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Optical gradient dipole forces for nanophotonic devices on a silicon-on-insulator chip

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We present optical gradient forces in nanophotonic structures on a silicon-on-insulator chip and explain how both attractive and repulsive optical force between two freestanding silicon waveguides can be obtained. Also a sensitive displacement detection scheme to record the optically induced vibrations is presented. Finally we discuss how smaller waveguide cross-sections (including slotted waveguides) lead to stronger optical forces and larger displacements, needed for practical applications such as all-optically tunable filters, switches and modulators.

Introduction

A world wide communication network like the internet relies on a global network of transparent optical fibers. These fibers are capable of transporting huge amounts of information and operate at large bit rates (Tb/s). However Optical-Electrical-Optical conversions for switching and routing limit the actual bandwidth so all-optical switching solutions are required. Although radiation pressure effects tend to be extremely small, optomechanics can provide a viable route here. Photon induced force can result in serious effects when the light is interacting with structures on the nanoscale. One well known example of optical gradient dipole force is trapping of polarizable microparticles in an optical trap [1]. Advances in fabrication and miniaturization now enable exploitation of the optical dipole gradient force in micromechanical resonators [2]. Recently all-optically tunable switching and routing was demonstrated using optomechanics [3]. Also the first demonstration of optical dipole gradient force on a silicon-on-insulator chip was reported [4].

Theory

In principle the optical force exerted on an object can be calculated directly using the Maxwell stress tensor formalism [5] when the electromagnetic fields surrounding the object are known, but this approach does not provide much physical insight. However an alternative formalism exists to describe the force exerted on a waveguide in terms of the eigenfrequency of the guided modes. In general the system will try to lower its energy and hence its eigenfrequency. If a guided waveguide mode is able to lower its eigenfrequency by moving (closer or further away from another object for example) a force will be exerted on the waveguide. Considering the fact that the mechanical work (force × displacement) done by the waveguide should equal the shift in eigenmode energy, following formula for the optical force can be derived [6]:

$$F = -\frac{1}{\omega}\frac{d\omega}{dg}\Big|_k \frac{PL}{c} n_g \qquad (1)$$

Here ω and n_g are the waveguide mode eigenfrequency and group index respectively and P is the optical power carried by this mode. L and g are the length and the displacement of the waveguide respectively. The force that we describe here is also sometimes called optical dipole gradient force. This is because from another point of view one can also argue that dipoles are induced in the material. From basic electromagnetic theory [5] we know that these dipole experience force along a field gradient resulting in the displacement of the waveguide.

In Figure 1 a single mode nanophotonic wire in Silicon-on-Insulator is shown. In order to enable the optical force to induce a displacement the SiO_2 needs to be removed locally such that a waveguide string is created. In addition a second wire is provided in close proximity of the first one. This way the eigenfrequencies of the guided modes depend on the spacing between the wires and in accordance with the above theorem an optical force can be induced.

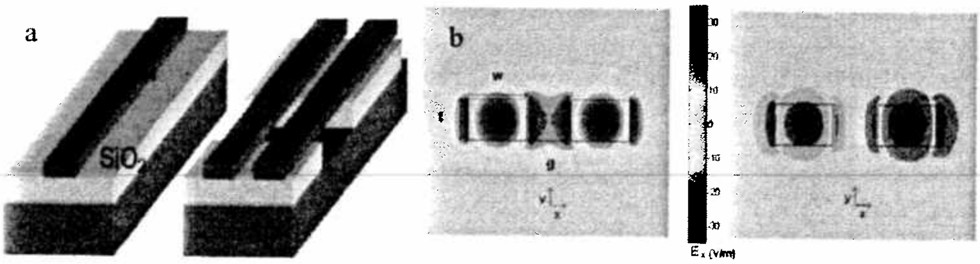

Figure 1: a) nanophotonic wire in Silicon-on-Insulator and underetched wire pair b) field profile of the first and second TE guided mode showing the symmetric and anti-symmetric character of both modes

Two guided TE-modes (Transverse Electric, electric field parallel to the substrate) are present now in this structure and their mode profiles are also shown in Figure 1b. The first order mode has a symmetric character while the second order mode is anti-symmetric in nature. The eigenfrequency of the symmetric mode decreases when the gap closes and by consequence an attractive force between the waveguides can be expected when this mode propagates through the waveguides. The anti-symmetric mode however decreases its eigenfrequency when the separation between the waveguides increases, hence a repulsive force can be expected for this mode.

Fabrication and characterization

The waveguides are created using 193nm Deep-Ultra-Violet lithography. The details of this process can be found elsewhere [7]. Afterwards a resist mask is applied using standard lithography with an open window at the place of the waveguide string pair. Finally the waveguide strings are released by etching the SiO_2 locally using buffered HF. After etching the samples are dried in a critical-point-dryer to avoid stiction and damage to the released strings. Light is coupled into the chip using standard grating couplers [8]. All optical force experiments further described in this proceeding were carried out in a high vacuum (10^{-4} mBar) environment. This way air damping of the optically induced vibrations is avoided and larger vibration amplitudes are possible for the same AC-force when the structure is excited resonantly.

Tunable force device

In order to control the excitation of the symmetric and anti-symmetric mode we need to control the phase of the fields that enter the double waveguide. This can be achieved by splitting up the light in two parts in a 3dB-splitter and feeding the light to the double waveguide region with one waveguide that is ΔL longer than the other. The fields will now appear with different phases when the wavelength is swept. This device is shown in Figure 2a. Intuitively fields arriving in phase will favour the symmetric mode while counter phase fields excite the anti-symmetric mode. By consequence a simple wavelength sweep enables us to tune the sign of the force between the waveguides from attractive to repulsive. This is confirmed by experimental results [9][10]. These are shown in Figure 2. We see that the normalized (for waveguide length and optical power in the device) optical force sweeps from -0.2pN/µm/mW (attractive) to 0.1pN/µm/mW (repulsive) which is in excellent agreement with theoretical predictions (see Formula 1). For a distinct wavelength in between we obtain a zero-force where the attractive and repulsive force cancel out each other.

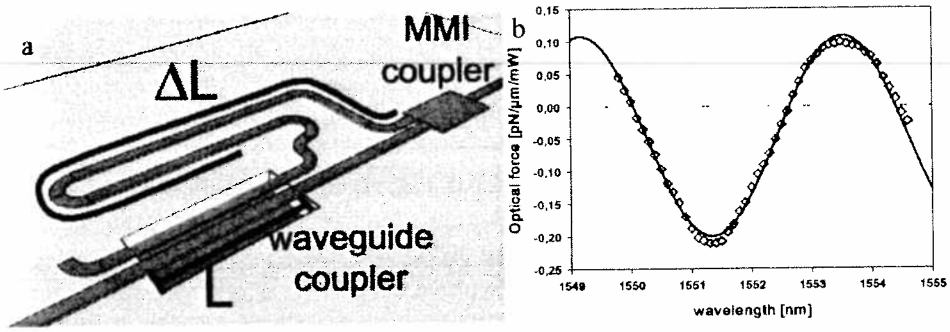

Figure 2: a) tunable force device, light enters through the MMI coupler, the fields arrive at the waveguide coupler region with different phases for different wavelengths b) experimentally obtained force showing that the force sweeps from repulsive (positive sign, above line) to attractive (negative sign, beneath line)

Slotted waveguide device

Although the previous device allows tuning of the force the maximum magnitude of the force obtained is limited to 0.2pN/µm/mW. If NOMS (Nano-Opto-Mechanical Systems) want to compete with integrated NEMS (Nano-Electro-Mechanical Systems) as large as possible optical forces are required. One obvious way to do this is to integrate an optical resonator in the system and 'recycle' photons. However such a system would be bandwidth limited which might be undesirable in some cases, so another manner to increase the force per photon might proof useful. Using Formula 1 we can calculate that in general smaller device cross-sections will result in higher forces. In particular the gap separation is of crucial importance. This is shown in Figure 3 where the force is calculated for a slotted waveguide with 230nm wide silicon beams for different gaps. We clearly see an exponential decay and expect a force of around 5pN/µm/mW for a gap of 120nm which is roughly 25 times higher compared to the double waveguide device. In addition the intensity in a slotted waveguide is the highest in the slot. For this reason thermal effects and other effects typical for silicon like two-photon-absorption are reduced, yet another advantage over the optical resonator approach. Experimentally we have obtained a force value around 3.5pN/µW/mW, indicating that significantly stronger forces are within reach [11]. Enhancing fabrication technology (smaller slot gaps) and combining this slotted waveguide scheme with an optical resonator will ultimately provide us with a large gradient force for small optical powers.

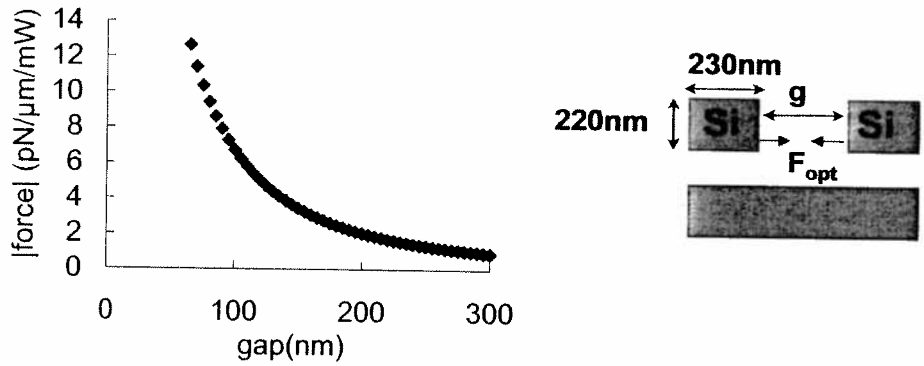

Figure 3: calculated optical force (pN/μm/mW) for a slotted waveguide with beam width 230nm, device dimensions are shown on the right

Conclusion

In this proceeding we reported on optical gradient forces in nanophotonic devices. We have shown that the sign of the optical forces on a silicon-on-insulator chip can be tuned from attractive to repulsive. We also discussed optical forces in a slotted waveguide and found higher optical forces for this device in good accordance with theory. Both devices are significant milestones towards functional integrated optomechanical circuits.

References

[1] S. Chu, "Laser manipulation of atoms and particles," Science, vol. 253, 861-866, 1991.

[2] P.T. Rakich, M.A. Popovic, R. Soljacic and E.P. Ippen, "Trapping, corralling and spectral bonding of optical resonances through optically induced potentials", Nature Photonics 1, 658-665, 2007.

[3] J. Rosenberg, Q. Lin and O. Painter, "Static and dynamic wavelength routing via the gradient optical force", Nature Photonics 3, 478-483, 2009

[4] M. Li, W. Pernice and H. Tang, "Harnessing optical forces in integrated photonic circuits", Nature 456, 480-484, 2008

[5] L. Novotny and B. Hecht, "Principles of Nano-optics", Cambridge University Press, 2006

[6] M. L. Povinelli, M. Loncar, M. Ibanescu, E.J. Smythe, J. Erich, S. G. Johnson, F. Capasso and J.D. Joannopoulos, "Evanescent-wave bonding between optical waveguides", Optics Letters 30, 3042-3044, 2005

[7] S. Selvaraja, P. Jaenen, W. Bogaerts, D. Van Thourhout, P. Dumon and R. Baets, "Fabrication of Photonic Wire and Crystal Circuits in Silicon-on-Insulator Using 193nm Optical Lithography", Journal of Light Wave Technology, 27(18), 4076-4083, 2009

[8] D. Taillaert, P. Bienstman and R. Baets, "Compact efficient broadband grating coupler for silicon-on-insulator waveguides, Optics Letters 29, 2749-275, 2004

[9] J. Roels, I. De Vlaminck, L. Lagae, B. Maes, D. Van Thourhout and R. Baets, "Tunable optical forces between nanophotonic waveguides", Nature Nanotechnology 4, 510-513, 2009

[10] M. Li, W. Pernice and H. Tang, "Tunable bipolar interactions between guided lightwaves", Nature Photonics 3, 464-468, 2009

[11] J. Roels, B. Maes, D. Van Thourhout and R. Baets, "Optical gradient force in a slot waveguide on a silicon-on-insulator chip", Proc. of Photonics Society Annual Meeting in Belek-Antalya (Turkey), 223-224, 2009