# Integrated Low-Power Blue Light PZT Silicon Nitride Ring Modulator for Atomic and Quantum Applications

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**Abstract:** We demonstrate a low-power, PZT stress-optic $Si_3N_4$ micro-ring blue light modulator with 5.4 million intrinsic Q, 10.5 MHz 3 dB bandwidth, and 760 MHz/V tuning for atomic and quantum applications including trapped barium ions. 

**OCIS codes:** (130.4110) Modulators; (140.4780) Optical resonators; (300.6520) Spectroscopy, trapped ion.

## 1. Introduction

Photonic integration of optical modulators is essential towards scalable miniaturization of atomic and quantum systems including trapped-ion and cold atom quantum computers [1, 2], atomic quantum sensors [3], and atomic clocks [4]. Many atomic species of interest require high-energy blue photons [5] and associated optical modulation and frequency control to perform laser cooling, repumping, and state preparation and measurement (SPAM) for qubit operations [6]. For example, trapped barium ion quantum experiments will benefit from integrated modulators operational at 493nm, which can replace power consuming, bulky acousto-optic modulators (AOMs) and electro-optic modulators (EOMs) [7]. CMOS-compatible silicon nitride ($Si_3N_4$) offers a promising platform for modulator integration due to its ultra-low waveguide losses from 405 nm to 2350 nm [8]. Lead zirconate titanate (PZT) stress-optic integrated modulators have shown to offer low-loss, low-power operation in the 1550 nm range [9]. However, these modulators have yet to be demonstrated at visible wavelengths. Here we report the fabrication and demonstration of a fully integrated PZT $Si_3N_4$ micro-ring modulator operating at 493 nm corresponding to the laser cooling transition used in $Ba^+$ trapped-ion quantum experiments. The device has a 3 dB modulation bandwidth of 10.5 MHz, intrinsic Q of 5.4 million, loaded Q of 1.4 million, tuning strength of 760 MHz/V, propagation loss of 0.15 dB/cm, and extinction ratio of 6.3 dB.

## 2. Experimental Results

Shown in Fig. 1 are the modulator experimental test setup (a), the waveguide and PZT actuator design (b), a photograph of the fabricated device (c), and a measurement of the resonator quality factor Q (d). The modulator resonator utilizes a 15 µm thick lower cladding, 20 nm thick and 2 µm wide $Si_3N_4$ waveguide, and 4 µm thick upper cladding to realize a 750 µm radius ring resonator with 1.4 million loaded Q, 5.4 million intrinsic Q, 38 GHz free spectral range, 6.3 dB extinction ratio, and 0.15 dB/cm propagation loss at 493 nm. The fully planar PZT is deposited on top of the upper cladding, laterally offset from the waveguide core, using a back-end process which avoids undercut or "pull back" structures commonly required in aluminum nitride (AlN) stress-optic modulators [10,11]. The device was tested at 493 nm using a DRS Daylight Stretto laser.

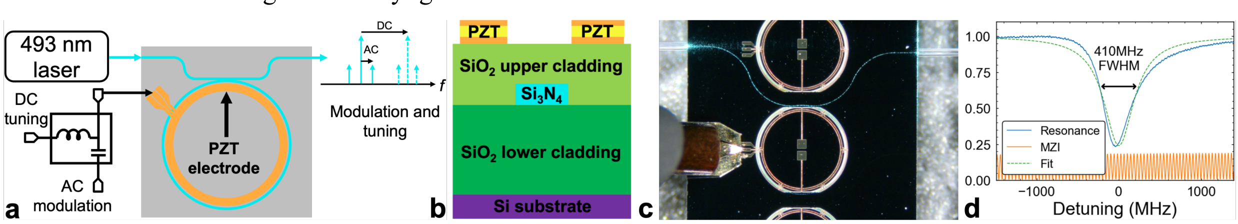


Fig. 1. **a** Schematic of the PZT-actuated $Si_3N_4$ ring modulator test setup for static tuning and AC small signal measurements. **b** Cross section of the silicon nitride waveguide and back-end deposited PZT actuator. **c** Microscope image of the fabricated device under test. **d** Resonator quality factor (Q) measurement. The orange trace is a 40.2 MHz free spectral range MZI used as a frequency ruler to measure and fit to the resonance.

By applying a DC voltage to the PZT, a lateral strain is induced in the silicon nitride, corresponding to a change in waveguide refractive index from the stress-optic effect. As a result, the resonance linearly shifts with a measured tuning coefficient of 760 MHz/V (0.6 pm/V) outside of the hysteresis regime (Fig. 2a, b), corresponding to the calculated values $V_\pi L$ = 11.8 V·cm and $V_\pi L\alpha$ = 1.8 V·dB. The PZT's high breakdown voltage, on the order of tens of volts, allows fast, linear frequency tuning of the resonance up to tens of GHz resonance shift. The leakage current is measured to be <1 nA with a 5V control signal corresponding to a power consumption of only 5 nW. The modulator is demonstrated by applying 10 MHz sideband modulation to generate an error signal (Fig. 2c). This error signal can be used for Pound-Drever-Hall (PDH) locking without direct modulation of the laser's current. The amplitude and phase of the small-signal modulation transmission response $S_{21}$ is measured by tuning the laser to the quadrature point of the resonator, applying a small signal up to 20 MHz, and measuring the response using a vector network analyzer. The results shown in Fig. 2d, e demonstrate a 3 dB modulation bandwidth up to 10.5 MHz, a 6 dB modulation bandwidth up to 13 MHz, and a 180° phase lag point of 4.7 MHz.

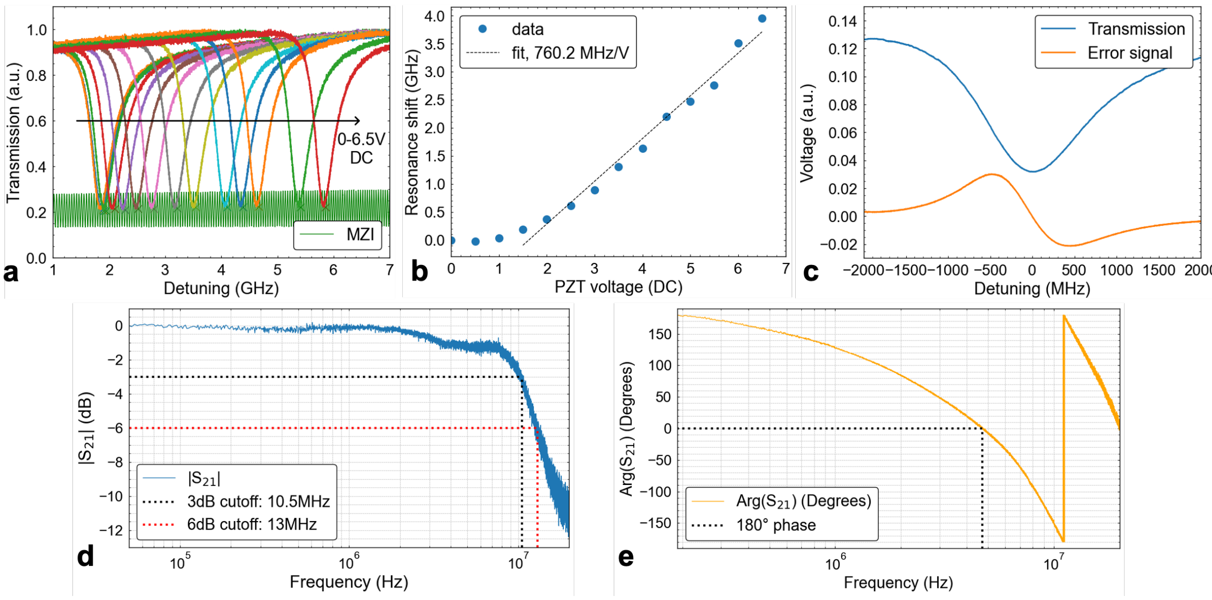


Figure 2. **a** Resonance's transmission spectra for applied DC voltages to the PZT electrode every 0.5V from 0V to 6.5V. **b** Static PZT tuning. Excluding the region of hysteresis from 0 to 1.5V, a linear tuning of 760 MHz/V is demonstrated. **c** By applying a 10 MHz small signal modulation to the PZT, an error signal is observed, and the transmission spectra broadens due to the sidebands. **d** Amplitude of $S_{21}$ frequency response measured by a vector network analyzer. **e** Phase of $S_{21}$ frequency response. The 180-degree phase lag is measured to be 4.7 MHz.

## 3. Discussion

We demonstrate a low-loss, blue light photonic integrated PZT stress-optic $Si_3N_4$ ring modulator operating at 493 nm, which is applicable to trapped-ion barium quantum experiments. The modulator has a $Q_i$ of 5.4M, $Q_L$ of 1.4M, 3 dB bandwidth of 10.5 MHz, tuning strength of 0.6 pm/V, and power consumption of only 5nW. By PDH locking the 493 nm laser to the ring modulator and actuating the PZT, this device could also be used for agile precision frequency control and as a fast amplitude shutter. Future work will focus on higher extinction ratio modulators at wavelengths corresponding to a wide array of useful atomic transitions for high-fidelity qubit entanglement.

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## References

[1] C. W. Hogle, et al. "High-fidelity trapped-ion qubit operations with scalable photonic modulators," npj Quantum Inf **9**, 1–6 (2023).
[2] M. Saffman, "Quantum computing with atomic qubits and Rydberg interactions: Progress and challenges," (2016).
[3] H. S. Stokowski, et al. "Integrated quantum optical phase sensor in thin film lithium niobate," Nat Commun **14**, 3355 (2023).
[4] A. D. Ludlow, et al. "Optical atomic clocks," Rev. Mod. Phys. **87**, 637–701 (2015).
[5] A. A. Savchenkov, et al. "Application of a self-injection locked cyan laser for Barium ion cooling and spectroscopy," Sci Rep **10**, 16494 (2020).
[6] I. Pogorelov, et al. "Compact Ion-Trap Quantum Computing Demonstrator," PRX Quantum **2**, 020343 (2021).
[7] A. Binai-Motlagh, et al. "A guided light system for agile individual addressing of $Ba^+$ qubits with $10^{-4}$ level intensity crosstalk," (2023).
[8] D. J. Blumenthal, et al. "Silicon Nitride in Silicon Photonics," Proc. IEEE **106**, 2209–2231 (2018).
[9] J. Wang, et al. "Silicon nitride stress-optic microresonator modulator for optical control applications," Opt. Express, OE **30**, 31816–31827 (2022).
[10] P. R. Stanfield, et al. "CMOS-compatible, piezo-optomechanically tunable photonics for visible wavelengths and cryogenic temperatures," Opt. Express, OE **27**, 28588–28605 (2019).
[11] A. Siddharth, et al. "Piezoelectrically tunable, narrow linewidth photonic integrated extended-DBR lasers," Optica **11**, 1062–1069 (2024).