Optimization of Brillouin Gain in Subwavelength Silicon Membrane Waveguides using a Genetic Algorithm

(Student paper)

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Brillouin optomechanics has a great potential for applications in communications, quantum and sensing. Here, we propose a new approach based on a combination of genetic algorithm optimization and subwavelength structuration in silicon waveguides to achieve a Brillouin gain of 3300 W^{-1}m^{-1} for a mechanical mode of frequency 14.79 GHz.

Keywords: *Brillouin scattering, subwavelength, genetic optimization*

INTRODUCTION

Brillouin scattering (BS) refers to the nonlinear interaction between optical and mechanical fields inside a material. BS has generated a great scientific interest due to its numerous applications in communications, sensing and quantum technologies [1]. In nanometric-scale geometries, BS is mediated by the complex interplay between electrostrictive forces and the radiation pressure on the boundaries of the structure [2-4]. As a result, Brillouin gain can be greatly enhaced. However, efficient Brillouin interactions require simultaneous confinement of optical and mechanical modes. Such optomechanical confinement is challenging in silicon-on-insulator (SOI) waveguides due to a strong phonon leakage towards the silica cladding [5-7]. A successful strategy to overcome this drawback is to isolate the silicon optomechanical waveguide by removing the silica cladding. Based on this concept, several membrane designs have been shown to exhibit large Brillouin gain [8-11]. Pedestal waveguides yield a Brillouin gain of 3000 W^{-1}m^{-1} [10], but the need for narrow width pedestals to optimize the Brillouin gain complicates the fabrication process and may compromise mechanical stability. On the other hand, the Brillouin gain in silicon membrane rib waveguides is limited to 1000 W^{-1}m^{-1} due to the very different confinement of optical and mechanical modes [9]. Photonic crystals with simultaneous photonic and phononic bandgaps have been proposed to maximize the Brillouin gain in silicon, achieving calculated values up to 8000 W^{-1}m^{-1} [12]. Nevertheless, the narrow bandwidth and high optical propagation loss, typically linked to bandgap confinement, may compromise the performance of these devices.

Subwavelength structuration represents a promising tool to control photonic and phononic modes in suspended silicon waveguides. Forward Brillouin scattering (FBS), which exhibits the highest gain in silicon nano-structures, relies on longitudinally propagating photons and transversally propagating phonons [5-7]. Hence, engineering the longitudinal and transversal subwavelength geometries would allow independent control of photonic and phononic modes. The exploitation of subwelength geometries has been proposed to optimize Brillouin gain in suspended silicon waveguides [13,14]. Still, they require several etch steps for the silicon layer, complicating device fabrication. Here, we propose a novel approach that yields high Brillouin gain by using subwavelength-structured Si membranes requiring a single-etch step of silicon, illustrated in Figure 1. We develop an optimization method to design the waveguide geometry, combining multi-physics optical and mechanical simulations with a genetic algorithm (GA) capable of handling a large parameter-space [15]. The optimized geometry yields a calculated Brillouin gain of 3300 W^{-1}m^{-1}, with minimum feature size of 50 nm, compatible with electron-beam lithography.

RESULTS

The proposed optomechanical waveguide geometry, depicted in Figure 1, comprises a suspended central strip of width $w_g = 400$ nm, anchored to the lateral silicon slabs by a lattice of arms with a longitudinal period of $\Lambda = 300$ nm, shorter than half of the optical wavelength, ensuring optical operation in the subwavelength regime. The whole waveguide has a fixed silicon thickness of $t = 220$ nm, allowing for single-etch step fabrication. The anchoring arms are segmented in several sections of width (W_i) and length (L_i), where the index $i = 1$ refers to the section contiguous to the waveguide core and the index $i = 5$, to the outermost section.

We implement an optimization method to design the waveguide geometry, combining multiphysics optical and mechanical simulations with a GA capable of dealing with a large parameter space [15]. For FBS, the optical and mechanical mode equations decouple and can be solved separately [7] using here COMSOL Multiphysics® software. We reduce the 3D structure to an equivalent 2D geometry by considering the effective index method and the in-plane stress approximation to compute the optical and mechanical modes, respectively. The Brillouin gain is computed afterwards using MATLAB® [6]. Based on the optomechanical calculations, the GA performs a process of fitness-based selection and recombination to produce a successor population, the next generation. Throughout the optimization process, the dimensions of the sections 1 to 4 are subject to variations within fabrication-oriented limits, while the dimensions of the outermost section remain fixed ($W_5 = 500$ nm, $L_i = 50$ nm) to ensure proper optical guidance.

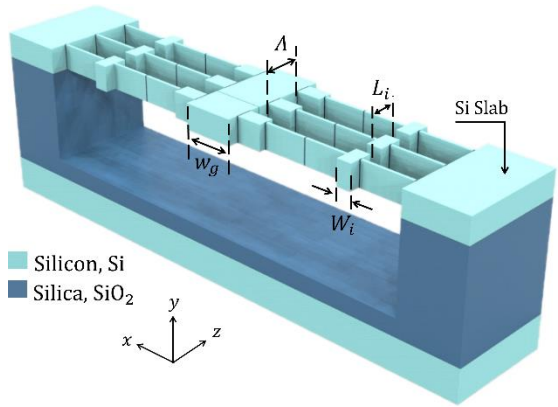

Figure 1: Proposed optomechanical waveguide. The width of the waveguide core ($w_g = 400$ nm), the period ($\Lambda = 300$ nm) and the dimensions of the outermost section ($W_5 = 500$ nm, $L_5 = 50$ nm) remain fixed throughout the optimization process. The thickness of the silicon slab is set to $t = 220$ nm.

The obtained Brillouin gain G_B as function of the number of generations is shown in Figure 2a. The convergence criterion is defined in terms of the difference in performance between the best design and the average of the whole population, $G_B(best) - G_B(average) < 10$ W^{-1}m^{-1} over at least 10 generations. The calculated field distribution for the x-component of the optical field (mode effective index is 2.36 and wavelength in vacuum of $\lambda = 1556$ nm) as well as the mechanical displacement are depicted in Figure 2b for the optimized 2D geometry. This structure exhibits a calculated Brillouin gain of $G_B = 3461$ W^{-1}m^{-1} for a mechanical mode with frequency 14.35 GHz and quality factor $Q = 3200$. Additionally, a full 3D simulation of the optimized geometry was carried out to verify the performance of the optimized geometry. The field distributions of the optical (mode effective index is 2.36 and wavelength in vacuum of $\lambda = 1549$ nm) and mechanical modes are presented in Figure 2c. The calculated Brillouin gain provided by this structure reaches $G_B = 3278$ W^{-1}m^{-1} for a mechanical mode of frequency 14.79 GHz and quality factor $Q = 4000$. These results show a good agreement between the simulations of the approximated 2D and the 3D geometries.

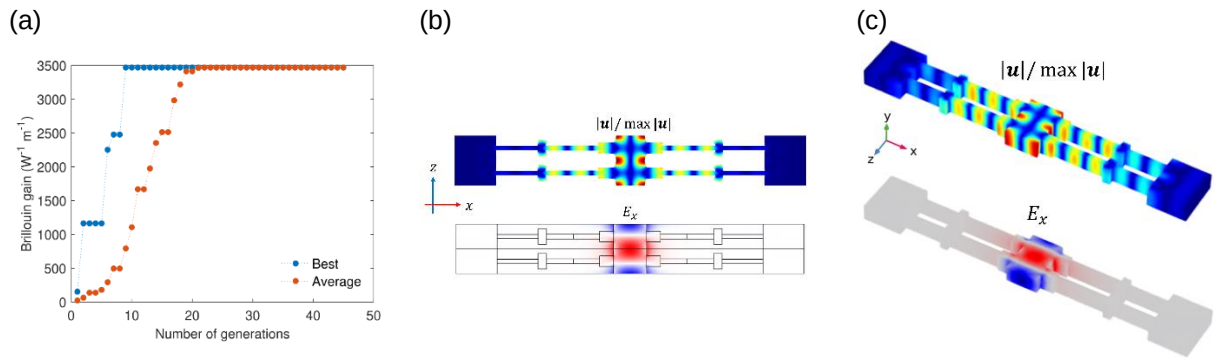

Figure 2: (a) Best (in blue) and average (in orange) Brillouin gain as function of the generation number during the optimization with genetic algorithm. (b) Optical and mechanical modes of the optimized 2D geometry. Normalized mechanical displacement for the mode with frequency 14.35 GHz (up) and x-component of the optical field at $\lambda = 1556$ nm in vacuum (down). (c) Optical and mechanical modes of the optimized 3D geometry. As before, normalized mechanical displacement for the mode with frequency 14.79 GHz (up) and x-component of the optical field at $\lambda = 1549$ nm in vacuum (down) are shown.

For comparison, previously reported silicon periodic waveguides achieved a calculated Brillouin gain of 8000 $W^{-1}m^{-1}$ with a frequency of 5 GHz for photonic crystal approach (photonic and phononic bandgap) [12], a gain of 1750 $W^{-1}m^{-1}$ with a frequency between 3.21 and 3.48 GHz for hybrid subwavelength (for MIR optical mode) and phononic crystal (for mechanical mode) [13] and a gain of 2000 $W^{-1}m^{-1}$ with a frequency of 9.1 GHz for subwavelength waveguide (for optical and mechanical modes) [14]. Our approach yields a gain of 3300 W-1m-1 with a frequency of 14.79 GHz. This result improves previous reported geometries based also on subwavelength structuration both in gain and mechanical frequency. Additionally, while it does not reach the gain provided by phoxonic crystal approach, our geometry may be more feasible in terms of optical propagation loss.

CONCLUSION

In conclusion, we propose a novel strategy to optimize Brillouin gain in subwavelength-structured silicon membranes requiring only one etch step. Based on this approach combining optomechanical simulations and a genetic algotithm optimizer, we present a original design that yields a Brillouin gain up to 3300 $W^{-1}m^{-1}$ for a mechanical mode of frequency 14.79 GHz. This result compares favourably to previously reported subwavelength-based Brillouin waveguides, requiring several etching steps [13]. Additionally, our results illustrate the potential of optimization for obtaining novel designs with improved performance in the context of Brillouin Scattering. Moreover, they show the reliability of computationally efficient optimizations based on approximated 2D simulations.

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