. Godet, J. Chrétien, L. Zhang, M. Pang, J.-C. Beugnot, and L. Thévenaz, "Large evanescently-induced Brillouin scattering at the surrounding of a nanofibre," Nat Commun **13**, 1432 (2022).

[9] Y. Antman, A. Clain, Y. London, and A. Zadok, "Optomechanical sensing of liquids outside standard fibers using forward stimulated Brillouin scattering," Optica 3, 510–516 (2016).