Thermal effects on the Brillouin frequency shift in strained optical silica nanofibers

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ABSTRACT

Silica optical nanofibers (ONFs) are waveguides drafted from standard SMF-28 fibers, tapered into near-micrometer diameter rods extending over several centimeters. The strong optical confinement and low propagation losses in ONFs significantly enhance nonlinear effects. In the context of Brillouin scattering, the high temperature sensitivity of these nanoguides can be exploited for sensor applications. In this work, we investigate temperature-induced frequency shifts in the Brillouin spectra of nanofibers, with a particular focus on impact of waveguide geometry and packaging.

Keywords: Brillouin scattering, tapered optical fiber, fiber sensor

1. INTRODUCTION

Brillouin scattering is a non-linear effect describing the coupling between light waves and thermal acoustic waves (phonons).[1] In optical nanofibers, the incident laser light interacts with several acoustic waves, each generating a backscattered optical Brillouin wave, frequency-shifted with respect to the acoustic resonance.[2–4] Previous work on Brillouin scattering in nanofibers has shown that these guides are highly sensitive to strain with a large elasticity. Indeed, due to their small cross-sectional dimensions and lengths of just a few centimeters, nanofibers are highly sensitive to deformation and can be strained up to 6% of their length.[5] This property enables the development of nanofiber-based optical stretcher and micronewton fibers force sensors.[6,7] Unlike standard optical fibers, where the cladding induces stress under temperature variations,[8,9] nanofibers feature an air cladding. This study investigates the impact of nanofibre forks and packaging on the Brillouin frequency shift temperature coefficient, in response to temperature variations; More precisely, we investigate the temperature-dependent shift of the Brillouin frequencies in nanofibers with different lengths and diameters.

2. EXPERIMENTAL MEASUREMENT

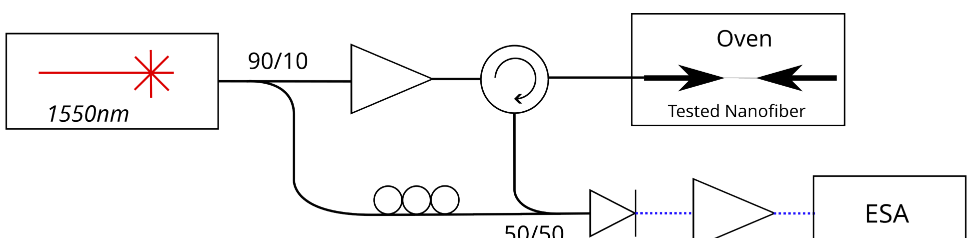

Figure 1. Experimental setup of a Brillouin heterodyne detection, with the nanofiber under test placed in a controlled temperature oven. The pump laser is a high coherent continuous fiber laser with a linewidth of 10 kHz. Blue doted lines represents the electrical links. ESA is an electrical spectrum analyzer.

To make the measurements of the Brillouin spectrum, a standard heterodyne detection system has been set up, presented in Figure 1. It consists of a high coherent continuous fiber laser separated in two arms by a 90/10

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coupler. One arm is amplified to 23dBm with an EDFA, and then send via a circulator in the tested nanofiber placed in a temperature-controlled oven. The back-scattered light is then collected by the circulator and coupled with the polarization controlled arm. The two arms interfere and the resulting signal is sent to a photo-diode. The electrical signal is then amplified and displayed on an ESA.

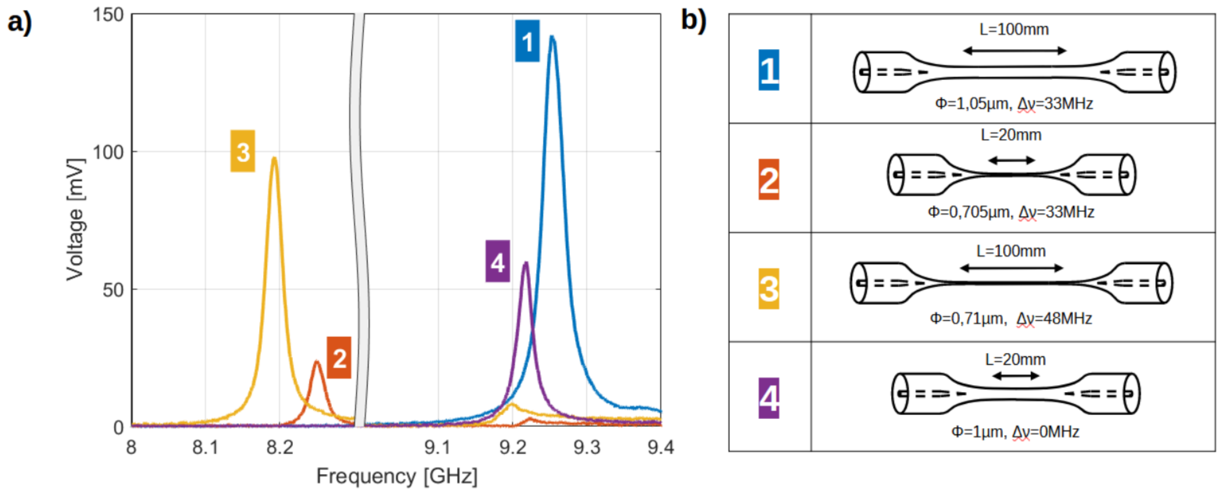

Figure 2. **Characterization of the nanofibers samples** a) Spontaneous Brillouin spectrum of the ONFs. b) ONF geometrical characteristics.

In this study, four nanofibers with varying lengths, diameters, and strain levels were tapered from SMF-28 fiber using the conventional heat-brush technique.[10–12] Following the stretching process, the nanofibers were enclosed in aluminum boxes to protect from external environment. Two of the fabricated nanofibers have an identical 100 mm length for respective diameters of 1.05 and 0.71 µm (referenced as ONF1, ONF3, respectively). The two others nanofibers have a shorter length of 20 mm for roughly the same diameters as the previous ones (0.705 µm for ONF2, 1 µm for ONF4).

Figure 2(a) presents the Brillouin spectra for these four nanofibers. It should be noted that these spectra have been realized at room temperature, with the oven off. The two nanofibers with a length of 100 mm correspond to the strongest interaction and therefore to the highest intensity peaks (ONF1 in blue, ONF3 in yellow). The lower-intensity peaks correspond to the Brillouin responses of 20 mm-long nanofibers (ONF2 in orange, ONF4 in purple). The diameter of the nanofiber influences the spectral frequency due to the phase-matching condition, which applies to different acoustic waves.[13] Additionally, we observe a difference of Brillouin resonance between the two ONFs with the same diameter, attributed to strain during the packaging. Specifically, ONF 1 exhibits a 33 MHz shift due to strain, ONF 2 shows an 81 MHz shift, ONF 3 experiences a 48 MHz shift, while ONF 4 remains unstrained. These values were determined by comparing the frequencies before and after packaging the ONFs. Figure 2(b) summarizes the key parameters of the tested fibers.

By varying the temperature of the nanofibers using an oven, Brillouin spectra were recorded for all four ONFs over a temperature range of 20°C to 50°C. The corresponding variations in Brillouin shift for each ONF are presented in Figure 3. Figures 3(a) and 3(b) illustrate the normalized Brillouin shift for nanofibers with diameters of 700 nm and 1 μm, respectively. In all samples, the observed frequency shift exceeded the theoretical value predicted by the temperature coefficient of silica glass.[14] Notably, compared to bulk silica glass, the Brillouin shift was amplified by a factor of three for the 100 mm nanofiber and by a factor of eight for the 20 mm nanofiber, highlighting a clear dependence on fiber clamp length on the packaging.

3. CONCLUSION

We showed that the temperature coefficient of Brillouin frequency in silica nanofiber is higher than the theoretical value for standard silica fiber. The packaging to maintain the nanofiber induced strain on silica nanofiber when

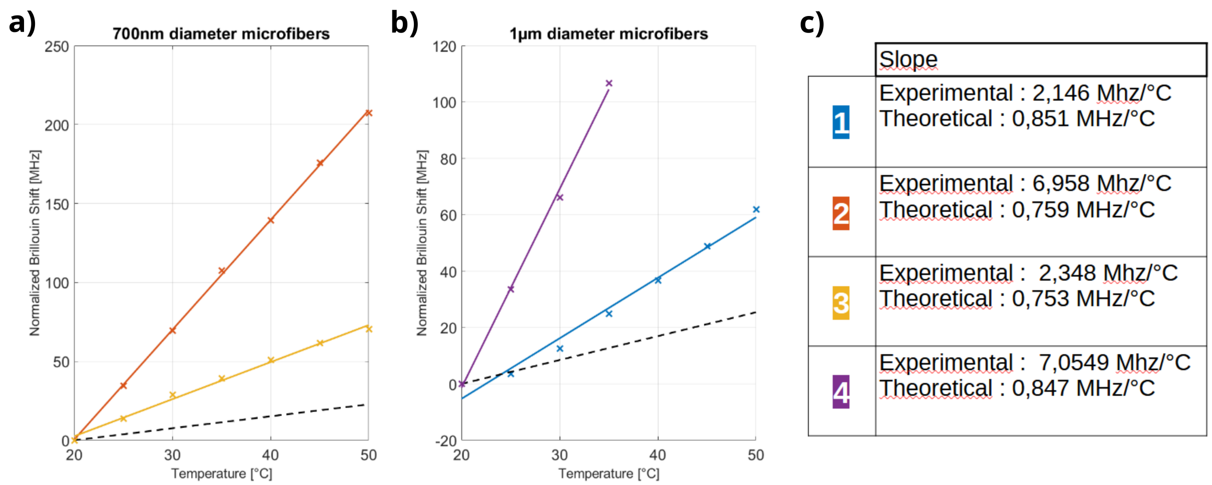

Figure 3. (a,b) Normalized Brillouin frequency shift of the ONF's, for a temperature variation range of 20°C-50°C. The dashed line represents the temperature coefficient in standard silica fiber. c) Slopes values corresponding to temperature coefficient of the ONF's. are summarized. The theoretical value are present for comparison.

temperature variations are applied. For a short nanofiber enclosed in a significantly longer box, the temperature coefficient is eight times higher than that of standard silica fiber. This can have a real interest for the development of ONF fiber temperature sensors. Future work will be dedicated to study the effect of material on nanofiber packaging.

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