Diffractive chips for magneto-optical trapping of two atomic species

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Abstract: We investigate diffractive grating chips that can be used as part of a magneto-optical trap (MOT) to trap both Rb and Cs atoms with a single input beam for each atom species.

Cold atoms are a platform for a number of emerging applications that include precision measurement of time [1] and rotation [2], and quantum computing [3]. To trap and cool neutral atoms for these applications, a magneto-optical trap (MOT) is usually used in which atoms are slowed by means of the Doppler effect and trapped via the addition of a magnetic quadrupole field. A conventional MOT uses three pairs of counterpropagating beams to cool atoms in three dimensions, where the six beams need to be aligned to the magnetic-field center independently. In the last decade, several works have shown that the setup can be simplified using grating chips, where only one incident beam is needed, creating multiple reflected and diffracted beams [4,5]. For such grating-based MOT (GMOT), it is important to balance the radiation pressure between the incident beam and the diffracted beams at the trapping center. Work has been done to analyze and characterize the balancing condition of one-dimensional (1D) gratings using scalar diffraction theory [5,6]. However, this method can be imprecise; for example, it cannot account for Rayleigh-Wood anomalies and surface-plasmon polaritons (SPPs) [8], and thus may not correctly identify the designs that result in maximum trapping efficiencies. Furthermore, precise design guidelines are not yet available for two-dimensional (2D) grating chips [Fig. 1(a)] which are easier to align due to their centerless geometry.

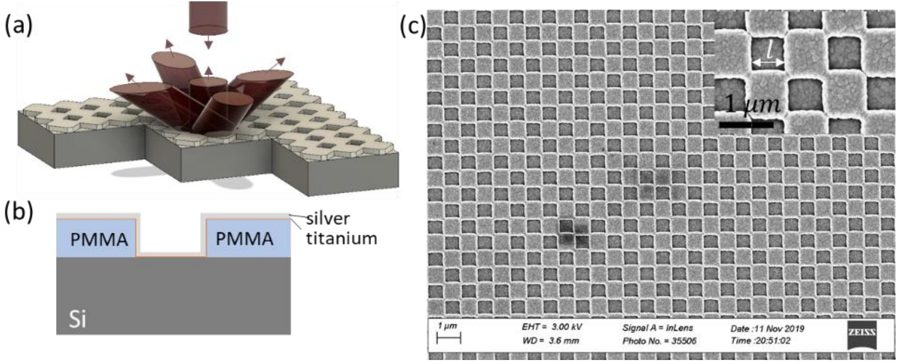

Figure 1 (a) Schematic of a 2D grating chip used for trapping atoms. A collimated incident beam generates five reflected or diffracted beams. The trapping area lies in the overlap region of all six beams where the radiation pressure is balanced. (b) Cross-section schematic of our fabricated 2D grating chip. From the bottom to the top: silicon substrate, PMMA resist checkerboard (thickness T' = 240 nm, pitch d = 977 nm), Ti adhesive layer ~150 nm, Ag ~160 nm. (c) SEM of our final grating structure. Side length of lower squares $l = 571$ nm; area duty cycle of higher squares $r = 66\%$.

In this work, using the finite-difference time-domain (FDTD) method, we simulated both 1D and 2D grating chips, with the incident beam modeled as a plane wave with a wavelength of 780 nm for trapping Rb atoms and 852 nm for Cs atoms. The balancing condition for each chip is described by the balancing efficiency (η_B) [6]:

$$\eta_B = \frac{\sum \eta_1}{1-\eta_0} \tag{1}$$

where $\eta_{0,1}$ is the diffraction efficiency of the 0th/1st order. η_B is ideally 100%, which is automatically satisfied for a lossless grating with $\eta_0 + \sum \eta_1 = 1$. For a practical grating that has loss due to scattering, absorption, or excitation of higher diffraction orders, $\eta_0 + \sum \eta_1 = 1 - loss$, thus Eqn. (1) becomes:

$$\eta_B = 1 - \frac{loss}{1-\eta_0} < 100\% \tag{2}$$

Larger loss and a stronger 0th order diffraction lead to a smaller η_B and a grating that is further away from the ideal balancing condition. Our calculations show that a 2D grating chip can simultaneously have $\eta_B > 90\%$ for both wavelengths [780 nm and 852 nm, structure indicated as the red star in Fig. 2(a, b)]. The diffractive chip has a patterned silicon substrate [pitch (d) of 978 nm, area duty cycle of higher squares (r) of 65%, and patterning depth (T) of 250 nm], and gold coating with thickness of 50 nm. The gold coating partially fills in the lower region and thus increases the area duty cycle of the higher region to 70%. We note that for some geometries we observed a surface-plasmon polariton (SPP) resonance in some gratings [e.g., black cross in Fig. 2(b, c)] that can hamper the balancing due to an increase in light absorption. We showed that this can be prevented using a thicker metal coating, e.g., with a thickness of 100 nm [Fig. 2(c)]. Furthermore, to test the robustness of our design, we studied a variety of 1D grating chips where the duty cycle was varied from unit cell to unit cell, simulating fabrication defects. We found that an 8% random variation from a 50% duty cycle (r) can cause result in approximately 5-15% of the incident light to be lost to scattering and absorption.

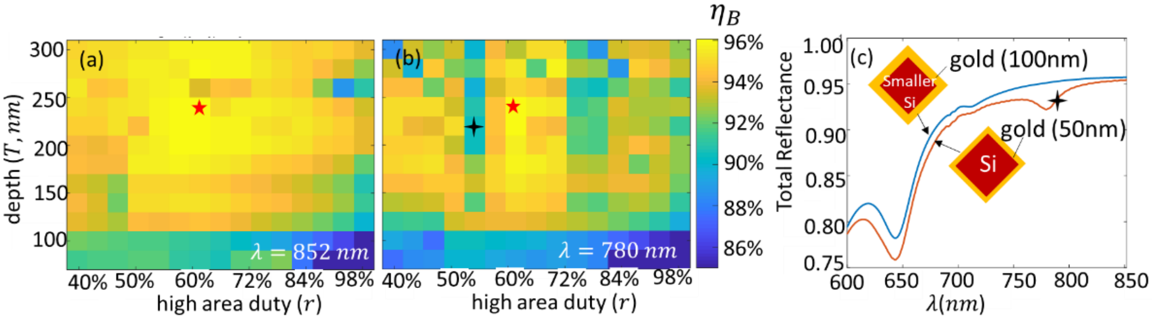

Figure 2 (a, b) Finite-difference time-domain (FDTD) simulations of the balancing efficiency η_B for gold-coated 2D grating chips. The incident beam is modeled as a plane wave with a wavelength of (a) 852 nm and (b) 780 nm. One unit cell is simulated, with periodic boundary conditions. The structure is a patterned silicon substrate (pitch d =978 nm, depth T =250nm) coated with gold that has thickness of 50 nm. η_B is calculated using Eqn. (1). (c) Comparison of the total reflectance of a simulated structure in (b, black cross) and the structure with the same duty cycle but a thicker gold layer (100 nm). The dip in reflectance at λ near 780 nm disappears for the larger gold thickness, which indicates that the feature is due to coupling to a surface-plasmon polariton (SPP) at the gold-silicon interface.

We fabricated 2D grating chips using electron-beam lithography. Unlike the simulated structure in Fig. 2, (a) PMMA e-beam resist was used to create the checkerboard pattern, which has thickness (T') of 240 nm; (b) silver was used as reflective coating due to its compatibility with alkali atoms [9]; (c) a titanium adhesive layer was sputtered before depositing silver; (d) the metal thickness was increased to partially fill in the lower region so as to reach a desired duty cycle (r). We ran another set of FDTD simulations and found that the structure with the area duty cycle $r = 67\%$ has high balancing efficiency for both wavelengths ($\eta_{B@780\ nm} = 93\%$ and $\eta_{B@852\ nm} = 95\%$). One fabricated chip [Fig. 1 (b, c)] has duty cycle $r = 66\%$, whose balancing efficiency was measured to be $\eta_B = 90\%$ for a circularly polarized Gaussian beam with wavelength of 780 nm, which agrees reasonably well with the simulation.

In conclusion, we investigated diffractive chips for simultaneously trapping Rb and Cs atoms with 780 nm and 852 nm lasers, respectively. We used full-wave simulations to determine the impact of different duty cycles, heights, metal coatings, and fabrication defects on the diffracted power, and thus the balancing efficiency (η_B) of the chip. We fabricated a 2D grating chip that has optimized geometry for trapping both atom species. Our work not only provides a guideline for designing 2D grating chips for the next generation of magneto-optical traps (MOTs), but also opens the door to the building of a grating-based MOT that can trap multiple atom species with the same structure.

This work is supported by the National Science Foundation (PHY-1839176) and by the ARL-CDQI program through cooperative agreement W911NF-15-2-0061.

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