Temperature and strain Brillouin sensing coefficients of heavily doped Germanium-core optical fibers

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Abstract: We experimentally demonstrate that recent heavily doped Germanium-core optical fibers up to 98% mol could advantageously be exploited to discriminate the effects of strain and temperature in distributed Brillouin fiber sensors.
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1. Introduction

Based on a nonlinear interaction between optical and acoustic waves, stimulated Brillouin scattering (SBS) has been applied in numerous optical fiber-based devices such as fiber lasers, microwave photonics and fiber sensors [1]. The latter application has significantly grown in the recent years based on the dependence of the frequency shift of Brillouin gain spectrum on both strain and temperature [2], [3]. Among the large range of optical fibers available for fiber sensors, Germanium-doped-core optical fibers appear as very attractive candidates due to their high Brillouin gain [4]. Brillouin frequency shift (BFS) dependences on strain and temperature have been recently characterized in optical fibers with GeO_2 doping up to 17-mol %, in particular it has been shown that such doping levels induce a decrease of sensitivity [5].

In this paper, we report the experimental measurements of BFS dependence on both strain and temperature in several GeO_2-doped-core silica fibers. We examine five fibers samples (3-m-long segments) from low (3.6% mol) to ultra-high (98 % mol) Germanium concentration. Our results show a resulting negative linear dependence of BFS for both strain and temperature variations. The strain and temperature coefficients decrease from 489.4 MHz/% (SMF-28 with 3.6-mol% GeO_2 core doping) to 213.8 MHz/% (High Nonlinear fiber with 98-mol % GeO_2 core doping) and 1.09 MHz/°C to 0.07 MHz/°C, respectively. In addition, we demonstrate a quadratic evolution of both strain and temperature coefficients as a function of GeO_2 concentration. For highly GeO_2 concentration (up to 98-mol %), temperature and strain coefficients are 15 times and 2.5 times smaller than SMF-28 fiber, respectively. Consequently, an almost-athermal fiber configuration is clearly evidenced. This remarkable behavior shows that heavily GeO_2-core optical fibers could be harnessed to discriminate strain and temperature in distributed Brillouin fiber sensors.

2. Experimental setup

Figure 1 depicts the experimental setup used for both stain and temperature measurements based on the backward SBS. In our experiment, we compared five fiber samples of Germanium-doped-core optical fibers from low doping level (3.6% mol, SMF-28), highly-nonlinear Fiber (21% mol, HNLF, Sumitomo), to strong doping levels: 53% mol (FORC), 75% mol (FORC), and 98% mol (FORC).

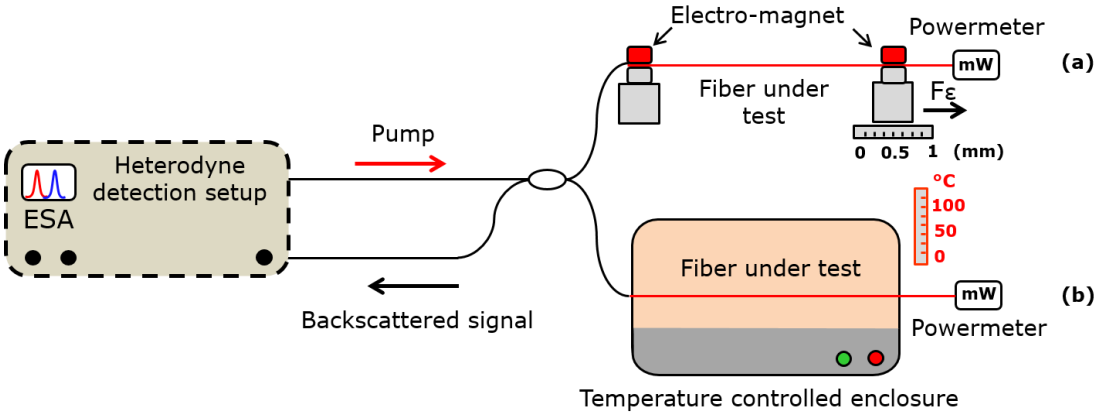

Figure 1: Experimental setup for (a) strain and (b) temperature measurements. ESA: Electrical Spectrum Analyzer.

The Brillouin frequencies of our optical fibers were experimentally measured using the heterodyne detection technique as described in Ref. [6]. To measure the strain dependence of BFS, each optical fiber under test (FUT) was fixed using electromagnets over the same length of 1m. A force was then applied upon the fiber to achieve increasing elongations and the resulting Brillouin frequency shift has been directly measured. Concerning the evolution of BFS as a function of temperature variations, the FUT was immersed into a thermal water bath filled with demineralized water. The temperature change was measured with an electronic thermometer. We made use of the heterodyne detection setup based on a continuous-wave laser operating at 1.55 µm with a narrow linewidth (< 10 kHz) to analyze the beating signal between the backward Brillouin Stokes signal and a small part of the pump signal. Note also that a power meter was also used to accurately monitor the fiber transmission during the process.

3. Experimental results

We first measured the Brillouin spectra of our five fiber samples at room temperature and without strain applied upon optical fibers. Figure 2(a) shows that the Brillouin frequency peak shifts from 10.85 GHz to 7.7 GHz for GeO_2 concentration increasing from 3.6-mol % (purple) to 98-mol % (black). Note that this large frequency tunability could be very useful for microwave applications. Figure 2(b) shows the corresponding BFS as a function of GeO_2-doping level. As can be seen, the BFS asymptotically decreases from 10.8 GHz down to 7.7 GHz for a 98% mol doping level. Interestingly, this nonlinear behavior is in excellent agreement with the theoretical additive model recently proposed by Dragic in Ref. [7]. This model allows to calculate the acoustic velocity as a function of GeO_2 doping taking into account the acoustic parameters of both pure GeO_2 and silica fibers.

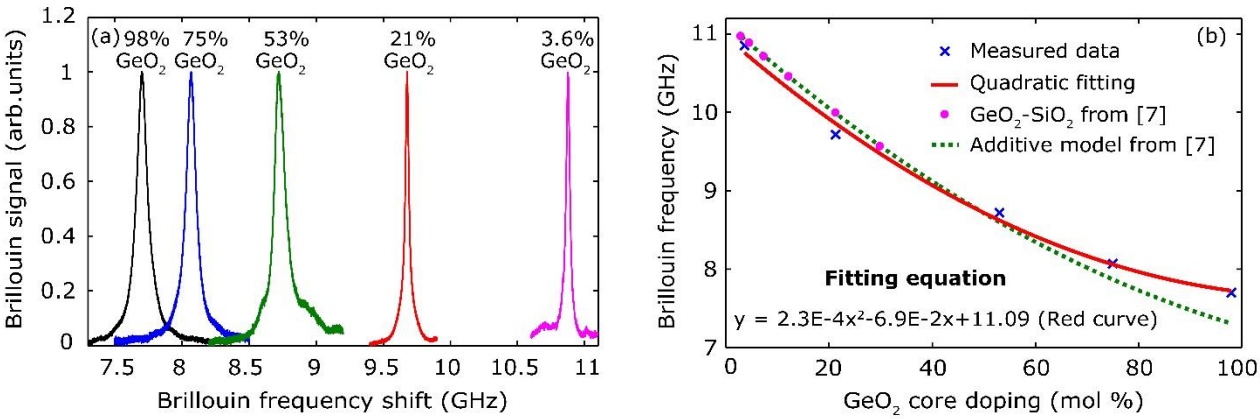

Figure 2. (a) Brillouin gain spectra for five different GeO_2 doped-core fibers at 1550 nm; (b) Brillouin frequency versus the GeO_2 doping level.

Next, we measured the backward Brillouin spectra for strain varying from 0% to 0.7% and temperature ranging from 20°C to 68°C. For strain measurement, we limited the strain variation up to 0.7% to prevent mechanical reliability issues of the optical fibers. Figure 3 shows the resulting strain and temperature dependences of BFS in our five fiber samples. In all cases, we observe that the BFS is a linear function of strain or of temperature, as in standard optical fibers [8]. The standard relationship is usually written as $\nu_B - \nu_{B0} = \alpha \cdot \Delta\varepsilon + \beta \cdot \Delta T$, where ν_{B0} is the BFS at room temperature, α and β are the strain and temperature coefficients, respectively. The strain coefficient decreases from 490 MHz/% (SMF-28 with 3.6-mol% GeO_2 core doping) to 214 MHz/% (98-mol % GeO_2 core doping). This is consistent with the results shown in Fig. 1(a). The Germanium doping indeed strongly modifies their acoustic properties and the acoustic velocity and the mass density, leading to both a strong decrease of the BFS and the strain coefficient. Figure 3(f) shows the strain coefficient as a function of GeO_2 concentration. For low GeO_2 doping level (< 25-mol %), the strain coefficient linearly depends on the concentration with a slope of -5.1 MHz/%/mol%, in good agreement with experimental results reported in Ref. [5]. When using higher concentrations (> 50-mol %), we clearly evidence the asymptotic evolution of BFS strain coefficient down to 214 MHz/% for 98% mol concentration.

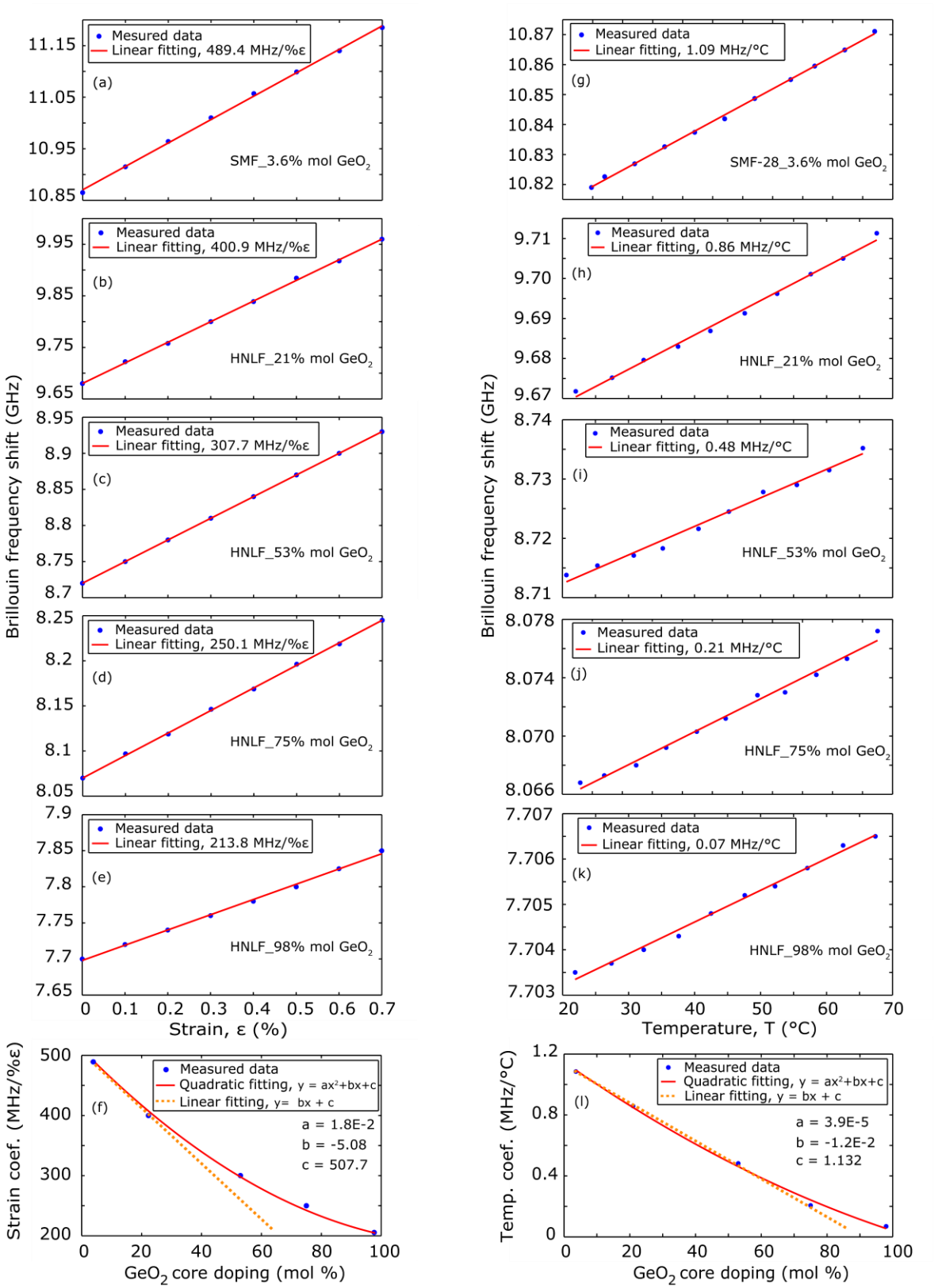

Figure 3: Brillouin frequency shift as a function of both strain and temperature for (a, g) SMF-28 fiber, Highly NonLinear Fiber (b, h) 21% mol GeO_2, (c, i) 53% mol GeO_2, (d, j) 75% mol GeO_2, (e, k) 98% mol GeO_2. (f, l) Strain and temperature coefficients as a function of GeO_2-doping level of the fiber core.

In Fig. 3, we confirm the linear dependence of the BFS as a function of temperature in all fiber samples (from 3.6-mol % to 98-mol %) as reported in Ref. [3]. Figure 3(l) shows the Brillouin temperature coefficient as a function of GeO_2 core doping level. It decreases from 1.09 MHz/°C (3.6-mol % concentration) to 0.07 MHz/°C (98-mol % concentration). Unlike the strain coefficient, the temperature coefficient decreases linearly up to 75-mol % via the least squares fitting with a slope of -0.012 MHz/°C.mol % and becomes quadratic for the concentration doping larger than 75-mol %. To fit correctly the experimental data, a quadratic curve was used (see Fig. 3 (f)). For ultra-high GeO_2 concentration (98-mol % core doping), we can clearly observe that the temperature coefficient is 15 times smaller than SMF-28 fiber (0.07 MHz/°C vs 1.09 MHz/°C) contrary to the strain coefficient which is almost 2 times smaller than SMF-28 (214 MHz/% vs 490 MHz/°C). For the temperature variation considered ranging from 20°C to 68°C, the temperature coefficient measured of ultra-high GeO_2 core concentration (98-mol %) does not change significantly. This properties can be used to design Brillouin fiber sensor to discriminate the temperature and strain effect in fiber [9].

4. Conclusion

To summarize, we have experimentally investigated the temperature and strain sensing potential of stimulated Brillouin scattering in new heavily GeO_2-doped-core optical fibers. We have shown in particular that, for ultra-high GeO_2-doped-core concentration (98-mol %), the temperature dependence of Brillouin frequency becomes almost negligible (0.07 MHz/°C) while its strain coefficient remains significant (214 MHz/%), compared to that of standard single-mode fibers (490 MHz/%). These results demonstrate the strong potential application of heavily Germanium-doped-core silica fibers for distributed Brillouin fiber sensors.

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6. References

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