Photonic integrated building-blocks for rubidium cold atom systems

Andrei Isichenko, Nitesh Chauhan, Jiawei Wang, Debapam Bose, Kaikai Liu, Mark W. Harrington, and Daniel J. Blumenthal
Department of Electrical and Computer Engineering, University of California Santa Barbara, Santa Barbara, CA, USA
danb@ucsb.edu

***Abstract*— We report on integrated silicon nitride photonics at 780 nm with resonators over 100M Q for laser linewidth narrowing and mm-sized, intersecting beam emitters for rubidium atom cooling and trapping. We discuss prospects for integrating these components and controllable locked lasers into cold atom systems-on-a-chip.**

***Keywords*— photonic integrated circuits, low loss waveguides, rubidium, cold atoms**

I. Introduction

Rubidium atomic systems are central to precision scientific systems such as clocks, quantum computers, and sensors. While these laboratory-based systems have become commercialized, the ability to broadly translate this technology outside of the lab is limited by their use of free-space lasers and optics that occupy tables and racks with increased cost and weight. Realizing these systems with CMOS foundry-compatible photonic integrated circuit (PICs) will improve their reliability and enable portability for emerging applications such as mobile gravity mapping [1], volcanic geophysical studies [2], and space-based atomic clocks [3]. Rubidium atoms are commonly probed at 780 nm, the D_2 transition of ^{87}Rb. Efforts towards their miniaturization rival the performance of table-top systems [4,5]. Yet, these approaches still utilize bulk optics and are difficult to scale to a larger multi-function systems.

Photonic integration using the silicon nitride (Si_3N_4) platform offers a set of passive and active devices [6] with optical waveguide losses at 780 nm as low as 0.36 dB/m and Qs as high as 145 million [7]. Here we report on advances in ultra-high-Q (UHQ) resonators for laser linewidth narrowing, ultra-low loss large mode volume resonators for stabilization, and large-area grating output couplers of mm-size beams for rubidium atom 3-D magneto-topical traps (MOTs). We describe several approaches to frequency noise reduction that utilize these properties such as self-injection locking (SIL) [7] and stimulated Brillouin lasers (SBL) [8], and stabilization to coil-reference cavities using Pound-Drever-Hall (PDH) locking. Finally, we describe controllable reference cavities and integrated frequency tracking with a 2-meter coil resonator.

II. Results

A. High-Q Resonators at 780 nm

The ultra-low loss 780 nm waveguide geometry consists of 15 µm SiO_2 lower cladding, a 40 nm thick 4 µm wide Si_3N_4 core and 6 µm SiO_2 upper cladding shown in Fig. 1(a). Fundamental TM mode is selected for its lower loss [9]. The measured intrinsic Q_i = 145 million and the loaded Q_L = 65 million and propagation loss of 0.36 dB/m (Fig. 1(b)). We also design waveguides in a higher-confining 120 nm core and measured Q_L = 2 M and loss 2.4 dB/m and this waveguide geometry is used for the grating beam emitters.

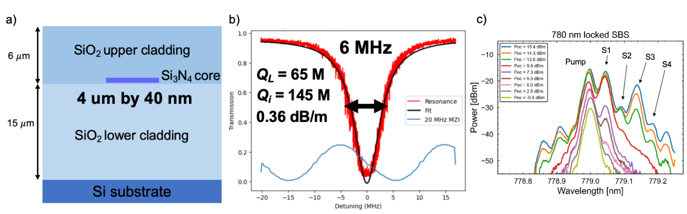

Fig. 1. (a) SiN waveguide cross section. (b) Q measurement of resonator indicate 0.36 dB/m loss. (c) The low loss enables SBS with multiple Stokes tones.

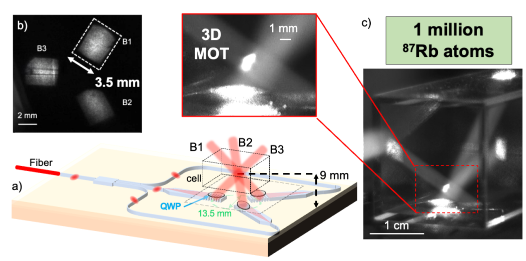

Fig. 2. (a) Beam delivery PIC. b) PIC beams incident on paper sheet; beam width 3.5 mm. c) PICMOT vapor cell with a 3D-MOT of 1 M atoms [10].

B. Large Area Beam Emitters for Atom Cooling

Photonic integration of a MOT beam interface requires the conversion of guided light to multiple free-space, large-area beams that converge within the atom vapor cell at specific angles. We demonstrate the first 3D-MOT using a PIC for beam expansion, collimation, and delivery. The beam delivery PIC (120 nm nitride) transforms 780 nm cooling and repump light into three 2.5 mm x 3.5 mm (e^{-2} diameter) collimated free-space beams producing a beam overlap volume of 17 mm^3 inside the vapour cell at a height 9 mm above the PIC (Fig. 2). Using this PIC delivery interface, we demonstrate a cloud of 1 million atoms at ~200 µK [10].

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C. Laser Linewidth Reduction and Control

The high Q, low loss, and material properties of the oxide clad silicon nitride waveguides enables strong feedback for laser Pound-Drever-Hall (PDH) stabilization and several orders of magnitude linewidth reduction using SIL and stimulated Brillouin scattering (SBS). The high Q enables mW-threshold ultra-low phase noise SBL [8] (Fig. 1(c)). Using a PDH lock to stabilize a 780 nm DBR laser to a 37 million Q_L resonator we measure a locked 3 kHz integral linewidth (reverse integral 1/pi, Fig. 3(b)). Using the 145 million Q_i resonator for SIL, where the strong optical feedback is achieved through resonant Rayleigh backscattering inside the resonator cavity, the laser noise is reduced and allows for stabilization of an ordinarily multi-mode Fabry-Pérot (FP) laser. The 780 nm SIL achieves a thermo-refractive-noise (TRN) limited FN, a sub-kHz integral linewidth, and a 600 mHz fundamental linewidth (Fig. 3(d)). There are trade-offs between performance and locking stability for SIL compared to PDH locking techniques. Leveraging the stability of the PDH lock, we demonstrate a thermo-optically tunable, UHQ reference cavity, for narrow linewidth spectroscopy tuning [11] where tunable resonator has a Q_i = 118 million, 0.44 dB/m loss, and a thermo-optic tuning range of >400 MHz (Fig. 4(a)). By ramping the metal tuner voltage, the locked laser is scanned across the D_2 line hyperfine transitions and the saturation absorption spectroscopy signal is shown in Fig. 4(b). We apply a 500 Hz ramp rate which is a sufficient speed for locking to a hyperfine transition to reduce long-term laser frequency drift. We show that a 2-meter coil resonator with 103 MHz FSR can be used as a frequency tracker to keep the scanning spectroscopy calibrated in real time during the laser frequency ramp (Fig. 4(c)).

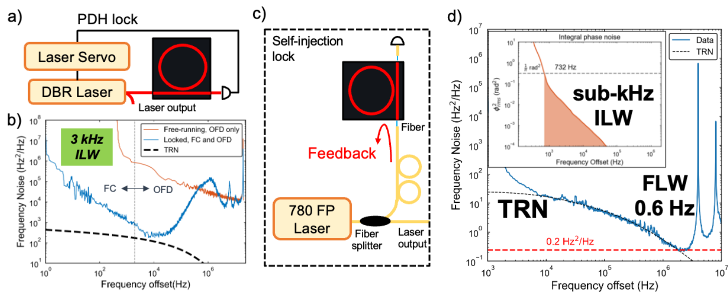

Fig. 3. (a) Setup schematic for PDH locking to resonator with a DBR laser and (b) frequency noise data. c) Schematic for SIL of a low-cost FP laser to the UHQ resonator. (d) Frequency noise for the SIL laser shows a TRN-limited noise with sub-Hz FLW and sub-kHz ILW.

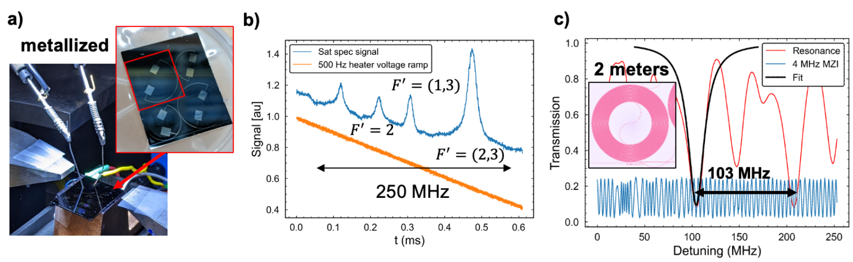

Fig. 4. (a) Metallized UHQ device. (b) Controlling locked laser ramping over Rb sat-spec transitions. (c) Frequency tracker using a 103 MHz FSR coil resonator.

III. Conclusion

We report advances in silicon nitride photonic components for a set of building blocks for experimental rubidium cold atom systems. The 780 nm high Q resonators are an enabling technology for narrow linewidth lasers and the large area beam emitters eliminate free-space optics in a cold atom MOT. Combining active control capabilities [12], especially with faster modulation [13], enables stabilization to an absolute spectroscopic reference which is a key component for atoms are resonantly probes. This combination of photonic components is suited for specific cold atom systems such as atom interferometry (AI). Here, the phase noise of the Raman lasers can be related to the readout sensitivity of an AI sensor [14] and a specific frequency control sequence for the cooling laser is needed for a low-temperature MOT [4]. Combing these components onto a single photonic chip can enable a new generation of integrated cold atom sensors and potentially new applications.

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