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Observation and enhancement of stimulated Brillouin scattering in tellurite covered silicon nitride waveguides.

(Student paper)

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We show, for the first time, stimulated Brillouin scattering in tellurite covered silicon nitride waveguides. In the standard geometry the measured peak gain coefficient is 4.5 $m^{-1}W^{-1}$. We further enhance the Brillouin gain by applying cladding engineering, reaching a peak gain coefficient of 8.5 $m^{-1}W^{-1}$.

Keywords: *stimulated Brillouin scattering, non-linear optics, tellurite, silicon nitride*

INTRODUCTION

Stimulated Brillouin scattering (SBS) is a third order non-linear optical effect, based on the interaction of optical and acoustic waves [1]. In SBS, the interference between two counterpropagating light waves, a probe and a higher frequency pump, create an acoustic wave through electrostriction. This acoustic wave then creates a moving grating through the photoelastic effect. The pump light is reflected by the grating, undergoing a Doppler shift in the process. As a result, the reflected light is downshifted to the frequency of the probe, resulting in a narrowband amplification. SBS on chip is an emerging field, and has shown promising results in applications including sensing and communications [2].

Traditionally, silicon nitride waveguides have low Brillouin gain coefficients, of 0.1 $m^{-1}W^{-1}$ or lower, [3, 4]. This is because silicon oxide cladded silicon nitride does not guide acoustic waves. We have previously shown that a multilayer waveguide can guide the acoustic waves, leading to a gain coefficient of 0.4 $m^{-1}W^{-1}$ [5]. Another option is to use hybrid integration of novel materials.

A promising material for on-chip SBS is tellurite, or tellurium oxide (TeO_2), which has shown to be a good opto-acoustic material [6]. Low loss circuits can be made with tellurite covered silicon nitride waveguides, showing losses down to 0.25 dB/cm [7]. These waveguides can be used for supercontinuum generation [7], and can also be doped

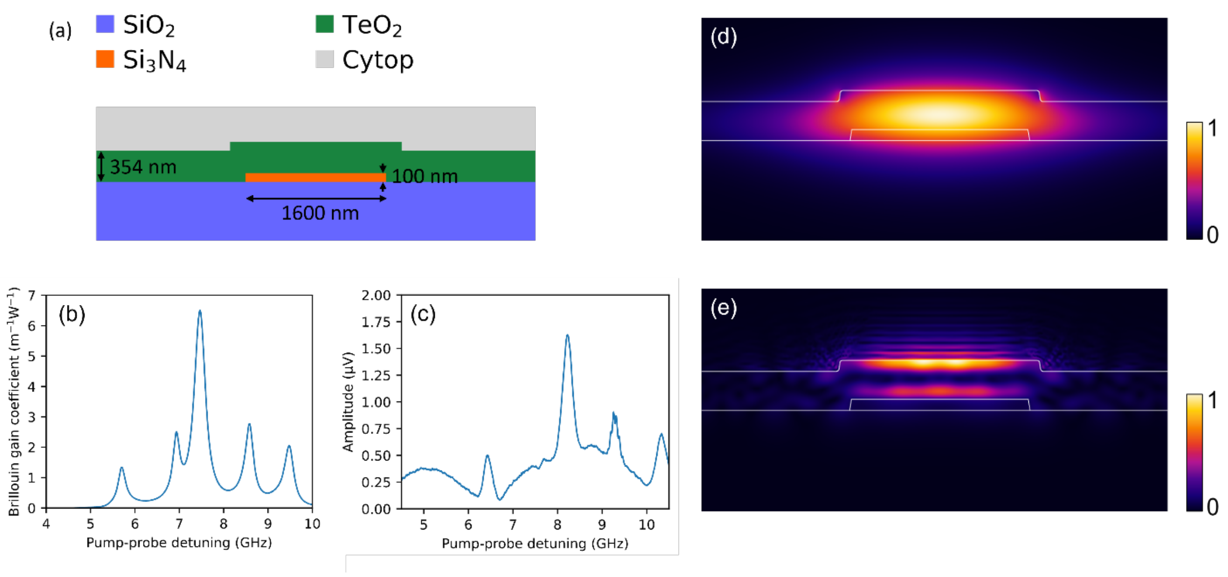

Figure 1: The tellurite covered silicon nitride waveguide. (a) the geometry of the waveguide. The Brillouin response of the waveguide (b) as simulated using COMSOL, and (c) as measured in the experiment. (d) the optical mode of the waveguide, and (e) the displacement field of the acoustic response of the highest Brillouin gain peak.

for use as on-chip amplifiers [8]. However, no investigation of SBS in these waveguides has been carried out thus far.

RESULTS

The first waveguide geometry for SBS considered here is shown in Figure 1 (a). The waveguide is patterned in a 100 nm thick silicon nitride layer. This layer is then coated with a 354 nm thick tellurite layer via sputtering, and cladded with Cytop, a fluoropolymer. The silicon nitride core of this waveguide is 1.6 µm wide. We used COMSOL to simulate the Brillouin response of our waveguide. The resulting gain spectrum can be seen in Figure 1(b), the highest Brillouin peak is 6.5 $m^{-1}W^{-1}$ at a frequency shift of 7.47 GHz. Figure 1 (d) shows the optical mode of the waveguide, and Figure 1(e) shows the displacement field of the acoustic response of the highest gain peak. The simulation tells us that there are multiple acoustic modes leading to a Brillouin interaction, resulting in multiple peaks.

The displacement field in Figure 1 (e) shows how the tellurite layer, as a softer material, is able to guide the acoustics, as expected. It also shows the acoustic waves leaking into the even softer polymer on top.

Figure 1 (c) shows the measured Brillouin response. We can use this to calculate the gain coefficient based on the pump power and waveguide length. The highest measured peak corresponds to a gain coefficient of 4.5 $m^{-1}W^{-1}$ at 8.22 GHz. Overall there is good agreement between spectra, and the peaks identified in the simulation are also visible in the measurement.

ENHANCING THE SBS GAIN THROUGH CLADDING ENGINEERING

As discussed before, the acoustic wave is leaking into the polymer cladding. This results in a reduction of the Brillouin gain, as the acoustic waves in the cladding cannot interact with the optics, preventing optimal opto-acoustic interaction. The polymer is also acoustically lossy, resulting in a further inhibition of the Brillouin process. In an effort to reduce the acoustic leakage, we introduce a thin layer of silicon oxide, a harder material, with a speed of sound of 5960 m/s, between the tellurite and polymer layers, thereby providing improved acoustic confinement. Figure 2 (a) shows the geometry of this new waveguide. Here a 200 nm layer of silicon nitride is covered by 299 nm of tellurite, which is then cladded by a 46 nm layer of silicon oxide, before adding the polymer layer.

Our simulations, depicted in Figure 2 (b) show that the addition of this layer has varying effects on the different acoustic modes. Some are suppressed, but one in particular is strongly enhanced, resulting in a doubling of the peak Brillouin gain. The new peak gain is 11 $m^{-1}W^{-1}$, with a frequency shift of 8.57 GHz. The acoustic response in Figure 2 (e) shows how the acoustic field in the polymer cladding has been reduced, as expected.

Figure 2 (c) shows the measured Brillouin response. Here we see 2 peaks which correspond to a Brillouin gain coefficient of 8.5 $m^{-1}W^{-1}$, at 7.11 and 8.91 GHz. This confirms the higher Brillouin gain achieved by the silicon oxide layer.

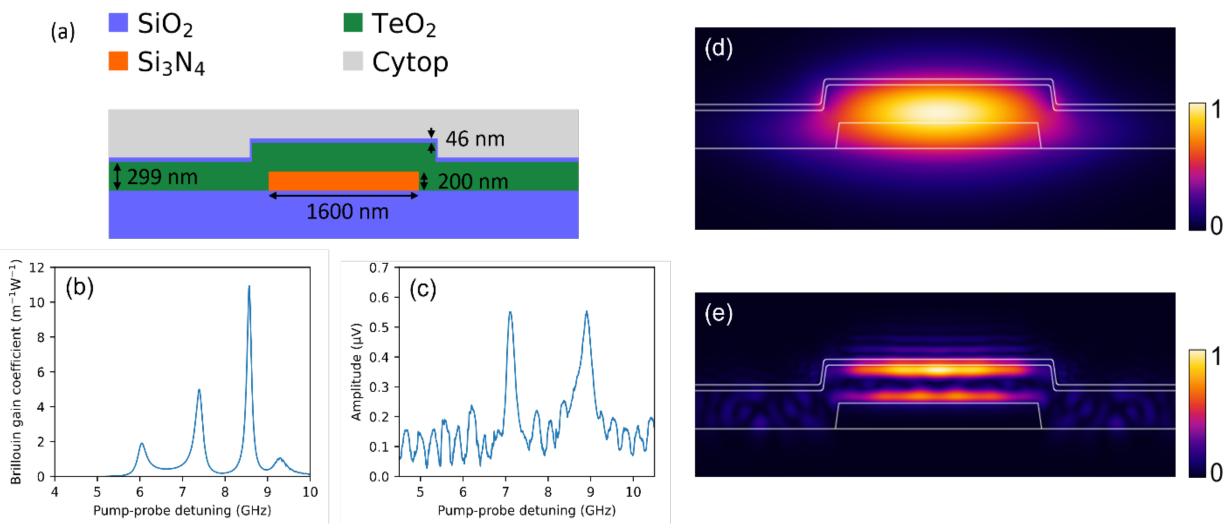

Figure 2: The tellurite covered waveguide with additional silicon oxide layer. (a) the geometry of the waveguide. The Brillouin response of the waveguide (b) as simulated using COMSOL, and (c) as measured in the experiment. (d) the optical mode of the waveguide, and (e) the displacement field of the acoustic response of the highest Brillouin gain peak.

DISCUSSION

We have shown the first stimulated Brillouin scattering in tellurite covered silicon nitride waveguides. The Brillouin response of these waveguides match the predictions of our simulations. We have also shown the enhancement of the Brillouin gain through cladding engineering, where we used a thin layer of silicon oxide to prevent acoustic leakage into the polymer cladding.

The simulations and experimental results of the enhanced Brillouin gain device do not match as well as those of the original device. This is likely due to uncertainty in the exact acoustic losses of the materials, which are unknown.

The thin silicon oxide layer reduced the acoustic field in the polymer, but it does not completely prevent it from leaking into the cladding. We can improve on this by fully cladding the waveguide in silicon oxide, which according to our simulations leads to a peak gain of 35 $m^{-1}W^{-1}$, with a frequency shift of 6.44 GHz. The next step is to develop this cladding to unlock this order of magnitude gain enhancement.

These results open the possibility for creating Brillouin devices on chip, such as narrowband lasers and signal processing components.

References

[1] R. W. Boyd, *Nonlinear Optics*. Elsevier Science Publishing Co Inc, 2008.

[2] 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.

[3] S. Gundavarapu *et al.*, "Sub-hertz fundamental linewidth photonic integrated Brillouin laser," *Nat. Photonics*, vol. 13, no. January, 2019.

[4] F. Gyger *et al.*, "Observation of Stimulated Brillouin Scattering in Silicon Nitride Integrated Waveguides," *Phys. Rev. Lett.*, vol. 124, no. 1, 2020.

[5] R. Botter *et al.*, "Guided-acoustic stimulated Brillouin scattering in silicon nitride photonic circuits," *Sci. Adv.*, vol. 8, no. 40, p. eabq2196, 2022.

[6] T. Yano, A. Fukumoto, and A. Watanabe, "Tellurite glass: A new acousto-optic material," *J. Appl. Phys.*, vol. 42, no. 10, pp. 3674–3676, 1971.

[7] N. Singh, H. M. Mbonde, H. C. Frankis, E. Ippen, J. D. B. Bradley, and F. X. Kärtner, "Nonlinear silicon photonics on CMOS-compatible tellurium oxide," *Photonics Res.*, vol. 8, no. 12, pp. 1904–1909, 2020.

[8] H. C. Frankis *et al.*, "Erbium-doped TeO2-coated Si3N4 waveguide amplifiers with 5 dB net gain," *Photonics Res.*, vol. 8, no. 2, p. 4, 2020.