Observation of Brillouin scattering in a high-index doped silica chip waveguide

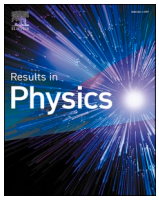
Maxime Zerbib, Van Thuy Hoang, J.C. Beugnot, Kien Phan Huy, Brent Little, Sai T. Chu, David J Moss, Roberto Morandotti, Benjamin Wetzel, Thibaut Sylvestre

Results in Physics 52 (2023) 106830

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp



Microarticle

Observation of Brillouin scattering in a high-index doped silica chip waveguide

M. Zerbib [a], V.T. Hoang [b], J.C. Beugnot [a], K.P. Huy [a], B. Little [c], S.T. Chu [d], D.J. Moss [e], R. Morandotti [f], B. Wetzel [b], T. Sylvestre [a,*]

[a] Institut FEMTO-ST, CNRS Université de Franche-Comté, ENSMM Sup Microtech, Besançon 25030, France
[b] XLIM Research Institute, CNRS UMR 7252, Université de Limoges, Limoges 87060, France
[c] QXP Technologies Inc., Xi'an, China
[d] Department of Physics, City University of Hong Kong, Tat Chee Avenue, Hong Kong, SAR, China
[e] Optical Sciences Centre, Swinburne University of Technology, Hawthorn, Victoria VIC 3122, Australia
[f] INRS-EMT, 1650 Boulevard Lionel-Boulet, Varennes, Québec J3X 1S2, Canada

ARTICLE INFO

Keywords:
Integrated photonics
Silicon photonics
Brillouin scattering
Nonlinear optics

ABSTRACT

We report the observation of Brillouin backscattering in a 50-cm long spiral high-index doped silica chip waveguide and measured a Brillouin frequency shift of 16 GHz which is in very good agreement with theoretical predictions and numerical simulations based on the elastodynamics equation. © 2023.

Introduction

Over the past decade, there has been renewed interest in the design and fabrication of integrated photonic chip waveguides to master and exploit stimulated Brillouin scattering (SBS) [1]. This inelastic scattering, whereby light interacts coherently with hypersonic acoustic waves, is a powerful and flexible nonlinear optical effect for processing light and microwave, as well as an invaluable tool for the development of optical sensors, frequency combs, and lasers [2–4]. While SBS has been exploited earlier on within optical fibers, it is only recently that it has been demonstrated in CMOS-compatible integrated waveguides based on chalcogenide (ChG), silicon (Si), or silicon nitride (SiN) in its stoichiometric composition (Si_3N_4) [5–7]. Here, we demonstrate on-chip Brillouin backscattering in a 50-cm long spiral high-index (n = 1.7) doped silica glass integrated waveguide [8,9].

Experiment and results

The cross-section of the doped silica glass waveguide is shown in Fig. 1(a). It includes a highly-doped silica glass (HDSG) core embedded in SiO_2 on a SOI wafer [9]. The core has a cross-section of 1.50 μm by 1.52 μm. The chip was pigtailed at both ends using carefully aligned and UV-glued polarization-maintaining optical fibers and the total insertion loss of the 50-cm long spiral waveguide has been measured to be 8.9 dB at $\lambda = 1550$ nm by using a high-resolution optical time domain reflectometer (OBR 4600 Luna Tech.). The OBR trace is shown in Fig. 1(b) for a spatial sampling resolution of 20 μm, and the linear loss has been estimated to be as low as 0.1 dB/cm. The Brillouin spectrum was then measured using a heterodyne technique [10], depicted in Fig. 1(c), in which the backscattered Brillouin signal from the photonic chip coherently interferes with a local oscillator and is further detected using an electrical spectrum analyzer (ESA). The resulting Brillouin spectrum is shown in Fig. 1(d) for an input continuous-wave power of 18 dBm at 1550 nm. The Brillouin frequency shift (BFS) and its full-width at half-maximum (FWHM) linewidth were found to be $f_B = 16$ GHz and $\Delta\nu_B \sim 350$ MHz, respectively.

From the Brillouin shift, we can deduce the speed of the longitudinal acoustic wave as $V_L = f_B\lambda/(2n_{\text{eff}}) = 7700\ \text{m.s}^{-1}$, where $n_{\text{eff}} = 1.61$ is the effective index of the fundamental optical mode, which is shown numerically in Fig. 1(e) (Top inset). This is in good agreement with theoretical prediction and numerical simulation shown in Fig. 1(d), where we plotted the computed Brillouin gain spectrum from the elastodynamics equation (for details about the numerical model, See Ref. [8]). The insets in Fig. 1(e) show the computed optical (top) and acoustic (bottom) transverse intensity profiles, respectively. For the optoacoustic simulation, we used the acoustic wave equation driven by

* Corresponding author.
E-mail address: Thibaut.sylvestre@univ-fcomte.fr (T. Sylvestre).

https://doi.org/10.1016/j.rinp.2023.106830
Received 12 May 2023; Received in revised form 14 July 2023; Accepted 3 August 2023
Available online 5 August 2023

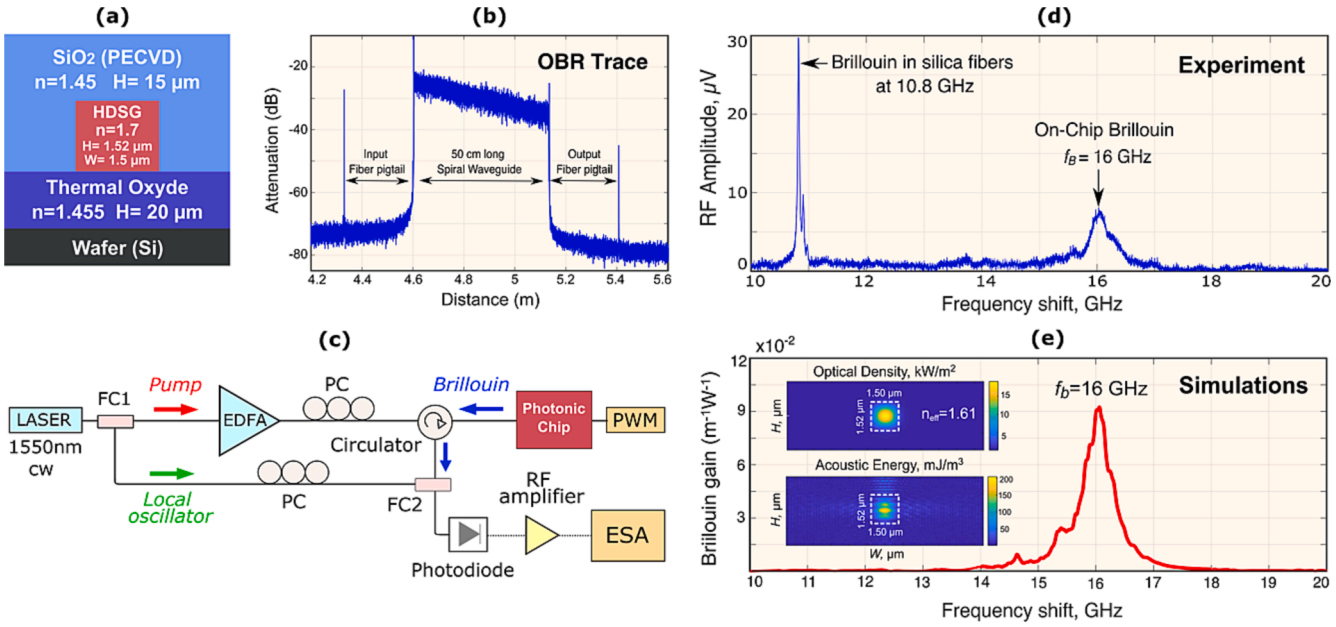


Fig. 1. (a) High-index doped silica chip waveguide cross section used for characterizing Brillouin scattering. (b) Optical backscatter reflectometer trace (spatial resolution = 20 μm). (c) Experimental setup for measuring the Brillouin backscattering spectrum. EDFA (Erbium doped fiber amplifier, PC polarization controller, FC: Fiber coupler; ESA: Electrical spectrum analyser, PWM: power meter). (d) Experimental Brillouin spectrum recorded for an input power of 18 dBm at 1550 nm, showing the Brillouin shift at 16 GHz for the high-index chip and at 10.8 GHz for the silica fibers in the setup. (e) Numerical simulation of the Brillouin gain spectrum. The insets show the computed optical (top) and acoustic (bottom) modes.

Table 1

Physical parameters	Refractive index, n	Density,ρ (kg/m^3)	Young Modulus, E (GPa)	Elastic Coefficients (GPa)	Elasto-optic Coefficients (Unitless)	Viscosity constants (Pa. s)
Highly-doped silica glass	1.7 (1550 nm)	2500	125.6	$C_{11} = 125.6$ $C_{12} = 25.76$ $C_{44} = 49.92$	$P_{11} = 0.12$ $P_{12} = 0.27$ $P_{44} = -0.073$	$\eta_{11} = 2.50.10^{-2}$ $\eta_{12} = 5.12.10^{-3}$ $\eta_{44} = 9.93.10^{-3}$

the electrostrictive stress that reads as [11]

$$\rho\frac{\partial^2 u_i}{\partial t^2}+\eta_{ij}u_j-c_{ijkl}\frac{\partial^2 u_l}{\partial_{x_k}\partial^2 x_j}=-\chi klij\epsilon_0\frac{\partial}{\partial x_j}E_k^{(P)}E_l^{(S)*} \quad (1)$$

where ρ is the material density, u_i are the displacement field components in 3D ($i \in \{x, y, z\}$), c_{ijkl} are the elastic tensor components. η_{ij} are the viscosity constants, χ_{kilj} is the electrostrictive tensor, and ϵ_0 is the vacuum permittivity, respectively. $E^{(P)}$ and $E^{(S)}$ are the optical pump and Brillouin Stokes fields. For the simulation shown in Fig. 1(e), we used the parameters listed in Table 1, taken from Ref. [12]. We found a peak gain of $g_b = 0.09\ m^{-1}W^{-1}$ from simulations, which is in quite good agreement with an estimation from the experimental spectrum (Fig. 1(d)), by comparing with the peak of silica fiber at 10.8 GHz with that of the chip at 16 GHz and their respective lengths ($g_b = 0.087\ m^{-1}W^{-1}$).

Conclusion

In summary, we have investigated, both experimentally and theoretically, Brillouin backscattering in a highly-doped silica glass photonic chip with refractive index n = 1.7 and relatively low loss at 1550 nm. We characterized a 50-cm long spiral waveguide, and found that the Brillouin spectrum features a broad (350 MHz) acoustic resonance near 16 GHz. We also compared the measured Brillouin frequency with theory and found very good agreement. Brillouin's gain was also estimated to be around $0.09\ m^{-1}W^{-1}$. These integrated waveguides could potentially find Brillouin-based applications, if we manage to increase the gain while reducing the linewidth. Finally, we note that SBS was also recently reported in low-index (n = 1.51) doped silica waveguide [13].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work has received funding from by the Agence Nationale de la Recherche (EIPHI Graduate School, ANR-17-EURE-0002), the Bourgogne Franche-Comté Région, the European Research Council (ERC) via the European Union's Horizon 2020 research and innovation programme under grant agreement No. 950618 (STREAMLINE project). B. W. further acknowledges the support of the Conseil Régional Nouvelle-Aquitaine (SPINAL project). R.M acknowledges funding from NSERC via the Discovery and Alliance Programs, as well as from the Canada Research Chair program.

References

[1] Eggleton BJ, Poulton CG, Rakich PT, Steel M, Bahl G. Brillouin integrated photonics. Nat Phot 2019;13(10):664–77.
[2] Marpaung D, Morrison B, Pagani M, Pant R, Choi D-Y, Luther-Davies B, et al. Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity. Optica 2015;2(2):76.

[3] Gundavarapu S, Brodnik GM, Puckett M, Huffman T, Bose D, Behunin R, et al. Sub-hertz fundamental linewidth photonic integrated Brillouin laser. Nature Photonics 2018;13:60–7.
[4] Bai Y, Zhang M, Shi Q, Ding S, Qin Y, Xie Z, et al. Brillouin-Kerr soliton frequency combs in an optical microresonator. Physical Review Letters 2021;126:063901.
[5] Pant R, Poulton CG, Choi D-Y, Mcfarlane H, Hile S, Li E, et al. On-chip stimulated Brillouin scattering. Optics Express 2011;19:8285–90.
[6] Kittlaus EA, Shin H, Rakich PT. Large Brillouin amplification in silicon. Nature Photon 2016;10(7):463–7.
[7] Gyger F, Liu J, Yang F, He J, Raja AS, Wang RN, et al. Observation of Stimulated Brillouin Scattering in Silicon Nitride Integrated Waveguides. Physical Review Letters 2020;124:013902.
[8] Ferrera M, Razzari L, Duchesne D, Morandotti R, Yang Z, Liscidini M, et al. Low-power continuous-wave nonlinear optics in doped silica glass integrated waveguide structures. Nature Photon 2008;2(12):737–40.
[9] Moss D, Morandotti R, Gaeta A, Lipson M. New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics. Nature Photon 2013;7:597–607.
[10] Godet A, Ndao A, Sylvestre T, Pecheur V, Lebrun S, Pauliat G, et al. Brillouin spectroscopy of optical microfibers and nanofibers. Optica 2017;4:1232–8.
[11] Beugnot J-C, Laude V. Electrostriction and guidance of acoustic phonons in optical fibers. Physical Review B 2012;86(22):224304.
[12] Shi Y, He L, Guang F, Li L, Xin Z, Liu R. A Review: Preparation, Performance, and Applications of Silicon Oxynitride Film. Micromachines 2019;10(8):552.
[13] K. Ye, Y. Klaver, O.A.J. Gordillo, R. Botter, O. Daulay, F. Morichetti, A. Melloni, D. Marpaung. "Brillouin and Kerr nonlinearities of a low-index silicon oxynitride platform." APL Photonics. 8. (5). 051302. (2023).