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Enhanced Forward Stimulated Brillouin Scattering in Silicon Photonic Slot Waveguide Bragg Grating

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Abstract

We study the forward stimulated Brillouin scattering process in a suspended silicon slot waveguide Bragg grating. Full-vectorial formalism is applied to analyze the interplay of electrostriction and radiation pressure. We show that radiation pressure is the dominant factor in the proposed waveguide. The Brillouin gain strongly depends on the structural parameters and the maximum value of orders of 10^6 $W^{-1}m^{-1}$ is obtained in the slow light regime, which is more than two orders larger than that of the stand-alone strip and slot waveguides.

Keywords: integrated optics devices, nonlinear, stimulated Brillouin scattering

1. Introduction

Stimulated Brillouin scattering (SBS) is an important third-order nonlinear process that results from the interaction between two optical waves and one acoustic wave [1, 2]. SBS has been extensively studied which leads to applications including distributed temperature sensing [3, 4], slow light [5-7], reconfigurable filters [8-10], optical isolators [11-12] and lasing [13-16].

In the past few years, there has been a surge in utilizing SBS in nanoscale photonic structures. Conventionally, SBS is viewed as an intrinsic material nonlinearity which is dictated by photo-elastic constant through the thermodynamical process of electrostriction [1]. However, this paradigm breaks down within nanoscale structures as the drastically enhanced radiation pressure at the waveguide boundaries cannot be neglected anymore [17]. This new form of boundary-induced nonlinearity significantly impacts the photon-phonon interaction. Thus, electrostriction, as well as radiation pressure, can be tailored through waveguide design to control the SBS gain in nanoscale photonic structures.

Waveguide material through which photons and phonons propagate is a key to harness SBS within nanoscale structures. Typically, materials with large refractive index and high photo-elastic constant are ideal for generating considerable SBS gain [18]. Chalcogenide, for example, has been used to obtain a large gain in a strip waveguide [19]. Meanwhile, silicon waveguide is expected to have a significant gain for its relatively large refractive index (about 3.5). However, it is difficult to observe the SBS process in silicon waveguides, which is mainly ascribed to the silica substrate on which silicon waveguides are usually fabricated using advanced CMOS technology. The small acoustic impedance mismatch between silicon and silica substrate leads to phonon leakage suppressing the photon-phonon interaction [18].

To conquer this problem, it is theoretically proved that a suspended silicon waveguide which is released from the silica substrate leaving no path for external phonon loss exhibits strong SBS gain of 10^4 $W^{-1}m^{-1}$ for both forward and backward SBS process [20]. The nontrivial interplay between the electrostriction force and radiation pressure gives rise to SBS gain in waveguides of hundreds of micrometers comparable to fibers of kilometers long. The feasibility of this scheme is validated through partially [21] and fully [22] suspended silicon waveguides. A further boost of the SBS gain coefficient can be realized through a novel waveguide structure design. Suspended slot waveguide is predicted to generate SBS gain of about 10^5 $W^{-1}m^{-1}$ due to the reinforcement of radiation pressure within the narrow gap [23]. Photonic crystal waveguide suspended in air is shown to dramatically enhance the SBS nonlinearity at the Brillouin zone boundary where group velocity is extremely slow [24, 25].

In this paper, we take a step forward to investigate the forward SBS gain in a suspended silicon slot waveguide Bragg grating. Three-dimensional finite element method (FEM) is used to simulate the optical and elastic modes with full-vectorial formalism. Simulation results show that the enhanced radiation pressure force between the narrow gap along with the decreased optical group velocity drastically increase the FSBS gain to about 10^6 $W^{-1}m^{-1}$.

2. Theoretical model

Stimulated Brillouin scattering is generated by pump and Stokes wave coupling through an acoustic wave. Both energy and momentum are required to be conserved during the SBS process:

$$\mathbf{q} = \mathbf{k_p} - \mathbf{k_s} \tag{1}$$

$$\Omega = \omega_p - \omega_s \tag{2}$$

where $\mathbf{q}$, $\mathbf{k_p}$ and $\mathbf{k_s}$ are the wavevectors of the acoustic, pump and Stokes waves with a frequency of Ω, ω_p and ω_s respectively.

Through particle fluxes conservation, the stimulated Brillouin scattering modal gain coefficient G can be described as [20]:

$$G(\Omega) = \frac{1}{\delta z}\frac{\omega_s}{\Omega}\frac{1}{P_p P_s}\int_{\delta V} \mathbf{f}\cdot\dot{\mathbf{u}}dV \tag{3}$$

where P_p and P_s are the powers of the pump and Stokes waves propagating along the z-axis, $\dot{\mathbf{u}}$ is the displacement velocity distribution excited by the optically induced force distribution $\mathbf{f}$. The integration is taken over δV, which is in a short segment δz of the waveguide.

For periodic waveguides, the integration is taken over a unit cell along the propagating direction. Furthermore, the power of pump and Stokes waves can be expressed as a function of the optical group velocity v_g and unit cell length a [26, 27]:

$$P_{p,s} = \frac{1}{2a}\cdot\varepsilon_0 v_g^{p,s}\int_{\delta V}\varepsilon_r(\mathbf{r})\left|\mathbf{E}_{p,s}(\mathbf{r},\omega_{p,s})\right|^2 dV \tag{4}$$

Considering the elastic loss where the quality factor Q of the elastic response is present [28], the SBS gain of a single elastic mode in a periodic waveguide has a peak value of:

$$G(\Omega) = \frac{2a\omega Q}{\Omega^2 v_{gp} v_{gs}}\frac{\left|\langle \mathbf{f},\mathbf{u}\rangle\right|^2}{\langle \mathbf{E}_p,\varepsilon\mathbf{E}_p\rangle\langle \mathbf{E}_s,\varepsilon\mathbf{E}_s\rangle\langle \mathbf{u},\rho\mathbf{u}\rangle} \tag{5}$$

where $\langle\ \rangle$ denotes the integration of the inner production over a single unit cell and ρ is the mass density of the waveguide material. To simplify the calculation, the assumption is made as in [28, 29] that $\omega_p \approx \omega_s = \omega$ and $k_p \approx k_s = k$. Besides, integrals of different optical forces are linearly summed in Eq. (5), which allow us to investigate the SBS gain induced by different optical forces independently.

Throughout this paper, we consider two kinds of optical forces: electrostrictive body force resulting from the nonzero photo-elastic constant and radiation pressure derived from the Maxwell stress tensor (MST). The electrostriction force in a waveguide is defined as [17]:

$$F_j = -\sum_i \partial_i \sigma_{ij} \tag{6}$$

where σ_{ij} is the electrostriction stress tensor. The tensor σ_{ij} can be further expressed as:

$$\sigma_{ij} = -\frac{1}{2}\varepsilon_0 n^4 \sum_{kl} p_{ijkl} E_k E_l \tag{7}$$

where p_{ijkl} is the photo-elastic constant of the material.

The radiation pressure on the waveguide boundary between material 1 and 2 is defined as [28]:

$$F_i = \left(T_{2ij} - T_{1ij}\right)n_j \tag{8}$$

The MST T_{ij} in the dielectric media is expressed as:

$$T_{ij} = \varepsilon_0\varepsilon_r(x,y)\left[E_i E_j - \frac{1}{2}\delta_{ij}|E|^2\right] + \mu_0\mu_r\left[H_i H_j - \frac{1}{2}\delta_{ij}|H|^2\right] \tag{9}$$

where E and H are the electric and magnetic components of the optical field.

3. Simulation results

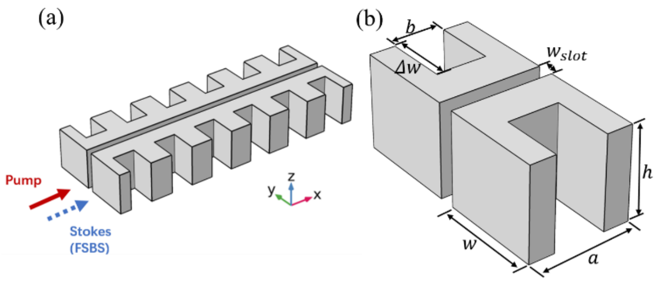

Fig. 1. (a) Proposed structure of the slot waveguide Bragg grating suspended in air. (b) Unit cell of the proposed structure

Using the formalism depicted in Sec. 2, we proceed to calculate the forward SBS gain coefficient in a suspended silicon slot waveguide Bragg grating. The waveguide structure is shown in Fig. 1(a) with a finite segment. The optical waves are tightly confined in the air slot while the elastic wave is guided within the silicon arms. In the simulation, we assume that the waveguide is axially infinite by applying Floquet boundary conditions to the unit cell shown in Fig. 1(b) on faces perpendicular to the propagation axis. The unit cell has three symmetry planes $x=0$, $y=0$ and $z=0$. We consider the case that the x-, y-, and z-axes coincide with [100], [010] and [001] symmetry directions of the monocrystalline silicon, respectively. Throughout this paper, we focus our analysis to intramode forward SBS process, where the pump and Stokes waves propagate in the same direction exciting elastic wave with wavevector $q \approx 0$ and are both in the fundamental quasi-transverse electric (quasi-TE) mode of the waveguide. Besides, the frequency range of the elastic modes is set to be below 20 GHz, which is small enough to satisfy the approximation that $\omega_p \approx \omega_s = \omega$. Simulation parameters for silicon are shown in Table 1. Note that we use an isotropic Young's modulus for easy comparison with [20, 23].

Table 1. Simulation Parameters for Silicon

Refractive Index n	Density ρ	Young's Modulus E	Poisson's Ratio ν	Photo-elastic Constant $[p_{11}, p_{12}, p_{44}]$
3.5	2329 kg/m^3	170×10^9 Pa	0.28	[-0.09, 0.017, -0.051]

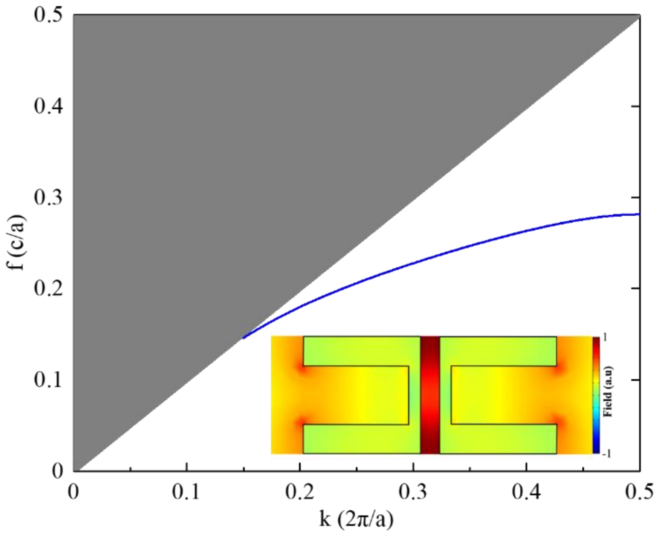

Fig. 2. Band diagram of the fundamental TE-like optical mode. The inset shows the top view of the electric field E_y distribution.

To begin with, we consider a waveguide with the structure parameters as follows: $a = 315nm$, $w = a$, $h = 0.9a$, $b = 0.5a$, $\Delta w = 0.9a$ and $w_{slot} = 0.16a$. The calculated band diagram of the fundamental quasi-TE mode is depicted in Fig. 2, where the shadowed area represents the light cone of air. The inset shows that the optical mode is tightly confined in the narrow gap. Due to the symmetry characteristic of the unit cell, the calculation of optical force distribution and elastic deformation only needs to be implemented to one arm of the waveguide.

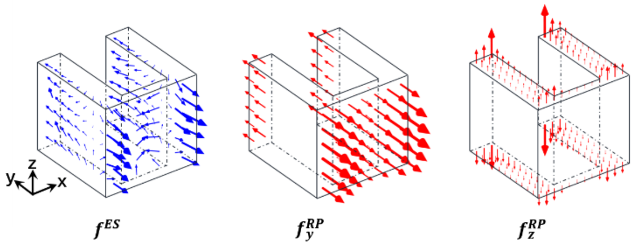

Fig. 3. Distributions of electrostriction body force and radiation pressure on the surface.

We select an operating point at $f = 0.203(c/a)$ $k = 0.244(2\pi/a)$ and compute the optical forces produced by the codirectionally propagating optical waves. The dominant component of the optical force is shown in Fig. 3, including electrostrictive body force (f^{ES}) and radiation pressure (f_y^{RP}, f_z^{RP}) on the surface. The forces are mainly in the transverse y-direction due to the dominant E_y component of the fundamental quasi-TE optical mode. This transverse nature of the optical force indicates that only elastic modes with large deformation in the y-direction are supposed to generate considerable forward SBS gain.

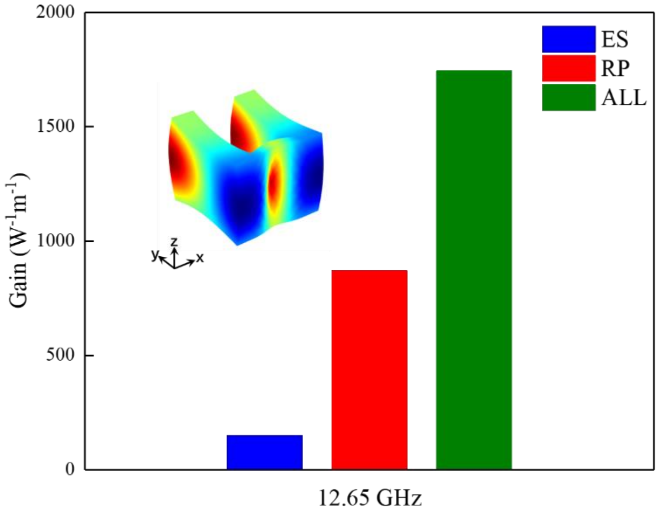

Fig. 4. The forward SBS gain coefficient of the elastic mode at 12.65 GHz. Blue, red and green bars represent electrostriction-only, radiation-pressure-only and the combination of two effects respectively. The colored inset shows the displacement component u_y. Red and blue correspond to positive and negative values of u_y. The deformation is proportional to the total displacement.

Armed with the calculated force distribution, we proceed to calculate the forward SBS gain using Equation (5) assuming phonon quality factor $Q = 1000$ for all elastic modes, as this Q is below the damping limit [20,28]. Besides, we assume that both arms of the waveguide stimulate the SBS process, which results in total forward SBS gain 4 times that of one arm alone [23]. As expected, only elastic modes with large displacement in the y-direction generate effective forward SBS gain. Fig. 4 shows that the elastic mode at 12.65 GHz generates a total gain of 1743.8 $W^{-1}m^{-1}$ which comes from the constructive combination of radiation pressure (870.8 $W^{-1}m^{-1}$) and electrostriction (150 $W^{-1}m^{-1}$). From now on, we focus on the forward SBS gain generated by this specific elastic mode due to the perfect agreement between the elastic deformation shown in Fig. 4 and the force distribution shown in Fig. 3. The contribution of electrostriction is much smaller than that of radiation pressure which can be explained by the dominant optical field distribution within the air slot rather than within the silicon arms.

Next, we utilize the slow light character of the proposed suspended slot waveguide Bragg grating to further enhance the forward SBS gain. The group velocity of the TE-like optical mode can be obtained by the derivative of the dispersion relation shown in Fig. 2. To make use of the slow light region near the Brillouin zone boundary, we set the wavelength of the optical mode to be 1550 nm and shift the operating point along the dispersion curve. It should be noted that, with a fixed wavelength, a different operating point along the dispersion curve corresponding to a different unit cell length a. As shown in Fig. 5, as k varies from $0.2(2\pi/a)$ to $0.498(2\pi/a)$, the corresponding a varies from 279.25 nm to 436.14 nm, meanwhile the group velocity decreases from 0.58c to 0.01c. Because the structural parameters are determined by the unit cell length a, the elastic modes of different length a share the identical elastic mode distribution with different frequencies. We focus our study on the specific elastic mode at 12.65 GHz when $a = 315nm$ as discussed before. The calculated forward SBS gain generated by this specific elastic mode is shown in Fig. 5. As can be seen, electrostriction and radiation pressure add up constructively, contributing to the total forward SBS gain. Combined with the ultra-low group velocity, these two effects lead to total SBS gain as high as 7.33×10^6 $W^{-1}m^{-1}$ near the Brillouin zone boundary.

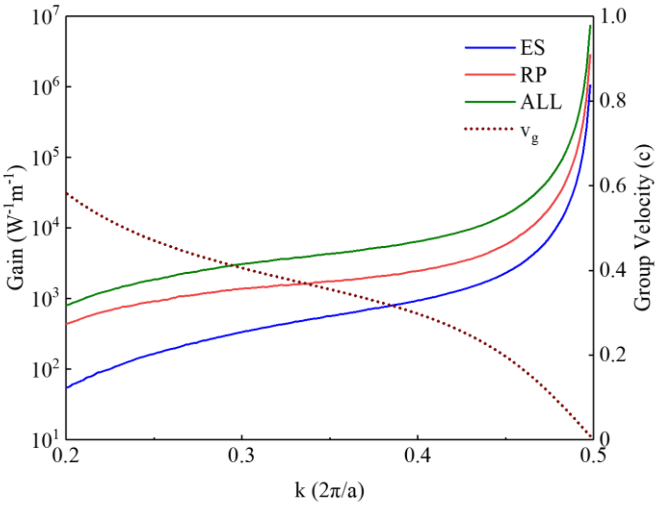

Fig. 5. Forward SBS gain generated by electrostriction (blue line), radiation pressure (red line) and total gain (green line), together with the group velocity (brown dotted line) as k varies from 0.2(2π/a) to 0.5(2π/a).

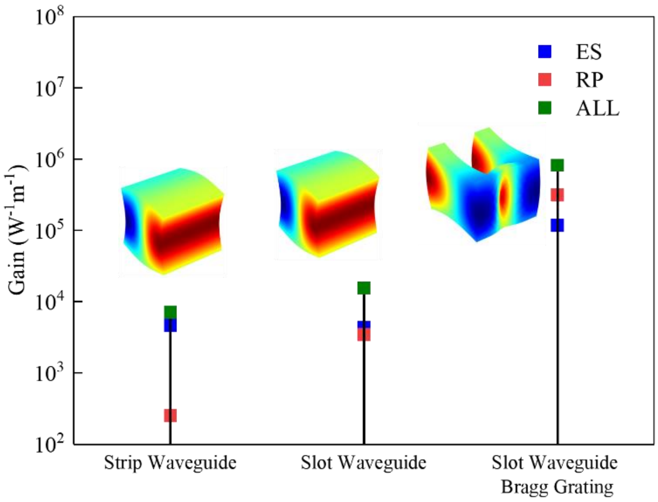

Fig. 6. Forward SBS gain generated by the slow-light slot waveguide Bragg grating in comparison to a strip waveguide and a slot waveguide. The colored inset shows the displacement component u_y. Red and blue correspond to positive and negative values of u_y. The deformation is proportional to the total displacement.

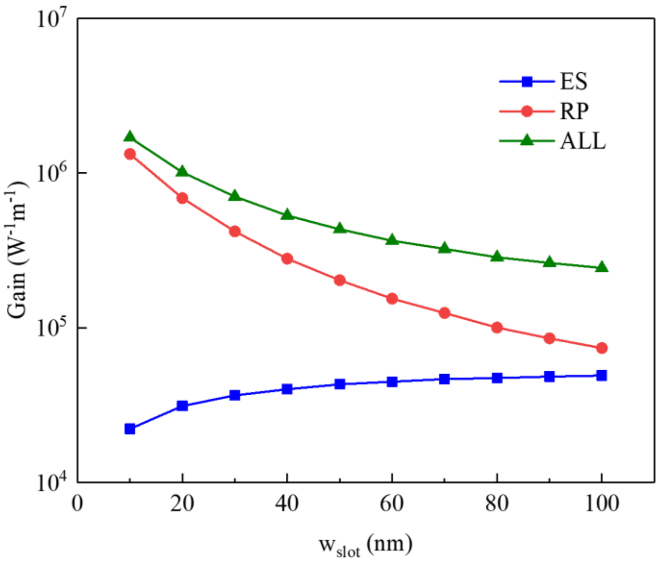

Fig. 7. Forward SBS gain generated by the slow-light slot waveguide Bragg grating with a varied slot width.

To illustrate the effect of the slow light characteristic of the proposed waveguide, we compare the forward SBS gain generated by three different structures all suspended in air: a stand-alone strip waveguide, a slot waveguide, and the proposed slot waveguide Bragg grating. The dimensions of the slot waveguide Bragg grating are $a = 436nm$, $w = a$, $h = 0.9a$, $b = 0.5a$, $\Delta w = 0.9a$ and $w_{slot} = 0.16a$. The value of a is chosen to be 436 nm in order to satisfy the slow light condition (0.028c) of the structure at the 1550 nm wavelength. The stand-alone strip and slot waveguides can be regarded as one arm of the slot waveguide Bragg grating with corrugation width $\Delta w = 0$. The strip waveguide and the slot waveguide generate the largest forward SBS gain with the same elastic mode at 9.07 GHz as depicted in Fig. 6. Electrostriction is the dominant factor in strip waveguide due to the large optical intensity within the silicon core, which generates a total gain of 7.12×10^3 $W^{-1}m^{-1}$ combined with the radiation pressure. Meanwhile, the total SBS gain generated by both arms of the slot waveguide is 1.55×10^4 $W^{-1}m^{-1}$. However, with the same slot width, the slot waveguide Bragg grating generates SBS gain of 8.18×10^5 $W^{-1}m^{-1}$, which is more than 100 and 50 times larger than that of the strip and slot waveguides, respectively. The enhancement is due to the relatively smaller group velocity imposed by the Bragg grating.

Moreover, the slot nature of the proposed structure indicates that giant enhancement of SBS gain can be obtained by further decreasing the slot width as suggested in [23]. Here, we explore the impact of the slot width on the forward SBS gain under the same slowing down factor. The dimensions of the slot waveguide Bragg grating are $a = 436nm$, $w = a$, $h = 0.9a$, $b = 0.5a$ and $\Delta w = 0.9a$ with w_{slot} varied from 10 nm to 100 nm. We calculated the band diagram and chose the operating point at $v_g = 0.044c$ by derivative of the dispersion relation for each slot width. Fig. 7 shows the scaling relation of forward SBS gain as w_{slot} is varied. It can be seen that radiation pressure becomes the dominant factor in extremely narrow slots and the total SBS gain can be further boosted by the largely enhanced radiation pressure. A total gain of 1.69×10^6 $W^{-1}m^{-1}$ is obtained by the constructive combination of radiation pressure (1.33×10^6 $W^{-1}m^{-1}$) and electrostriction (2.22×10^4 $W^{-1}m^{-1}$). Note that the optical frequencies at different slot widths are slightly different from each other due to the different operating point in the dispersion curve. The impact of the shifted optical frequency is negligible according to Eq. (5).

4. Summary

We have analyzed the forward SBS process in a periodic suspended slot waveguide Bragg grating. We show that the radiation pressure is the dominant factor with narrow slots. Electrostriction adds constructively to radiation pressure, generating considerable forward SBS gain. Besides, the periodic structure provides decreased group velocity near the Brillouin zone boundary. Exploiting this particular character, giant enhancement of forward SBS gain can be achieved in this waveguide. The role of the slot width is discussed showing that further enhancement of forward SBS gain can be achieved using a narrow slot. A total gain of orders of 10^6 is demonstrated which is two orders of magnitude larger than stand-alone strip and slot waveguides. It is believed that the slow group velocity together with the narrow slot provides a powerful platform for light-sound interaction through forward SBS process.

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