The peak gain shift due to the temperature dependency of the carrier escape rates from QD levels to the WL is also investigated. The temperature dependency of the escape times from ES to WL and from GS to ES are predefined in the RE model. It can be concluded from the definition of the escape times that the larger dots will have a larger escape time (slower escape rate) from ES to WL (τ_{eES}) than the smaller dots. As temperature drops, the escape rate for larger dots will decrease more than smaller dots. Thus there will be a higher contribution of gain from larger dots due to this lower escape rate. This will shift the peak of gain to longer wavelength. Similarly, the temperature-dependent escape time τ_{eGS} from GS to ES will result in more contribution of gain from GS since the rate will also decrease as temperature drops. This also results in a red shift of the peak of gain.

The two mechanisms discussed above both give contribution to the shift of the gain peak. But they result in opposite directions of the shift. Since both measurement and simulation show an overall blue shift, it can be concluded that the mechanism of carrier filling is more significant than that of carrier escape when temperature changes.

Conclusion

In this contribution we have presented the measured temperature-dependent gain spectra for single-layer InAs/InP(100) QD-SOAs in the 1.6 to 1.8 µm wavelength range. The measured QD-SOAs which are InAs dots grown on a thin InAs QW, show higher gain values than that of previous five-layer QD-SOAs. The blue shift of peak gain as temperature change has been analyzed using an improved RE model. A good match can be obtained for all temperatures when all effects are taken into account. This type of QD material can be a good candidate to be used in QD lasers or photodetectors for long-wavelength OCT applications.

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An ultra-high frequency optomechanical oscillator

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The coupling of optical and mechanical degrees of freedom has applications ranging from mass spectroscopy and force detection to even tests of quantum mechanics. Rapid advances in the past years have shown conclusively that the strong field gradient near waveguides can be exploited for actuating optomechanical devices. Most devices studied so far oscillate at megahertz-frequencies. We aim to increase the speed of these vibrations by several orders of magnitude. To this end, we consider very stiff devices. In order to compensate for their smaller deflections, we enhance the optical gradient force by confining the light into a nanogap.

Introduction

Optomechanics has attracted a great deal of interest in recent years. Research has targeted both practical applications, such as mass spectroscopy and signal processing, and fundamental research, such as mesoscale quantum mechanics. [1] The main idea is to use light to make on-chip nanostructures move. The force light exerts on a body comes in two varieties. First, the *scattering force* is simply the result of momentum transfer between a photon and the body on which it impinges. This is the force that makes a comet's tail point away from the sun, as noted by Kepler in the 16th century.

On the other hand, the *gradient force* is related to variations in the electromagnetic field intensity. To get a feeling for this force, one can think of a polarizable particle entering a region with strong field gradients. The field induces a dipole in the particle. Subsequently the particle will be accelerated towards the region with the strongest field. This is the principle underpinning optical tweezers, which trap microparticles like living cells, DNA and bacteria in the waist of a powerful laser beam. Since macroscopic structures such as integrated photonic wires are a collection of dipolar subunits, they are also affected by a varying optical field intensity. We put this effect to work in the ultra-high mechanical frequency range. Such fast oscillations are necessary to realize high-speed sensing devices and to further progress towards the quantum regime of mechanical oscillators. [2]

Partially underetched slot waveguide

The nanostructure we treat here is a silicon-on-insulator slot waveguide, see figure 1. The cross-section of such a waveguide is typically a square of side 220 nm. The waveguides are separated by a gap of size $g \approx 100$ nm. This device is interesting for optomechanics for two reasons:

- The small gap allows for strong confinement of the optical mode, which enhances the optical gradient force.
- The waveguides are extremely stiff, which results in vibration frequencies exceeding 1 GHz. However, their displacement is also smaller. This is a fundamental trade-off: frequencies and mechanical displacements are inversely related.

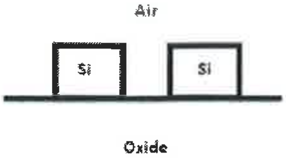


Figure 1: Top view (left) and cross-section of a slot waveguide (right).

To increase the mechanical movement, we consider a scenario in which the waveguides are partially underetched with hydrofluoric acid (HF). Such structures have been studied before [2], but only in the case they were completely underetched. The novelty of our approach lies in the partial underetch.

Mechanical eigenmodes

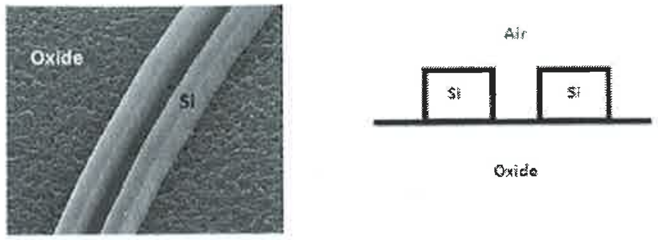
We calculate the mechanical eigenmodes of these waveguides with the commercial finite-element package COMSOL. The first three eigenmodes are shown in figure 2. We are particularly interested in the left flexural mode. This mode couples best to the optical mode and is predicted to have the largest mechanical quality factor, see further on. Figure 3 depicts the dependency of the eigenfrequencies of these modes on the undercut. They all vibrate faster than 1 GHz for undercuts below 45%.

Figure 2: First three mechanical eigenmodes of a partially underetched waveguide. The colors indicate the size and the arrows the direction of the displacement.

Mechanical quality factor

The mechanical Q-factor determines the amplitude of the vibration under resonant excitation. It is critical to engineer this factor properly. Unfortunately, predicting this parameter is notoriously hard. Many mechanisms are at play. Among the most important are air damping, thermoelastic damping and clamping loss. However, nanofluidic theory predicts reduced air damping in the microwave regime. [3] Furthermore, a simple model for thermoelastic damping [4] suggests a minimal Q-factor of 10^4 associated with this loss mechanism. Therefore we expect clamping loss to be dominant.

In a COMSOL eigenfrequency study, it is possible to introduce a matching layer with an imaginary Young's modulus and density. This layer absorbs the incoming elastic waves, ideally without reflections. Using such a layer, we calculate the clamping loss limited Q-factor of the fundamental mode, see figure 4. The other modes have a significantly lower Q, as expected given the larger pillar displacement. Our intuition is confirmed



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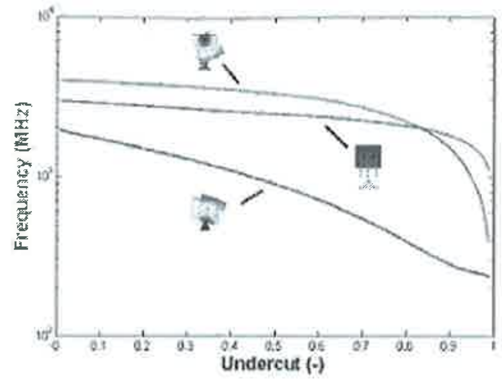

Figure 3: Underetch dependency of the mechanical eigenfrequencies. Note that the second and third mode switch color near an undercut of 85%.

in this case: larger undercuts result in smaller support loss. Other studies have shown excellent agreement of such simulations with experiment. [5] Simulations based on a phenomenological parameter related to acoustics [6] can also be reproduced this way. Another trade-off is encountered here. At low undercuts we get large frequencies, but low Q-factors. The choice of undercut depends on the application.

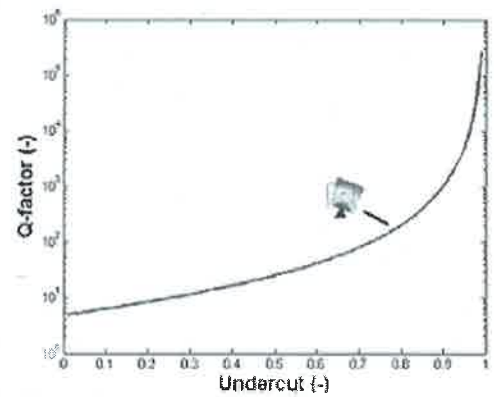

Figure 4: Clamping loss limited Q-factor of the fundamental mode.

Optical gradient force

A seminal paper in 2005 [7] showed how the optical gradient force can be calculated as $F = \frac{1}{c}\frac{dn}{dg}$, with n the effective index. The derivative ought to be calculated at fixed frequency. Thus we calculate the gradient force for the TE-mode of this slot waveguide. At low gaps there is also a TM-mode, but its optical force is much smaller. Indeed, the TE-mode is strongly confined in the gap due to the discontinuity of the E_x-component at the transition silicon-air. The results are shown in figure 5. The graph clearly demonstrates the need to explore structures with smaller gaps.

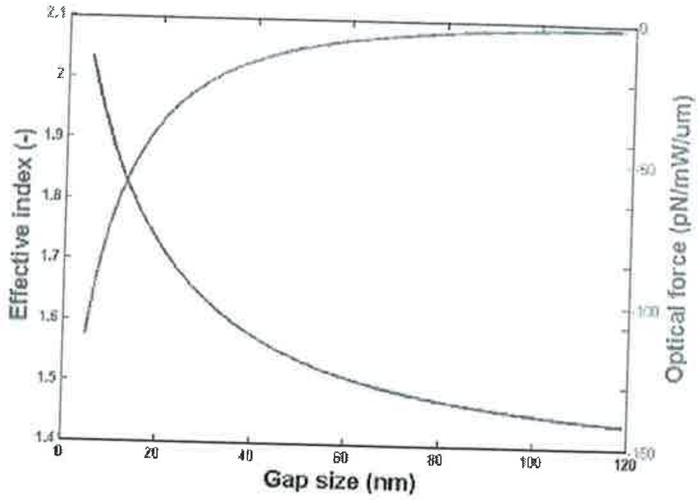

Figure 5: Dependency of the optical gradient force on the gap size.

Conclusion

We have studied the optical and mechanical properties of a novel high-frequency mechanical oscillator. Simulations of the optical gradient force show the need to pursue smaller slot-gaps. Mechanically we encounter a trade-off between frequency, stiffness and Q-factor. The experimental verification of these predictions is in the pipeline.

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