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Invited Paper

Integrated stabilized lasers and circuits for atom cooling, trapping, and interrogation

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ABSTRACT

Visible light laser and optical systems are the heart of precision applications including quantum computing, atomic clocks and precision metrology. As these systems scale in terms of number of lasers, wavelengths, and optical components, their reliability, weight, size, and power consumption will push the limits of using traditional laboratory-scale lasers and optics. Visible light photonic integration is critical to overcoming these bottlenecks and to enable portable and low cost applications. Solutions must deliver low waveguide losses, low laser phase noise and high stability lasers, and key functions such as modulation and wavelength shifting, in a wafer-scale CMOS foundry compatible platform. In this talk we will cover integration of visible light photonics and key components for atom cooling, trapping and interrogation, in the ultra-low loss silicon nitride (Si_3N_4) waveguide platform, including ultra-narrow linewidth stabilized lasers, ultra-low loss waveguides, ultra-high Q resonators, modulators, filters, beam emitters and other components. Higher level functional integration will be covered as well as atom cooling demonstrations.

Keywords: Photonic integration, narrow linewidth lasers, visible light photonics, atom cooling.

1. INTRODUCTION

Photonic integration can improve the reliability, reduce the cost and size, and enable scalability, of traditionally table-top sized precision lasers and optics for visible light applications such as optical atomic clocks [1-3], precision spectroscopy [4, 5] and metrology [6, 7], atomic sensors [8-10], and quantum information sciences and applications [11-14]. For example, atomic, molecular and optic (AMO) applications [15] rely on racks of lasers and table-sized optics to perform spectroscopy, trap and cool, manipulate, and probe just a single atom, ion, molecule or quantum gate. Today's optics infrastructure presents challenges to scaling the number of atoms, ions or qubits, in order to improve the sensitivity of a quantum sensor or computational complexity of a quantum computer. For visible light AMO systems, waveguide loss is paramount to the preservation of photons [16] and resonator Q plays a critical role in laser linewidth narrowing, phase noise reduction and filtering [17]. Photonic integration can address these requirements [18] and key functions including photon routing, optical filtering [19], free-space beam formation [20, 21], and hybrid tunable [22] and ultra-low linewidth lasers [23, 24]. The silicon nitride integration platform [25, 26] offers a wafer-scale, CMOS compatible, photonic integration platform that delivers ultra-low waveguide and ultra-high Q resonators, and can implement other key functions such as modulation, across the 400 - 900 nm wavelength range, and can realize these advances. An example of an integrated visible light atom cooling, trapping, and interrogation system on-chip is shown in Figure 1.

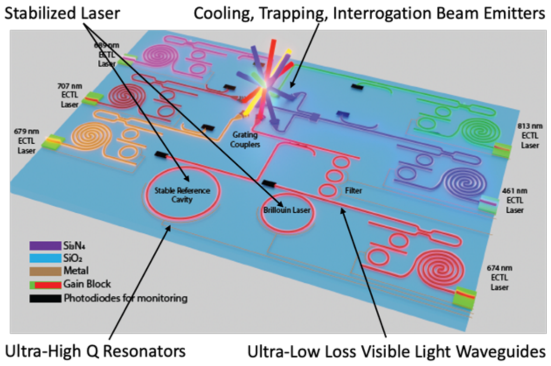

Figure 1. Illustrative example application of visible light photonics for integrated atom cooling, trapping, and interrogation (adapted from [16]).

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2. INTEGRATED STABILIZED LASERS

Photonic integrated laser stabilization has been achieved by locking a semiconductor laser to a Si$_3$N$_4$ 4.0 m long photonic integrated coil resonator (Fig. 2). Using a Pound-Drever Hall (PDH) lock, an integral linewidth of 36 Hz and Allan deviation of 1.8x10^{-13} at 10 ms, and 2.3 kHz/s drift were demonstrated [27]. The 1550 nm coil resonator stabilization cavity measures a 49.1 MHz free spectral range (FSR), intrinsic 80 million Q, and loaded 55 million Q. Laser stabilization has also been reported using dual integrated bus-coupled ring resonator cavities [28].

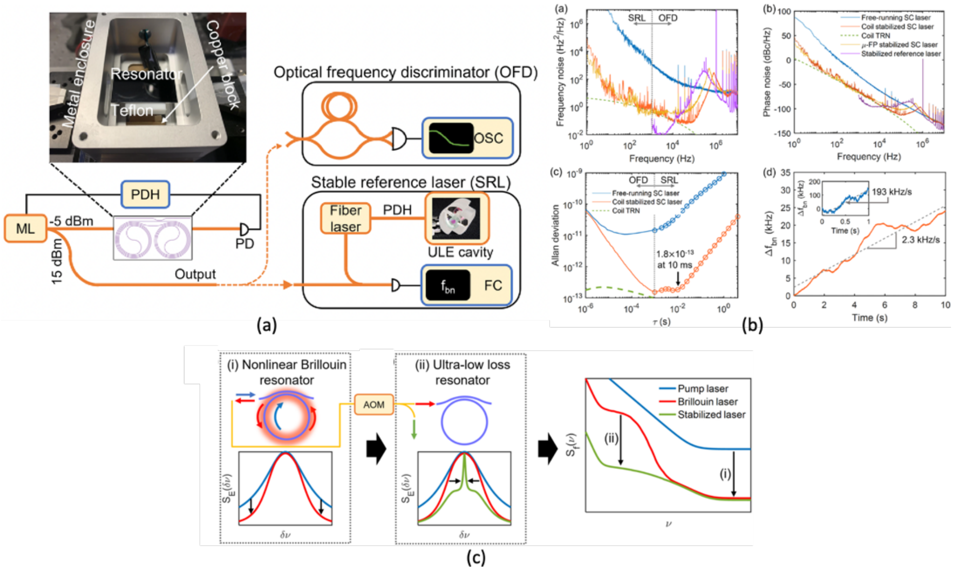


Figure 2. Examples of Si$_3$N$_4$ integrated stabilized lasers. (a) Coil resonator stabilized semiconductor laser. (b) Frequency noise, linewidth, and ADEV of (a). (c) Dual integrated cavity stabilized Brillouin laser.

3. VISIBLE LIGHT PHOTONIC COMPONENTS

Taking inspiration from these systems, we leverage the properties of nonlinear and ultra-low loss resonators fabricated using the silicon nitride (Si$_3$N$_4$) waveguide platform [26] components needed for AMO laser and optical systems. With losses as low as 0.034 dB/m and transparency from 405 nm through the infrared (IR) [16, 17], the Si3N4 waveguide platform is a versatile solution for integrating stable lasers. Additionally, the Si$_3$N$_4$ waveguide platform is wafer-scale and CMOS foundry compatible, enabling integration of a wide variety of photonic elements at the chip-scale. We have implemented ultra-low fundamental linewidth SBS lasers, PDH locked to ultra-high Q and large mode volume resonators, and sensitive dual-mode resonator designs for frequency drift correction. These results include: (i) Low phase noise lasers (ii) stabilization cavities, and (iii) frequency stabilized lasers. Examples include Visible and IR SBS integrated lasers [23, 24] and integrated reference cavities and modulators: Fig. 3 (a) 4-meter integrated coil-resonator for 36 Hz integral linewidth 1550 nm laser [29] and an integrated 3-meter 40 million Q coil-resonator yielding a 4.2 kHz linewidth at 674 nm [30], (b) 0.034 dB/m loss waveguides in a 200 mm wafer-scale Si$_3$N$_4$ integration platform realizing a 720 million Q resonator and 380 µW threshold SBS laser at 1550nm [17] (c) ultra-low loss PZT actuated ring modulator for photonic control [31], (d) 422 million Q resonator [32], and (e) a nonlinear cavity locked to an ultra-low loss cavity to reduce the Si$_3$N$_4$ Brillouin laser linewidth to 330 Hz integral linewidth and 6.5×10^{-13} FFN at 8 ms [28].

4. ATOM COOLING AND TRAPPING

Cold atoms are central to precision atomic applications including timekeeping and sensing. The 3D magneto-optical trap (3D-MOT), is commonly used to produce a cloud of cold atoms. These traps require the delivery of multiple, large area, collimated laser beams to an atomic vacuum cell. We have demonstrated a ^{87}Rb 3D-MOT using a fiber-coupled photonic integrated circuit to deliver all necessary beams to cool and trap more than 5 x 10^{6} atoms to near 200 µK in a trapping volume that is an order of magnitude smaller than that of an equivalent atom number diffraction grating MOT [33] (Fig. 4). The silicon nitride photonic circuit transforms fiber-coupled 780 nm cooling and repump light via waveguides to three orthogonal non-diverging 2.5 mm x 3.5 mm free-space cooling and repump beams directly interface to the rubidium cell. This full planar, CMOS foundry-compatible integrated beam delivery is compatible with other components, such as lasers and modulators, promising system-on-chip solutions for cold atom applications.

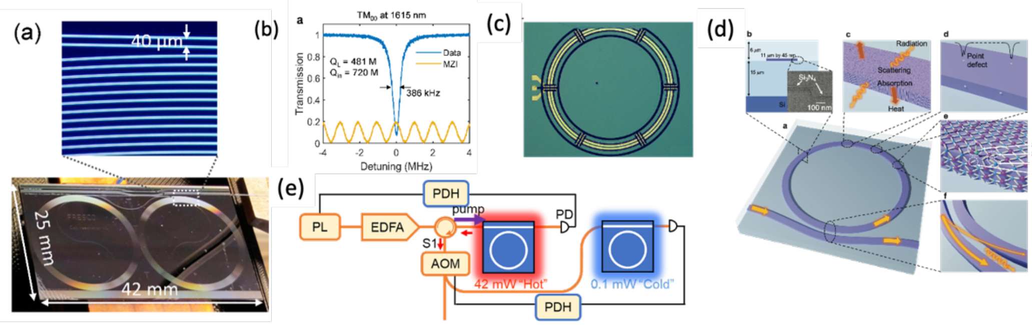
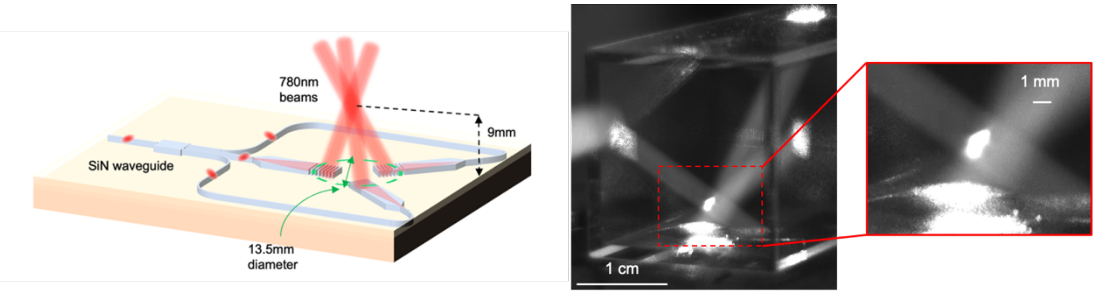


Figure 3 (a) Photonic integrated coil resonator, (b) 720 million Q integrated resonator, (c) low loss, low power, silicon nitride PZT stress-optic microresonator modulator, (d) 422 million Q planar integrated all-waveguide resonator, (e) self-similar ultra-high Q Si3N4 integrated resonators for Brillouin laser linewidth narrowing and stabilization.



(a) (b)

Figure 4. (a) Photonic integrated 3 collimated 780 nm cooling and repump beam delivery PIC. (b) Demonstration of PIC beam deliver in an ^{87}Rb 3D-MOT.

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