Design and Simulation of Cantilever Beam with a Bragg Grating based Optomechanical Senor for Atomic Force Microscopy in COMSOL

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Abstract:

Silicon photonics has shown great potential in bringing together mechanical probes and optical cavity as compact sensors for many sensing applications. In this work, we present the integration of a waveguide Bragg grating (WBG) onto a cantilever beam, utilizing a Silicon-on-insulator (SOI) structure as an optomechanical sensor for atomic force microscopy (AFM). The flexibility of the COMSOL Multiphysics software enables us to model the mechanical characteristics of the cantilever and link the mechanical bending effects to the optical transmission simulations. Within these simulations, the nanoscale force applied to the cantilever tip results in cantilever beam deformation, represented by a picometer scale shift in optical resonance frequency. The simulation is carried out for the proposed Bragg grating design, featuring 80 gratings, and attains a force sensitivity approximately 16 m/N, corresponding to a cantilever stiffness 0.06 N/m.

Keywords: silicon photonics, waveguide Bragg grating, cantilever, AFM

1.Introduction

Atomic force microscopy (AFM) has been widely acknowledged as a crucial tool for surface imaging, force measurement, and localization. It serves as a standard technique for nanoscale force spectroscopy [1,2]. Recent advancements in MEMS and nanophotonics have demonstrated the potential to enhance conventional AFM performance, offering a broad range of cantilever stiffnesses [3], exceptionally high frequencies and quality factors [4], and cost-effective, rapid fabrication on a single silicon chip [5]. Consequently, silicon photonics has emerged as a promising avenue for integrating mechanical probes with optical cavities, creating compact sensors for diverse sensing applications.

Latest developments in silicon photonics have enabled the successful integration of Bragg gratings onto the Silicon-on-insulator (SOI) slab, demonstrating their potential for optical sensing applications, as demonstrated in references [6, 7, 8]. Leveraging the capabilities of waveguide Bragg gratings (WBG) on the SOI slab, we investigate the fusion of WBG with a cantilever, leading to the development of compact sensors for atomic force measurements. Within this framework, micro scale cantilevers are employed, a size range challenging to efficiently transduce using free-space optical methods due to pronounced diffraction effects. These effects arise when the cantilever's width falls below the detection beam waist, competing with the reflection of the detection laser at the cantilever tip and limiting the AFM sensitivity. Microscale cantilever-based optomechanical sensors typically involve a vibrating cantilever that incorporates an optical cavity on its surface. When a force is exerted in the cantilever's tip, the resulting bending strain induces a change in the refractive index within the core, leading to a shift in the wavelength of the resonance. Consequently, an optical readout system that relies on the changes in transmitted or reflected power at the wavelength of interest is employed, effectively eliminating the need for a deflection laser in the process.

In this context, the resonance shift phenomenon is influenced by various factors, including the strain induced on the WBG due to the bending of the cantilever, deformation of the straight waveguide, and three-dimensional alterations in refractive index. These effects should all be taken into account. As a result, there is a critical need for a numerical model capable of simulating the entire process of light transmission and its response to cantilever deformation caused by applied force. This model, relying on finite element simulations, will grant a comprehensive comprehension of this intricate process. Its significance lies in its role as a pivotal instrument for guiding design improvements, streamlining fabrications, and providing valuable support for characterization of the fabricated devices.

2. Design and Simulation

The structure of the proposed cantilever-based optomechanical sensor is illustrated in Figure 1. It consists of a silicon dioxide (SiO2) cantilever, silicon (Si) waveguides, and a cantilever tip. WBG is specifically designed with a Si core, SiO2 substrate, and air cladding.

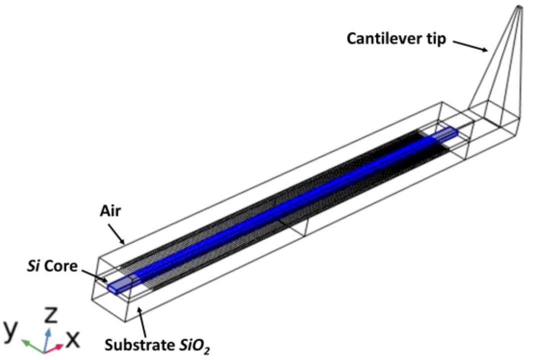

Figure 1. Schematic of waveguide Bragg grating cantilever. Blue: Core with gratings.

When the signal propagates through the Bragg grating, it undergoes reflection at all interfaces, leading to a relative phase difference between the input signal and the reflected light. Accordingly, after multiple reflections, only those wavelengths achieving constructive interference are highly reflected, while others cancel each other out and pass through the grating. These reflected signals are confined to a narrow band centred around the Bragg wavelength. Any change in the core's refractive index causes a shift in the reflected wavelength, allowing for force sensing by monitoring the wavelength shift or reflected power change of the resonant wavelength peak. The Bragg wavelength (λ_B) associated with peak reflectivity can be determined using Bragg's equation,

$$\lambda_B = 2 \cdot \Lambda \cdot n_{eff}$$

where Λ is the grating period, n_{eff} is the effective refractive index averaged over the unit cell.

The parameters for the width and height of the rectangular waveguide core layer are determined using the effective refractive index method [9] and the guided mode cutoff condition [10]. In our

WBG simulation model design, we select a waveguide width for the Bragg grating, equal to 540 µm to ensure single-mode transmission within the waveguide. The geometric model of the silicon waveguide is established based on the single-mode transmission condition of a rectangular waveguide with a width of 500 µm. The thickness of the silicon waveguide in the chosen device layer is 220 nm. Silicon is chosen as the core material for the waveguide, with a refractive index of 3.46 at 1550 nm. Silicon dioxide serves as the waveguide cladding material, with a cladding refractive index of 1.45 at 1550 nm. A period of 0.32 µm with 50% periodicity is selected to design the Bragg wavelength, which is set at 1530 nm.

A resonance shift Δλ due to the change of refractive index Δn can be expressed by,

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n}{n}$$

Previous studies have examined how strain, both in-plane and out-of-plane, impacts the light transmission or reflection from a nanostructured material deposited on a substrate [11][12]. They have also investigated how the bandgap of materials changes under strain to isolate the strain's effect on the optical properties of the device [13]. In this work, we employ finite element methods (FEM) to delve into the impact of strain on the refractive index of silicon. Specifically, we explore how the optical spectrum shifts when a specified force is applied perpendicular to the cantilever tip, either compressing it or extending it.

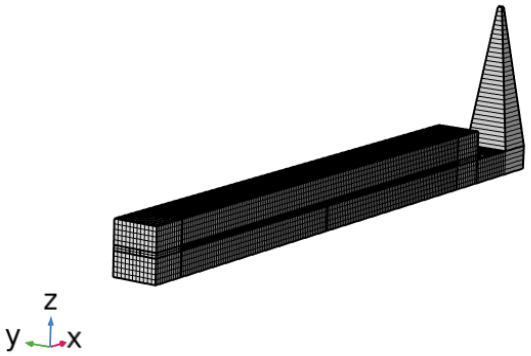

Figure 2. Mesh of the waveguide Bragg grating cantilever.

We conducted a numerical analysis of the geometry shown in Figure 1 using COMSOL Multiphysics Finite Element Modelling software. The software generated a user-controlled swept mesh, as depicted in Figure 2. To achieve a high-frequency response, we selected specific dimensions for the cantilever, and the substrate width was set to 2 µm.

For our mechanical study, we employed the Solid Mechanics Physics interface and assumed a Linear Elastic Material Model in a Frequency Domain study. The first half of the WBG, away from the tip side, was set as fixed, while a force of 1 µN was applied to the tip. The results of the stress simulation are illustrated in Figure 3(a) and (b).

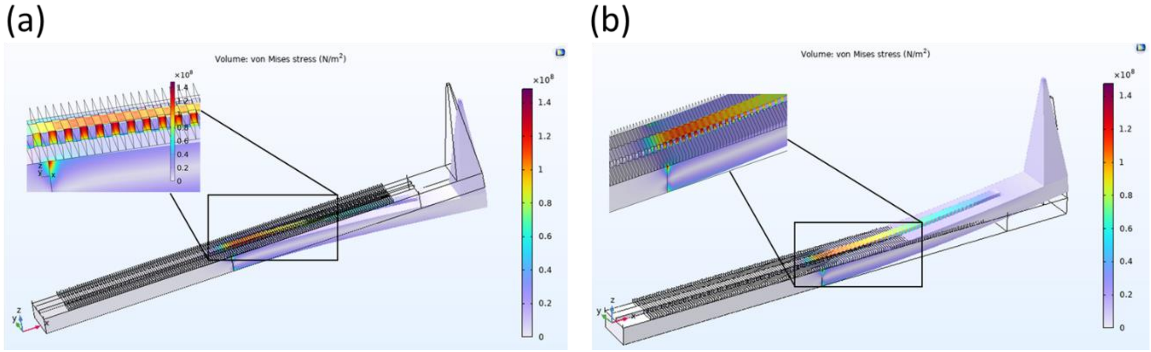

Figure 3. Stress simulation with $1\mu N$ force exerted on the cantilever tip (a) force is parallel to negative z direction (b) force is parallel to position z direction.

To study optical transmission, we employed the electromagnetic wave interface in frequency domain. We positioned an excitation source with a spatial distribution matching the fundamental waveguide mode on the left side of the waveguide. The reflected power was then observed at the left side of the waveguide. In order to obtain a reflection spectrum, we varied the wavelength of the excitation source as a parameter and conducted a parametric sweep across different wavelengths. To mitigate any reflections from the boundaries of the computational window, we applied first-order scattering boundary conditions.

3. Results and Discussions

In Figure 4, we present the reflectance spectrum of the WBG under steady conditions (dashed line) as a function of wavelength. The solid line represents the reflectance spectrum under the condition where a 100 µN force is applied parallel to the positivise z-direction on the cantilever tip, as shown in Figure 3(b). It's worth noting that when an external force is applied to the tip, there is a noticeable 1.6 nm red shift in the resonance. This shift is attributed to changes in the refractive index caused by the bending of the waveguide.

Additionally, we selected a specific wavelength, 1540 nm, which falls on the right side of the stop band. We conducted a parametric sweep for increasing forces at this wavelength. Figure 5 displays the reflected power as a function of the applied force to the tip, where the force is parallel to the negative z-direction, corresponding to the result in Figure 3(a). We observe that as the force increases, the reflected power decreases, indicating a blue shift in the resonance. Consequently, we can determine the direction of the applied force by monitoring the increase or decrease in reflected power at the specified wavelength or the red or blue shift in the resonance across the entire spectrum.

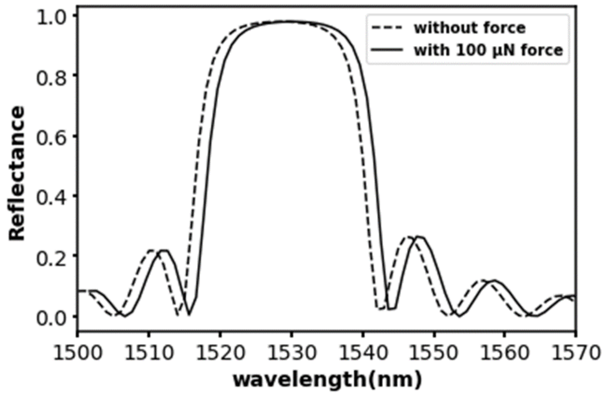

Figure 4. Reflectance spectra as functions of wavelength.

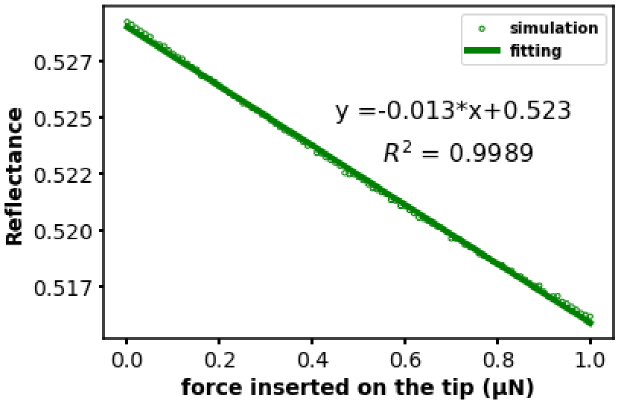

Figure 5. Reflected power as functions of force inserted to the cantilever tip at wavelength 1540 nm.

4. Conclusion

In this research paper, we designed and simulated a 3D Bragg grating-based optomechanical sensor using COMSOL Multiphysics software. This sensor is built upon a single-mode symmetric slab waveguide featuring planar Bragg gratings. It was designed with core dimensions in the sub-micron range, allowing for seamless integration into the evolving field of miniaturized photonic circuits.

To incorporate force sensitivity into the waveguide Bragg grating (WBG), we considered the fundamental change in refractive index induced by strain. We observed the strain's effects on the model in the form of shifts in the reflectance wavelength spectrum. During the simulation, we applied a series of forces ranging from 0 to 1 μN, and we observed a force sensitivity of approximately 16 m/N. Utilizing physics interfaces within the wave optics and structural mechanics module, we harnessed various features, including boundary mode analysis, frequency domain analysis, stationary study, and the ability to couple different simulation results.

To the best of our knowledge, this represents the first comprehensive 3D coupled finite element analysis aimed at understanding the mechanical stress-induced effects on electromagnetic wave simulations. This study serves as a crucial reference point for guiding the design and experimentation of optomechanical sensors.

5. Acknowledgement

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