Ultra-sensitive Brillouin nanofiber force sensor

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Abstract: We used Brillouin scattering in silica nanofiber to demonstrate a microNewton force sensor having weak optical losses and using only one access of the nanofiber. The measurements are in good agreement with the theoretical model.

OCIS codes : (060.2370) Fiber optics sensors; (290.5900) Scattering, stimulated Brillouin

1. Introduction

Fiber force sensor, offering both a broad detection range and a high sensitivity, is essential for several applications from earthquake monitoring to automation system [1]. Due to the small transverse dimension, the tapered optical fiber have a number of optical and mechanical properties that make them very attractive for both fundamental physics and technological applications [2-5]. Contrary to standard telecom fiber where the Brillouin scattering effect is characterized by a single Lorentzian resonance centred at 10.86 GHz (@ 1550nm), in tapered silica fiber, we identified several Brillouin resonances at different frequencies from 5 GHz to 10 GHz coming from surface, shear and compression elastic waves [6]. In this work, we used the high sensitivity of Brillouin scattering to longitudinal strain and the nanoscale cross-section of nanofiber (the waist part of the tapered fiber) in order to design a very sensitive force at the 10^{-6} Newton range. We report a point fibre force sensor with sensitivity up to 0.66 µNewton/MHz by using a nanofiber diameter of 630 nm.

2. Theory and Experimental Results

The longitudinal force F_z applied to a longitudinal strain ϵ_z on silica nanofiber is defined, in the case where $\epsilon_z < 2\%$, by the linear Hooke's law $F_z = E\epsilon_z A$, with E the Young modulus of the material, $A = \frac{\pi}{4}d^2$ the aera of the nanofiber section, and d the corresponding diameter. We can see that the force is a function of the diameter squared and therefore, for a given strain, smaller diameters allow us to have access to smaller force. To measure microNewton range of the applied force, we use Brillouin scattering phenomenon which is highly sensitive to the material strain. We can express the dependence of the Brillouin frequency shift (BFS) to the force by the sensitivity S, defined by

$$\mathrm{S} = \frac{\mathrm{d}\nu_\mathrm{B}}{\mathrm{dF_z}} = 4\frac{\nu_\mathrm{B}\,\mathrm{C}_\epsilon}{\pi \mathrm{E d}^2}$$

This expression clearly shows that the sensitivity of the BFS to the force is proportional to the Brillouin strain coefficient C_ϵ, linked to the nature of elastic waves [7], and scales inversely with the square of the nanofiber diameter.

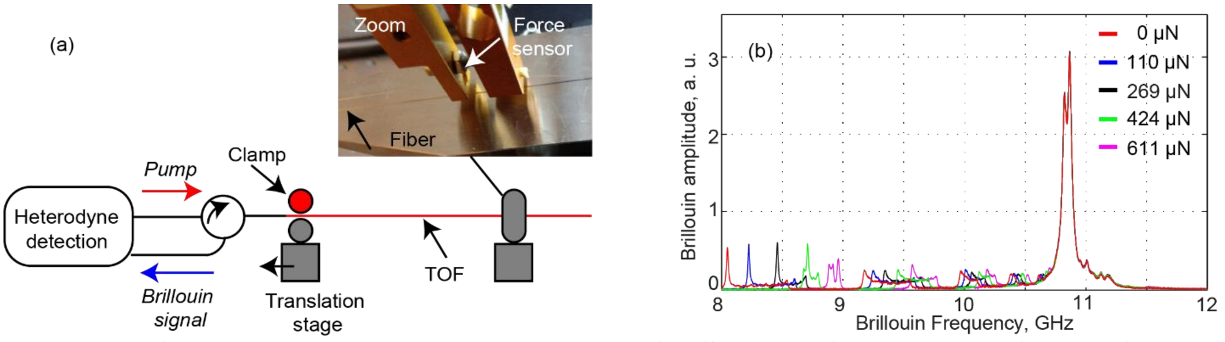

Fig. 3 (a) Sketch of the experimental setup to measure the Brillouin spectrum for different applied force. Zoom, picture of the optical fiber connected to commercial strain gauge. (b) Experimental Brillouin spectrum in tapered optical fiber with a diameter of 630nm for 5 different applied forces.

The tapered optical fibers are produced from commercial optical fibers using well know heat-brush technique. The geometrical parameter of tapered optical fiber as nanofiber diameter and homogeneity are estimated by Brillouin spectroscopy [8]. The experimental setup for measuring the BFS as a function of the applied force is depicted in Figure

3. We used a commercial strain gauge which is able to measure forces in the 10^{-3} Newton range. A picture of the fiber fixed on the force sensor is displayed in Fig. 3(a). One end of the taper is fixed to the translation stage while the other end is fixed to the force sensor. After benchmarking of force sensor, we moved the translation stage by step of 100µm and measured the spontaneous backscattering Brillouin spectrum using heterodyne detection.

3. Discussions

Figure 3(b) shows the experimental spectrum of spontaneous Brillouin backscattering in nanofiber with diameter equal to 630nm for five different applied forces. We observe many resonances, including those due to the nanofiber part in the range (8 GHz-9 GHz), the taper transitions (9 GHz to 10.8 GHz) and the untapered optical fibers (10.8GHz). As we can see, the most sensitive resonance to longitudinal force is the one from nanofiber part because its cross-section is the thinnest and then the strain is much higher than the transitions part.

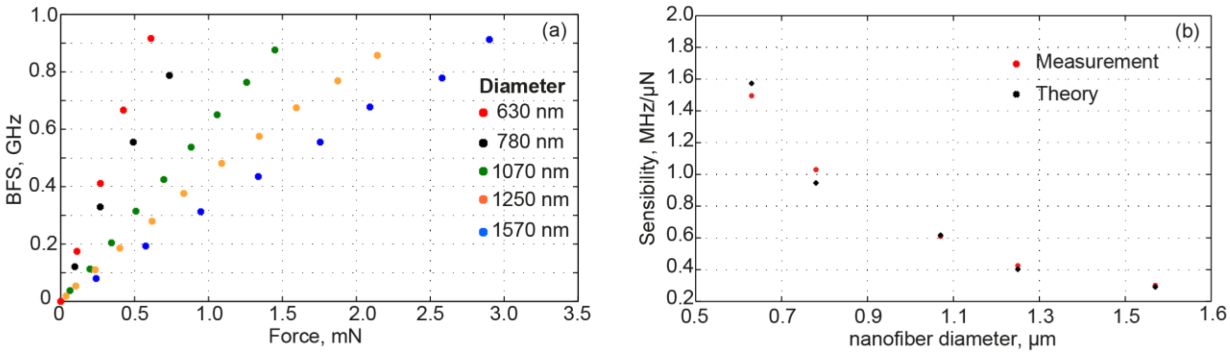

Fig. 4 (a) BFS as a function of applied force for different diameters of tapered optical fibres (red) 630 nm, (black) 780 nm, (green) 1070 nm, (orange) 1250nm, and (blue) 1570 nm. (b) Brillouin sensitivity as a function of the nanofiber diameter, experiment (red) and theory (black).

In figure 4(a), the experimental results of BFS as a function of applied force are shown with 5 different nanofiber diameters in the range from 1.57µm to 630 nm. The slopes corresponding the sensitivities S are plotted as a function of the nanofiber diameter in figure 4(b) and compared to the theory using equation 3. One can derive a force sensitivity of about 1.5 MHz/µN, or 0.66 µN/MHz, for a diameter of 630nm. This means that force sensitivity is higher by more than five orders of magnitude compared to an untapered fiber. The analytical model is in good agreement with experimental measurement.

To conclude, we have experimentally investigated the force sensing potential of Brillouin scattering in tapered silica optical fiber. The linear dependence of Brillouin resonance from compression elastic wave is in good agreement with analytical model. Sensibility (1 MHz/µN) and dynamic ratio (1:2000) can be tune with diameter of taper and the total losses is not modified and below 0.1dB. These results demonstrate the strong potential of tapered optical fiber for vibrational acoustic sensor.

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4. References

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