Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

2nd generation beam shapers

Deliverable no.: D57
Due date: 30/7/2015
Actual Submission date: 15/9/2015
Authors: imec
Work package(s): WP5
Distribution level: RE[1] (NAVOLCHI Consortium)
Nature: document, available online in the restricted area of the NAVOLCHI webpage

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Executive Summary

In the first half of the project we focused on electrostatically moving grating couplers. In the second half of the project we worked towards the development of ultracompact grating couplers that can be used to couple light from CQD-embedded SiN waveguides upwards to a detection system. An extensive design effort was carried out and grating couplers were fabricated. Efficiencies of over 80% can be expected when including a bottom mirror. Characterisation of passive grating couplers was carried out and initial experiments with CQD-embedded layers show coupling of the emitted light through the grating coupler.

Change Records

Version	Date	Changes	Author
1 (submission)	2015-09-15		Dries Van Thourhout, Yunpeng Zhu, Jie Wang

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1. Introduction

In the first half of the project we focused on electrostatically actuated grating couplers. This work was completed in the first reporting period. For the second period, the original plan was to focus on the design of grating couplers allowing to couple a transmitter and receiver chip through free space over distances from 0.1 to 1.0 mm. We started this work with a high level design study, reported in section 2, estimating the distance that can be expected and the form factor of the grating that should be used. From this study it became clear the achievable improvement in coupling distance/minimum pitch when designing focussing grating couplers compared to standard grating couplers would be less than a factor two. This, together with the fact that in the demonstrator foreseen this vertical coupling between two chips was no longer relevant and strong overlap with earlier published results from Oracle led to the decision to shift focus to work more linked to the colloidal quantum dot (CQD) devices developed in WP4. Therefore we designed and fabricated a new type of ultra-compact grating couplers than can couple light from SiN waveguides (with embedded CQD) to a microscope objective for the in-depth characterisation of these CQD.

2. Design of grating couplers for chip-to-chip coupling

The pictures below summarize the results of the high level study carried out to evaluate the potential of coupling light between chips using focussing grating couplers. These figures show the different tradeoffs involved. For coupling over short distances it is better to use small grating couplers, which allow a reduced device pitch and broader wavelength operation (smaller gratings = stronger grating with less periods = broadband operation). However, these gratings have stronger diffraction and if coupling over larger distances is needed the size of the grating has to be increased to reduce diffraction and keep the device to device pitch minimal. However, the device to device pitch increases (along the black line for in figures below, for optimized case) and the optical bandwidth decreases. Figure 1 gives the case of a standard grating, whereby the light is directly diffracting as soon as it leaves the grating coupler. Figure 2 shows the case of using a focussing grating coupler, whereby the reachable chip-to-chip distance is roughly doubled. One can deduce that, e.g. for a chip-to-chip distance of 1mm, a grating pitch of at least 0.1mm is required.

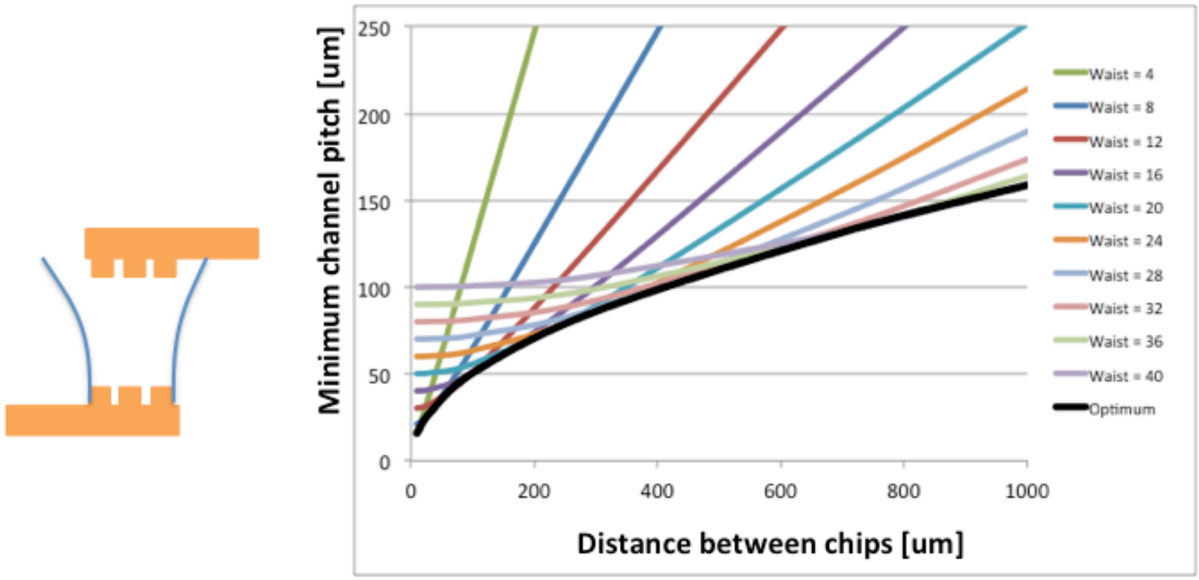
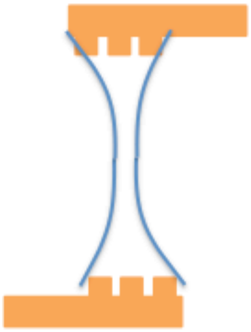


Figure 1Minimum channel pitch as function of distance between chips for different initial grating sizes (grating size equal to beam waist)



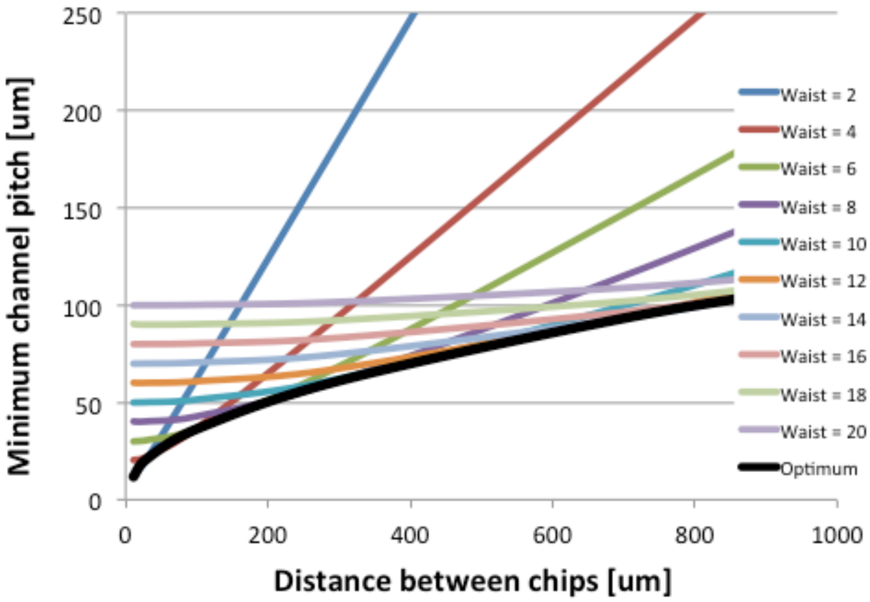


Figure 2 Minimum channel pitch as function of distance between chips for different initial grating sizes (focusing gratings)

Based on these results we designed gratings aimed at coupling over distance of 0.1, 0.5 and 1.0mm total distance and initiated their fabrication. However, given the limited gain in pitch and/or distance these focussing grating couplers offer and give the fact that coupling two chips vertically is no longer considered relevant in the project, we decided to focus the remaining effort in this task on the design and fabrication of grating couplers which are more relevant for the CQD-platform developed in WP4.

3. Ultra-compact grating couplers for SiN-QD platform

As described in WP4, imec together with UGent developed a platform whereby colloidal quantum dots are embedded in a SiN-stack. The possibility of using these quantum dots as single photon emitters is currently being investigated. In such applications it is important to efficiently couple the light from the SiN waveguide with embedded quantum dot to a microscope objective, for further analysis. Inspired by earlier work from the Vucovic group[2] which demonstrated such a grating coupler for a III-V semiconductor material system, we studied the possibility of using a deeply etched, ultra compact grating as shown in Figure 3 to realize this coupling. Compared to III-V semiconductor SiN has a considerable lower index contrast with air so it is not a priori trivial this is indeed possible. Therefore we carried out extensive simulations of the proposed device.

Figure 3a gives a schematic view of the proposed device: a suspended SiN-waveguide with embedded CQDs is attached to a compact, spherical high contrast grating. Light propagating in the waveguide will be coupled upwards by the grating. Grating and waveguide are suspended to increase the index contrast and optimise the efficiency. To enhance the upwards coupling with

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[2] Faraon, Andrei, et al. "Dipole induced transparency in waveguide coupled photonic crystal cavities." Optics express 16.16 (2008): 12154-12162.

respect to the coupling towards the substrate a mirror can be added below the grating (DBR-mirror or, as drawn here, a gold mirror). Figure 3b shows the relevant grating parameters to be optimised.

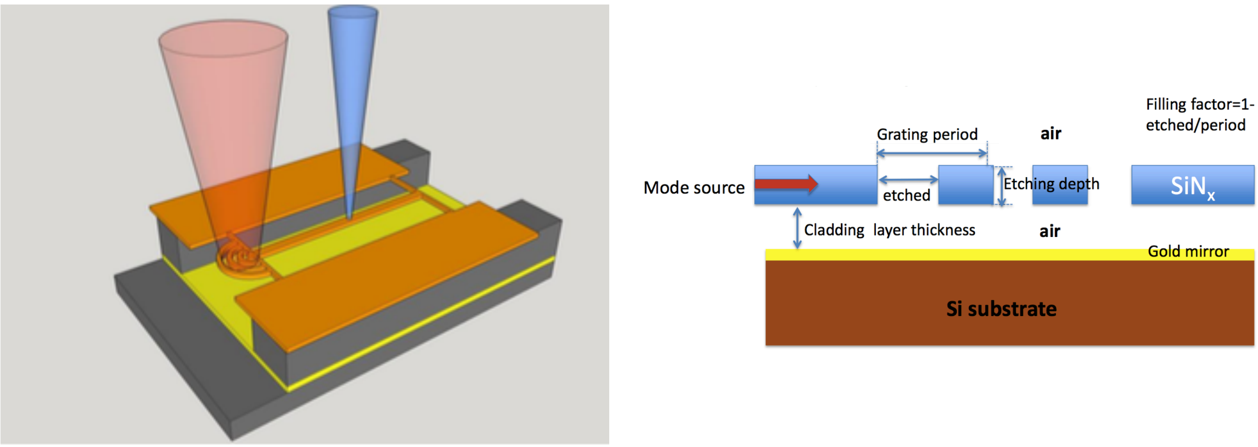
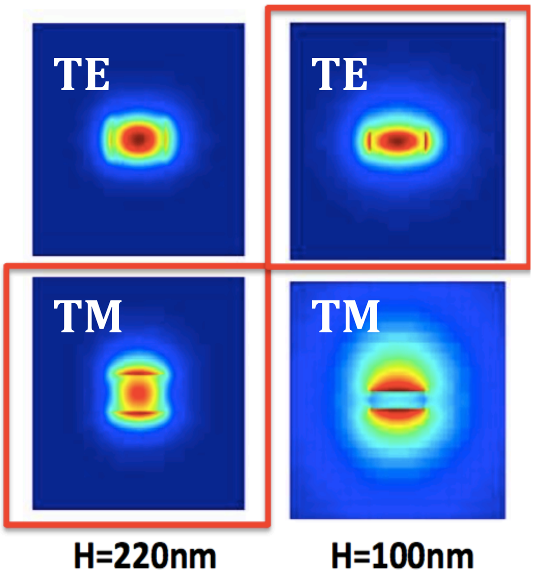


Figure 3 a) Schematic view of proposed ultra-compact grating coupler. The «blue» beam excites a QD embedded in the SiN-waveguide. Light emitted by the QD is coupled in the waveguide and then coupled upwards to the microscope objective through the compact grating coupler (red beam). b) Relevant parameters used in the simulations

The height of the SiN-waveguide was chosen according to a recent study carried out by us in a project parallel to NAVOLCHI: we demonstrated[3] that the coupling of a dipole (or hence a CQD-emitter) to a waveguide, with a given polarization can be optimised by selecting the correct waveguide parameters. From these study we concluded that a 220nm (110nm) thick SiN layer is ideal for selectively coupling to the TM (TE) mode. The according modal profiles are shown in Figure 4. For that reason we focussed further simulations on defining TE-gratings for a 100nm thick SiN-layer and TM-gratings for a 220nm thick layer.



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[3] S. Bisschop, A. Guille, Z. Hens, D.V. Thourhout, E. Brainis. ”Broadband enhancement of light emission and polarization dependent coupling in silicon nitride slot waveguides.” Optics Express 23.11(2015):13713-13724

Figure 4 Optical field (intensity profile) in SiN waveguides (suspended in air) with height resp. 220nm and 100nm.

Simulations were carried out first with 2D-FDTD and then verified with 3D-FDTD. Figure 5 shows some results of the extensive optimisation effort carried out, confirming that the 2D and 3D simulations give similar results. Without bottom mirror, close to 50% of the light can be couled upwards (to an objective with NA=0.8).

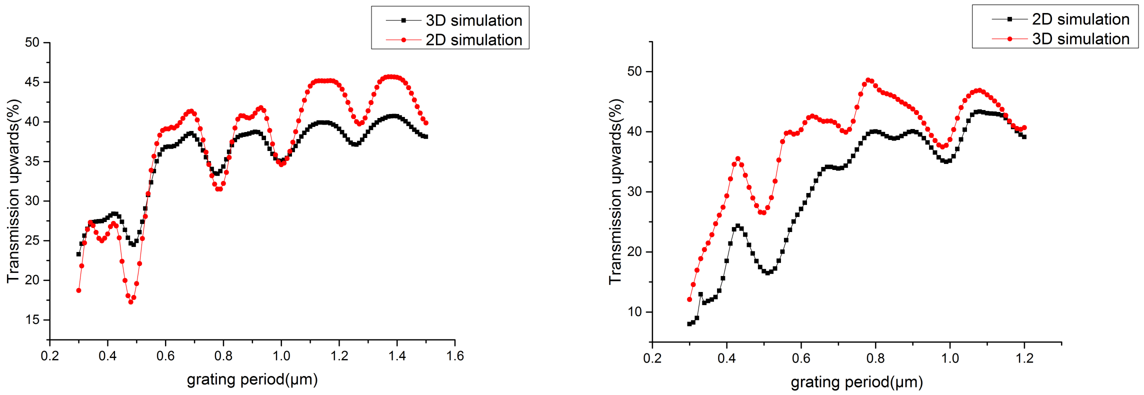

Figure 5 Upwards coupled power as function of grating period for 100nm and 220nm thick SiN layer (no bottom mirror, air suspended, wavelength=620nm).

Figure 6 shows the upwards power as function of the number of grating periods. Obviously the power increases with increasing number of periods. However, for both layer thicknesses 3-4 periods are actually sufficient, much less than for standard gratings optimised for coupling to optical fiber.

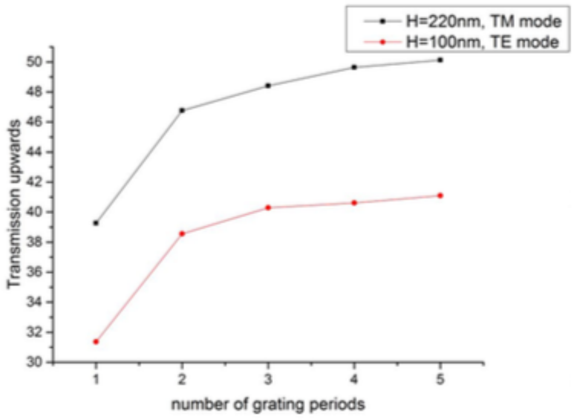

Figure 6 Required number of periods

Next we added a high reflective bottom substrate. Optimising the distance between bottom substrate and grating coupler allows coupling efficiencies of up to 87%.

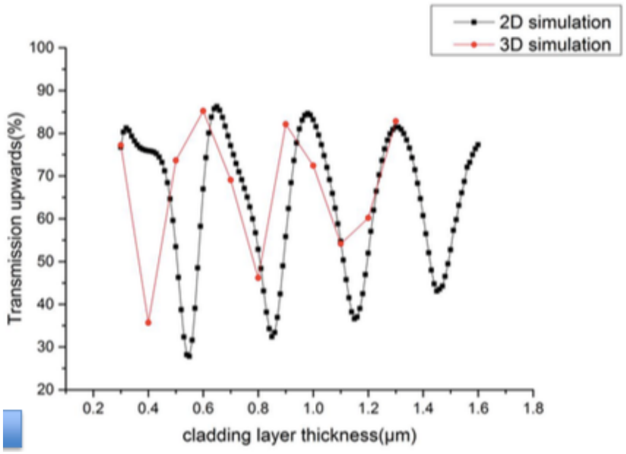

Figure 7 Coupling efficiency when including bottom mirror, as function of distance between bottom mirror and grating (for 100nm SiN layer).

Figure 8 illustrates the fabrication scheme used, without and with adding a gold reflection layer below the grating coupler. Figure 9a shows a SEM-picture after etching the SiN-layer. The grating couplers were defined using ebeam lithography. Next they were released by etching the underlying Silicon layer (KOH). In initial experiments this resulted in the collapse of the SiN-beams towards the substrate (Figure 9b). To avoid this, we then started using cPD (critical point drying) and tensile strained SiN-layers. This resulted in successfully fabricated structures both on standard substrates and on gold mirror substrates (Figure 10).

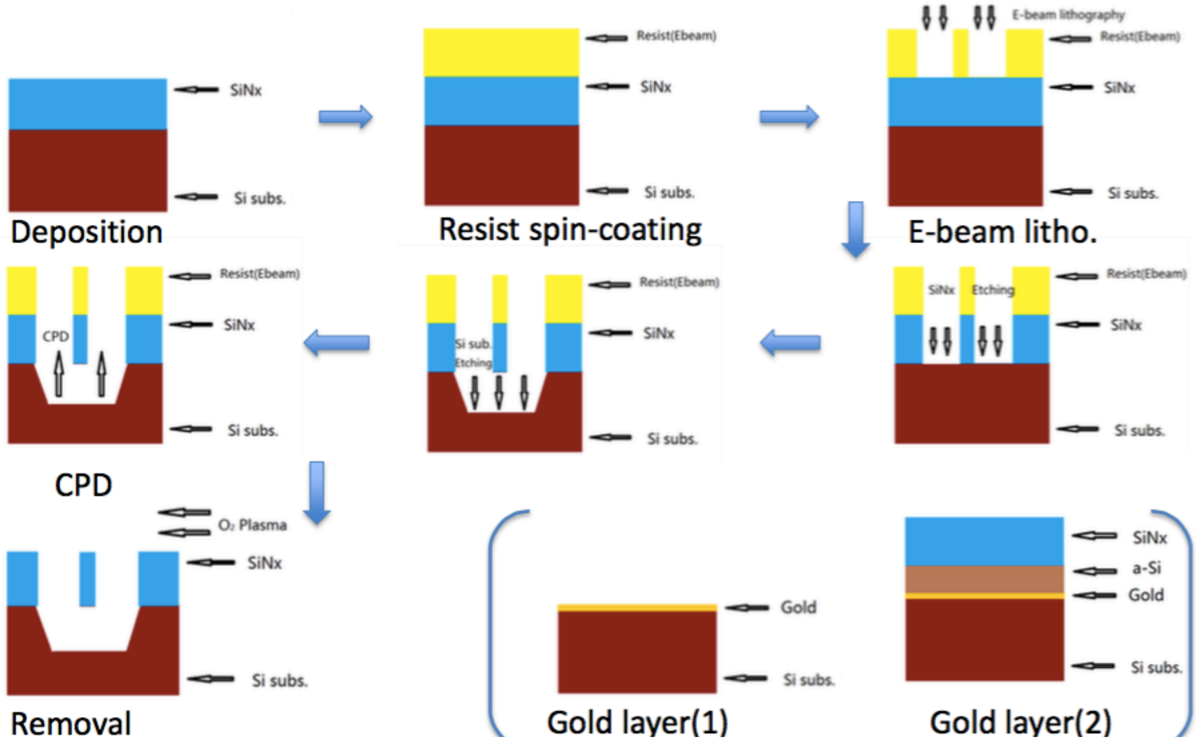

Figure 8 Fabrication scheme for suspended SiN grating couplers

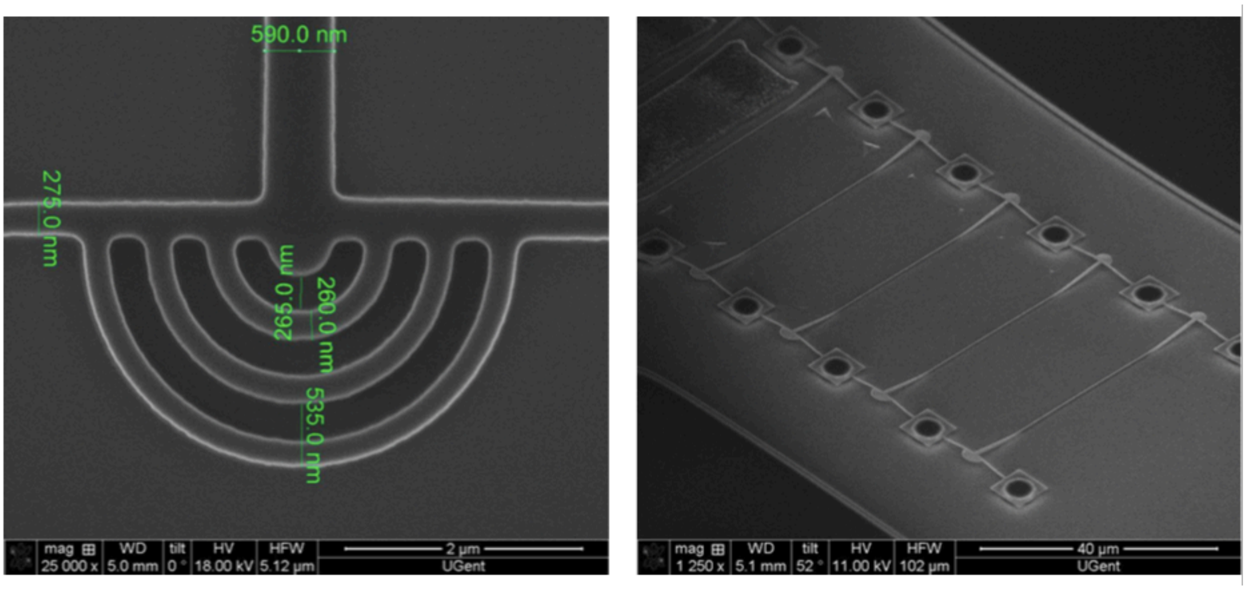

Figure 9 SEM picture of grating couplers before (left) and after release (right). After release the SiN-beams collapse

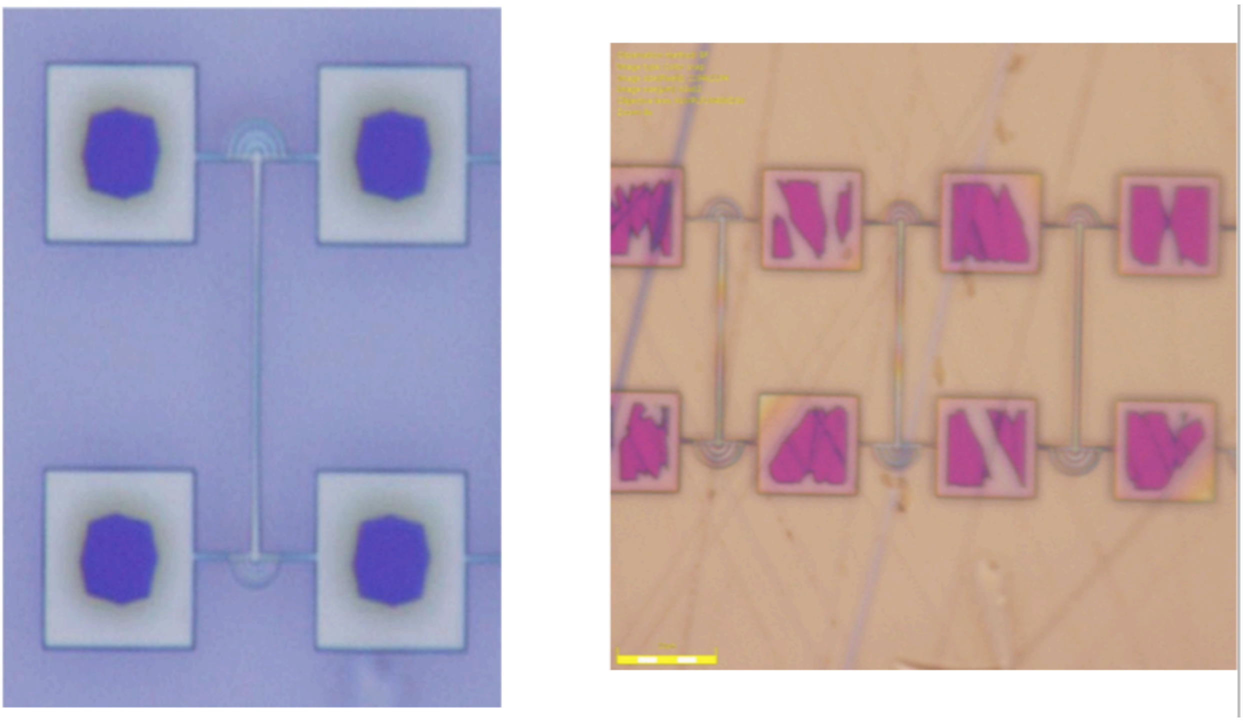

Figure 10 Microscope image of grating couplers after process improvement. Beams are now fully suspended both on standard substrates (left) and with gold bottom mirror (right)

Direct characterisation of the coupling efficiency of these gratings is not trivial. Therefore we fabricated a series of grating couplers with varying properties (in this case varying grating period) connected to a grating couplers with constant efficiency. In this way we can compare the relative coupling efficiency of the differing grating couplers with simulation results. An example is given in Figure 11a. Relative good agreement with simulations is obtained. Figure 11b shows the farfield of one of the grating couplers.

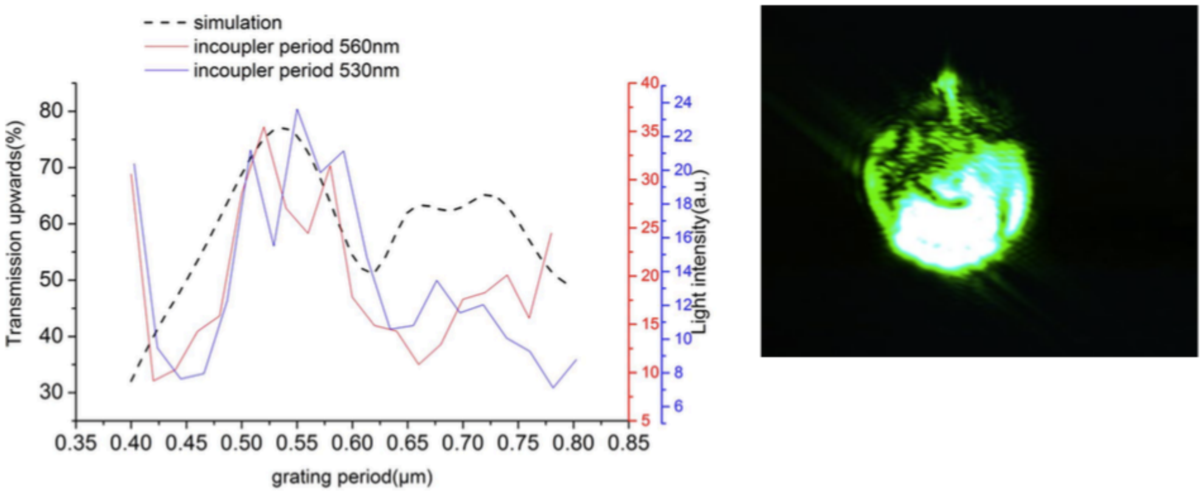

Figure 11 (a) Measured transmission efficiency (relative) as function of grating period for fabricated grating couplers. (b) Far field emission.

Figure 12 shows a similar chip, but now having CQDs embedded in the SiN-layer. If the CQDs are locally pumped, light is coupled in the waveguide and then coupled out through the grating coupler, as is clearly visible. The next step is to reduce the number of CQDs embedded in the layer to reduce the background noise and to evolve to a true single QD-emitter.

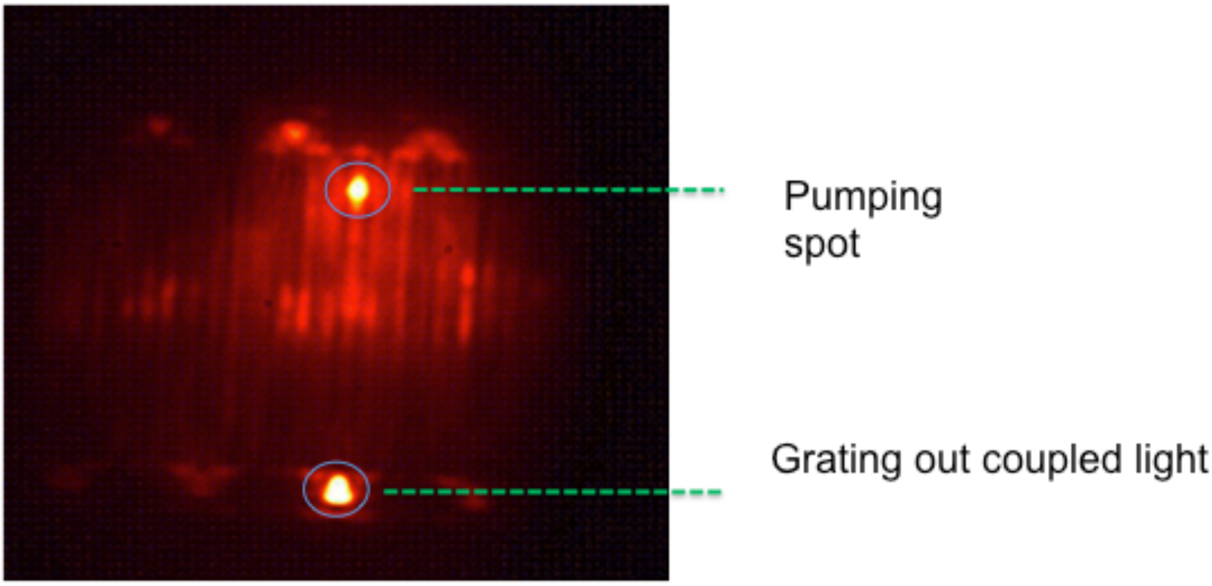

Figure 12 Pumping SiN-beam with embedded CQDs

Finally, we evaluated the possibility of using these ultracompact grating couplers to couple between 2 different waveguide layers. Up to 35% coupling efficiency can be reached (no bottom mirrors) as shown in Figure 14.

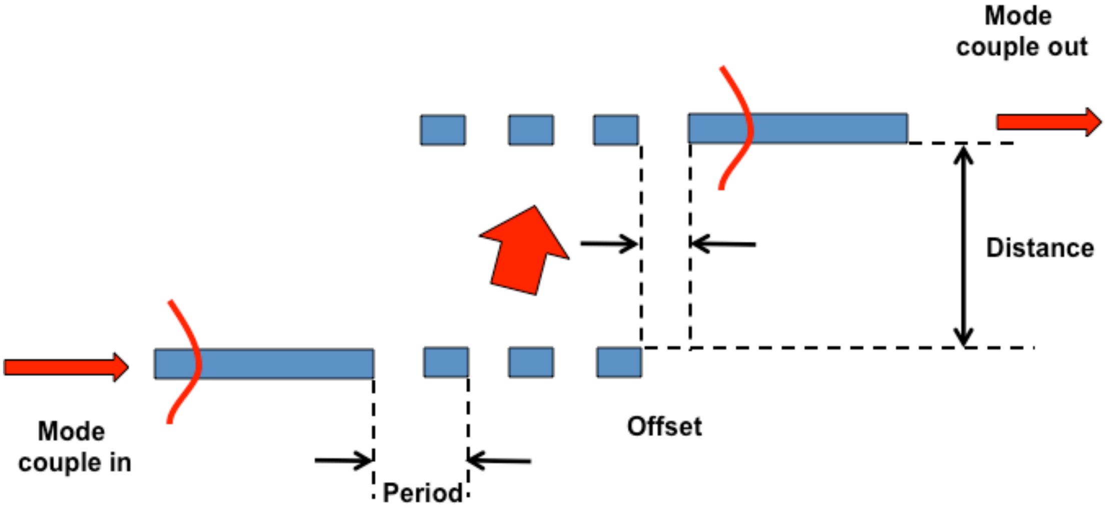

Figure 13 Schematic view of ultra-compact grating couplers used for coupling between 2 waveguide layers.

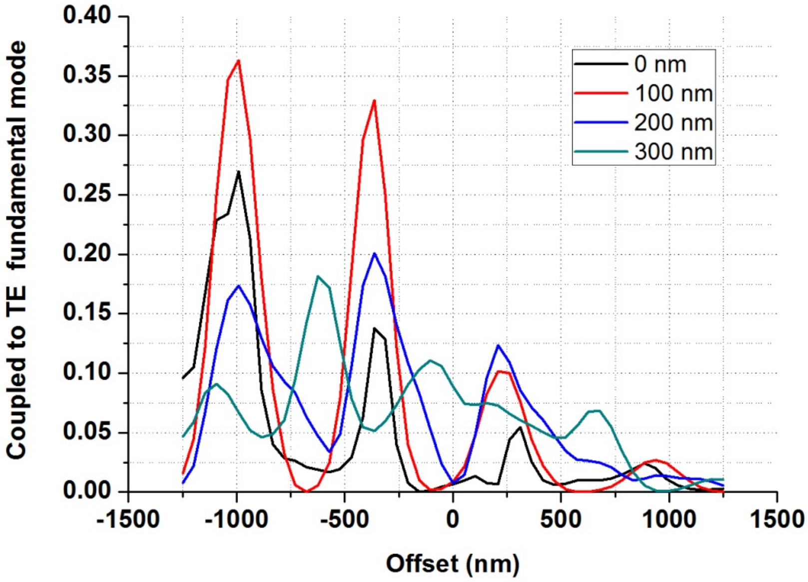

Figure 14 Coupling efficiency for setup shown schematically in Figure 13. The parameter is the vertical distance between both waveguide layers.

4. Conclusion

We designed and fabricated a new type of very compact grating couplers that can be used to couple light from suspended SiN-waveguides upwards to a high-NA microscope objective. When including a bottom mirror coupling efficiencies above 80% are predicted. Experimental results of passive gratings are in line with simulations. First characterisation of SiN-devices with embedded CQDs show coupling of the CQD-photoluminescence through the grating coupler. These grating couplers might become an important tool in characterising complex integrated networks developed for quantum optics applications.