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Pressure-independent Brillouin Fiber Optic Sensors for temperature measurements

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ABSTRACT

Fiber Optic Sensors (FOSs) based on Brillouin scattering are widely used in large infrastructures to detect modifications over large distances. In doped silica fibers the Brillouin Frequency Shift (BFS) is proportional both to temperature and strains. In this work we establish that the sensitivity of FOSs to hydrostatic pressure can be forecast from the behavior of the glass under hydrostatic compressions in a diamond anvil cell. It is shown that the BFS under a hydrostatic pressure is a manifestation of the elastic anomaly observed in silica glass. This anomaly vanishes in GeO_2 glass and accounts for the decrease of the sensor sensitivity when the GeO_2 doping concentration increases in a silica fiber. The progressive vanishing of the anomaly in sodium aluminosilicate glasses which contain the same amount of silicon dioxide (75%) but differ in the Na_2O and Al_2O_3 ratio allows to determine the composition of a glass with a BFS independent of the pressure. Such a glass composition will provide a pressure-independent temperature FOSs.

1. Introduction

The fiber optic domain is at present in considerable expansion and reaches the market place fast. Fiber Optic Sensors (FOSs) have undergone considerable improvement during the last 25 years with developments allowing them to monitor varied environmental parameters (temperature, pressure, strain, humidity, chemicals…) and to be applied in several fields of technology (aerospace, medicine, chemistry, telecommunications…) [1–3]. Among fiber sensor systems sensitive to temperature and strains variations, one of the most extensively developed is based on Brillouin scattering because of its strong dependence on these two environmental factors [4]. Temperature and strain Brillouin distributed fiber sensors are used in civil infrastructure (bridges, railways, land monitoring…), geotechnical structure and pipeline monitoring, and also in larger variety of structures (competition yachts, experimental vehicles, aircrafts…) [5] to detect modifications over large distances (20–30 km). These measurements are performed in the infrared, mainly at 1.550 μm, which corresponds to the minimum attenuation of the silica optical fibers.

Brillouin scattering is an inelastic light scattering corresponding to the interaction of light with thermally excited acoustic phonons [5,6] and give information on the elastic behavior of the material.

In the case of optical fibers, backscattering geometry is used. In this geometry the Brillouin Frequency Shift (BFS) ν_{180} is linked to the longitudinal sound velocity (V_L) [7]

$$\nu_{180} = \frac{2n\,V_L}{\lambda_0} \tag{1}$$

where λ_0 and n are respectively the laser excitation wavelength and the optical index. V_L is a function of the density ρ, the bulk modulus K and the Young modulus E according to the relation:

$$V_L = \sqrt{\frac{3K(3K+E)}{\rho(9K-E)}}. \tag{2}$$

In a first approximation the BFS variation ($\Delta\nu$) with temperature (T) and longitudinal strain (ε) can be expressed linearly:

$$\Delta\nu = C_t * T + C_\varepsilon * \varepsilon. \tag{3}$$

With C_t, the frequency–temperature coefficient and C_ε, the frequency–longitudinal strain coefficient. Typical values for silica fibers at $\lambda_0 = 1550$ nm are $C_t = 1$ MHz/°C and $C_\varepsilon = 0.05$ MHz/με [8].

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For a BFS submitted to a high hydrostatic pressure P a similar formula can be written:

$$\Delta\nu_p = C_t * T + C_p * P \quad (4)$$

with C_p, the frequency–pressure coefficient.

In the case of optical fiber sensors, the stimulated Brillouin scattering (SBS) is often used. SBS is driven through an electrostriction process (material compression under the influence of the electric field) generating an acoustic wave when the fiber core is excited by the incident pump signal [9–11]. Stimulation corresponds to the enhancement of the Brillouin signal by the presence of another intense electromagnetic wave (called the pump wave) that reinforces the spontaneous scattering. With a 10 ns pulse pump laser the time distance conversion allows a resolution of 1 m and measurements on several tens of kilometers [8].

Most of the sensors are based on optical telecommunication fibers and composed of a silica core doped by Germanium dioxide (GeO_2). Brillouin optical fiber sensors are sensitive both to strains and temperature effects and it is a challenge to separate these effects as in practical use both occur [12]. Prediction of glass compositions that give rise to strain and temperature independent Brillouin frequency shifts was recently proposed in BaO-silicate fibers [13] and a-thermal Brillouin frequency shift was obtained for sapphire all glass optical fibers containing 38 mol% alumina [14]. In this paper we will discuss the potentiality of silicate based fibers taking into account the role of the fiber composition to monitor the response sensitivity of the Brillouin sensor to hydrostatic pressure. These sensors can be of interest in various high pressure environments like in submarine measurements. This discussion is based on recent works which studied the in situ behavior of the silica BFS by hydrostatic compression experiments performed on silicate glasses and germania glass [15,16] and molecular dynamics simulations [17,18]. The possibility to obtain silicate fibers with hydrostatic pressure independent BFS is shown.

2. Experimental set-up

A diamond anvil cell (DAC) high pressure device, Chervin type from the Laboratoire de Physique des Milieux Condensés — University Pierre et Marie Curie (France), equipped with ultra-low fluorescence diamonds allows in situ Brillouin compression experiments. Using liquid argon as a transmitting medium, a quasi-hydrostatic pressure is applied on the samples. The use of a DAC cell, where the external pressure is applied by a membrane loaded with a high pressure gas, allows a very progressive increase or decrease of the pressure applied on the sample with steps down to 0.2 GPa.

Brillouin experiments were performed with a JRS Sandercock Fabry–Perot tandem interferometer coupled with a microscope in back scattering geometry using the 532 nm frequency-doubled excitation of a YAG:Nd^{3+} laser.

3. Results and discussion

In the following, we will use the in situ high pressure compressive Brillouin experiments realized on silica and sodium aluminosilicate glasses to predict what would be the pressure sensitivity of Brillouin sensors made with such materials.

3.1. Silica

The evolution of pure silica glass BFS at 532 nm during an hydrostatic compression in a DAC up to 6 GPa is shown on Fig. 1. The minimum of the BFS at 2.2 GPa corresponds to the well-known elastic anomaly [19] and the initial slope at Patm is equal to −3.3GHz/GPa.

Molecular dynamics simulations by Huang and Kieffer [17] and Mantisi et al. [18] describing silica glass under hydrostatic compression

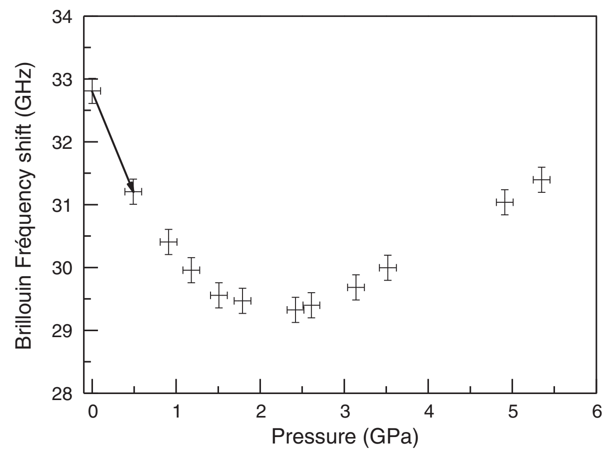

Fig. 1. Evolution of the Brillouin frequency shift for pure silica glass during a compression up to 6 GPa. The black arrow corresponds to the initial slope at Patm and is equal to −3.3 GHz/GPa.

(Fig. 2) show that the bulk modulus K of silica decreases when the pressure increases and has a minimum at 7 GPa.

This minimum, described as the silica anomaly, is only in qualitative agreement with experimental observations as often observed in molecular dynamics simulations (experimental minimum at 2.5 GPa). The important result obtained from Huang and Kieffer simulations [17] (Fig. 2) is that the bulk modulus decreases for an increasing pressure. The bulk modulus K is related to the BFS through Eqs. (1) and (2). A positive BFS variation $\Delta\nu$ (Eq. (3)) as function of the tensile stress increase is observed whereas a negative variation results from a hydrostatic compression (Eq. (4)). This is a manifestation of the elastic anomaly corresponding to an increase of the bulk modulus for negative pressure (Fig. 2). Indeed, for a “normal glass” the elastic moduli and also the longitudinal sound velocity increase when the pressure increases. In a normal glass, the sound velocity decreases as function of the tensile stress intensity. Fig. 2 also shows that the linear approximation (cf Eq. (4)) is only valid close to the atmospheric pressure.

Our experimental results can be used to predict the BFS for a compression of an optical fiber at 1.550 μm from the Brillouin shift at 0.532 μm which is equal to −3.3 GHz/GPa. Taking into account the ratio of both wavelengths the pressure coefficient C_p at 1.550 μm is:

$$C_p = -3.3\ (0.532/1.550) = -1.1\ \text{GHz/GPa}.$$

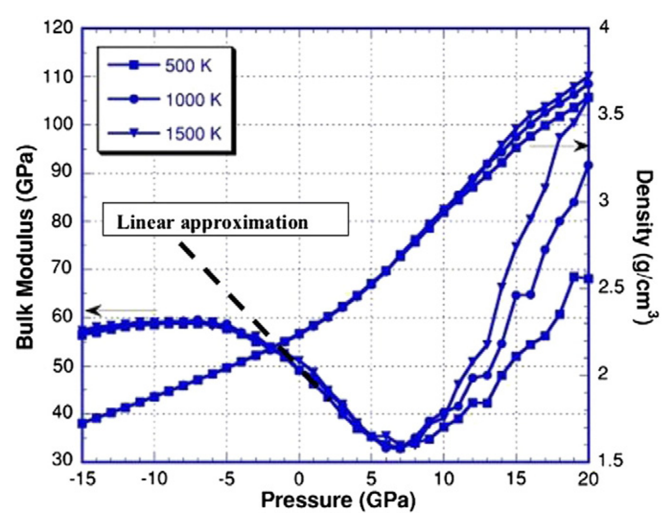

Fig. 2. Silica anomaly: bulk modulus and density evolution versus pressure determined by Molecular Dynamic Simulations (from [17]).