Integrated Frequency-agile 780 nm PZT Silicon Nitride Ring Modulator and Application to sub-Doppler Atom Cooling

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Abstract: We demonstrate a 780 nm PZT-on-Si_3N_4 stress-optic ring modulator with 2.8 million Q, 11 MHz modulation bandwidth, and 1 GHz/V static tuning. The modulator enables precise laser frequency control for sub-Doppler cooling of rubidium atoms. © 2025 The Author(s)

1. Introduction

Precision laser modulation and frequency control are essential for atomic experiments including atomic quantum sensors [1,2] , timekeeping [3], and quantum computing [4]. Realizing field-deployable quantum sensors such as cold atom interferometers requires the miniaturization of the laser system and associated functions including frequency shifting [5] and GHz-speed modulation [2,6]. In particular, for rubidium systems operating at 780 nm, these functions typically rely on bulk-optic, power consuming components such as acousto-optic modulators (AOMs) or 1560 nm modulators combined with frequency doubling second harmonic generation (SHG). A critical next step is to develop efficient visible light and near-IR (NIR) modulators at wavelengths associated with atomic transitions such as at the 780 nm D_2 transition for rubidium. Modulators realized in the CMOS-compatible silicon nitride (Si_3N_4) waveguide platform are especially important for atomic applications due to the commensurate ultra-low losses for laser stabilization [7], wide transparency window (405 nm – 2350 nm) [8], and compatibility with other photonics for atomic, molecular and optical (AMO) physics experiments. The stress-optic effect using lead zirconate titanate (PZT) actuators on Si_3N_4 offers wideband DC to >10s of MHz bandwidth modulation, does not affect optical loss, and consumes only 10s of nW of power [9]. Yet to date, operation in non-undercut, back-end deposited PZT has only been demonstrated at 1550 nm [10] .

In this paper we report the demonstration of an agile photonic integrated PZT actuated stress-optic ultra-low loss Si_3N_4 ring resonator modulator operating at 780 nm, corresponding to the D_2 rubidium spectroscopy line. We measure a 6dB modulation bandwidth of 11 MHz and a tuning coefficient of 1 GHz/V measured over a 10 GHz tuning range. The 750 µm radius optical resonator achieves a loss of 0.19 dB/cm and a loaded Q of 2.3 million. The modulator can operate in an agile mode where the ring is swept at a rate commensurate with its bandwidth and an arbitrary precision frequency control sequence is generated. We demonstrate application in this mode to sub-Doppler cooling of rubidium atoms with a control sequence designed for polarization gradient cooling (PGC). A 780 nm DBR laser is stabilized to the modulator and a precise fast time-voltage locked frequency control sequence is applied to the PZT actuator, achieving 100 MHz linear detuning in 3 ms which is sufficient for a rubidium cold atom sub-Doppler frequency detuning sequence.

2. Experimental results

The design and fabricated 780 nm SiN PZT ring resonator modulator is shown in Figs. 1a-c. We measure the performance with a 780 nm DBR laser input to the modulator and characterizing the DC resonance tuning and the small signal AC modulation response to voltage applied to the PZT electrodes. The ring resonator has a 750 um ring radius corresponding to a 42 GHz free-spectral range (FSR). The device consists of a 15 µm SiO_2 lower cladding, a 120 nm thick and 900 nm wide Si_3N_4 core, and a 4 µm SiO_2 upper cladding (Fig. 1c). The planar layer of PZT is 1 um thick and is deposited on top of the waveguide between two Pt thermal tuner electrodes, all without the added complexity of undercut structures [11,12] . For the TM-mode resonance we measure a Q_i = 2.8 M, Q_L = 2.3 M, and propagation loss 0.19 dB/cm (Fig. 1d). The PZT actuator enables linear tuning over a broad range. The optical transmission spectrum (Fig. 2a) shows resonance tuning as a function of DC control voltage from 0 to 10 V and a resonance shift corresponding to a linear tuning of 1 GHz/V (Fig. 2b). The leakage current is measured to be < 1 nA at 10 V applied voltage indicating a power consumption of 10 nW. The small-signal electrical-to-optical modulation response S_{21} is measured using a network analyzer. The 780 nm laser is tuned onto the quadrature point of the resonance to measure the modulation response. The 6 dB cutoff frequency is measured to be 11 MHz and the 180° phase-lag point is 5.8 MHz (Fig. 2c). By applying modulation sidebands at 5 MHz to the modulator directly, we generate an error signal for PDH locking, without the need to apply direct current modulation to the laser (Fig. 2d).

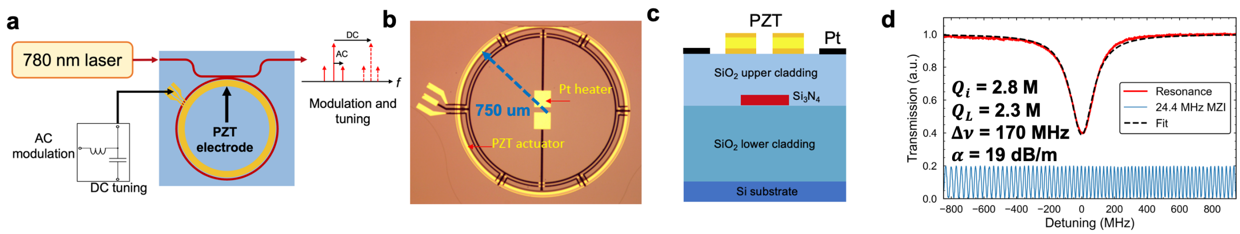

Figure 1. a) Schematic for the 780 nm PZT silicon nitride optical modulator capable of small signal modulation and static DC tuning. b) Image of the fabricated device. c) Cross-section of the silicon nitride ring modulator with PZT actuator and Pt thermal tuner. d) Quality factor (Q) measurement of the modulator. The MZI fringe pattern (blue trace) with a calibrated free spectral range (FSR) of 24.4 MHz is used as a frequency ruler to measure the full-width-at-half-maximum (FWHM) of the resonance (red trace).

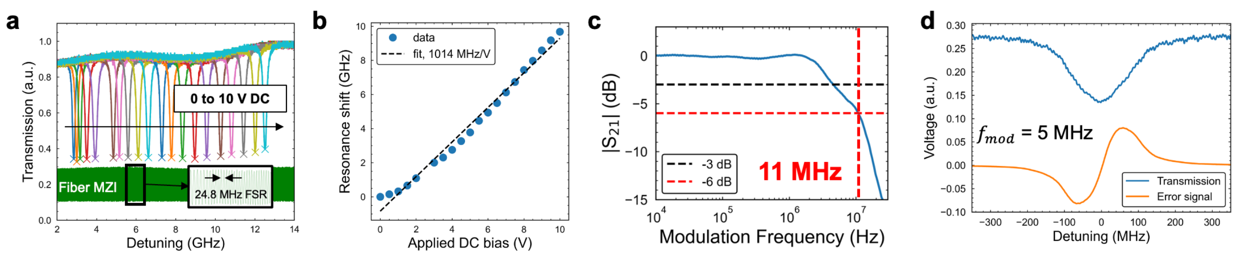

Figure 2. a) Transmission spectra for single resonance as a function of applied bias voltage to the PZT. (b) The resonance frequency shift as a function of the applied DC bias. The measured tuning strength is 1 GHz/V ≈ 2 pm/V. (c) Frequency response of the PZT stress-optic small-signal modulation. The 6-dB modulation bandwidth is 11 MHz. d) PDH error signal generated by applying a 5 MHz modulation directly to the modulator.

Next, we demonstrate the application of the PZT ring modulator as an agile locked laser frequency tuner for a laser frequency control sequence in a rubidium cold atom ensemble. This enables cooling atoms in a magneto-optic trap (MOT) to below the 150 μK Doppler limit, a technique known as polarization gradient cooling (PGC) [13]. This approach requires the MOT cooling laser to be linearly red-detuned by 30 to 100 MHz in a span of a few ms [2]. The schematic for demonstrating and measuring the locked laser tuning is shown in Fig 3a. We PDH-stabilize a 780 nm DBR laser to the ring resonator and apply a voltage sequence to the PZT electrodes. The locked laser tracks the resonance within the bandwidth of the PDH feedback loop and a PZT-actuated resonance shift corresponds to a laser frequency shift. We measure the DBR laser frequency detuning using a heterodyne beat-note with a rubidium D_2 line spectroscopy-stabilized ECDL reference laser. The frequency shift is recorded on an electronic spectrum analyzer

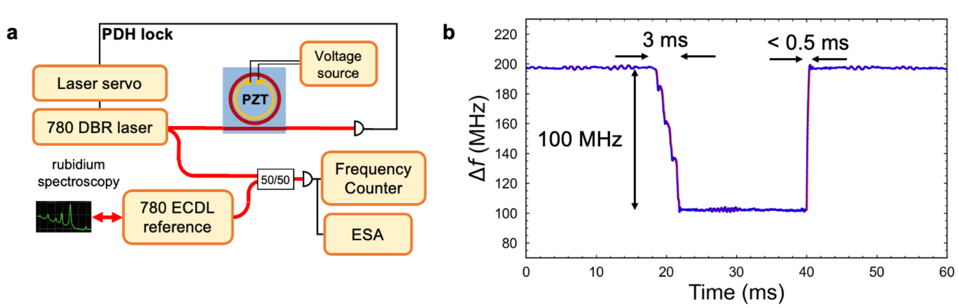

Figure 3. (a) Schematic for measuring laser frequency tuning for a DBR laser stabilized to the PZT-actuated agile resonator. The beat-note with a rubidium spectroscopy-stabilized reference laser is measured on a frequency counter. b) Heterodyne beat-note as a function of time with a sub-Doppler cooling laser frequency control waveform applied. Red and blue traces correspond to traces from subsequent cycles.

(ESA) and a frequency counter (FC). We realize a linear frequency ramp over 100 MHz in 3 ms that settles to a fixed frequency (Fig. 3b). The laser returns to the original frequency of the control sequence in a step response time of < 500 us and the tuning sequence is shown for two subsequent cycles. This control can be extended to referencing to spectroscopy to maintain an absolute frequency using a dual-stage lock [14]. Combined with synchronized magnetic field and intensity control, this sequence is sufficient to prepare the rubidium cold atom ensemble to a sub-Doppler temperature necessary for cold atom interferometry experiments.

3. Conclusion

We demonstrate a low-loss, PZT-actuated SiN ring modulator at 780 nm with 2.8 million intrinsic Q, 1 GHz/V tuning efficiency, and 11 MHz modulation bandwidth The modulator is wideband, operating from DC to 11 MHz, making it suitable for amplitude and phase modulation as well as laser frequency control applications. By locking a 780 nm semiconductor laser to the resonator and applying a voltage to the PZT actuator we achieve precise and agile laser frequency control. Importantly, this technique is independent of the laser locking scheme and can be extended to high bandwidth self-injection locking [14]. We demonstrate the control sequence for cooling rubidium atoms below the Doppler limit, achieving a 100 MHz linear detuning in 3 ms. The SiN waveguide thickness is identical to that used for photonic-integrated large-area beam delivery [15] and offers a path towards integrated cold atom quantum sensors.

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