10 dB Brillouin gain in silica nanofibers

Maxime Zerbib[a], Simon Colombel[a], Jérôme Salvi[b], Kien Phan Huy[a,b], and Jean-Charles Beugnot[a]

[a]Institut FEMTO-ST, UMR 6174 CNRS-Université de Franche-Comté, Besançon, France
[b]SUPMICROTECH-ENSMM, 25000 Besançon, France

ABSTRACT

Stimulated Brillouin scattering, a fundamental nonlinear optical process, involves the coherent interaction of photons with acoustic phonons in a waveguide, and finds a wide range of applications in signal processing or in optical sensing. In this work, we achieve the amplification of an optical probe signal by exploiting stimulated Brillouin scattering in two optical nanofibers fabricated with very similar diameters and placed in series, demonstrating an amplification larger than 10 dB.

Keywords: Brillouin scattering, Tapered optical fiber

1. INTRODUCTION

Optical nanofibers are highly suitable candidates for studying Brillouin scattering,[1] thanks to their suboptical and sub-acoustic wavelengths dimensions.[2,3] In these ultra-low-loss guides, light guided by the silica/air interface experiences strong confinement, thereby enhancing nonlinear effects.[4,5] In the case of Brillouin scattering, the guided light interacts with various types of acoustic waves (phonons), including longitudinal, transverse, and surface modes.[6,7] Exceptional elasticity of nanofiber was demonstrated and used to realized fibers stretcher.[?,8] In recent work, we demonstrated experimentally a Brillouin efficiency of 15 m-1W-1 in an 18-cm long optical nanofiber with a waist diameter of 990 nm, based on a pressure acoustic wave.[9] This represents a Brillouin efficiency more than 65 times larger than in standards single mode fibers. However, the interaction length of several centimeters limits the energy transfers through the Brillouin process. To overcome this limitation, we propose to use several nanofibers with the same geometrical properties to increase the interaction length. As a result, we observe a 12 dB Brillouin gain with the nanofibers connected in series. The effect of diameter on Brillouin efficiency is investigated. The experimental method to obtain the same acoustic frequency resonance in nanofibers is also presented. This work opens different possibilities to create very efficient Brillouin waveguides for signal processing and coherent laser applications.

2. DUAL-NANOFIBERS SYSTEM

For this study, two optical nanofibers with close geometric parameters were fabricated by tapering standard silica SMF-28 fibers. The tapering process was performed using a conventional heat-brush technique.[10]

The parameters of both nanofibers (ONF1 and ONF2) are listed in the table in Figure 1(a). ONF1 and ONF2 exhibit diameters of 940 and 945 nm, respectively, and both are 18 cm-long (waist region). The waveguides diameters were measured using the Brillouin spectroscopy method[11] and lengths from a Rayleigh reflectometer.

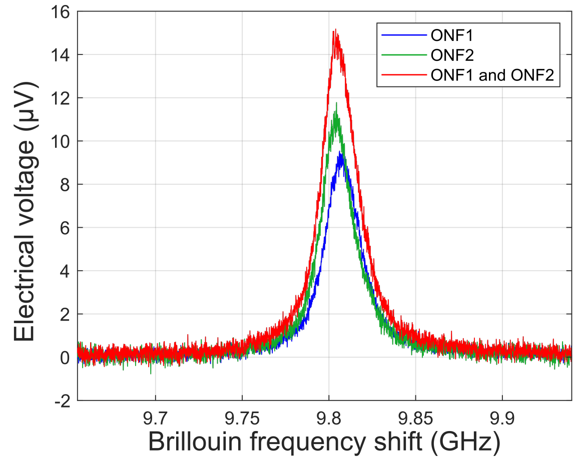
Figure 1(b) illustrates the spontaneous Brillouin responses for each guide separately (blue, green) as well as for the entire system composed of both (red). Nanofiber 1 (ONF1) exhibits a resonance whose Brillouin shift is measured at 9,8075 GHz while nanofiber 2 (ONF2) shows a 9.85 GHz shift. The Brillouin resonance of both nanofibers finds a maximum at a central frequency of ν_B^{1+2}=9,804 GHz. It is important to note that these spectra were measured after the nanofibers were deposited onto a support, a process that induces strain on the waveguides. The primary consequence of this strain is a red shift in each Brillouin frequency, which facilitates frequency matching during packaging. Thus, at the end of the packaging process, the frequency difference

Further author information: (Send correspondence to JC Beugnot)
JC Beugnot : E-mail: jc.beugnot@femto-st.fr

(a)

	ONF1	ONF2
Diameter (nm)	940	945
Length (cm)	18	18

(b)



(c)

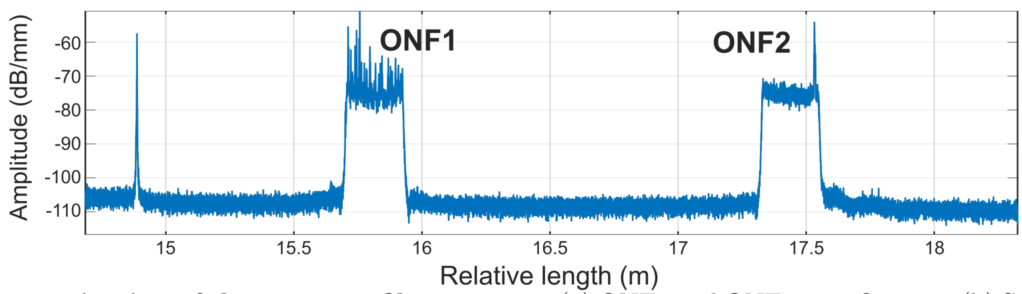


Figure 1: **Caracterization of the two-nanofiber system.** (a) ONF1 and ONF2 specifications (b) Spontaneous Brillouin response measured with an heterodyne detection. (c) Rayleigh reflectometry trace of the two-nanofiber system.

between the two Brillouin responses is of the order of 3,5 MHz. Finest frequency alignment methods will be discussed in the Perspectives section.

Figure 1(c) shows a distributed measurement of Rayleigh backscattering along the system composed of the two nanofibers. This trace was obtained from an optical backscatter reflectometer (OBR4600, Luna). The indicated length is relative as it depends on the effective index considered. In the case of Figure 1(c), the index is calculated assuming waveguides with a diameter close to 940 nm ((n_{eff}=1,1)). The scattering at the two nanofibers is indicated by the markers "ONF1" and "ONF2". In the regions of diameter reduction, the scattering amplitude gradually increases to a level close to -75 dB/mm. Conversely, as the diameter increases in the increasing transitions, the scattering amplitude returns to the initial plateau (-110 dB/mm). The waist of the nanofibers is characterized by a plateau where the scattering amplitude remains constant. It is possible to notice the presence of small scattering peaks on both nanofibers. Nanofiber ON1 is particularly affected, which can be explained by the presence of dust on the waveguide. These defects are the main cause of optical losses on the system.

3. BRILLOUIN AMPLIFICATION CONFIGURATION

Optical nanofibers have attracted significant scientific and technological interest due to their Brillouin scattering properties. Specifically, the strong optical confinement facilitates the excitation of acoustic waves through a stimulated process. In recent work, we investigated the efficiency of this process in optical nanofibers, demonstrating a Brillouin laser effect with a single waveguide placed in a fiber cavity.[9] For this study, we implemented a Brillouin amplification setup for an optical probe, tuned around the Brillouin resonance of a dual-nanofiber system. The pump-probe experimental set-up is depicted on Figure **??** (a).

A laser emits a signal at λ_0=1550 nm which is split into two paths using a fiber coupler (FC). The upper path is used to shape the probe signal frequency. After passing through a first set of polarization controllers (PC), the

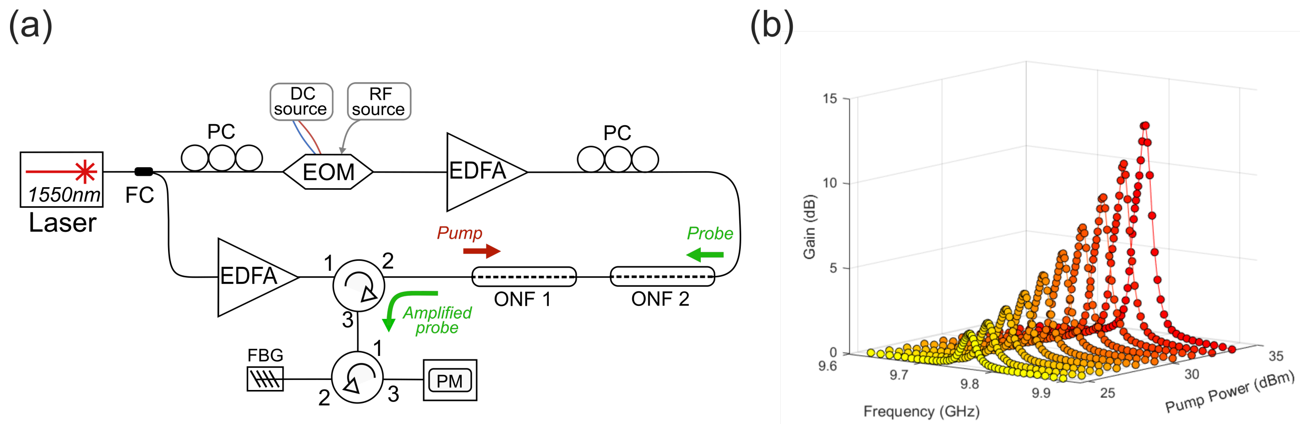


Figure 2: **Pump-probe experiment for Brillouin amplification in two nanofibers placed in series.** (a) Experimental set-up for pump-probe measurements. The probe reaches the nanofibers in the opposite direction to the pump . A sweep of its frequency is carried out from an RF source connected to an electro-optic modulator (EOM). ONF1,2 : optical nanofibers; FC: fiber coupler; EDFA: erbium-doped fiber amplifiers; EOM: electro-optic modulator; PC: polarization controllers; FBG: fiber Bragg grating; PM: optical powermeter. (b) Probe signal amplification in two nanofibers placed in series by stimulated Brillouin scattering as a function of the scanning frequency and the pump power.

light reaches an electro-optic modulator (EOM), which generates optical sidebands spaced by the frequency of the radio-frequency (RF) signal. The probe is then amplified (EDFA) and transmitted to the nanofibers (ONF1, ONF2) after a second set of polarization controllers. The pump, which corresponds to the lower path from the coupler (FC), is amplified and then transmitted *via* a circulator to the nanofibers in the opposite direction to the probe. At this stage, the pump and probe are frequency detuned from the Brillouin shift. Provided that the polarizations are aligned, the probe is amplified through a stimulated Brillouin scattering process before being transmitted *via* the circulator to a second circulator. This last is connected at output 2 to a tunable Bragg grating (FBG) operating in reflection mode. The filtered probe, centered around the Brillouin Stokes resonance of the system, is then sent to output 3 towards a power-meter (PM).

Using this setup, a frequency scan is performed on the probe signal, around the Brillouin frequency, and its amplification is measured at each step with the pump turned on and off. It should be precised that at each pump power, the drift in the Brillouin frequency due to thermal effects in nanofibers is considered for the frequency scan of the probe. The results are presented in Figure 2(b). The 3D figure illustrates the gain (in dB) of the probe (vertical axis) as a function of the scan frequency (GHz). The third axis corresponds to the increased power of the pump (in dBm).

It is notable that when the probe's scan frequency is off the Brillouin resonance, the gain with the pump on relative to when it is off is negligible, close to 0 dB. However, when the probe frequency coincides with the Brillouin resonance, a gain curve appears. This observation confirms the presence of a stimulated Brillouin interaction, the pump energy being transferred to the probe. Furthermore, as the pump power increases, the gain of the amplified probe grows exponentially. The gain on the probe goes from 2,09 dB for a pump power of 24,5 dBm to 12,59 dB for a pump power of 35,5 dBm. These absolute gain values are significant and represents an improvement over a single-nanofiber system. The Brillouin efficiency coefficient $g_B(m^{-1}W^{-1})$ of the dual-nanofiber system corresponding to these experimental is $g_B = 4,4\,m^{-1}W^{-1}$, which represents approximately 21 times greater than the value in a standard SMF-28 fiber.[12]

4. CONCLUSION AND PERSPECTIVES

In conclusion, we have demonstrated a Brillouin amplification effect in a system composed of two nearly identical nanofibers arranged in series. The power gain of the probe reached up to 12,59 dB. This efficiency is limited by the method used to align the frequencies of the two nanofibers. indeed, although they have similar diameters, and the applied strain on each fiber during packaging allows for frequency detuning adjustment, a 3,5 MHz offset is observed. During amplification, this primarily results in a broadening of the resonance, thereby impacting the maximum gain. Other factors also contribute to the limitation of the maximum gain. For instance, the experimental setup does not allow for simultaneous optimization of the polarization of the pump and probe signals in both nanofibers. This consequently limits the intensity of the Brillouin interaction. Additionally, the two nanofibers may respond differently to temperature increases associated with higher power levels, potentially inducing further frequency shifts.

For future experiments, we plan to inject a pressurized gas into the stainless steel tubes in which the nanofibers supports are inserted. This will alter the light-guiding conditions by affecting the effective refractive index of the optical mode through the evanescent field. Preliminary theoretical and experimental results anticipate a tunability of the Brillouin frequency of the order of 10 MHz, by controlling the gas pressure.

ACKNOWLEDGMENTS

This work has received funding from the European Union's Horizon Europe research and innovation program under grant agreement uCAIR (101135175), EQUIPEX+ SMARTLIGHT platform (ANR-21-ESRE-0040), EIPHI Graduate School (ANR-17-EURE-0002).

REFERENCES

[1] Brillouin, L., "Diffusion de la lumière et des rayons X par un corps transparent homogène - Influence de l'agitation thermique," *Annales de Physique* **9**(17), 88–122 (1922).

[2] Beugnot, J.-C., Lebrun, S., Pauliat, G., Maillotte, H., Laude, V., and Sylvestre, T., "Brillouin light scattering from surface acoustic waves in a subwavelength-diameter optical fibre," *Nature Communications* **5** (2014).

[3] Ren, L., Wang, W., Xu, K., Zhu, L., Wang, J., Shi, L., and Zhang, X., "Stimulated brillouin scattering in micro/nanophotonic waveguides and resonators," *Nanophotonics* (0) (2025).

[4] Xu, W., Zerbib, M., Iyer, A., Huy, K. P., Beugnot, J.-C., and Renninger, W. H., "Ultranarrow-linewidth stimulated brillouin scattering with fundamental acoustic waves," *APL Photonics* **10**(1) (2025).

[5] Lebrun, S., Bouhadida, M., Dampt, T., Fauvel, M., Larat, C., Azzoune, A., Beugnot, J.-C., and Divay, L., "Design of composite optical nanofibers for new all-solid-state raman wavelength converters," *Journal of the European Optical Society-Rapid Publications* **20**(2), 37 (2024).

[6] Zerbib, M., Romanet, M., Sylvestre, T., Wolff, C., Stiller, B., Beugnot, J.-C., and Phan Huy, K., "Spin-orbit interaction in nanofiber-based brillouin scattering," *Optics Express* **31**(14), 22284–22295 (2023).

[7] Yang, F., Gyger, F., Godet, A., Chrétien, J., Zhang, L., Pang, M., Beugnot, J.-C., and Thévenaz, L., "Large evanescently-induced brillouin scattering at the surrounding of a nanofibre," *Nature Communications* **13**(1), 1432 (2022).

[8] Godet, A., Chretien, J., Huy, K. P., and Beugnot, J.-C., "Micronewton nanofiber force sensor using Brillouin scattering," *Optics Express* **30**(2), 815–824 (2022).

[9] Zerbib, M., Deroh, M., Sylvestre, T., Huy, K. P., and Beugnot, J.-C., "Stimulated brillouin scattering in silica optical nanofibers," *APL Photonics* **9**(10) (2024).

[10] Birks, T. A. and Li, Y. W., "The shape of fiber tapers," *Journal of Lightwave Technology* **10**(4), 432–438 (1992).

[11] Godet, A., Ndao, A., Sylvestre, T., Pecheur, V., Lebrun, S., Pauliat, G., Beugnot, J.-C., and Huy, K. P., "Brillouin spectroscopy of optical microfibers and nanofibers," *Optica* **4**(10), 1232–1238 (2017).

[12] Eggleton, B. J., Steel, M. J., and Poulton, C. G., [*Brillouin Scattering Part 2*], vol. 110, Academic Press (2022).