Efficiency of UV-written out-of-plane gratings for beam delivery on quantum chips

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Abstract: We analyze analytically and numerically the efficiency of UV-written tilted Bragg gratings for optical beam delivery from integrated waveguides towards atom or ion clouds trapped above the chip for quantum technology applications. © 2022 The Author(s)

1. Introduction

Many quantum technology applications require the precisely controlled interaction between light and quantum matter, e.g. for quantum state preparation, manipulation, and readout. For scalability of this technology, it is desirable for the light to be brought on-chip via integrated optical waveguides, while the quantum particles, such as clouds of atoms or ions, are trapped in microscopic vacuum cells above the chip.

One method to couple light out of an integrated waveguide and into free space is using direct UV writing to create a tilted Bragg grating [1]. This fabrication technique involves focusing two UV beams to form an interference pattern in a silica chip, resulting in a periodic refractive index modulation with small refractive index contrast [2]. By controlling the grating period and index modulation along the waveguide, target light beams of specific spot shape and size can be designed. In contrast to more common etched surface gratings, UV-written gratings do not suffer from surface roughness which minimizes any stray light which can compromise quantum processing.

Here, we investigate the viability of such out-of-plane grating couplers for current quantum chips based on trapped clouds of atoms and small chains of ions. We derive an analytic method to design gratings generating arbitrary shapes of light beams and verify our designs by finite element simulations. Using realistic fabrication parameters, we finally calculate the coupling efficiency depending on grating length and beam delivery angle.

2. Grating design for beam shaping

We first derive analytically the scattering efficiency of a tilted Bragg grating as a function of grating index modulation, period, and tilt angle following the approach of Yoshino [3],

$$n_g\left(x,y\right) = n_{co} + \left[\Delta n + \Delta n_g(x)\sin\left(\left(\frac{2\pi}{\Lambda} + \frac{2\pi n_{\text{eff}}}{\lambda}\cos\phi\right)\left(x - y\tan\theta\right) + \Phi(x)\right)\right] e^{-\left(\frac{y}{\sigma}\right)^2}, \tag{1}$$

where, the solution is based on defined field at the target, $\mathbf{E}(x) = \mathbf{E}_0(x)e^{-i\Phi(x)}$. The design of gratings for the generation of an arbitrarily shaped beam then proceeds as follows: (1) define the target electric field at the target location above the chip; (2) propagate it to the chip surface and, after diffraction at the chip surface, to the waveguide location; (3) from the resulting electric field required at the waveguide and the analytical scattering efficiency, calculate the grating index modulation and period as a function of position.

An example of this procedure is shown in Fig. 1 for the generation of a Gaussian beam emitted backwards at an angle of 30° to the normal of the surface, focused at a point 5 mm above the surface with a spot size of 10 µm.

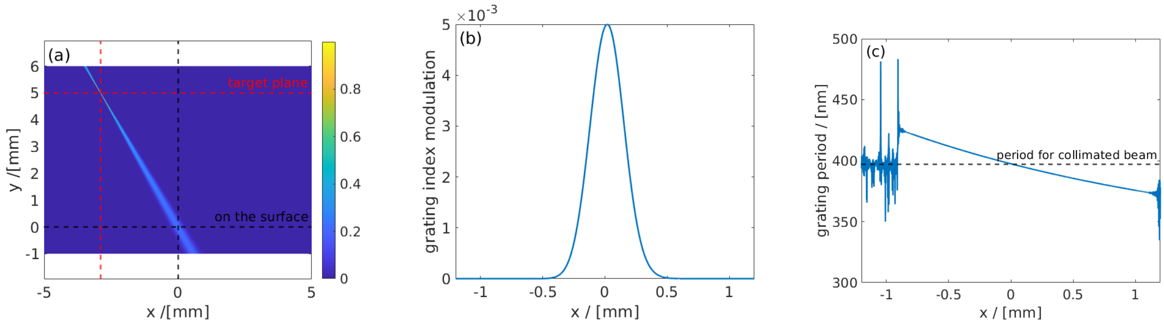

Fig. 1. Grating design for the emission of a 30° tilted Gaussian beam. (a) Beam propagation between target position, chip surface, and grating location. (b) Required grating refractive index modulation to generate the beam in (a), and (c) the corresponding grating period.

Here the waveguide core layer has a refractive index of 1.4608, the cladding of 1.4555 at the chosen wavelength of 780 nm. The core and cladding layers have a thickness of 5 µm and 15 µm, respectively. In this work, the analytical and numerical calculations are performed in a 2D geometry, i.e., for infinite waveguide width. For the final grating design, we can then calculate the overall conversion efficiency from the guided mode into the target beam by integration of the scattering efficiency over the grating length.

3. Coupling efficiency

We validate our analytical formula of the grating scattering efficiency by comparison with finite element simulations in Comsol Multiphysics® in Fig. 2 (a) as a function of grating index modulation, showing excellent agreement. Here only a short grating length of 80 µm is chosen, which would be suitable for focusing light into a tight spot for a single (or a few) trapped ions, similar to Fig. 1. We note that the efficiency is relatively low, of the order of 0.5 to 10% for realistic index variations, scaling with the square of the index variation. Using longer gratings of 10 mm, e.g. suitable for generating large beams to illuminate a cloud of trapped neutral atoms, the efficiency rises to close to 100% for realistic grating index modulations, as shown in 2 (b).

The overall scattering efficiency also depends on the target direction of the emitted beam and the grating tilt angle, as shown in Fig. 2 (c). For optimum coupling the tilt angle needs to match half of the target beam emission angle when Bragg reflection from the grating periodicity and Fresnel reflection from the tilted grating planes coincide. Tilt angles away from 45° (normal emission) lead to slightly larger scattering efficiency because tilting of the beam implies an increased beam coverage on the grating; moreover, at grazing angle emission more grating planes contribute coherently to the emission at every point which also enhances reflectivity.

The examples in Fig. 2 (c) are for similar parameters as in Fig. 1: Gaussian beams with focus of 10 µm at 5 mm above the chip surface. The maximum efficiencies for a maximum grating index modulation of 5×10^{-3} are 17.5% at emission normal to the surface (0° scattering angle) and 25.1% for emission at -30° scattering angle.

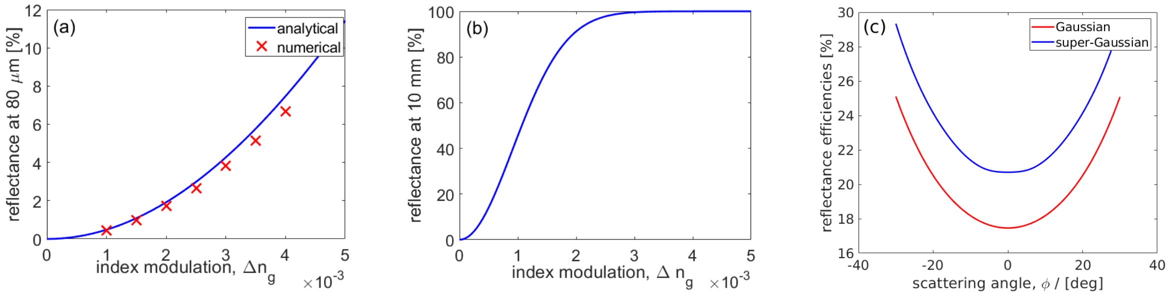

Fig. 2. (a) Comparison of analytically calculated scattering efficiency (solid) and finite element simulations (crosses) for uniform gratings of 80 µm length vs grating index modulation. (b) Scattering efficiency of 10 mm long uniform gratings vs grating index modulation. (c) Total scattering efficiency of gratings generating beams tilted at scattering angle optimized for a gratings generating Gaussian and super-Gaussian beams with waist 10 µm and at 5 mm above the chip surface.

4. Conclusions

Our simulations predict out-of-plane coupling efficiencies of 6.6 dB/mm under the most optimistic assumptions of experimentally achievable index contrasts with direct UV written gratings for short grating lengths suitable for small spot sizes, for example compatible with trapped ion quantum processors. This may be sufficient for laser cooling of ions, but not in general for quantum gate operations. On the other hand, for larger spot sizes, as e.g. used for clouds of trapped atoms, these gratings provide an efficient method for on-chip beam generation. Furthermore, we note that UV-written gratings do not introduce additional surface roughness and thus should reduce undesired stray light compared to etched surface gratings.

References

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