Analysis of thermally tunable Brillouin scattering based RF filter

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Brillouin net gain has been demonstrated in SOI free standing waveguides offering interesting perspectives in RF filtering. We investigated the possible use of speed of sound temperature dependency in order to tune the mechanical frequency of such waveguides. We explore designs allowing addressing independently different section of the wave guide in order to increase the full width half maximum of the resonance or to map the waveguide topography (especially its width) and correct inhomogeneous broadening effect (reducing the mechanical line width).

Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear process coupling an optical and a mechanical field [1]. Brillouin resonance has been demonstrated with different silicon waveguide geometries [2],[3]. As demonstrated in [5], it can be used as a tunable and narrow band RF filter. The strong dependency of mechanical resonance frequency, Ω, to the waveguide width allows tailoring of Ω but is also responsible for the decrease in mechanical quality factor, Q, in case of fabrication imperfections. We propose a design based on a free standing TE waveguide (see below). For a 450nm width and 220nm thick waveguide we expect a 9.4 Ghz breathing mode similar to the one observed in [2] and [3].

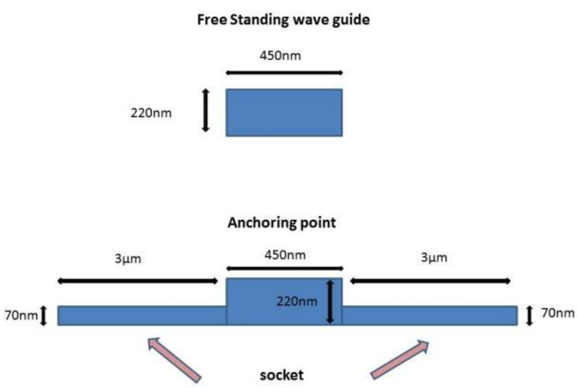

Fig. (1) Cross section of the TE waveguide socket taper

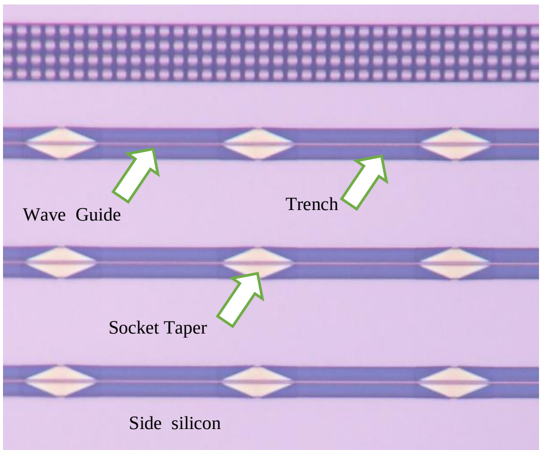

Fig. (2) Top view of SOI TE waveguide with

We study the possibility of thermal tuning based on the design described in [2]: a free standing wave guide (FSWG) suspended by 70 nm (Socket) bridges placed periodically every 25µm (see figures (1) and (2)).

Mechanical and optical mode

We propose to use a TE_{00} mode (figures (3) and (4)) in order to excite the fundamental horizontal mechanical breathing mode (figure (5)) .

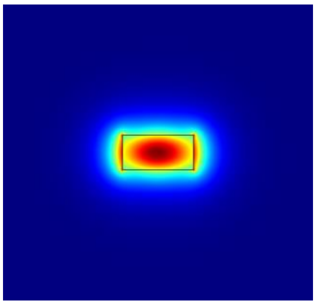

Fig. (3) TE mode of FSWG

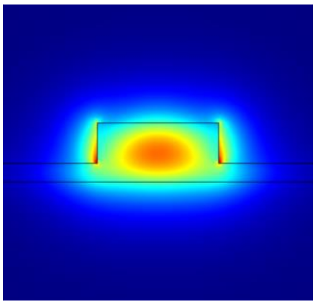

Fig. (4) TE mode of socket wg

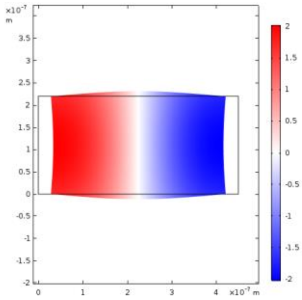

Fig. (5) 9.7GHz mechanical mode

For a 450 nm width and 220 nm hight wave guide, a mechanical mode at 9.7 GHz with a gain coeffecient $G=10^4$ is obtained as demostrated in [3].

Mechanical frequency temperature dependency

Previous measures have shown that Ω can be very accurately modeled using a simple phononic Fabry-Perrot model: $\Omega = v/2w$ with *v*, the sound velocity, and *w*, the width of the wave guide. According to literature the thermal sound velocity sensitivity is

$$S_{th} = \frac{1}{v}\frac{\Delta v}{\Delta T} = -6.10^{-5} K^{-1}$$

We can deduce the frequency shift ΔΩ for temperature variation of ΔT:

$$\Delta\Omega(\Delta T) = \Delta T.\Omega.S_{th}$$

The observed inhomogeneous broadening correspond to a drop of Q from 1000 to 400. This value has been obtained by comparing the width of the Brillouin gain profile for different FSWG length. In order to correct it, a maximum temperature difference ΔT

$$\Delta T = \frac{\Delta\Omega}{\Omega.\mathrm{Sth}} = \frac{1}{\mathrm{Sth}.400} = \frac{1}{-6.10^{-5}.400} = \frac{1}{-2{,}4.10^{-2}} = 41.6\ °C$$

should be reached. We will now evaluate the power needed to reach such a temperature elevation.

Heat transfer simulation

In order to tune the waveguide section temperature, we propose to deposit heaters on the silicon lying on the side of the trench (as defined in figure (2)). The higher thermal conductivity of silicon compared to buried oxide allows for an efficient thermal transfer.

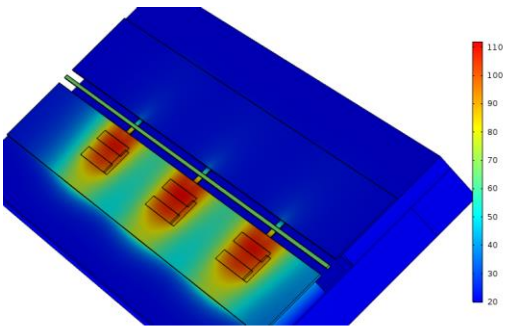

Fig. (5) FEM simulation of thermal transport

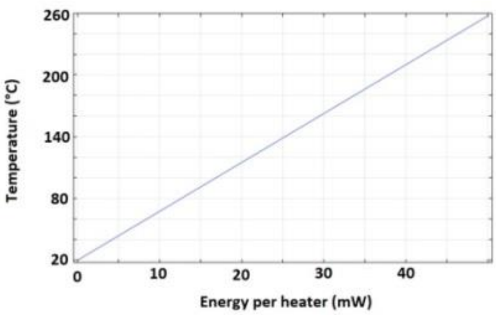

Fig. (6) FSWG temperature vs. heating power per heater

We use finite element simulation in order to evaluate the conversion from electrical power dissipated in the heater to temperature elevation in the waveguide (see figure (6)]). As shown in figure (7), 10 mW per heater allows an increase of 40°C, enough to compensate the inhomogeneous broadening previously observed.

Other factors

Different factors can impact the efficiency of the heating of the free standing waveguide. For instance, the closer the heater is to the side silicon/trench limit, the higher the temperature increase for a given electric power (see figure (8)). Moreover (as shown in figure (9)) the under etching of the side silicon, where heaters are deposited, increase the attainable temperature of FSWG for a constant heating power. Indeed, less heat is dissipated through the buried oxide and can then be conducted through the socket.

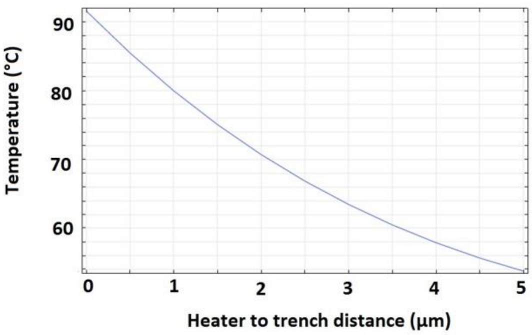

Fig. (8) ΔT vs. heater to edge distance for 10 mW

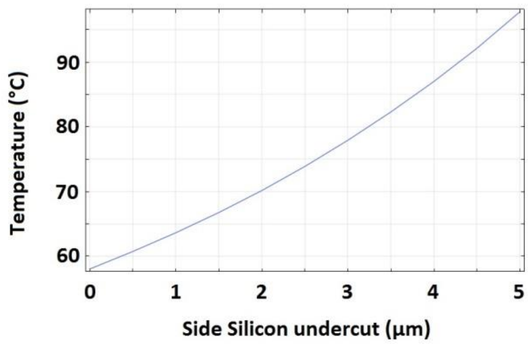

Fig. (9) ΔT vs. under etched distance for 10 mW

Analytical analysis of the Lorenzian resonance tuning

The gain profile on the Stokes line (or depletion of the anti-Stokes) can be described by a Lorenzian curve. In the described configuration we can calculate the gain profile as follows:

$$f(\Omega) = \sum_{n=1}^{N} f_n(\Omega, T_n) = \sum_{n=1}^{N} \left(\frac{1}{N} \frac{a_0}{1 + \frac{(\Omega - \Omega_0 + \Delta T_n.\Omega.\mathrm{Sth})^2}{\Gamma^2}} \right)$$

with N, the total number of FSWG segments, each heated up to a temperature ΔT_n above room temperature, and Γ, the half width half maximum. In figures (10) and (11), we use $\Omega/\Gamma = 200$, which is comparable to conservative experimental values. In figure (10) we plot the Stokes spectrum for different heating power assuming N=8 FSWG segments. The FSWGs are heated with maximum heating power, P, with each segment heated in a constantly increasing manner such that the first segment is heated at P/8 and the last segment heated at P. The maximum heating power is tuned from 8mW to 60mW.

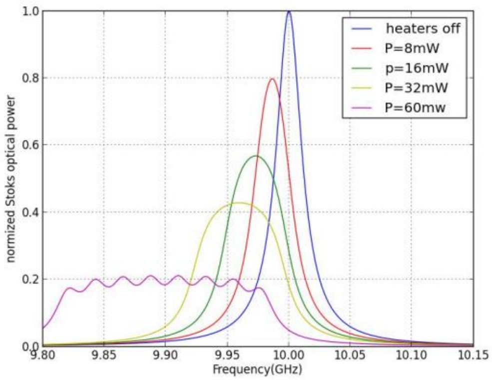

Fig. (10) Resonance broadening, Stokes power vs. heater power

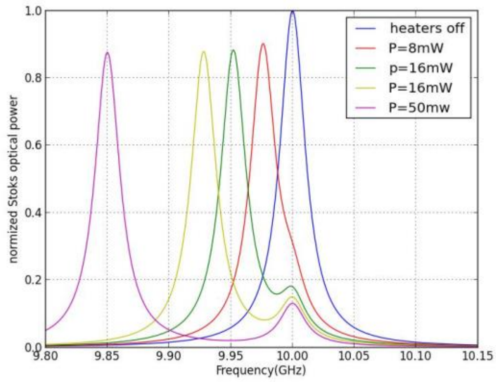

Fig. (11) FSWG width mapping: Stokes power vs. heater power

Individual tuning also allows us to measure the resonance frequency, Ω_n, of each individual FSWG segment. In figure (11) the segment under study is kept at room temperature (heater off) and the other 7 are heated by the same amount of power, P, and gradually increasing P from 8mW to 50mW. We can see that for 32mW and more it is possible to distinguish the resonance frequency Ω_0 of the segment under study. This corresponds to a resonance frequency shift, $\Delta\Omega_n/\,\Gamma > 2.5$. For an arbitrary number of segments N, this number can be found from:

$$f_0(\Omega_0) > \sum_{n=2}^{N} f_n(\Omega_0)$$

$$\frac{1}{N}\ a_0 > \sum_{n=1}^{N}\left(\frac{1}{N}\frac{a_0}{1+\frac{(\Delta T_n.\Omega_0.\mathrm{Sth})^2}{\Gamma^2}}\right) = \frac{\mathrm{N}-1}{N}\ \frac{a_0}{1+(\Delta T_n.\Omega_0.\mathrm{Sth})^2/\Gamma^2}$$

$$\Delta\Omega_n/\,\Gamma > \sqrt{\mathrm{N}-2}$$

Furthermore, by obtaining the resonance frequency, Ω_0, we will be able to accurately evaluate the width of the waveguide segment $\Omega = v/2w$ as mentioned previously.

Conclusion

This analysis shows that thermal tuning of free standing waveguides offers multiple functionalities including compensation of inhomogeneous broadening, mapping of the width of FSWG, and shaping of the Brillouin gain profile, while using reasonable electric power.

References

[1] Léon Brillouin (1914) Diffusion de la lumière par un corps transparent homogène. Comptes Rendus 158, 1331

[2] Laer, V., Bazin, A., & Kuyken, B. (n.d.). Net on-chip Brillouin gain based on suspended silicon nanowires. *New Journal of Physics*, *17*(11),

[3] Van Laer, R., Kuyken, B., Van Thourhout, D., & Baets, R. (2015). Interaction between light and highly confined hypersound in a silicon photonic nanowire. *Nature Photonics*, *16*

[4] Van Laer, R., Sarabalis, C. J., Baets, R., Van Thourhout, D., & Safavi-Naeini, A. H. (2017). Thermal Brillouin noise observed in silicon optomechanical waveguide. *Journal of Optics*, *19*,

[5] B.Morrison and al. (2014). Tunable microwave photonic notch filter using on-chip stimulated Brillouin scattering. *Optics Communications*, *313*