Ultra-compact silicon nitride grating coupler for microscopy system

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Grating couplers have been widely used for coupling light between photonic chips and optical fiber. For some quantum-optics and bio-optics experiments on the other hand, there is a need to achieve good light coupling between photonic chips and a microscope system. Here we propose an ultra-compact silicon nitride grating optimized for coupling to a microscope system. The grating coupler is about 4x2 um^2 in size. 3D-FDTD simulations show that up to 80% of the light @ 532 nm can be coupled upwards.. We fabricated the grating coupler by electron beam lithography and preliminary experimental results show the relationship between coupling efficiency and grating period.

Introduction

Single-photon sources are important for quantum computing, quantum cryptography, and random number generation [1]. Colloidal CdSe/ZnS core-shell quantum dots have been shown to be a potential candidate as single-photon emitter in the visible wavelength range [2]. We demonstrated a silicon nitride (SiN) platform to combine these quantum dots with low loss waveguides [3]. This platform offers good thermal and mechanical stability, opening the potential to introduce more complex integrated circuits to perform quantum optics experiment with photons confined and propagating in a photonic circuit. From extensive simulation we defined waveguide dimensions optimized for broadband enhancement of single photon emission in a single waveguide mode [4]. However, we still need to find a way to couple the emission as much as possible from these waveguides to a microscope based photon counting system.
Grating couplers have now extensively been used to couple light between optical fiber and photonic integrated circuits. They are convenient and efficient and do not need any post-processing like polishing waveguide facets. However, grating couplers optimized for fiber chip coupling typically have dimensions similar to those of the core of a single mode optical fiber, around 9μm, not compact enough for some microscopy applications. On the other hand, single mode optical fibers have a small numerical aperture (NA) compared to a typcial microscopy system, In this paper, we propose one type of compact silicon nitride grating coupler working at visible wavelength range, aiming for high coupling efficiency from waveguide to microscopy system with a certain NA.

Simulation

As shown in Figure 1, for a grating coupler, the parameters that we can optimize are the period of the grating, the etching depth, the filling factor, the number of periods and the distance between grating and substrate. We choose silicon nitride (n=1.96@532nm) as the waveguide material and fixed the thickness of the waveguide at 220nm.

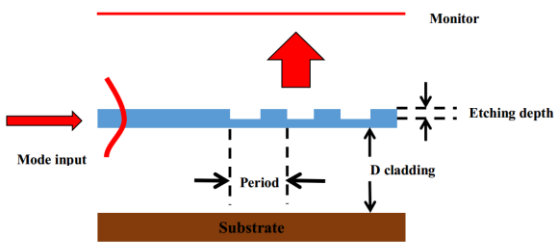

Fig. 1. The schematic of the grating coupler

We choose to etch through the grating to increase its contrast while in the meantime also making the fabrication process easier. The filling factor was fixed to 0.5 to guarantee an easier process and high efficiency. The monitor has been placed 0.5µm above the grating to check the upwards power scattered by the grating coupler. As a starting point for more time consuming 3D-simulations, we used 2D finite-difference time-domain (FDTD) simulations to optimize the parameters of the compact grating coupler.

We scanned the period of a grating without substrate and consisting of 3 periods and compared the upwards coupled power Fig. 2 shows the result of the 2D scan with TE polarization, which indicates the period plays a main role in the upwards coupled power. The first peak around 550nm is the 2nd order diffraction for this waveguide structure at 532nm, which efficiently deflects light upwards.

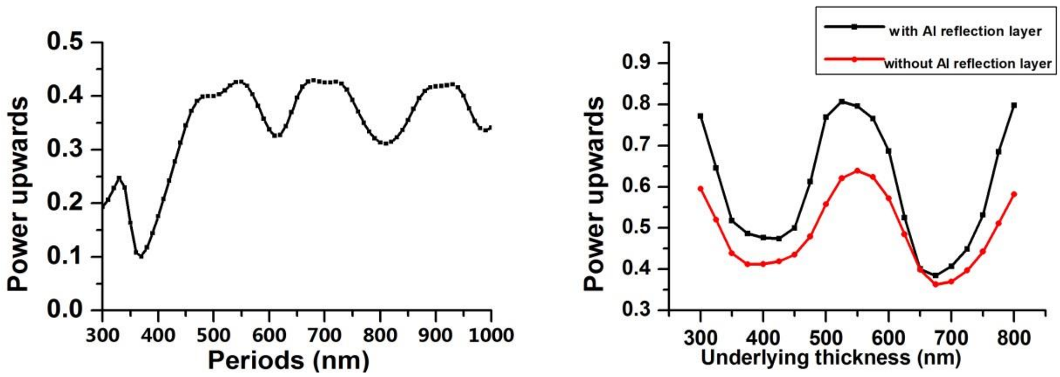

Fig. 2. (a) 2D FDTD simulation results of grating period length vs power upwards. (b) 2D FDTD simulation results of underlying thickness sweep: black one is silicon substrate with Al as reflection layer, red one is silicon substrate without Al as reflection layer

The distance between the substrate and the grating plays a major influence in controlling the upward efficiency. Without substrate, the grating deflects the light upwards and downwards equally because of the symmetric index distribution. With the substrate, the light radiated downwards by the grating coupler will get reflected at the substrate interface. By carefully choosing the distance between grating and substrate, this field can interfere constructively with the field coupled directly upwards. From the red curve in fig.2 (b) we can see the reflection from the substrate indeed plays a major role and more than 50% upwards coupled light can be obtained. By adding an aluminum layer to enhance the reflection, we can get an even more efficient device, as shown by the black curve in fig. 2 (b).

Since an ultra-compact grating coupler is desired, we also simulated the influence of the number of periods. Fig. 3 shows the upwards coupled power as function of the number of periods. From the result, we can derive the conclusion that 3 periods is good balance between coupling efficiency and compactness of the grating coupler.

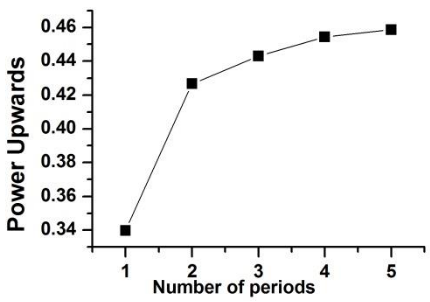

Fig. 3. 2D FDTD simulation result of number of period vs power upwards

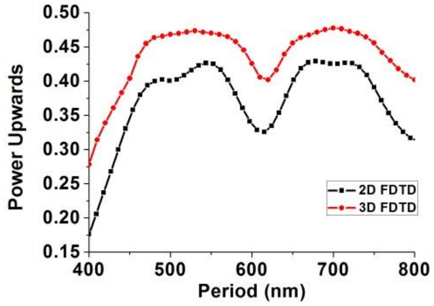

Fig. 4. 2D and 3D FDTD simulation results comparison

We also performed 3D FDTD simulation to compare with the 2D FDTD simulation results. Fig.4 shows the comparison of upwards coupled power in a 2D and 3D simulation without substrate. The 2D and 3D simulation results agree with each other well, which indicate that the 2D FDTD simulation is indeed a good starting point to perform the grating coupler simulations.

Design and fabrication

We would like to test the relationship between coupling efficiency to a microscopy system and the period of the grating coupler. The idea is to fabricate short waveguides with grating couplers at both sides. By fixing the grating coupler's period at one side, we can assume a constant power is coupled into the waveguide. We sweep the other side grating couplers' periods. By measuring the out coupled power from the grating couplers with different period length, we can compare the experimental results with the simulated results.

We fabricated the testing structures by electron beam. Figure 5(a-f) schematically shows the fabrication flow of the test structure. Firstly, a 220nm thick SiN layer is deposited onto a silicon wafer by an optimized plasma enhanced chemical vapor deposition (PECVD) process performed at a temperature of 270 $^{\circ}$ at high frequency. Then followed by spin coating Ebeam resist and Ebeam patterning, the sample is etched by reactive ion etching (RIE). Next, an alkaline based wet etching is carried out to remove the substrate under the grating and waveguide, while still leaves some pillar under the supporting pad to support the whole structure. Then a critical point drying (CPD) process is carried out to release the structure. Finally, oxygen plasma cleaning is needed to remove the Ebeam resist residual. Fig.6 shows the SEM picture of the fabricated structure.

Characterization

We measure the grating coupler structure by using a micro-photoluminescence setup. Fig. 7 shows a schematic of the measurement setup. The laser beam is focused on the grating coupler while the iris diaphragms block the reflection of the input beam and let the out coupled light pass through. The intensity of the out coupled light can be detected by the detector.

Fig. 8 shows the measurement results. The out coupling efficiency is influenced by the grating coupler's period length. The measured results agree reasonably well with the simulated results.

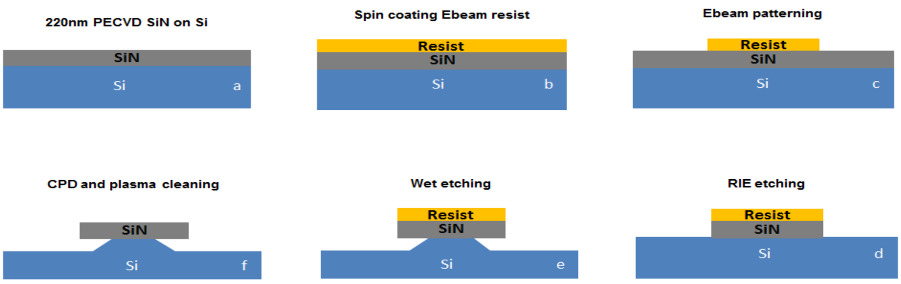

Fig. 5. Schematics of the fabrication flow of ultra-compact grating coupler

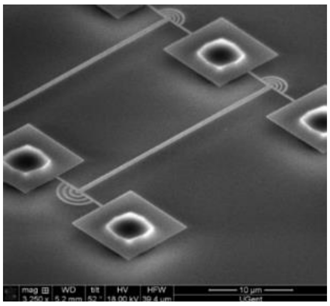

Fig. 6. SEM picture of the fabricated structure

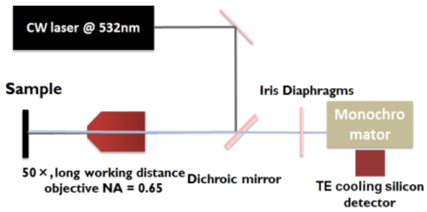

Fig. 7. Schematics of the measurement setup

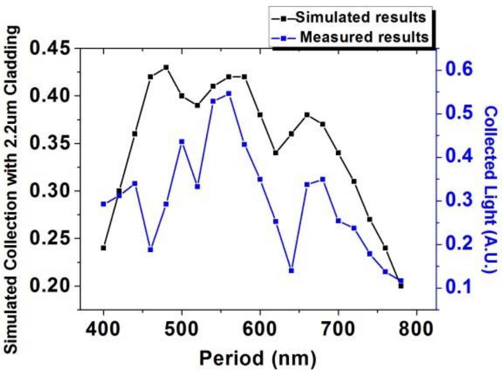

Fig. 8. Measurement results: the black curve is the simulated power couple to a microscopy system with NA=0.65, the underlying thickness is 2.2um as fabricated sample; the blue curve is the measurement results.

Acknowledgements

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