Design and Material Selection for Enhancing Brillouin Scattering in Integrated Waveguides

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We discuss the material properties necessary for the enhancement of stimulated Brillouin scattering in integrated waveguides. We use these properties to design a Brillouin active waveguide based on a silicon nitride platform. Then we show our simulation results to confirm our material selection.

Introduction

Stimulated Brillouin scattering (SBS) is a third order nonlinear optical process, that is based on the interaction of acoustic and optical waves, as can be seen in Figure 1. The interest for SBS induced in integrated photonic circuits has recently been renewed, as it proven to be useful in RF and optical signal processing, and the design of optical components such as lasers and isolators [1]. Designing these circuits to achieve high SBS gain requires insight into both the optical and acoustic behaviour of the circuits.

The SBS gain can be expressed as

$$G = e^{\frac{g_0 L_{eff} P_{pump}}{A_{eff}}} \quad (1)$$

where L_{eff} is the effective length of the waveguide, accounting for any losses, P_{pump} is the pump power, A_{eff} is the effective area, and g_0 is the Brillouin gain coefficient that can be expressed as

$$g_0 = \frac{4\pi^2 n^7 p_{12}^2 \eta}{\lambda^2 c \rho v_a \Gamma}. \quad (2)$$

Here n is the refractive index of the material, p_{12} is its photoelastic constant, η is the overlap coefficient, describing the overlap between the acoustic and optical modes, λ is the wavelength of the light, ρ is the material density, v_a is the speed of sound, and Γ is the acoustic loss.

We see from Eq. (2) that a high gain coefficient requires overlap of optical and acoustic modes. This can be achieved by designing a waveguide that can guide both optical and acoustic modes. Optical guidance through total internal reflection can be achieved when the refractive index of the core is higher than the refractive index of the cladding. Acoustic guidance can be achieved in the same way, by choosing a core whose speed of sound is

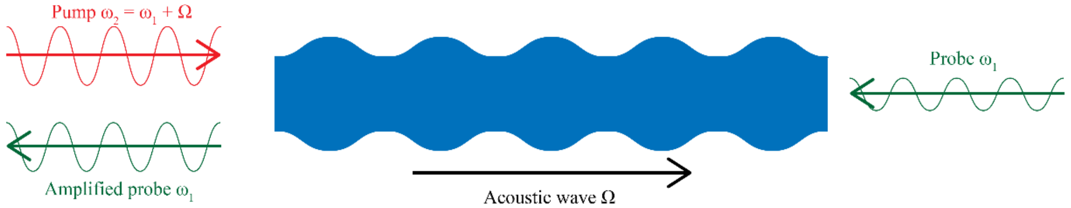


Figure 1: a schematic overview of the stimulated Brillouin scattering process. The interference pattern created by the pump and probe light create an acoustic wave through electrostriction. This acoustic wave modulates the refractive index of the waveguide material through the photoelastic effect, creating a moving grating. This grating then reflects the pump light, which undergoes a Doppler shift, matching its frequency with that of the probe light. The result is a narrowband amplification of the probe light.

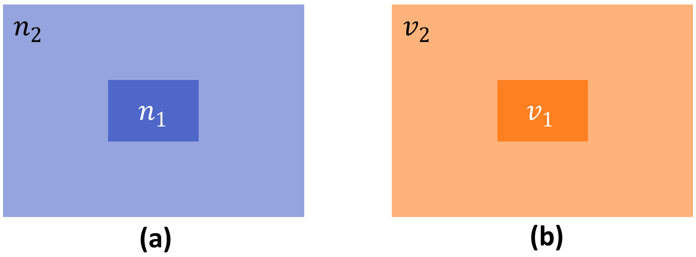


Figure 2: Schematic drawings of **(a)** an optical waveguide (n_1>n_2) and **(b)** an acoustic waveguide (v_1<v_2). Here, n_i is the refractive index of the material, and v_i is the speed of sound of the material.

lower than that of the cladding, causing an effect similar to the total internal refraction seen in optical waveguides. An overview of these conditions can be seen in Figure 2.

Material selection

If we want to design a waveguide that is able to confine both acoustic and optical waves, we have to select materials that fulfil both of the requirements mentioned in the previous section. This means that we want our core to have a higher refractive index and a lower speed of sound than the cladding. Table 1 shows the properties for the materials that have been most relevant to our research.

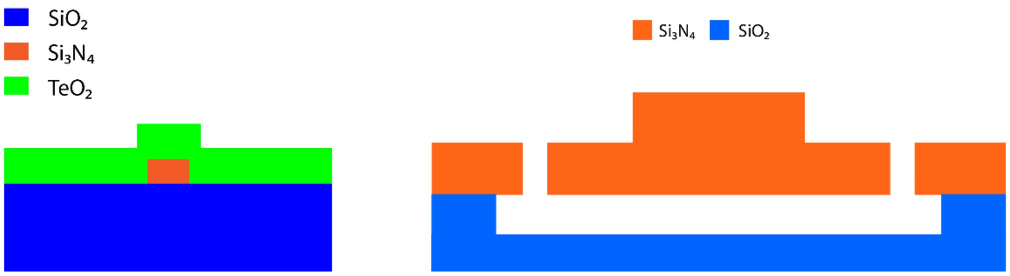
One material group that has been researched are chalcogenides, especially arsenic trisulfide (As_2S_3), which has been used for creating SBS active waveguides [2]. These waveguides are cladded in silicon oxide (SiO_2), and as can be seen in Table 1, the properties of these two materials allow guidance of both optics and acoustics.

Another material option that has been researched is silicon [4, 5]. The activation of SBS in silicon has been achieved by suspending the waveguides, which prevents the acoustics from leaking out of the waveguide.

Our goal is to create SBS active waveguides that are based on a low loss silicon nitride (Si_3N_4) platform [5]. The Si_3N_4 platform creates waveguides with very low (non-linear) losses, which allows the creation of long waveguides that can support high powers, which results in a higher gain, as is described in Eq. (1). These waveguides are cladded with SiO_2, and if we check the properties in Table 1, we see that the refractive indices are as expected for an optical waveguide, but the speeds of sound do not correspond to acoustic guidance. This means that a standard SiO_2 cladded Si_3N_4 waveguide will not guide acoustic modes, which reduces the gain coefficient.

Table 1: selected materials and their properties.

Material	Refractive index	Photoelastic constant	Speed of sound (m/s)
Silicon oxide (SiO_2)	1.45	0.27	5960
Silicon nitride (Si_3N_4)	2.00	0.047	10500
Silicon (Si)	3.48	0.017	8433
Tellurium oxide (TeO_2)	2.089	0.241	4250
Arsenic trisulfide (As_2S_3)	2.4	0.24	2600



(a) **(b)**

Figure 3: Schematic drawing of **(a)** the TeO_2 coated Si_3N_4 waveguide, **(b)** suspended silicon nitride rib waveguide.

One way to enhance the SBS interaction in the silicon nitride platform is through hybrid integration. This means that we combine the platform with another material, that allows us to guide the acoustics as well as the optics. We have selected tellurium oxide (TeO_2) for this purpose. TeO_2 has a refractive index that is similar to that of Si_3N_4, which results in optical guidance in the TeO_2 - Si_3N_4 interface [6]. The speed of sound in TeO_2 is lower than the speed of sound in both Si_3N_4 and SiO_2, which enables the TeO_2 to guide the acoustics. The geometry we settled on is a single strip of Si_3N_4, coated with a layer of TeO_2, as depicted in Figure 3(a)

Another option of enhancing the SBS interaction is to suspend the waveguides, as has been done in silicon. Our design features a rib waveguide, that will be suspended by trenches on either side, and where the underlying SiO_2 is removed through under-etching. The geometry can be seen in Figure 3(b).

Simulations

We used simulations to confirm our choices in materials. These simulations were done using NumBAT, an open source tool that can perform simulations for optical and acoustic modes, and calculate the strength of their interaction [7]. This is expressed in a gain coefficient that is equal to $\frac{g_0}{A_{eff}}$ as seen in Eq. (1).

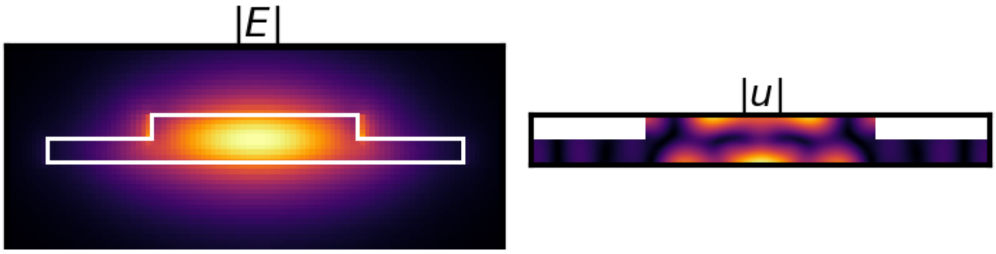
Figure 4 shows the simulated modes found for the tellurite coated waveguide, note how the optical mode is present in both the TeO_2 and the Si_3N_4, and how the TeO_2 layer confines the acoustics.

Figure 5 shows the simulation results for the modes in the rib waveguide. Note how the acoustic mode solver disregards the surrounding air, resulting in a blank background.

Figure 6 shows the gain spectra calculated for both waveguides. Note the difference between the frequency shift in the two materials. This is a result of the difference in speed

(a) **(b)**

Figure 4: Simulated modes of the TeO2-coated Si_3N_4 waveguide, with **(a)** the electric field showing the optical mode and **(b)** the displacement field showing the acoustic mode.



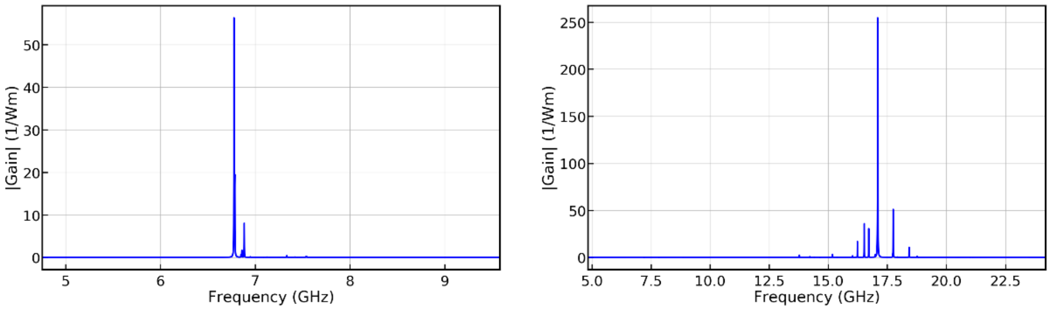
(a) **(b)**

Figure 5: the simulated modes for the suspended rib waveguide, with **(a)** the electric field showing the optical mode and **(b)** the displacement field showing the acoustic mode.

of sound between the materials, as the interaction requires the wavelength of the optical and acoustic wave to be similar.

Conclusion

We have explained the basic principle behind SBS, and how it requires optical and acoustic guidance in a single waveguide. We saw how existing Si_3N_4 waveguides are unable to guide acoustics. We proposed two different methods of creating Si_3N_4 based waveguides that can guide acoustics, one using hybrid integration of other materials, and one based on waveguide geometries. We used simulations to test the acoustic guidance, and estimate the Brillouin gain coefficients for these waveguides.



(a) **(b)**

Figure 6: the calculated gain spectra for **(a)** the tellurite coated waveguide and **(b)** the suspended rib waveguide. The values correspond to $\frac{g_0}{A_{eff}}$ as seen in Eq. (1).

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