



# Silicon nitride stress-optic microresonator modulator for optical control applications

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**Abstract:** Modulation-based control and locking of lasers, filters and other photonic components is a ubiquitous function across many applications that span the visible to infrared (IR), including atomic, molecular and optical (AMO), quantum sciences, fiber communications, metrology, and microwave photonics. Today, modulators used to realize these control functions consist of high-power bulk-optic components for tuning, sideband modulation, and phase and frequency shifting, while providing low optical insertion loss and operation from DC to 10s of MHz. In order to reduce the size, weight and cost of these applications and improve their scalability and reliability, modulation control functions need to be implemented in a low loss, wafer-scale CMOS-compatible photonic integration platform. The silicon nitride integration platform has been successful at realizing extremely low waveguide losses across the visible to infrared and components including high performance lasers, filters, resonators, stabilization cavities, and optical frequency combs. Yet, progress towards implementing low loss, low power modulators in the silicon nitride platform, while maintaining wafer-scale process compatibility has been limited. Here we report a significant advance in integration of a piezo-electric (PZT, lead zirconate titanate) actuated micro-ring modulation in a fully-planar, wafer-scale silicon nitride platform, that maintains low optical loss (0.03 dB/cm in a 625  $\mu\text{m}$  resonator) at 1550 nm, with an order of magnitude increase in bandwidth (DC - 15 MHz 3-dB and DC - 25 MHz 6-dB) and order of magnitude lower power consumption of 20 nW improvement over prior PZT modulators. The modulator provides a >14 dB extinction ratio (ER) and 7.1 million quality-factor (Q) over the entire 4 GHz tuning range, a tuning efficiency of 162 MHz/V, and delivers the linearity required for control applications with 65.1 dB·Hz<sup>2/3</sup> and 73.8 dB·Hz<sup>2/3</sup> third-order intermodulation distortion (IMD3) spurious free dynamic range (SFDR) at 1 MHz and 10 MHz respectively. We demonstrate two control applications, laser stabilization in a Pound-Drever Hall (PDH) lock loop, reducing laser frequency noise by 40 dB, and as a laser carrier tracking filter. This PZT modulator design can be extended to the visible in the ultra-low loss silicon nitride platform with minor waveguide design changes. This integration of PZT modulation in the ultra-low loss silicon nitride waveguide platform enables modulator control functions in a wide range of visible to IR applications such as atomic and molecular transition locking for cooling, trapping and probing, controllable optical frequency combs, low-power external cavity tunable lasers, quantum computers, sensors and communications, atomic clocks, and tunable ultra-low linewidth lasers and ultra-low phase noise microwave synthesizers.

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## 1. Introduction

The silicon nitride ( $\text{Si}_3\text{N}_4$ ) photonic integrated platform [1,2] delivers ultra-low waveguide losses and broad passive functionality across the visible through the IR wavelength range [3,4] in a planar wafer-scale, CMOS-compatible process. This platform has the potential to provide the benefits of integration, namely low-cost, portability, low-power, scalability, and enhanced reliability to a

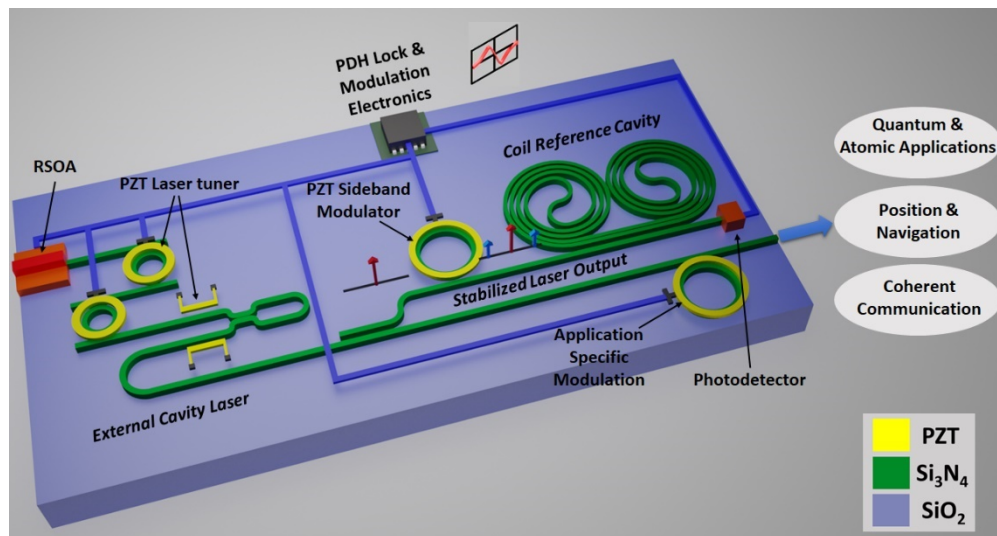
wide range of applications including quantum information sciences and applications [5,6], optical atomic clocks [7,8], precision metrology [9,10], atomic, molecular and optical [11], microwave photonics [12,13], fiber optic precision frequency distribution [14–16], and energy efficient communications [17]. A ubiquitous function among these applications is optical actuation and modulation, to perform tuning and control functions including wavelength shifting, sideband and sweep modulation, and phase shifting, with low optical insertion loss and modulation bandwidths from DC to 10s of MHz and higher. Examples include laser locking to reference cavities and atomic transitions [18] and optical channel tracking in fiber communications [19]. Today, these systems use power-consuming bulk-optic electrooptic (EOM) [20] and acousto-optic (AOM) [21] modulators to implement control loops such as the PDH [22,23] and proportional, integration and derivative (PID) [18,24]. Devices and functions that will benefit from integrated, low power, active modulation include hybrid tunable lasers [25], optical frequency combs [26,27], Brillouin lasers [4,28,29], atomic and ion transition trapping, cooling and locking [7,30], laser stabilization [31], phase lock loops [14], and cryogenic applications [32,33]. Yet it has remained a challenge to transition these modulators to the silicon nitride platform while maintaining the ultra-low optical loss in a CMOS-compatible, wafer-scale process. Therefore, integrated control modulators that maintain the desirable properties of the silicon nitride platform, as well as low-power consumption, are needed.

There have been efforts to realize tuning and modulation in ultra-low loss silicon nitride photonics. Silicon nitride has a high third-order Kerr nonlinearity which is suitable for generating octave-spanning frequency comb [34], however, due to its centrosymmetric crystal structure, silicon nitride has a small second-order Pockels effect with a maximum electro-optic (EO) coefficient of  $8.31 \pm 5.6$  fm/V [35] and cannot make use of free-carrier modulation like silicon [36]. Conventional thermal tuning approaches support bandwidths up to 10 kHz [37] with 40 mW silicon nitride tuners [33]. Integration of nonlinear materials and silicon nitride waveguides introduces second-order nonlinearities for EO modulation, for example lithium niobate [38], ferroelectrics [39], and zinc oxide [40]. These methods offer modulation bandwidths above 1 GHz, however, they suffer from large optical losses, increased fabrication complexity, high power consumption and can have limited material optical wavelength range. The stress-optic effect offers a broad optical bandwidth, moderate electrical bandwidth, and low power consumption. Stress-optic actuated silicon nitride waveguides have been demonstrated using piezoelectric materials like aluminum nitride (AlN) [32,41] and PZT [42,43]. AlN actuation utilizes acoustic resonant enhancement due to its relatively small piezoelectric coefficient (AlN:  $e_{31,f} = 1.02$  C/m<sup>2</sup>, PZT:  $e_{31,f} = -18.3$  C/m<sup>2</sup> [44]) and tuning efficiency which is an order of magnitude weaker than that of PZT [45]. The under-etched PZT approach results in high loss, low Q, limited modulation bandwidth (< 1 MHz) and is difficult to make compatible with planar wafer-scale integration [43]. Progress has been made with planar processed PZT actuators including a Mach-Zehnder interferometer (MZI) phase modulator [42] with a modulation bandwidth of 629 kHz and high optical loss.

In this paper, we report demonstration of a low-power photonic integrated PZT actuated stress-optic microresonator modulator for optical control functions, realized in the CMOS-compatible ultra-low loss silicon nitride platform. The waveguide-offset, fully planar design achieves 0.03 dB/cm loss in a 625  $\mu$ m radius resonator operating at 1550 nm, with a DC - 15 MHz 3-dB and DC - 25 MHz 6-dB modulation bandwidth, an order of magnitude improvement over prior PZT stress-optic modulators [43], and power consumption of 20 nW. The resonator has an intrinsic Q of 7.1 million, which is over 10 times larger than prior state of the art [43] and 14 dB ER over a 4 GHz tuning range. The modulator resonance tuning coefficient is measured to be 1.3 pm/V (162 MHz/V) and corresponding half-wave voltage-length products are  $V_{\pi}L = 43$  V·cm and  $V_{\pi}L\alpha = 1.3$  V·dB. The IMD3 SFDR is measured to be 65.1 dB·Hz<sup>2/3</sup> and 73.8 dB·Hz<sup>2/3</sup> at 1 MHz and 10 MHz, respectively. We demonstrate the use of this modulator in two applications,

first as a double sideband (DSB) modulator in a laser frequency stabilization PDH lock loop, and second as a laser frequency tracking filter. Since the modulation is based on stress-optic induced changes in the silicon nitride, this design will work with ultra-low loss visible to IR designs with only small waveguide design changes to operate in the visible [3]. The silicon nitride waveguide layers are completely fabricated in a CMOS compatible process and can withstand temperatures up to 1200 C. The PZT is a back-end process that is deposited at a lower temperature on the silicon nitride wafers after the CMOS process, and is therefore compatible with the ultra-low loss silicon nitride process. This advance in ultra-low loss waveguide modulators will enable chip-level control to be integrated with other ultra-low loss silicon nitride components [1] for a wide range of visible to IR applications, including atomic and molecular quantum sensing, computing and communication, controllable optical frequency combs, low-power stabilized lasers, atomic clocks, and ultra-low phase noise microwave synthesizers.

An example in the silicon nitride platform that can employ this modulator is a frequency stabilized laser, illustrated in Fig. 1. With this potential application, the low-power tuning PZT actuator can be used to fine tune a silicon nitride dual-resonators vernier laser [25] and carrier lock the laser to an on-chip coil reference cavity [46] using the double sideband modulator and a PDH lock loop [22]. The stabilized laser output can be further modulated for locking to applications such as quantum and atomic applications, position and navigation, and coherent communications.

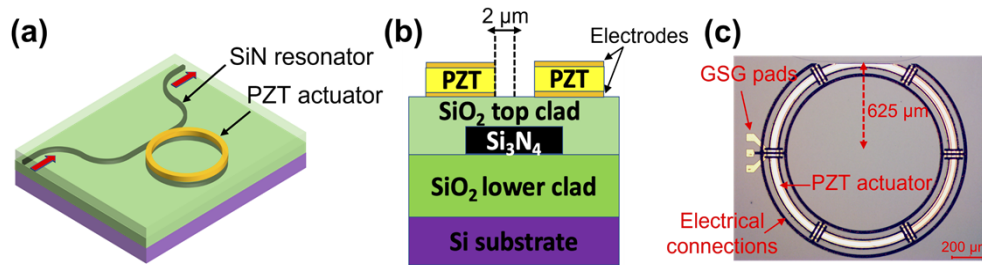


**Fig. 1.** Illustrative example application of PZT-actuated modulator for control functions in an external cavity laser (ECL). The PZT actuator can be used to tune and control the ECL, and generate sidebands to further stabilize the laser fluctuation by Pound-Drever Hall (PDH) locking to an ultra-high Q reference cavity. The stabilized output can be modulated (optional) based on specific applications.

## 2. Modulator design & characterization

The stress-optic modulator consists of a silicon nitride ring resonator and a monolithically integrated PZT actuator, as shown in Fig. 2(a). The ring resonator has a radius of 625  $\mu\text{m}$  and is fabricated using the silicon nitride ultra-low loss CMOS-compatible waveguide process described in [47]. The 175 nm thick LPCVD deposited Si<sub>3</sub>N<sub>4</sub> waveguide core is sandwiched between a 15  $\mu\text{m}$  thermally grown lower cladding oxide on a silicon substrate and a 6  $\mu\text{m}$  thick TEOS-PECVD

deposited top cladding oxide, as illustrated in Fig. 2(b). Chemical-mechanical polishing (CMP) is performed on top of the upper layer oxide to planarize the surface. A 500 nm PZT layer with upper and lower platinum (Pt) electrodes and TiO<sub>2</sub> adhesion layer are deposited and patterned laterally offset from the waveguide core by 2 μm with respect to its center. The PZT actuator dimensions and waveguide-offset are designed to achieve a large lateral strain effect across the nitride core while minimizing overlap with the optical mode, and therefore minimize optical losses, as indicated in Fig. 2(b) and described in further detail in section 1 of the supplementary materials. A top-down photograph of the fabricated device is shown in Fig. 2(c). Further details of the fabrication process are described in the section 2 of the supplementary materials.

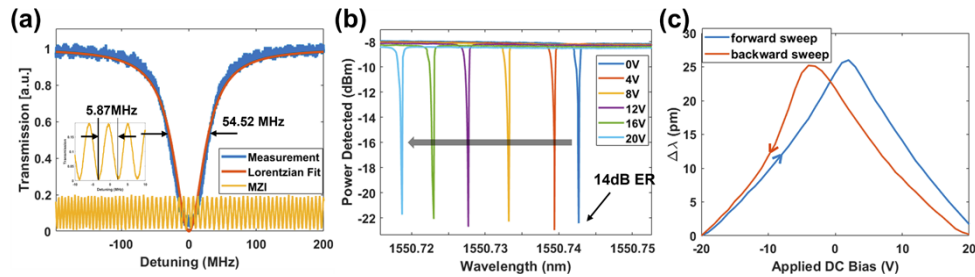


**Fig. 2.** (a) Illustration of the stress-optic microresonator modulator, the PZT actuator (yellow) is monolithically integrated on top of the Si<sub>3</sub>N<sub>4</sub> resonator without under-etching process. (b) The cross-section of the device, the PZT actuator is placed on top of the waveguide with 2 μm offsets to achieve best performance without affect the optical loss. (c) The optical image of the fabricated device.

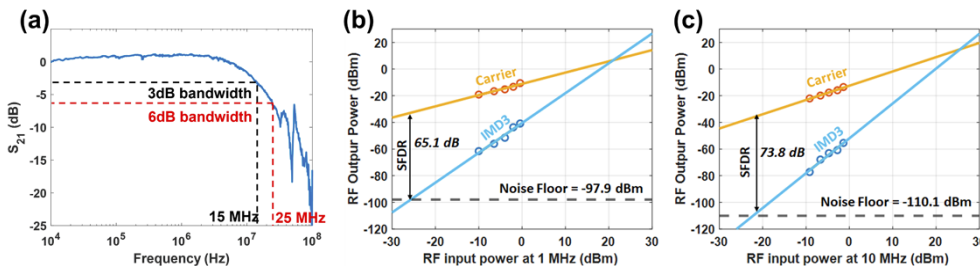
The full-width-at-half-maximum (FWHM) of the modulator resonance is measured to be 54.52 MHz at 1550 nm using a radio frequency (RF) calibrated unbalanced MZI with 5.87 MHz free-spectral-range (FSR) as a frequency ruler [48], as shown in Fig. 3(a). The measurement yields a 7.1 million intrinsic Q, a 3.6 million loaded Q, and a corresponding 0.03 dB/cm waveguide loss. Static tuning of the PZT actuator shifts the ring resonance as a function of applied bias voltage is shown in Fig. 3(b). The electric field is applied to the PZT actuator electrodes using a DC probe and strain is induced through the piezoelectric effect which changes the waveguide refractive index. We measure a 14 dB ER across the full 4 GHz tuning range, as the applied voltage is varied from 0 V to 20 V. Nonlinearity and hysteresis is observed in static tuning by sweeping the DC bias voltage in both forward (from -20 V to 20 V) and backward (from 20 V to -20 V) direction, as shown in Fig. 3(c), which is due to the ferroelectric nature of PZT [43,49]. The average tuning coefficient is -1.3 pm/V or -162 MHz/V. The half-wave voltage-length product  $V_{\pi}L$  of the modulator is calculated to be 43 V·cm and  $V_{\pi}L\alpha$  when taking the waveguide loss into account is 1.3 V·dB, which is comparable to the state-of-art phase modulators [39,43,50]. We measure the electrical power consumption to be 20 nW at 20 V bias voltage using a precision source and measure unit (Keysight B2902A) with 100 fA measurement resolution.

The small-signal electrical-to-optical modulation response  $S_{21}$  is measured by modulating a semiconductor diode laser (Velocity TLB-6730) tuned to the FWHM point of the resonance, a calibrated fast photodetector (Thorlabs DET01CFC, bandwidth 1.2 GHz) and a vector network analyzer (Keysight N5247B PNA-X). As shown in Fig. 4(a), the 3-dB and 6-dB modulation bandwidths are 15 MHz and 25 MHz respectively. Using an effective bandwidth model for ring resonator modulators operating off-resonance [51], we estimate the actuator RC bandwidth to be 120 MHz, and the effective optical bandwidth of the resonator to be 80 MHz. Based on the 3-dB measurement shown in Fig. 4(a), we estimate (see Supplemental materials section 5) the optomechanical PZT response to be approximately 15 MHz, and therefore, the current limiting factor.





**Fig. 3.** (a) The Q measurement of the resonator. The calibrated Mach-Zehnder interferometer (MZI) with a 5.87 MHz free-spectral-range (FSR) acts as a frequency ruler (yellow trace) to measure the full-width-at-half-maximum (FWHM) of the resonator resonance (blue trace). (b) The optical transmission spectrum of the static tuning of the device. The resonance has a 14 dB extinction ratio (ER) across the 4 GHz tuning range. (c) The PZT hysteresis measured with reverse biasing. The average tuning coefficient is  $-1.3$  pm/V or  $-162$  MHz/V.

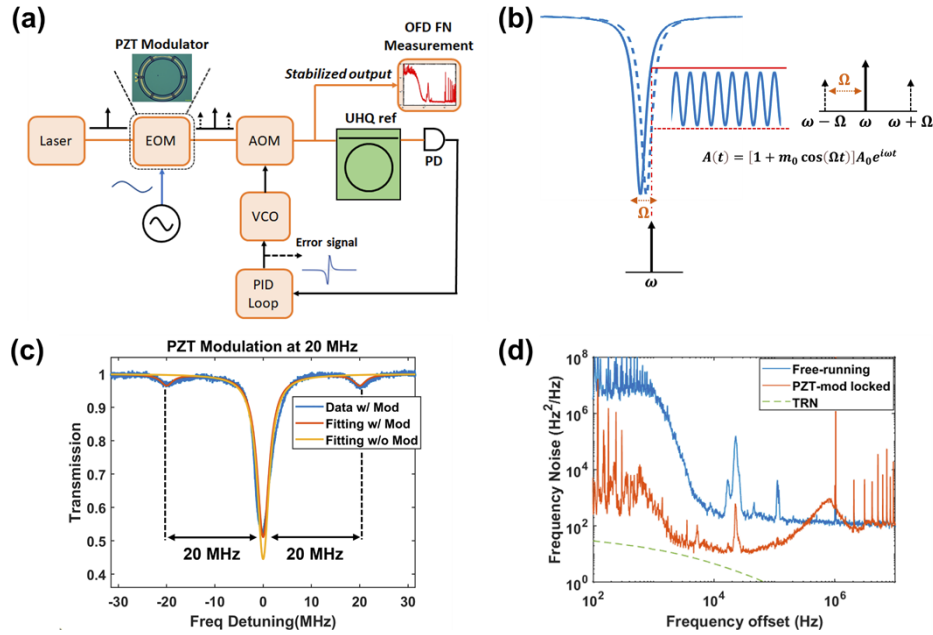


**Fig. 4.** (a) The frequency response ( $S_{21}$ ) indicates that the 3-dB and 6-dB modulation bandwidth is 15 MHz and 25 MHz, respectively. (b) and (c) RF output power of the fundamental and third order intermodulation distortion (IMD3) component as a function of RF input power of the ring modulator at 1 MHz and 10 MHz.

We characterize the modulator linearity for applications such as PDH locking, by measuring the IMD3 SFDR [52–54]. The SFDR is defined as the signal level at which the noise floor and power of the third order distortion tone are equal. The two-tone test is performed by applying two closely placed RF signals to the modulator and measuring the intermodulation components at the optical output using an electrical spectrum analyzer (ESA). The measured noise floor is  $-97.9$  dBm/Hz at 1 MHz and  $-110.1$  dBm/Hz at 10 MHz. IMD3 SFDR values of  $65.1$  dB $\cdot$ Hz $^{2/3}$  and  $73.8$  dB $\cdot$ Hz $^{2/3}$  are measured at 1 MHz and 10 MHz, respectively (Fig. 4(b) and (c)). Further details of the SFDR measurement are described in the section 4 of the supplementary materials.

### 3. Control applications

Two control applications are demonstrated, PDH stabilization of a laser to an optical reference cavity [22] and laser carrier tracking [55]. Figure 5(a) shows the PDH locking experimental setup. The PZT modulator is used in place of an EOM that is typically used in PDH stabilization, to generate double sidebands on the laser carrier. An AOM is used to frequency shift the DSB modulated carrier and lock it to a reference cavity resonance. The reference cavity is an integrated silicon nitride bus-coupled resonator with an ultra-high Q of  $10^8$  and large mode volume of  $2.9 \times 10^6$   $\mu\text{m}^3$  [56]. The narrow resonance provide by the high Q is utilized to suppress the laser frequency noise fluctuations and the large mode volume is chosen to reduce the thermo-refractive noise (TRN) floor.



**Fig. 5.** Laser stabilization demonstration. (a) A semiconductor laser is PDH locked to an ultra-high Q (UHQ) reference cavity using the PZT modulator as a double sideband (DSB) modulator (typically done using an electro-optic modulator (EOM)). The double sideband modulated carrier is frequency shifted by an acousto-optic modulator (AOM) and locked to the quadrature point of an UHQ integrated reference resonator using a proportional–integral–derivative (PID) control loop that drive a voltage-controlled oscillator (VCO) AOM frequency shift control signal. The resulting stabilized frequency noise is measured using an unbalanced fiber MZI optical frequency discriminator (OFD). (b) Illustration of DSB modulated carrier. (c) Measured DSB spectrum of the laser signal with and without the PZT DSB modulation, showing the 40 MHz sidebands with modulation depth of 0.48. (d) Measured frequency noise (FN) power spectral density for the free-running (blue trace) and stabilized laser (red trace) showing 40 dB close to carrier noise reduction and near thermo-refractive noise (TRN) limited performance for the 1 kHz to 10 kHz frequency range. The simulated TRN limit for this UHQ reference cavity is shown in the dashed green trace. PD, photodetector.

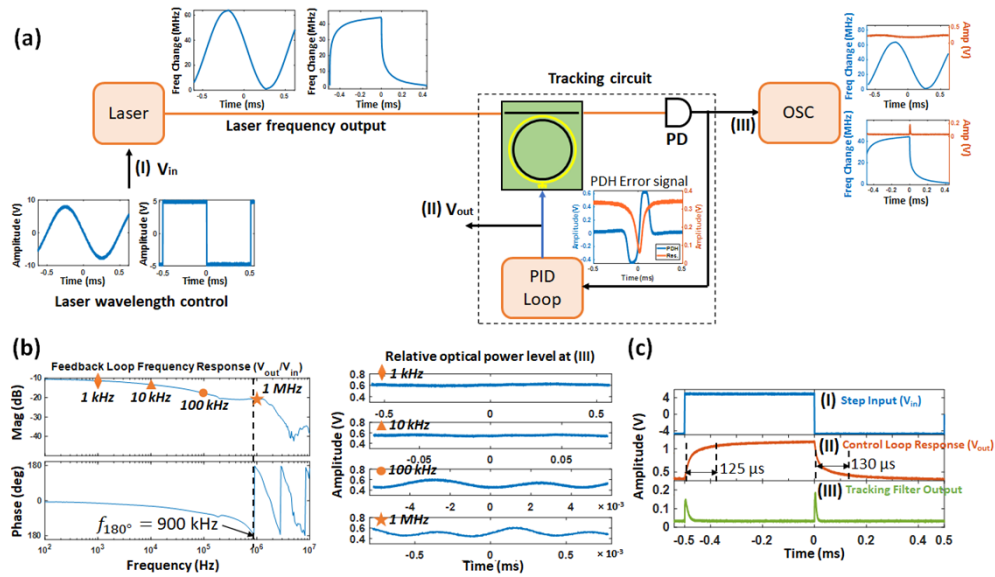
The modulation depth of the DSB modulated carrier is an important consideration for laser noise stabilization. In this experiment, a 20 MHz, 8 V peak-to-peak sinusoidal voltage is applied to the PZT actuator (Fig. 5(b)). Amplitude modulation produces a modulation depth that can be approximated by:

$$A(t) = [1 + m_0 \cos(\Omega t)] A_0 e^{i\omega t} = A_0 e^{i\omega t} + \frac{m_0 A_0}{2} e^{i(\omega + \Omega)t} + \frac{m_0 A_0}{2} e^{i(\omega - \Omega)t} \quad (1)$$

The sideband modulation depth at  $\omega \pm \Omega$  (Fig. 5(c)) is calculated to be  $m_0 = 0.48$  by fitting Eqn. (1) to the measured response with the sideband-to-carrier power ratio  $\frac{m_0^2}{2} = 12\%$ . The laser frequency noise (FN) is measured using the self-delayed homodyne laser frequency noise method with an unbalanced fiber MZI optical frequency discriminator (OFD) [57] with an FSR of 1.03 MHz. The power spectral density of the frequency noise as a function of frequency offset from carrier is shown in Fig. 5(d). The stabilized laser frequency noise (red curve) is reduced by four orders of magnitude (~40 dB) compared to the unstabilized laser over the frequency range 100

Hz to 1 kHz and reduced by two orders of magnitude ( $\sim 20$  dB) at 10 kHz frequency offset. The laser stabilization locking circuits has a bandwidth of  $\sim 1$  MHz where the servo bump can be seen in the stabilized frequency noise measurement. The TRN floor is calculated for the silicon nitride high Q resonator as shown in the green dashed curve in Fig. 5(d). The stabilized laser is able to achieve close to the TRN limit for this cavity over the frequency range of 1 kHz to 10 kHz. The demonstrated PZT-actuated ring modulator can be an ideal on-chip and low power solution to the bulk EOM component and provide enough bandwidth in a PDH locking circuit for laser stabilization.

Demonstration of the PZT modulator as an automated laser carrier tracking filter is shown in Fig. 6. Laser carrier tracking is important for monitoring and stabilizing wavelength changes to minimize the wavelength drift and spectral misalignments which cause power loss and signal distortion in fiber communications [55]. In this experiment, the stress-optic modulator resonance is locked to the laser output using a PDH locking circuit, as shown in Fig. 6(a). The PDH error signal (shown in the inset) indicates the deviation between the resonator resonance and the laser tone. The PDH servo uses the error signal to control the PZT actuator to lock the resonance to the laser carrier. To demonstrate the tracking function, we measure the filter output in response to a sinusoidal varying output wavelength and to a step response output wavelength shift of the tunable laser. The sinusoidally varying or step input signal ( $V_{in}$ ) is applied to the optical frequency modulation control input of a Velocity TLB-6730 laser. The small signal frequency response of the tracking loop, including the individual responses of the laser, the PZT actuator, the photodetector and the PID loop, is characterized by  $V_{out}/V_{in}$  as shown in Fig. 6(b). The bandwidth of the system, characterized at the  $180^\circ$  phase lag point, is  $f_{180^\circ} = 0.9$  MHz and is mainly limited by the tunable laser bandwidth wavelength control of approximately 1 MHz. As shown in right-side of Fig. 6(b), within the lock bandwidth, the optical level at the tracking filter output of the signal is maintained at a constant value (within 3% at 1 kHz and 10 kHz) with the external signal dithering. When the applied signal reaches 1 MHz, which is near a bandwidth resonance, the optical output of the filter fluctuates. The tracking system step response is measured and shown in Fig. 6(c), where the blue trace is the applied step signal (1 kHz square waveform) to the laser frequency tuning, and the red trace is the control loop response measured at the input to the PZT actuator. The tracking filter output shows the stabilization time (90% to 10%) in response to the step wavelength change at the input. The time to stabilize the lock is approximately 130  $\mu$ s and the settling time is approximately 8  $\mu$ s. With proper bandwidth design, this integrated PZT modulator can be used to monitor and track the signal carrier drift and filter the desired signals in communication links.



**Fig. 6.** (a) The PZT-actuated ring modulator is locked to the laser in a PID locking loop, when an external signal is applied to the laser, the locked modulator will respond to the signal dithering and track the laser carrier. The scope at the output port recorded the optical level fluctuation (orange) with the signal dithering in the laser signal (blue). (b) The total response of the feedback loop shows the bandwidth is close to 1 MHz. (c) Step input, control loop response, and tracking filter output stabilization time (from 90% to 10%)  $\sim 130 \mu s$  with  $\sim 8 \mu s$  settling time.

#### 4. Discussion

We report a photonic integrated optical modulator for control applications based on a stress-optic PZT actuated ultra-high Q silicon nitride waveguide microresonator. The modulator is a fully planar design, fabricated in an ultra-low loss silicon nitride wafer-scale, CMOS-compatible integration platform [1]. We demonstrate 0.03 dB/cm loss in a 625  $\mu m$  radius ring operating at 1550 nm, an order of magnitude improvement in modulation bandwidth (DC - 15 MHz 3-dB and DC - 25 MHz 6-dB), an order of magnitude decrease in power consumption of 20 nW, a Q of 7.1 million and 14 dB ER across the full tuning range, and tuning efficiency of 162 MHz/V. The PZT design is offset from the waveguide core and optical mode, resulting in a resonator Q and modulation extinction ratio that are relatively constant over the entire 4 GHz tuning range. We also characterize the modulator linearity, an important parameter for many control applications, measuring  $65.1 \text{ dB}\cdot\text{Hz}^{2/3}$  and  $73.8 \text{ dB}\cdot\text{Hz}^{2/3}$  third-order intermodulation distortion spurious free dynamic range at 1 MHz and 10 MHz respectively. These results are presented in Table 1 along with comparable integrated ring modulators based on electro-optic and stress-optic actuation. Our modulator provides an order of magnitude lower power consumption with ultra-high Q, low loss, and ER,  $V_\pi L_\alpha$  and a tuning sensitivity consistent with control applications. Based on the model presented in [51], we estimate the optomechanical PZT response to be approximately 15 MHz, and therefore, the current limiting factor of the bandwidth. Looking forward, the modulation bandwidth can be further improved by optimizing the optomechanical design and the tuning strength can be improved using a thicker PZT film as well as a thinner oxide cladding.

The PZT actuator was used in two application demonstrations, laser PDH stabilization and laser carrier tracking. Laser stabilization improved the close to carrier frequency noise of a laser by 4 orders of magnitude using an ultra-high Q resonator of the same nitride platform. The



**Table 1. Summary of this work with comparable integrated ring-resonator modulators**

Modulator	Actuation	3dB BW (MHz)	Loss (dB/cm)	$V\pi L\alpha$ (V·dB)	Tuning (pm/V)	Q	ER (dB)	Power
SiN + LN / Ring [38]	LN/EO	NA	0.32	9.8	1.78	$Q_{in} = 185$ K	27	NA
LN / Ring [50]	LN/EO	10 -30,000	3	5.4	7	$Q_L = 50$ K	10	NA
AlN / Ring [58]	AlN/EO	40 - 2,300	0.6	61	0.53	$Q_L = 800$ K	10	NA
SiN + PZT / Ring [39]	PZT/EO	100 - 33,000	1	3.3	13.4	$Q_L = 2.2$ K	10	NA
SiN / MZI [42]	PZT/SO	0.629 <sup>c</sup>	NA	NA	NA	NA	25	300 nW
SiN / MZI [59]	PZT/SO	1.18 <sup>c</sup>	< 0.1	1.6	NA	NA	NA	< 1 uW
SiN / Ring [43]	PZT/SO	<1 <sup>c</sup>	0.3	1.1	25.75	$Q_L = 86$ K	15	160 nW
SiN / Ring [45]	AlN/SO	91.71 <sup>b</sup>	0.02	NA	0.12	$Q_{in} = 15$ M	NA	300 nW
SiN / Ring [60]	PZT/SO	NA	0.01	NA	4.16	$Q_{in} = 15$ M	NA	NA
<b>SiN / Ring (This work)</b>	<b>PZT/SO</b>	<b>DC - 15 (3 dB)/DC - 25 (6 dB)</b>	<b>0.03</b>	<b>1.3</b>	<b>1.3</b>	$Q_L = 3.6$ M <sup>a</sup> $Q_{in} = 7.1$ M <sup>a</sup>	<b>14<sup>a</sup></b>	<b>20 nW</b>

EO: electro-optic modulation; SO: stress-optic modulation.

<sup>a</sup>Across the 4 GHz tuning range.

<sup>b</sup>Resonant mechanical mode operating at one frequency only.

<sup>c</sup>Only reported at one frequency.

compatibility of this planar modulator with other silicon nitride devices, e.g., filters, Brillouin lasers, stabilization cavities, will lead to the next level of functions on-chip. Tracking circuits are useful when aligning modulators to wavelength-division multiplexing (WDM) transmitter channels, for filtering a channel or aligning add/drop filters for a WDM transmission system or network. Other applications that will benefit from photonic integration with this modulator include frequency comb control [45], and tunable stimulated Brillouin scattering (SBS) [61]. Since the modulation is based on the stress-optic effect in the silicon nitride waveguide core, and the optical mode does not overlap with the actuators, the modulator design can be transferred to the visible range with a simple waveguide design change (thickness and width), and maintain the low waveguide loss properties for AMO applications such as strontium transitions in the 461 nm to 802 nm wavelength range [3] and rubidium transitions in the 780 nm range as well as other atomic and molecular species with transitions across the nitride transparency window (405 nm – 2350 nm). The wide optical transparency window enabled by the stress-optic modulation extends the application with low-loss silicon nitride integration to the visible [29] for atomic clock and quantum applications. In general, atomic, molecular and optical applications that make use of power consuming bulk-optic modulators, frequency shifters, and other components, will benefit from control modulator integration.

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**Disclosures.** The authors declare no conflicts of interest.

**Data availability.** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Supplemental document.** See [Supplement 1](#) for supporting content.

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