EPJ Web of Conferences **287**, 06011 (2023) https://doi.org/10.1051/epjconf/202328706011
*EOSAM 2023*

# Spin-orbit interaction through Brillouin scattering in nanofibers

*Maxime Zerbib*[1,*], *Maxime Romanet*[1], *Thibaut Sylvestre*[1], *Christian Wolff*[2], *Birgit Stiller*[3,4], *Jean-Charles Beugnot*[1], *Kien Phan Huy*[1,5]

[1]FEMTO-ST Institute, UMR 6174 CNRS-Université de Franche-Comté, 25030 Besançon, France
[2]Center for Nano Optics, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark
[3]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany
[4]Department of Physics, University of Erlangen-Nuremberg, Staudtstr. 7, 91058 Erlangen, Germany
[5]SUPMICROTECH-ENSMM, 25000 Besançon, France

**Abstract.** Spin-orbit interactions (SOI), describing the transfer of a spin degree of freedom to an orbital angular momentum (OAM), have been widely explored in recent opto-acoustic studies for applications mainly in spintronics and for topological insulators [1]. We report the observation of SOI by Brillouin scattering in an optical nanofiber. Specifically, we describe the transfer of a spin degree of freedom from light incident to the nanofiber to an acoustic vortex with a topological charge of order 2 in the form of OAM. Coupled with the phase matching condition for the energy conservation during Brillouin scattering, it results in a backscattered wave with a spin opposite to the incident wave. This observation allows considering applications of opto-acoustic Brillouin memory based on polarization conversion through a SOI [2].

## 1 Brillouin scattering in nanofibers

Optical nanofibers (ONF) are advantaged candidates for the study of nonlinear effects due to their small diameters with dimensions inferior to the optical and acoustic wavelengths. Specifically, the strong confinement of photons and phonons leads to a strong Brillouin backscattering (BS) in these guides. BS results from the interaction between an optical wave (pump) and the acoustic waves of a medium which gives rise to the generation of counter-propagating optical waves (Stokes) frequency-shifted with comparison to the pump by Doppler effect (**Fig.1**).

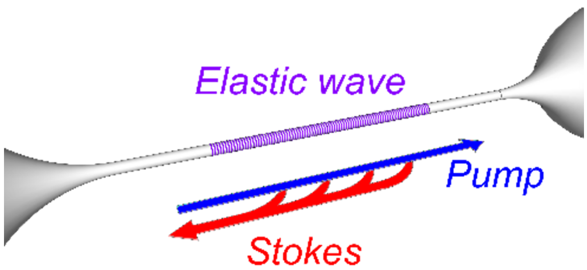


**Fig. 1.** Schematic of Brillouin backscattering in a nanofiber.

The experimental set-up illustrated in **Fig.2.(a)** allows the detection of BS in an ONF. The acoustic signature of a 730 nm diameter ONF through its Brillouin spectrum reveals the existence of longitudinal and transverse acoustic resonances (**Fig.2.(b)**) [3]. The L01,2,3 peaks are related to the Stokes signals backscattered by the longitudinal phonons. The TR21 signal is scattered by the torso-radial phonon oscillating at a frequency of 5.4 GHz.

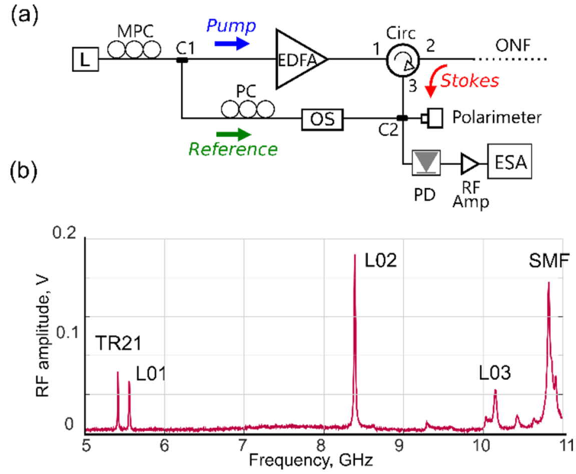


**Fig. 2.** BS detection in an ONF. (a) Heterodyne BS detection set-up. L: laser; MPC: motorized polarization controller; C1,2: couplers; PC: polarization controller; EDFA: Erbium Doped Fiber Amplifier; Circ: circulator; OS: optical switch; PD: photodiode; RF amp: radio-frequency amplifier; ESA: Electrical spectrum analyser. (b) Brillouin spectrum of 730 nm diameter ONF.

The experiments and the simulations showed that the Stokes signals backscattered in the ONF were all polarized in the same way as the pump except for the TR21 signal which was polarization scrambled. Moreover, theoretical, and experimental results revealed that when the state of polarization (SOP) of the pump is circular, the TR21 Stokes signal becomes polarized, in a SOP orthogonal to the pump.

## 2 Theoretical description

The polarization scrambling of the TR21 mode-induced Stokes signal is explained by the degeneration of TR21 into two orthogonal modes: $TR21_+$ and $TR21_\times$

* Corresponding author: maxime.zerbib@femto-st.fr

(**Fig.3. (a)**). This degeneration originates from the slight ellipticity of the transverse section of the nanofiber.

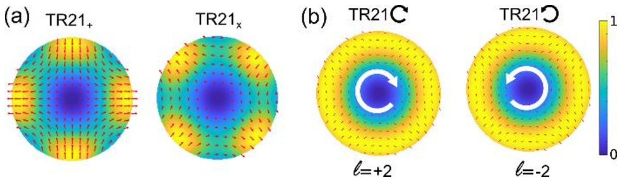


**Fig. 3.** Numerical calculation of transverse profiles of the degenerated TR21 phonons. The red arrows show the transverse displacement field, and the false colors show the normalized transverse kinetic energy. (a) $\mathrm{TR21}_{+}/\mathrm{TR21}_{\times}$basis. (b) TR21 ↻/↺ basis.

The simulations showed that $\mathrm{TR21}_{+}$ and $\mathrm{TR21}_{\times}$ do not have the same impact on the polarization of the backscattered Stokes wave (**Table 1**). Each of these modes has a thermal origin, their temporal superposition is incoherent, and the resulting TR21 Stokes signal is polarization scrambled.

**Table 1.** TR21 degenerated acoustic mode numerically computed for different pump and Stokes states of polarization (SOP). *H* = horizontal, *V* =vertical.

| Phonon | Pump SOP | Stokes SOP |
|---|---|---|
| $\mathbf{TR21}_{+}$ | H<br>V | H<br>-V |
| $\mathbf{TR21}_{\times}$ | H<br>V | V<br>H |
| $\mathbf{TR21}_{+/\times}$ **(incoherent)** | H<br>V | unpolarized<br>unpolarized |

Our model also predicts that when the pump wave is circularly polarized, then the TR21 Stokes wave is circularly polarized in a state orthogonal to the pump. In this case, the circularly polarized pump wave interacts with one of the two following modal solution of the $TR21_{+/\times}$ phonons superposition:

$$\mathrm{TR21} \circlearrowright = \mathrm{TR21}_{\times} + i * \mathrm{TR21}_{+}$$
$$\mathrm{TR21} \circlearrowleft = \mathrm{TR21}_{\times} - i * \mathrm{TR21}_{+}$$

These solutions describe acoustic vortices carrying an orbital angular momentum (AOM) $l = \pm 2$ (**Fig.3. (b)**). The conservation of the total angular momentum (AMC) during Brillouin backscattering thus implies a spin-orbit interaction between the pump wave spin ($s_p$), the TR21↻ /↺ acoustic vortex AOM ($l$) and the Stokes wave spin ($s_s$). At the end the Stokes wave is polarized with a spin opposite to the pump. AMC relation: $s_p = l + s_s$.

## 3 Experimental observations of SOI

The heterodyne detection setup in **Fig.2.(a)** allows to detect a Brillouin spectrum (**Fig.2.(b)**) while keeping information on the Stokes light polarization. Indeed, after a calibration procedure on the reference wave SOP, the projection of the backscattered signal on the reference signal at coupler C2 gives us information on the Stokes SOP. Two co-polarized signals will interfere in a maximum optical beat while two signals with crossed SOP do not interfere. **Fig.4.** represents the TR21 Stokes SOP measurement through the intensity of the optical beat as a function of the pump SOP.

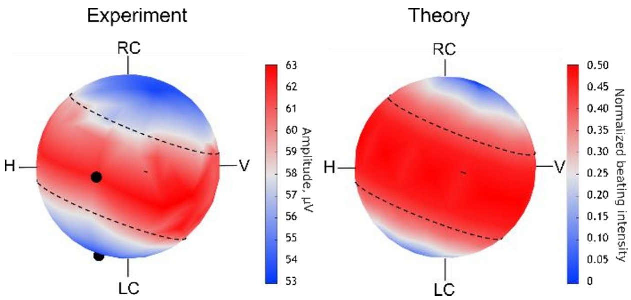


**Fig. 4.** SOP dynamics of the TR21-mode induced BS Experiment (left) and theory (right) TR21 peak intensity represented in false colors on the Poincaré sphere describing the pump SOP.

For the experiment, we vary the pump SOP to reach points distributed over the whole Poincaré sphere, and we extract the intensity of the TR21 peak on the Brillouin spectrum. The intensity is represented in false color. As the SOP of the reference beam did not change throughout the experiment, we can infer the dynamics of the TR21 Stokes signal SOP as a function of the pump SOP. We then observe the two regimes: depolarized TR21 Stokes (linear pump SOPs in red) and TR21 Stokes circularly cross-polarized (circular SOPs pump, in blue). This result agrees with our theoretical predictions.

## 3 Conclusion

Our findings complement recent research on angular momentum conservation in chiral on photonic crystal fibers [4] and standard single-mode fibers using forward Brillouin scattering [5]. Our observations contribute to a deeper understanding of spin-orbit interaction (SOI) in Brillouin scattering and have potential applications for non-reciprocal devices and Brillouin-based optical memories [2,4].

## References

1. K. Y. Bliokh, F. J. Rodríguez-Fortuño, F. Nori, and A. V. Zayats, “Spin-orbit interactions of light,” Nat. Photonics 9, 796–808 (2015)
2. Merklein, M., Stiller, B., Vu, K., Madden, S. J. & Eggleton, B. J. A chip-integrated coherent photonic-phononic memory. Nat Commun 8, 574 (2017).
3. A. Godet, A. Ndao, T. Sylvestre, V. Pecheur, S. Lebrun, G. Pauliat, J.-C. Beugnot, and K. P. Huy, "Brillouin spectroscopy of optical microfibers and nanofibers," Optica 4, 1232-1238 (2017).
4. X. Zeng, W. He, M. H. Frosz, A. Geilen, P. Roth, G. K. L. Wong, P. S. J. Russell, and B. Stiller, “Stimulated Brillouin scattering in chiral photonic crystal fiber,” Photonics Res. 10, 711–718 (2022).
5. G. Bashan, H. H. Diamandi, Y. London, K. Sharma, K. Shemer, E. Zhavi, and A. Zadok, “Forward stimulated Brillouin scattering and optomechanical non-reciprocity in standard polarization maintaining fibres,” 413 Light. Sci. & Appl. 10, 119 (2021).