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Mitigating the Brillouin strain and temperature cross-sensitivity in heavily GeO₂-doped-core optical fibers

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Abstract. We demonstrate an athermal Brillouin strain sensor using heavily GeO₂-doped optical fibers. We also report nonlinear evolution of Brillouin temperature sensitivity as a function of wavelength and strong Brillouin gain in these fibers.

Over the last decade, distributed optical fiber temperature and strain sensors based on stimulated Brillouin scattering (SBS) have seen significant improvement to achieve high performances in terms of sensitivity, sensing range and spatial resolution [1–3]. They are currently widely used in several application areas, including structural health monitoring and security asset integrity [1-6]. However, despite these advantages, conventional SBS-based sensors are still limited by the temperature and strain cross-sensitivity of the Brillouin frequency shift (BFS). Their discrimination remains a critical challenge [4,5], and to date, only a few methods have been demonstrated and reported to overcome this cross sensitivity [6–8].

In this paper, we report an experimental study of strain and temperature impact on BFS in highly GeO₂-doped-core silica optical fibers. We specifically examine five optical fiber samples from low (3.6 % mol) to ultra-high (98 % mol) GeO₂ core content. We observe an athermal property using an heavily GeO₂-doped-core silica fibers [9]. Two ways to realize athermal fibers have been investigated by engineering the polymer-coating diameter and changing the pump wavelength. We also demonstrate a nonlinear evolution of the SBS tem-

perature coefficient as a function of wavelength. These interesting properties could be used to reduce the tensile strain and temperature cross-sensitivity in Brillouin fiber sensors. The BFS of these GeO₂-doped optical fibers were experimentally measured using the heterodyne detection technique, as described in Ref [10] and shown in Fig. 1. 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 with a resolution of a few μm , and the resulting Brillouin gain spectrum was measured. Using an electrical spectrum analyzer (ESA). Concerning the evolution of BFS as a function of temperature, the fibers were immersed into a thermal water bath filled with demineralized water. The temperature change was measured with an electronic thermometer with a precision of 0.1°C. We used the standard heterodyne detection setup based on a tunable continuous-wave laser operating at telecommunication wavelength (C and L Bands) with a narrow linewidth (<10 kHz) to analyze the beat note between the backward Brillouin Stokes signal and a small part of the pump signal. It is worth noting that a power meter was also used to accurately monitor the fiber transmission during the process.

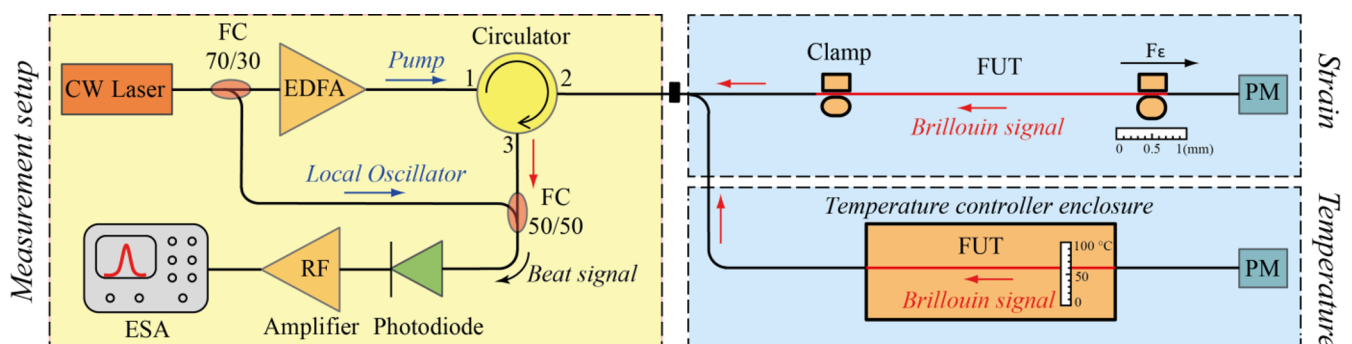


Figure 1: Scheme of the experimental setup for measuring the Brillouin strain and temperature sensing coefficients by heterodyne detection. CW laser: continuous wave laser, FC: fiber coupler, EDFA: erbium-doped fiber amplifier, PM: power meter, RF: Radio frequency, ESA: electrical spectrum analyzer, PM: power-meter, and FUT: fiber under test.

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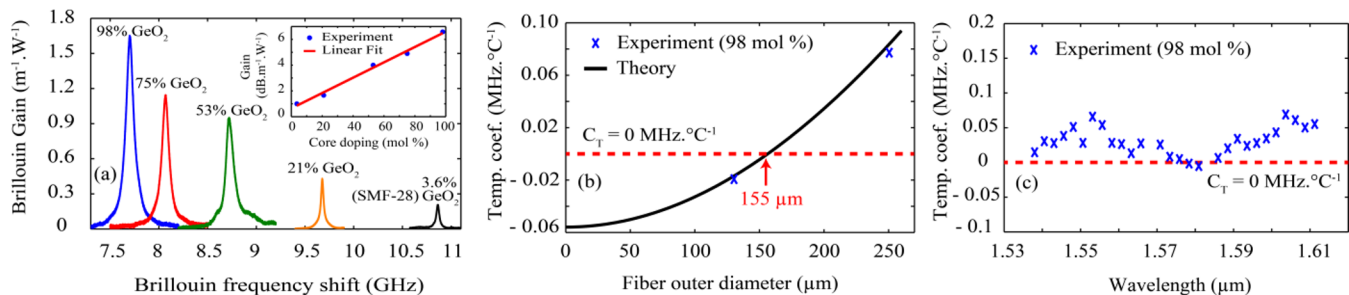


Figure 2: (a) Experimental Brillouin gain spectra measured at 1550 nm in five distinct GeO₂-doped core fibers from low (3.6 % mol) up to ultra-high (98 % mol) doping level. Inset: Brillouin gain efficiency as a function of GeO₂ core content. (b) Polymer coating effect on Brillouin temperature coefficient at 1550 nm wavelength. (c) Evolution of SBS temperature sensitivity as a function of pump wavelength (Both C and L Bands).

Figure 2 (a) shows the measured backward Brillouin gain spectra in five distinct GeO₂-doped core fibers from low (3.6 % mol) up to ultra-high (98 % mol) doping level at room temperature without applied strain using pump probe setup at 1550 nm [10]. As it can be seen, the BFS reduces from 10.85 GHz (SMF-28 fiber) up to 7.7 GHz when increasing GeO₂ core content. In germanosilicate-core fibers, the doping level dramatically changes the elastic properties, in particular, the acoustic phonon velocity and the mass density. The longitudinal acoustic velocity strongly decreases when increasing the core doping level. More importantly, the Brillouin gain significantly increases with doping level due to the strong light and elastic wave confinement. The measured SBS gain for ultra-high doping (98 % mol) is around 6.5 times larger than standard single mode fiber (SMF-28, low doping level 3.6 % mol). Figure 2 (b) shows both experimental (blue dots) and theoretical (red curve) results using heavily GeO₂ core doped fiber (98 % mol). We made used analytical equations reported previously [9]. Our results show that a fully athermal optical fiber could be achieved by reducing the coating thickness down up to around 155 μm . We observe that the temperature sensitivity ($-0.02 \text{ MHz}/\text{C}$) is very close to $0 \text{ MHz}/\text{C}$ without the polymer coating, thus proving that a remarkable athermal behavior is only related to the ultra-high GeO₂ doping level of the fiber core. More importantly, by monitoring the optical coating thickness of the fibers, we could modify coating thermal strain effect on SBS temperature measurements. Consequently, a perfect athermal optical fiber could be readily developed. Note that the strain coefficient in this specialty fiber remains significant (214

$\text{MHz}/\%$ versus 489 $\text{MHz}/\%$ for standard silica fiber). On the other hand, athermal property could be achieved by tuning the pump wavelength as shown in figure 2 (c). We plotted the Brillouin temperature coefficient as a function of pump wavelength (C and L Bands), which evolves in a nonlinear way. The Brillouin frequency becomes insensible to the temperature variation around 1580 nm pump wavelength meaning that athermal behavior can reach at such pump wavelength.

To conclude, we have investigated the temperature and strain sensing potential of stimulated Brillouin scattering in highly GeO₂-doped-core optical fibers. We have shown in particular that, for ultra-high GeO₂-doped-core concentration (98-mol %), the temperature sensitivity becomes almost negligible ($0.07 \text{ MHz}/\text{C}$) while its strain coefficient remains significant (214 $\text{MHz}/\%$), compared to that of standard single-mode fibers (489 $\text{MHz}/\%$). At 1550 nm, this fiber exhibits an athermal point by reducing up to 30 μm the polymer coating diameter. We also demonstrated that the athermal behavior can be reached using a pump wavelength around 1580 nm. These experimental results demonstrate the strong potential application of heavily Germania-doped-core silica fibers to mitigate the strain and temperature cross-sensitivity in Brillouin fiber sensors. Current efforts are deployed to better understand and improve the athermal properties by implementing a heating-cooling cycles test as well as numerical modeling of both stress and mechanical impact on modal properties.

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