Detection of nanometer-scale diameter changes in optical fibers with forward stimulated Brillouin scattering

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Abstract. We investigate the potential of forward-stimulated Brillouin scattering in optical fibers to detect changes of the fiber diameter with nanometer resolution.

1 Introduction

In recent years, forward stimulated Brillouin scattering (FSBS) has arisen great interest driven by its potential applications, in particular for fiber optic sensing [1-6], and fiber optic metrology [7-9]. Forward-stimulated Brillouin scattering (FSBS) is an opto-mechanical interaction consisting on the interaction of two copropagating optical waves with transverse acoustic mode resonances (TAMRs) of the optical fiber. TAMRs in optical fibers show high Q factor and quite large sensitivity to changes of the elastic properties and geometry of the fiber, as well as on the properties of the medium surrounding the fiber. Thus, many physical/ chemical/biological magnitudes affecting the fiber, the fiber cladding and/or the medium surrounding the fiber can eventually be monitored by FSBS with excellent resolution and detection limits.

In this communication, we present an experimental work performed to explore the limits of this sensing mechanism. We investigate the ability to detect small changes in the optical fiber diameter, and we show that nanometer resolution is readily achievable.

2 Experimental results and discussion

Figure 1 shows the experimental setup. A pump and probe scheme was developed with two different light sources delivered into the fiber under test (FUT). TAMRs of the FUT were excited by short optical pulses, while the oscillation of the TAMRs was probed by a low intensity CW optical beam. The pump laser was a Nd:YAG Q-switched microchip laser that emitted linearly polarized optical pulses of 700 ps duration at 20 KHz repetition rate at 1064 nm wavelength. The probe laser was a tunable laser diode emitting in the C-band. A set of waveplates and a fiber polarization controller were used for polarization control of pump and probe beams. An optical fiber WDM and a dichroic beam splitter were used to combine/split both beams. Using a linear polarizer, we detect the polarization modulation produced by the torsional-radial $TR_{2,m}$ acoustic modes in the optical probe signal. Resonant frequencies of $TR_{2,m}$ acoustic modes were obtained from the FFT of the probe optical signal.

We investigated the resonance frequency shift of torsional-radial modes with the fiber diameter. Using SMFe-28 optical fiber, we prepared a range of optical fiber samples with slightly reduced diameter, comprised in the range 120−125 µm. Fiber diameter reduction was performed in a controlled manner using a fusion-and-pulling processing technique. For referencing purposes, in all experiments, the FUT investigated included a 5 cm segment of the pristine fiber (nominal diameter of 125 µm) followed by a 4 cm segment of the processed optical fiber.

Figure 2 (a) shows part of the radio-frequency (RF) spectrum of the probe optical signal obtained when the FUT consisted on just 5 cm of the pristine fiber. Each peak in the RF spectrum was produced by the oscillation of a given torsional-radial mode. When the FUT comprised two fiber segments of different diameter, the oscillation of a $TR_{2,m}$ mode led to two peaks in the spectrum, each peak corresponding to each fiber section. Figure 2 (b) was obtained for a FUT comprising 5 cm of pristine fiber and 4 cm of fiber with 124 µm diameter.

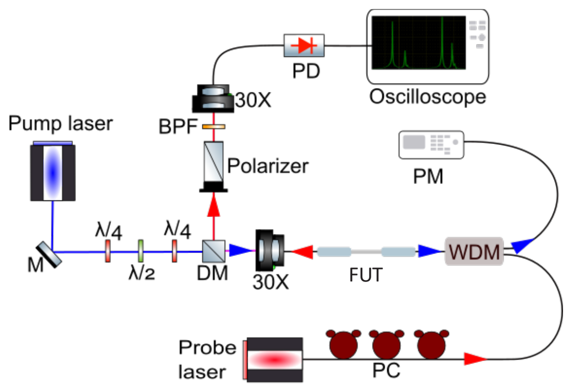

Fig. 1. (a) Experimental arrangement. BPF: bandpass filter; PM: power meter; M: mirror; PD: fast photodiode; DM: dichroic mirror: WDM: fiber optic wavelength-division

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multiplexer; PC: optical fiber polarization controller; FUT: fiber under test.

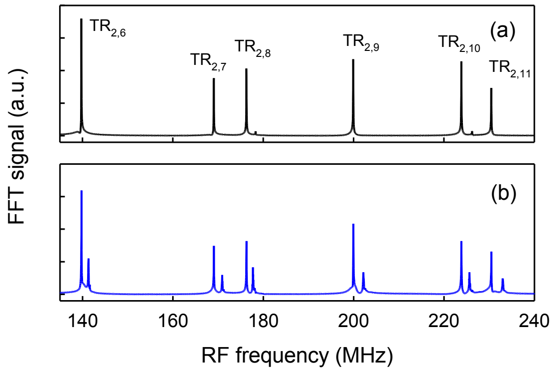

Fig. 2. Radio-frequency spectrum of the probe signal for (a) a 5 cm long section of pristine uncoated optical fiber (125 µm nominal diameter) and (b) a concatenated optical fiber structure comprising 5 cm of pristine optical fiber followed by 4 cm of 124 µm diameter fiber.

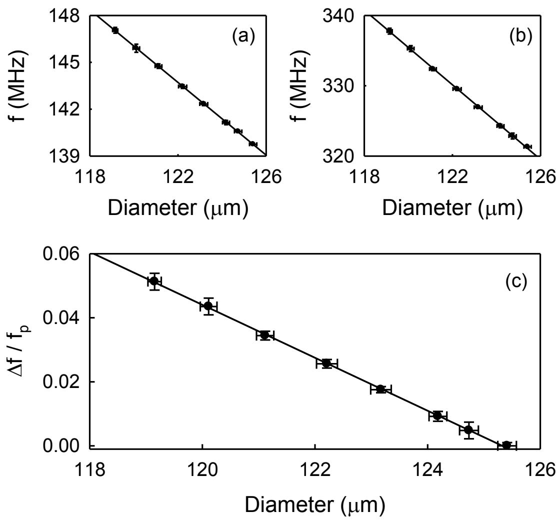

Fig. 3. Frequency as a function of fiber diameter for modes (a) $TR_{2,6}$ and (b) $TR_{2,15}$. (c) Relative frequency shift as a function of fiber diameter.

Table 1. Resonance frequency, frequency shift rate, full-width half maximum and resolution of resonances.

f_p (MHz)	$\Delta f/\Delta d$ (kHz/nm)	*FWHM* *(kHz)*	*Resolution* *(nm)*
230.9	-1.91	84	4.4
321	-2.65	122	4.6
409	-3.39	209	6.2

The frequency shift of $TR_{2,m}$ modes, Δf, as a function of fiber radius was investigated for the different resonances. Peaks shifted linearly with the fiber diameter. Figure 3 (a) – (b) shows the results for resonances $TR_{2,6}$ and $TR_{2,15}$. The shift rate, $\Delta f/\Delta d$, is – 1.163 kHz/nm and – 2.655 kHz/nm, respectively. While the frequency shift rate is different for each mode, the relative frequency shift $\Delta f/f_p$, where f_p is the resonance frequency of the mode in the pristine fiber, is very close for all of them. This agrees with the theoretical analysis that predicts that $\Delta f/f_p$ is determined by the relative fiber diameter change. Figure 3 (c) shows $\Delta f/f_p$ for the particular case of $TR_{2,21}$ resonance. The slope is -8.26 μm^{-1} which is in very good agreement with the expected value.

The smallest fiber diameter change that can eventually be detected by this method depends on the sensitivity, i.e. $\Delta f/\Delta d$, and also on the spectral bandwidth of the peak. The sensitivity increases with the mode order, but the spectral bandwidth also does it. Using the experimental results reported and assuming that our experimental system is capable of resolving a frequency shift equal to 1/10th of the resonance's FWHM, we estimated the resolution provided by each individual resonance. Table 1 summarizes the result for some resonances studied in the experiment.

3 Conclusions

Our experiments confirm that nanometric changes of fiber diameter can be detected by FSBS. The results obtained suggest the development of FSBS-based fiber opto-mechanical sensors for different applications. Together with a suitable transducer mechanism, applications in fields such as chemical and biological sensing can be envisaged.

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References

1. Y. Antman, A. Clain, Y. London, A. Zadok, Optica **3**, 510 (2016).
2. D. M. Chow, L. Thévenaz, Opt. Lett. **43**, 5467 (2018).
3. Y. London et al., J. Lightwave Technol. **39**, 6637 (2021).
4. Y. Xu, X. Zhao, Y. Li, Z. Qin, Y. Pang, and Z. Liu, Sens. Actuators B, **348**, 130702 (2021).
5. K. Shemer et al., Opt. Express **30**, 39321 (2022).
6. L. A. Sánchez, A. Díez, J. L. Cruz, M. V. Andrés, Opt. Express **30**, 14384 (2022).
7. L. A. Sánchez, A. Díez, J. L. Cruz, M. V. Andrés, Sensors **23**, 318 (2023).
8. Hua et al., Light: Advanced Manufacturing, **2**, 25 (2021).
9. L. A. Sánchez, A. Díez, J. L. Cruz, and M. V. Andrés, Opt. Express, **30**, 42, (2022).