Photonic Integrated Si_3N_4 Ultra-Large-Area Grating Waveguide MOT Interface for 3D Atomic Clock Laser Cooling

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Abstract: We describe a silicon nitride (Si_3N_4) photonic integrated circuit (PIC) designed to deliver non-diverging 780nm free-space optical cooling beams to an ^{87}Rb atomic magneto optic trap (MOT) via fiber coupled ultra-large-area 3.88mm x 2.08mm gratings
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Introduction: Atomic clocks offer precise positioning, navigation and timing for a wide variety of applications [1-3], yet today these systems are constructed using tightly coordinated sets of free-space laser beams and bulky optics to cool, pump and probe the atomic species confined in a magneto optic trap (MOT) [4-6]. Wider deployment of atomic clocks will require integration of the lasers and optical interfaces to reduce cost, size and power consumption and decrease sensitivity to environmental conditions.

In a typical ^{87}Rb atomic clock, a complex arrangement of six orthogonal 780nm free-space laser beams are configured to intersect within a MOT to cool the Rb species to 90µK for subsequent interrogation by a probe or pump beam [7]. To drive down the cost and complexity as well as improve the robustness of these systems, PICs will be required to interface pump and probe lasers, delivered by optical fibers, to free-space beams with required geometry and beam quality. Such PICs pose unique integration challenges including low loss visible light fiber-coupled waveguides, visible light passive components including splitters and combiners, and low loss waveguide-to-free-space ultra-large-area gratings uniformly fabricated over mm-scale areas that emit non-diverging beams at pre-designed angles. Prior related integration work includes a ^{87}Rb atomic clock fiber-coupled probe laser PIC interface that couples a Si_3N_4 fiber-coupled waveguide to a 120µm diameter beam emitted at approximately 90° from a 300µm x 300µm area grating forming a beam waist of 160µm inside a Rb MOT [8,9]. However, to date, integration of the fiber to free-space PIC interface for 3D MOT cooling beams for Rb atomic clocks has not been reported.

Here, we describe the design, fabrication and measurement of a Si_3N_4 PIC that interfaces a fiber-coupled 780nm laser to 3D orthogonal MOT cooling beams. Each beam is emitted at 54.7° from the surface, with all three beams intersecting at a position located 9mm above the PIC surface as shown in Figure 1(a). The measured beam cross-sectional area is 3.88mm x 2.09mm which corresponds to a waveguide to free space mode area factor increase of 18.26×10^6, over a 20X factor increase over the largest previously reported [see ref. 9]. The interface PIC is capable of delivering a ^{87}Rb saturation intensity of 3.57713mW/cm^2 [10] via 0.293mW per beam. The measured loss from fiber input to beam power, including fiber coupling, single mode waveguide propagation, three waveguide power splitter, and waveguide grating emitters, totals 20.88dB. This interface efficiency only requires the fiber coupled laser power of 35.9mW to reach saturation intensity at the MOT. Several methods can be used to convert these beams to the required circularly polarized light including quarter wave-plates on the chip surface, top-layer cladding coatings, coatings on the MOT windows or metamaterials grown on surface of chip [11].

Results: Large diameter, non-diverging free-space beams are generated using apodized, chirped gratings, formed by partially etching a Si_3N_4 waveguide layer at the end of a large-area adiabatic single mode waveguide to slab waveguide beam expander as shown in Figure 1(b). The basic waveguide structure is a visible light guide shown in Figure 1(c) employing a 90nm thick Si_3N_4 core deposited and etched on top of 15um thick thermally grown oxide, with an 6um thick TEOS-PECVD upper cladding deposited oxide layer. The optical mode is confined to an area of 444um^2 in the single mode guide, as shown in the field profile fig. 1(c). A 11.43 mm long adiabatic beam expander is used with the 90nm thick Si_3N_4 waveguide core shown in figure 1(e). The three gratings are located at 120° positions centered on a circle of radius 13.5mm. Each grating is designed to emit at an angle of 54.7° from surface which was calibrated by measuring test gratings with different periods around a theoretical calculated value, as shown in figure 2(a). This produces three beams that intersect at a 9 mm distance from the chip surface as illustrated in figure 1(a). We use two step etch process developed at UCSB [12] that is calibrated for a 10nm partial etch.

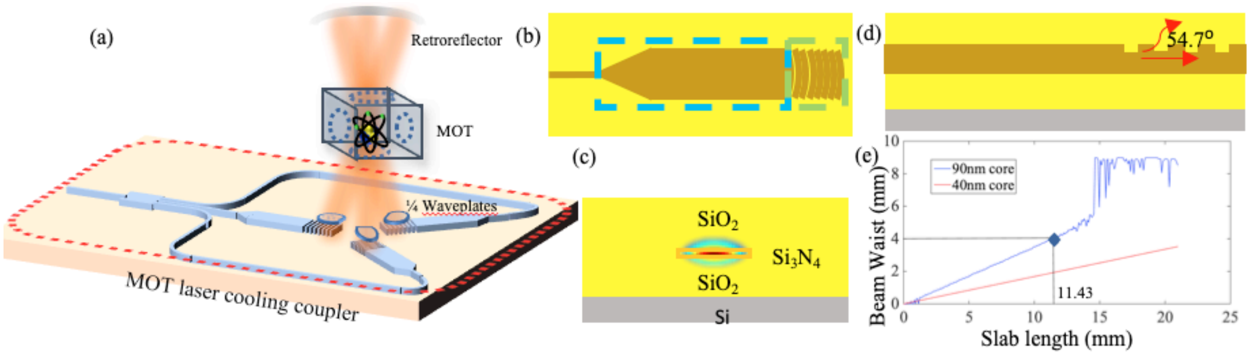

Figure 1: (a) Red dotted line illustrates the 3D three-beam PIC to interface a fiber-couple cooling laser and MOT. (b) Top-view of slab waveguide beam expander (blue) and gratings (green). (c) Waveguide cross section with 90nm silicon nitride waveguide core (d) Sideview of gratings formed with 10nm partial core etch. (e) Simulated beam waist vs. length of expander and design point.

Light is launched from a fiber into the single mode waveguide, expanding to a lateral Gaussian profile at the end of the slab beam expander. The Gaussian grating illumination profile is converted to a uniform grating illumination using a curved grating design. The free-space beam cross-sections of fabricated devices were measured using a calibrated imaging surface and camera positioned at varying locations from the chip surface to determine the beam size and collimation factor. The fiber to beam loss was measured using an integrating sphere and a 780nm detector. The average size of the diffracted beams is measured to be 3.88mm x 2.09mm. The beam divergence is measured to be 3.21mrad x 6.057mrad, corresponding to a beam M factor of 40.74 x 40.07. Our full size gratings produced a higher diffraction order mode as seen in figure 2(b). These mode does not intersect in MOT and hence neither contributes nor is detrimental to cooling. The measured beam diameter vs. distance from chip is plotted in figure 2(c). The collimation lengths are calculated to be 34.5cm and 1.17m, which are much longer than the required 10.5mm x 3 working distance for a retro-reflected MOT beam geometry.

The total power loss for each beam is measured to average 20.88dB for the 54.7° diffracted mode for each of the three beams. For a power an atomic saturation intensity of 0.293mW, this loss translates to a required fiber coupled laser power is 35.9mW. In conclusion, our devices meet two major requirements for a fiber coupled MOT interface: non-divergence and power delivery to atomic MOT saturation power. In addition, the interface PIC achieves a mode increase of 18.26×10^{6} for transformation of a $0.444\mu m^2$ area waveguide mode to $8.1092 mm^2$ free-space beam area. In future designs, we plan to increase the area of the diffracted mode and decrease the fiber to beam power loss.

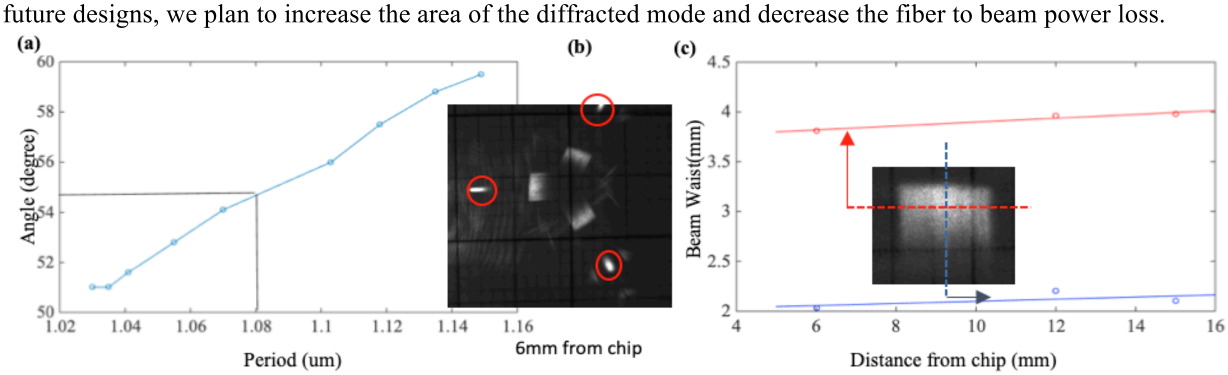

Figure 2: (a) Measured Exit angle for different period for fabricated device (b) Image of diffraction beam pattern at 6mm from image surface, the three rectangular diffraction modes are desired modes with an exit angle of 54.7 while the ones encircled are higher order modes, they do not interfere with cooling as they do not converge where the desired beam converges and are included in the 20.88dB loss mentioned for each beam (c) The graph of beam waist vs distance from chip, plotted for both axis of our rectangular diffraction pattern

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