Investigations on Brillouin and Kerr properties of a low-index silicon oxynitride platform

(Student paper)

Kaixuan Ye[1], Yvan Klaver[1], Oscar A Jimenez Gordillo[2], Roel Botter[1], Okky Daulay[1], Francesco Morichetti[2], Andrea Melloni[2], and David Marpaung[1,*]

[1] Nonlinear Nanophotonics, MESA+ Institute of Nanotechnology, Department for Science and Technology, Applied Nanophotonics, University of Twente, 7522 NB Enschede, The Netherlands
[2] Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, 20133, Italy
[*] david.marpaung@utwente.nl

We investigate the Brillouin and Kerr properties of a low-index (n=1.513 @ 1550 nm) silicon oxynitride (SiON) platform. We observed, for the first time, the backward SBS in SiON waveguides. The measured Brillouin gain coefficient is around 0.3 m-1W-1. We also characterized its nonlinear parameter γ, which is around 0.02 m-1W-1. This work presents a low-index photonic integrated platform that is both Brillouin and Kerr active.

Keywords: *Stimulated Brillouin scattering, four-wave mixing, silicon oxynitride*

INTRODUCTION

Stimulated Brillouin scattering (SBS), which is an interaction between optical and acoustic waves, is currently revolutionizing the photonic integrated circuit designs. Featuring a narrow-band (tens of MHz) gain resonance shifted around tens of GHz away from the pump light, the on-chip SBS plays a significant role in microwave photonics, narrow-linewidth integrated lasers, and on-chip nonreciprocal light propagation [1]. Efficient on-chip SBS process requires a relatively large photoelastic coefficient p12 and simultaneously guiding of both the optical and gigahertz acoustic waves in a waveguide, making it difficult to be realized in most integrated platforms.

Silicon oxynitride (SiON) is a highly-developed integrated platform that has appealing properties including low propagation loss, wide transparency window, lack of multi-photon absorption effects, and stress-free fabrication [2]. The mainstream SiON platforms usually have a relatively high refractive index that is close to Si3N4 [2,3]. The high refractive index induces a high nonlinear index and makes it useful for the Kerr-based nonlinear optic applications. Nevertheless, those SiON waveguides have a meager photoelastic coefficient p12. Moreover, the acoustic velocity in those SiON waveguides is also higher than in the cladding, leading to a poor guidance of the acoustic wave. Plagued by these two problems, the SBS effect is too weak and has never been detected in SiON waveguides before.

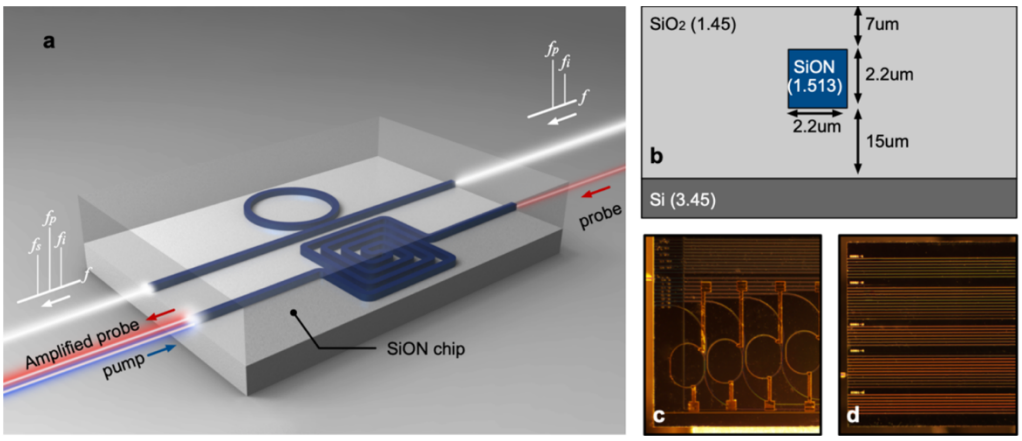

Fig. 1. (a) Artistic representation of the SiON waveguides, showing the four-wave mixing (FWM) process in an all-pass microring resonator and the backward stimulated Brillouin scattering (SBS) in a spiral waveguide. (b) The cross section of the SiON platform in our work. (c) The chip photograph of the SiON microring resonators with a FSR of 50 GHz. (d) The chip photograph of the 5-cm SiON straight waveguide.

In this work, we investigate the Brillouin and Kerr properties of a SiON integrated platform with a relatively lower refractive index (n=1.513 @ 1550 nm). Contrasting to SiON platforms mentioned above, the SiON platform

investigated here has a larger photoelastic coefficient p12, lower acoustic velocity, and a larger cross section, all of which contribute to an enhanced SBS effect. We observed, for the first time, the backward SBS in the SiON waveguide. We also characterized the Brillouin gain coefficient gb of the SiON waveguides with different widths. Furthermore, we measured the nonlinear parameter γ and nonlinear index n2 of this SiON platform with four wave mixing experiments in a ring resonator. This platform is both Brillouin and Kerr active and opens the way to explore the interplay between the SBS and Kerr effect and even build unique applications like Brillouin-assisted Kerr frequency comb in an integrated platform.

RESULTS

We performed the backward SBS and four-wave mixing experiments in single-pass (spiral or straight) waveguides and microring resonators respectively, as shown in Fig.1(a). The cross section of this platform is shown in Fig.1(b) [4]. The 2.2 µm-thick SiON layer has a refractive index n of 1.513 at 1550 nm. It is on top of a 15 µm SiO2 layer and is covered by a 7 µm-thick SiO2 upper cladding. The refractive index contrast Δn between the core and the cladding is 4.4%, guaranteeing a bending radius of 600 µm with negligible radiation losses. Fig.1(c) shows the photograph of the microring resonators in this platform with a free spectral range (FSR) of 50 GHz and coupling coefficients varying from 0.05 to 0.8. Fig.1(d) shows the photograph of several groups of 5-cm straight waveguides with different widths. The measured propagation loss of those straight waveguide is around 0.25 dB/cm with coupling loss of round 3 dB/facet.

We first built a finite element model in COMSOL to estimate the SBS response of the SiON waveguides in this work. The simulated optical field and the corresponding acoustic response of the 2.2 µm-wide SiON waveguide are shown in Fig.2 (a) and (b), respectively. The optical field is well confined around the SiON core area because of the total internal reflection (TIR). However, the TIR condition does not hold for the acoustic response because the acoustic velocity of the SiON (~ 6.2 km/s) is higher than that of the SiO2 (~5.9 km/s). As a result, part of the acoustic field would scatter into the cladding as shown in Fig.2(b). Nevertheless, most of the acoustic field still remains inside the SiON core because of the relatively large cross section area. This results in a large overlap between the optical and acoustic fields, and consequently, contribute to a relatively large Brillouin gain coefficient.

To verify the simulation results, we characterized the SBS responses of the SiON waveguides with a pump-probe experimental apparatus [5]. The pump and probe light are intensity-modulated at slightly different frequencies and coupled into the opposite facets of the waveguide. We keep the pump frequency fixed at around 192 THz (around 1561 nm) while sweeping the probe at frequencies down shifted from the pump by about 15 GHz. When the frequency difference between the pump and the probe is close to the Brillouin frequency shift of the SiON waveguide, the probe will experience the SBS gain and a peak will be detected at the lock-in amplifier.

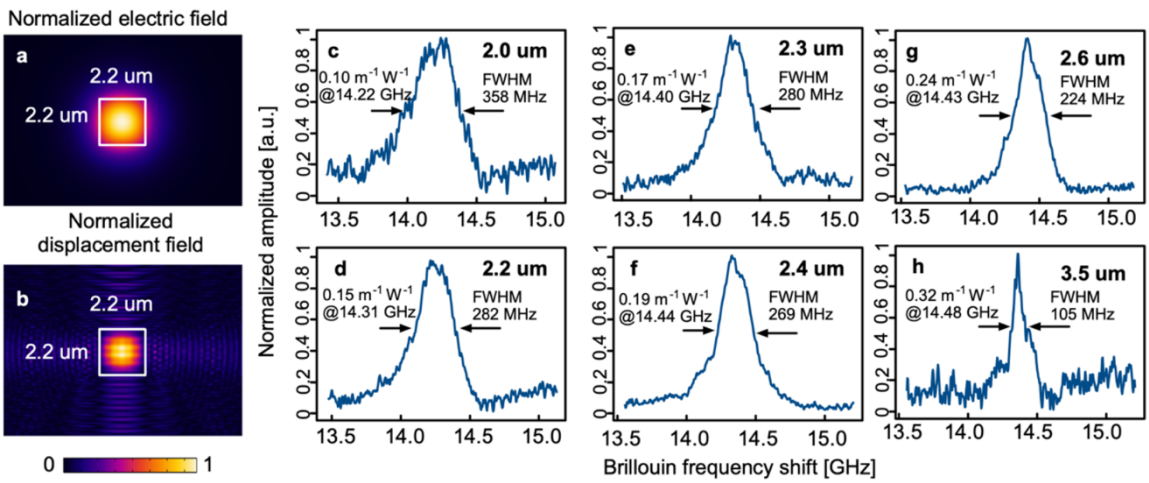

Fig. 2. (a) Simulated optical mode of the SiON waveguide. (b) Simulated acoustic response of the SiON waveguide. (c)-(h) Measured SBS gain spectra of the 2.0 µm, 2.2 µm, 2.3 µm, 2.4 µm, 2.6 µm, and 3.5 µm-wide SiON waveguides, respectively.

Several 5 cm-long SiON waveguides are characterized to investigate the influence of waveguide width on the Brillouin gain spectra, and the measured SBS responses of the 2.0 µm, 2.2 µm, 2.3 µm, 2.4 µm, 2.6 µm, and 3.5 µm-wide waveguides are shown in Fig.2(c) to (h), respectively. All waveguides show a clear peak well above the noise floor with the Brillouin frequency shift increases from 14.22 GHz for the 2.0 µm waveguide to 14.48 GHz for the 3.5 µm waveguide. The Brillouin gain coefficient gb increases from 0.1 m-1W-1 to around 0.32 m-1W-1 when the

waveguide width increases from 2.0 µm to 3.5 µm. In the meantime, the linewidth of the SBS peak reduces from 358 MHz to around 105 MHz. The increasing Brillouin gain coefficient and the narrowing SBS linewidth indicates better acoustic confinement when the SiON waveguides become wider.

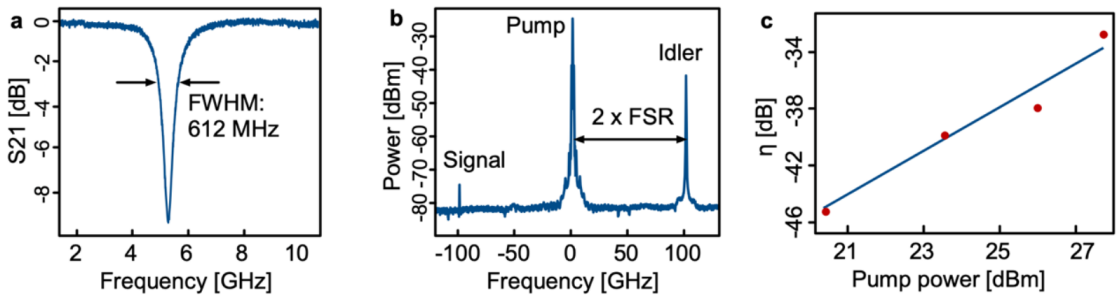

Fig. 3. (a) Measured resonance response of the SiON ring resonator. (b) Measured four-wave mixing response of the SiON ring resonator. (c) Conversion efficiency of the four-wave mixing at different pump power.

We further investigated the Kerr properties of this SiON platform. Previous SiON platforms are widely used for Kerr-based nonlinear optics applications because of the large nonlinear parameter γ. However, the nonlinear parameter γ are highly dependent on the refractive index and the geometry of the waveguide. The SiON waveguide in this work has relatively lower refractive index and a larger cross section compared with other SiON platforms [2,3], and the nonlinear parameter γ of the SiON waveguide in this platform has never been characterized before. We devised a four-wave mixing (FWM) experiment for the nonlinear index characterization. The all-pass ring resonator is used to enhance the FWM in the SiON waveguide so that the contribution from fibers in the setup can be ignored.

To calculate the field enhancement factor of the FWM process in the ring resonator, we first characterized the resonance response of the ring resonator, as shown in Fig.3 (a). The ring resonator applied in our experiment is made of the 2.2 µm-wide SiON waveguide and it has a FSR of 50 GHz and a power coupling coefficient of 0.05. The measured FWHM is around 612 MHz with an extinction ratio of 8.9 dB, corresponding to a Q factor of 330 k and a propagation loss of 0.27 dB/cm. Fig. 3 (b) shows the measured FWM response of the 50 GHz SiON ring resonator. A clear peak is shown at 2 FSR down shifted from the pump frequency, which is the signal generated from the FWM process between the pump and idler in the ring resonator. The nonlinear index n2 and nonlinear parameter γ of the SiON waveguide in this platform can be calculated from the conversion efficiency between the idler and the signal. Fig. 3 (c) shows the conversion efficiency of the FWM process at different pump power. The calculated γ and n2 of the 2.2 µm-wide SiON waveguide is around 0.024 m-1W-1 and 4.16 m2/W, respectively.

DISCUSSION

In this work, we investigated the Brillouin and Kerr properties of a SiON integrated platform with a relatively low refractive index. We observed, for the first time, the backward SBS response of those SiON waveguides. We also measured its nonlinear index n2 and nonlinear parameter γ. These SiON waveguides can be fabricated in a versatile and low-loss integrated platform and can potentially lead to a plethora of Brillouin/Kerr-based applications, including narrow-bandwidth microwave photonic filter, and narrow-linewidth lasers, and optical frequency combs.

REFERENCES

[1] B. J. Eggleton, C. G. Poulton, P. T. Rakich, M. J. Steel, and G. Bahl, Brillouin integrated photonics, Nat. Photonics, vol. 13, pp. 664-677, 2019.

[2] D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, New CMOS-compatible platforms based on silicon nitride and hydex for nonlinear optics, Nat. Photonics vol. 7, pp. 597–607, 2013.

[3] G. Piccoli, M. Sanna, M. Borghi, L. Pavesi, and M. Ghulinyan, Silicon oxynitride platform for linear and nonlinear photonics at NIR wavelengths, Opt. Mater. Express vol. 12, 2022.

[4] F. Morichetti, S. Grillanda, S. Manandhar, V. Shutthanandan, L. Kimerling, A. Melloni, and A. M. Agarwal, Alpha radiation effects on silicon oxynitride waveguides, ACS Photonics, vol. 3, pp. 1569–1574, 2016.

[5] R. Botter, K. Ye, Y. Klaver, R. Suryadharma, O. Daulay, G. Liu, J. van den Hoogen, L. Kanger, P. van der Slot, E. Klein, M. Hoekman, C. Roeloffzen, Y. Liu, and D. Marpaung, Guided-acoustic stimulated Brillouin scattering in silicon nitride photonic circuits, Sci. Adv., vol. 8, pp. 2196, 2022.