Simulation study on the optomechanical interaction of suspended graphene on silicon slot waveguide

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The field of optomechanics studies the interaction between electromagnetic radiation and mechanical motion mediated by radiation pressure. By using 2-dimensional Materials like graphene or monolayer molybdenum disulfide (MoS2) as ultralight mechanical resonators, large zero point motion can be achieved. This also, simultaneously opens up new possibilities for realizing CMOS compatible silicon photonics based optomechanics. A simulation study of one such device composed of a graphene membrane suspended over a Si slot waveguide is performed. Several key figure of merits - the zero-point motion, the optomechanical coupling rate and the Brillouin gain of the device are estimated. Also their dependence on the waveguide geometry and the fermi energy of graphene is studied.

Introduction

Optomechanics is the radiation pressure assisted interaction between the optical and mechanical degrees of freedom of a resonator [1]. Graphene is an excellent candidate for nano-mechanical resonators owing to its low mass and large stiffness [2]. It is also CMOS compatible and can be integrated with Silicon photonics to realize novel optomechanics architectures. In addition the transparency of graphene can be controlled by varying its doping through electrostatic gating, which facilitates the opportunity to explore dispersive and dissipative coupling in a single device. The simplest optomechanical device is a graphene membrane suspended over a slot waveguide as shown in the schematic Fig.1. The graphene can be suspended via transfer printing [3]. For such a system, the Brillouin gain (G_{SBS}) is given by [4]:

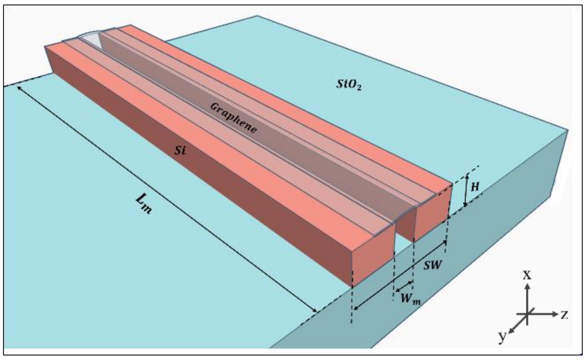

Fig. 1: Schematic of device under consideration: graphene (grey) is transferred onto a Si (brown) slot waveguide on oxide (blue). Parameters: $SW = 500nm + W_m$ and $H = 220nm$.

$$G_{sbs} = 2\omega_0 \frac{Q_m}{k_{eff}} \left(\frac{1}{c} \frac{dn_{eff}}{dx} \right)^2 \quad (1)$$

where, ω_0 is the vacuum angular frequency of light (for $\lambda_0 = 1.55\mu m$), Q_m is the Q-factor of mechanical resonantor, c is the vacuum velocity of light, n_{eff} is the real part of effective index, k_{eff} is the stiffness per unit length of the membrane and is defined as $k_{eff} = m_{eff}\, \Omega_m^2$. With m_{eff} defined as the effective mass per unit length of the membrane and Ω_m is the angular frequency of the mechanical resonator. The cavity optomechanics equivalent of the Brillion gain is the single photon optomechanical coupling rate (g_0), given by [5]:

$$g_0^2 = v_g^2 \; \frac{\hbar\omega_0 \, \Omega_{\mathrm{m}}}{4 \, L_m} \; \left(\frac{G_{sbs}}{Q_m}\right) \tag{2}$$

where, v_g is the group velocity of the optical mode, L_m is the length of the mechanical resonator. The zero point fluctuation amplitude (x_{zpf}) for the membrane is given by [1]:

$$x_{zpf} = \sqrt{\frac{\hbar}{2m_{eff} \, L_m \, \Omega_m}} \tag{3}$$

To estimate the key figure of merits (x_{zpf}, G_{SBS} and g_0) for the waveguide optomechanics system- the membrane mechanics (L_m, Ω_m) and optics (n_{eff}, v_g) are to be determined.

Graphene membrane mechanics

The suspended graphene flake is modelled as a doubly clamped rectangular membrane and is analyzed using the finite element (FEM) technique on COMSOL. Specifically, the

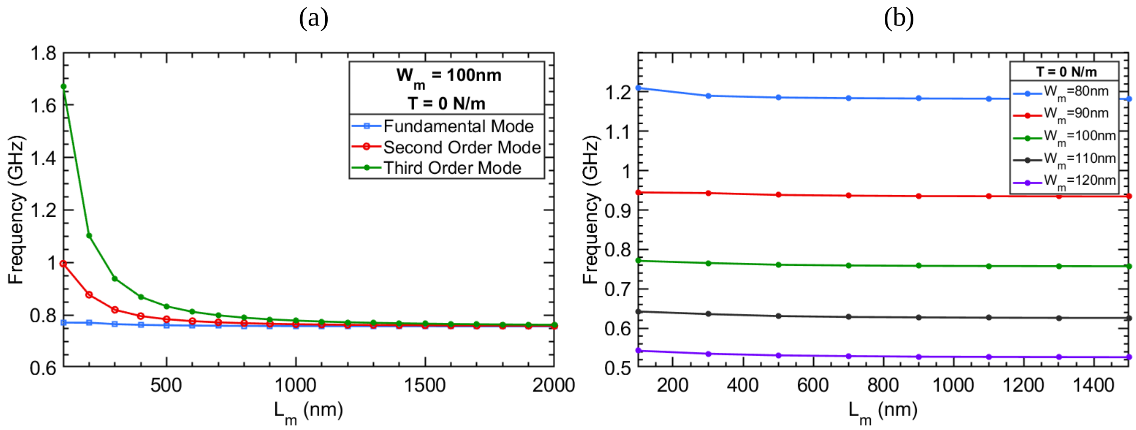

Fig. 2: Frequency vs membrane length. (a) For the first three modes under no tension. (b) Fundamental mode for different W_m under no tension. Note that the frequency becomes independent for $L_m > 10 \times W_m$.

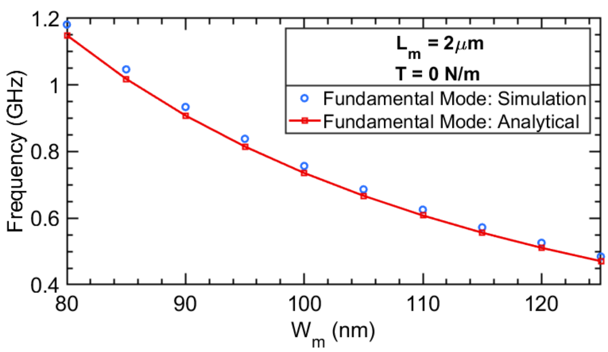

Fig. 3: Frequency vs W_m for a graphene membrane of $L_m = 2\mu m$ under no tension. The analytical model (Eq.4) in red matches the FEM simulations in blue.

frequency (f_m) dependence on the membrane geometry (L_m, W_m) is studied. A small tension (T) in graphene is introduced during the transfer process by the viscoelastic stamps [2] but this is neglected in the simulations.

The membrane length sweep (Fig.2) is performed, we observe that the frequency becomes flake length independent beyond $L_m > 10 \times W_m$ irrespective of the mode or W_m. A similar sweep on the graphene width for $L_m = 2\mu m$ is presented in Fig.3. For the large membrane length limit ($L_m > 10 \times W_m$), the fundamental mechanical frequency (f_m) is given by [6]:

$$f_m = 1.03 \frac{t}{W_m^2} \sqrt{\frac{E_Y}{\rho}} \tag{4}$$

Where, *t (=0.335nm)* is the thickness of graphene, E_Y *(=1TPa)* is the young's modulus of graphene and ρ ($= 2200 \; kg/m^3$) is the effective volume density of graphene. The analytical model (Eq.4) and the simulations are in good correspondence, as seen in Fig.3.

The m_{eff} (kg/m) of the fundamental mechanical mode is calculated on COMSOL and plotted for different widths in Fig.4a. In the case of doubly clamped membranes: $m_{eff} \approx \frac{m_0}{4\times L_m}$. Where, m_0 (kg) is the real mass of the membrane. From the calculated f_m and m_{eff}, the zero-point motion amplitude is determined using Eq.3 and plotted in Fig.4b. The x_{zpf} increases with the increase in the membrane width because $f_m \propto 1/W_m$.

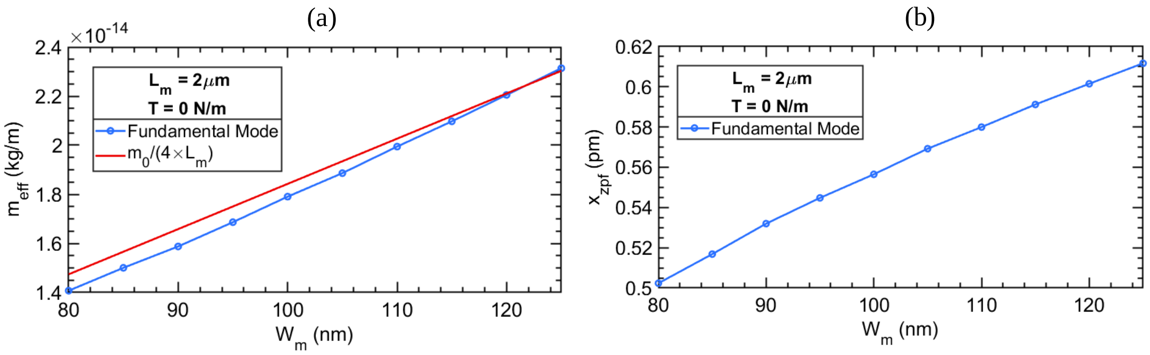

Fig. 4: (a) m_{eff} vs W_m for the first mode of the mechanical resonator. The red curve $\left(\frac{m_0}{4\times L_m}\right)$ is the approximated effective mass of bridges. (b) Zero point motion amplitude as a function of W_m.

Graphene – slot waveguide optics

The perturbation of the refractive index as a result of displacing the graphene membrane vertically (along x axis in Fig.1) with respect to the slot is calculated using Finite difference time domain (FDTD) method on Lumerical Mode solutions. The fundamental TE slot mode is chosen because of the good overlap between the mechanical displacement and optical field. Effective indices curves are obtained for different slot widths (W_m) as

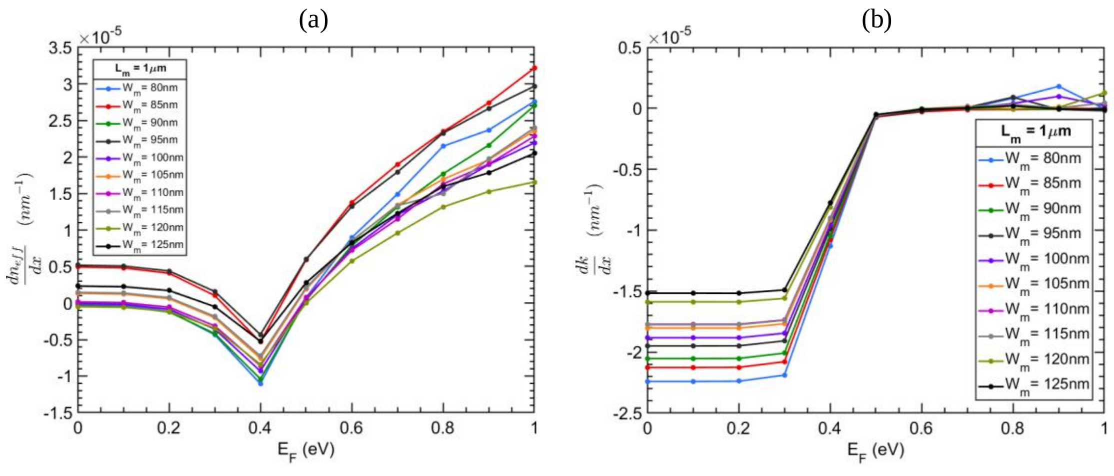

Fig. 5: Refractive index change per unit displacement of membrane as function of graphene fermi energy for different widths. (a) For real part of refractive index. (b) Imaginary part of refractive index.

function graphene position from the simulations. The corresponding $\frac{d_{neff}}{dx}$ and $\frac{dk}{dx}$ are extracted and plotted as function of graphene fermi energy (E_F) in Fig.5. We observe that the absorption per unit displacement $\left(\propto \frac{dk}{dx}\right)$ increases as the slot width increases (W_m) and is negligible for $E_F > 0.4\,eV$ because of the absence of inter-band absorption in graphene. Whereas the real part of the effective index $\left(\frac{d_{neff}}{dx}\right)$ shows no clear dependence of on the width. But exhibits a clear trend of increasing as the doping ($|E_F|$) increases.

Optomechanics

For a graphene resonator of fixed length $L_m = 2\ \mu m$ under no tension suspended over a silicon slot waveguide. The mechanical FEM simulations can used to determine the k_{eff} of the resonator. Along with the $\frac{dn_{eff}}{dx}$ obtained from the optical FDTD simulations (see Fig.5a), the optomechanical interaction figure of merits: G_{SBS} and g_0 are calculated using Eq.(2-3) and plotted for different waveguide widths in Fig.6. A realistic mechanical Q-factor of $Q_m = 100$ is assumed in estimating the Brillouin gain [2]. It's to be noted that the presence of any tension in the membrane increases its stiffness, in turn reducing the G_{SBS}. The simulated Brilloiun gain is compareable to the gain observed in other Si nanophotonic waveguide based systems [4,7] and clearly demonstrates that waveguide optomechanics using graphene on Si photonics platform is worth exploring.

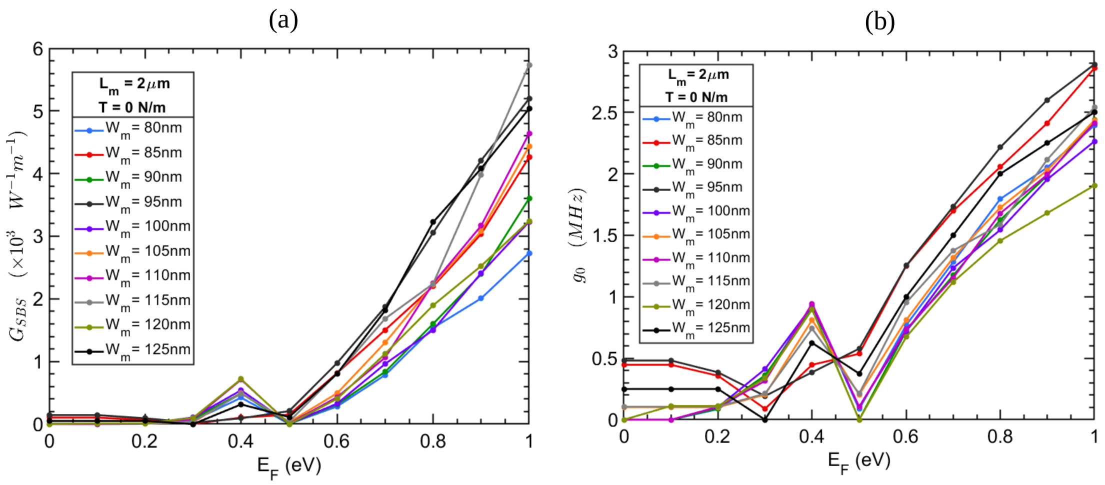

Fig. 6: Optomechanical figure of merits. (a) Brillouin gain vs graphene fermi energy for different membrane widths. (b) Single photon coupling strength vs graphene fermi energy for different membrane widths.

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References

[1] M. Aspelmeyer, T.J. Kippenberg, and F. Marquardt, "Cavity optomechanics," Reviews of Modern Physics, vol. 86, 1391-1452, 2014

[2] A. Castellanos-Gomez, V. Singh, H.S.J. Van Der Zant and G.A. Steele, "Mechanics of freely-suspended ultrathin layered materials," Annalen der Physik, vol.527, 27-44, 2015

[3] F. Pizzocchero, L. Gammelgaard, B.S. Jessen, J.M. Caridad, L. Wang, J. Hone, P. Bøggild, and T.J. Booth, "The hot pick-up technique for batch assembly of van der Waals heterostructures," Nature communications, vol. 7, 11894, 2016

[4] W. Qiu, P. T. Rakich, H. Shin, H. Dong, M. Soljačić and Wang, Z, "Stimulated Brillouin scattering in nanoscale silicon step-index waveguides: a general framework of selection rules and calculating SBS gain," Optics express, vol. 21, 276-280, 2013

[5] R. Van Laer, R. Baets, and D. Van Thourhout, "Unifying Brillouin scattering and cavity optomechanics," Physical Review A, vol. 93, 1-15, 2016

[6] J. S. Bunch, A.M. Van Der Zande, S.S. Verbridge, I.W. Frank, D.M. Tanenbaum, J.M. Parpia, H.G. Craighead and P.L. McEuen, "Electromechanical resonators from graphene sheets," Science, vol. 315, 490-493, 2007

[7] R. Van Laer, B. Kuyken, D. Van Thourhout and R. Baets, "Interaction between light and highly confined hypersound in a silicon photonic nanowire," Nature Photonics, vol. 9, 199-203, 2015