Ultra-low loss silicon nitride ring modulator with low power PZT actuation for photonic control

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Abstract: A wafer-scale PZT-actuated ultra-low loss, low-power, stress-optic Si_3N_4 ring modulator is realized with 7 million Q, 0.03 dB/cm loss, 20 nW power consumption and 20 MHz 3-dB bandwidth, is demonstrated to track a laser. © 2022 The Author(s)

1. Introduction

Silicon nitride (Si_3N_4) photonics is a CMOS-compatible, wafer-scale integration platform [1], that delivers ultra-low loss [2,3] and broad optical transparency from 405 nm to the IR [4]. The Si_3N_4 platform has the potential to lower the cost, size, and weight of a wide range of systems for applications including fiber communications, atomic clocks, quantum sensors, communications and computing, optical gyros and precision metrology. In addition to low loss and high quality factor (Q), these applications require moderate bandwidth (e.g., < 100 MHz) modulation for device and system control functions including laser locking and stabilization with Pound-Drever-Hall (PDH) feedback [5], optical frequency comb stabilization [6], filter locking and tracking for wavelength division multiplexing (WDM) [7], pilot tones and control channels [8], and phase modulation to mitigate fiber nonlinearities [9]. Modulation in the Si_3N_4 waveguide platform has been demonstrated using the Pockels effect in lithium niobate [10], ferroelectric material [11] and zinc oxide [12] for modulation bandwidths greater than 1 GHz, however, these methods introduce large optical losses and have high power consumption. Use of the stress-optic effect to tune Si_3N_4 waveguides has been demonstrated using aluminum nitride (AlN) [13] and lead zirconate titanate (PZT) [14,15], however these prior works depended on the low induced strain of AlN and require acoustic resonance modes (leading to narrow band modulation), or the use of under-etched PZT actuated Si_3N_4 waveguides. In the case of AlN, the tuning efficiency is nearly ten times weaker than PZT due to its smaller piezoelectric coefficient [6]; although a CMOS-compatible released structure has been achieved with improved responsivity [13], the fabrication complexity is high. The wafer-scale approach in [14] demonstrated a PZT stress-optic MZI phase modulator with modulation bandwidth limited to 629 kHz and relatively high losses. The under-etched approach in [15] involves complex fabrication, is not wafer-scale CMOS compatible, is susceptible to environmental conditions, yields high losses resulting in an 86,000 Q and 0.65 dB/cm loss, and the mechanical properties limits the modulation to low bandwidth (1 MHz). Therefore, wafer-scale and CMOS compatible PZT integration, that preserves the ultra-low loss in silicon nitride waveguides, provides moderate bandwidths for widely used feedback control functions, and has low power consumption is needed.

In this paper we demonstrate an advancement in the state-of-the-art for fully planar PZT actuated, ultra-low loss silicon nitride modulators, with low power consumption, for photonic control applications. We demonstrate a fully planar process resulting in a 1250 μm diameter ring modulator, with 20 MHz 3-dB and 25 MHz 6-dB modulation bandwidth, 14 dB extinction ratio (ER) across the tuning range, 7 million intrinsic Q, and demonstrate its use in locking a resonator filter to a laser carrier. Previously, static tuning of these resonators was reported in [16]. Here, the tuning coefficient is measured to be -1.6 pm/V and tuning efficiency taking optical losses into account is measured to be $V_\pi L\alpha = 1.3$ V·dB. As shown in Fig. 1(a), the 175 nm thick Si_3N_4 waveguide layer is sandwiched between the bottom thermal oxide cladding layer and the top TEOS-PECVD oxide cladding layer. The 500 nm thick PZT film with electrodes are deposited and patterned on top of the cladding with planar wafer-scale processing, without complex fabrication steps like released structure or under-cutting [13,15]. When an electric field is generated in the PZT film by applying a voltage across the top and bottom electrodes, the PZT film strains due to the piezoelectric effect, leading to a change in the waveguide effective refractive index. The ring resonator has an ER of over 14 dB, and the waveguide loss and resonator Q are preserved after PZT fabrication and its resonance can be detuned by over 4 GHz at 20 V bias voltage, as shown in Fig. 1(b). We measure a low power consumption of 20 nW, which is due to the low leakage current of PZT, measured to be below 1 nA. The planar processed stress-optic modulator with low power tuning can enable various photonic integration applications. For example, it can be used as a locked WDM filter for locking onto a desired channel at a receiver or add/drop multiplexer in a WDM fiber communications link. The modulator bandwidth is suitable for closed loop PDH locking applications such as laser stabilization [5].

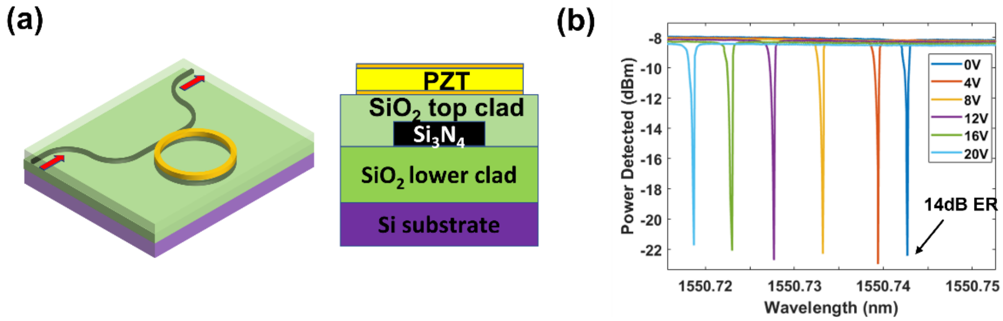

Fig. 1 (a) 3D schematic and the cross-section of the silicon nitride ring modulator with PZT actuator on top. (b) The PZT static tuning of the 1250 μm diameter ring-bus resonator, the 14 dB ER resonance can be tuned by 32 pm with a change of 20 V.

2. Experimental results

We measure the modulation bandwidth using the configuration shown in Fig. 2(a). The electrical-to-optical small-signal 3-dB response is measured at 20 MHz and the 6-dB response up to 25 MHz, as shown in Fig. 2(b). The tunable laser is biased at the full-width-half-maximum of the optical resonance and S_{21} is measured using a vector network analyzer (Keysight N5247B PNA-X) with -5 dBm RF signal applied to the PZT actuator. The noise floor indicated in Fig. 2(b) is taken by repeating the measurement without the RF probing. The cavity photon lifetime is calculated using $\tau_{ph} = \lambda Q/2\pi c$ to be around 6 ns, leading to an estimated cavity photon lifetime limited cut-off frequency $f_{cut-off} = 1/2\pi\tau_{ph}$ of ~26 MHz. Therefore, the main limiting factor of this modulator's frequency response is the long cavity photon lifetime due to the high resonator quality factor. The bandwidth of the modulator can be further flattened and increased by optimizing actuator and the cavity and coupler designs [17] to decrease RC and the cavity photon lifetime, as well as by roughening the Si substrate to damp the vertical propagating acoustic modes.

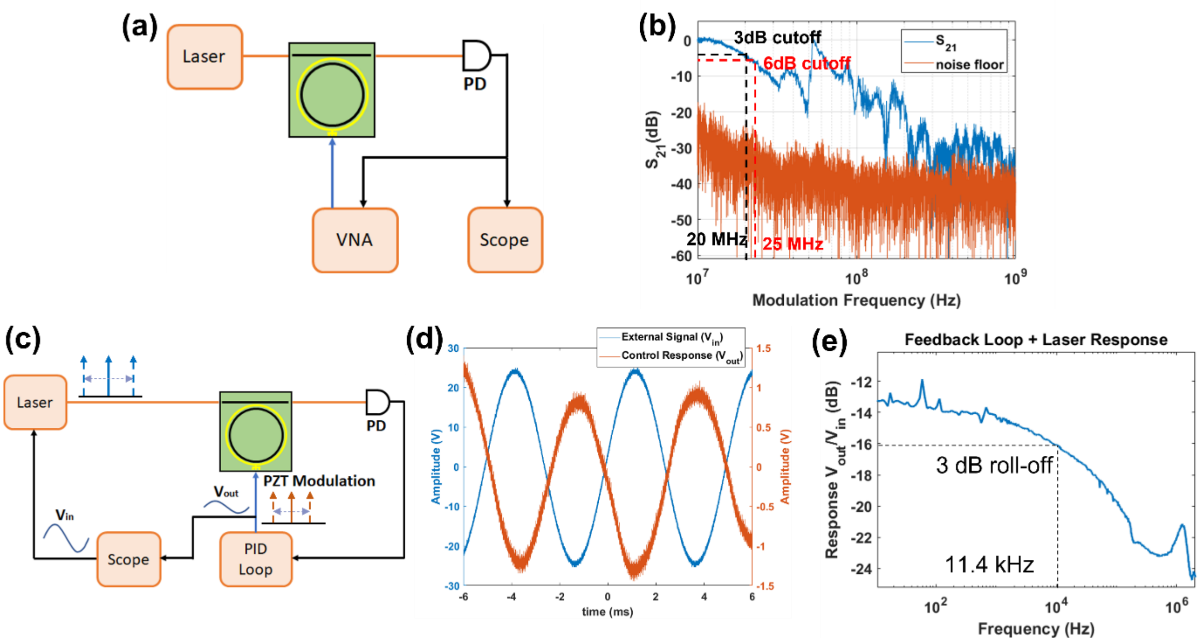

Fig. 2 (a) Experimental diagram for small-signal frequency response measurements of the stress-optic modulator at 1550 nm. (b) The 3-dB and 6-dB modulation bandwidth is ~ 20 MHz and 25 MHz, respectively. (c) Experimental diagram of the resonator locked to laser demonstration. An external signal drives the laser output wavelength via current modulation, the PZT adjusts the ring resonator to track the laser optical signal via the servo output and the PID control loop. PD, photodetector. PID loop, proportional–integral–derivative control loop. (d) A sinusoidal signal at 200 Hz (blue) is applied to the laser to modulate the wavelength and the PZT modulation tracking signal (orange) is measured as the servo control response on an oscilloscope. (e) The frequency response of the control loop and laser response, indicated as V_{out}/V_{in}, shows the 3-dB bandwidth is 11.4 kHz which is limited by the laser frequency response.

Demonstration of the PZT actuation for tracking a laser carrier is shown in Fig. 2(c). The ring resonator is locked to an external cavity diode laser (Velocity TLB-6700) in a similar fashion as a PDH lock loop [5] so that the resonator's resonance stays aligned with the laser output frequency. The PDH error signal and a proportional–integral–derivative

(PID) servo are used for the control and tracking loop. To demonstrate the tracking performance, an external signal V_{in} (sinusoidal wave at 200 Hz, shown as the blue lines in Fig. 2(d)) is applied to the laser as a current modulation and the control signal V_{out} at the servo output (orange lines in Fig. 2(d)) is used to drive the PZT so that the resonator tracks the laser. The feedback frequency response, including the response of the laser, PZT modulator, photodetector and the PID loop, is measured with a VNA by taking the signal V_{out} and V_{in} from the setup shown in Fig. 2(c). The 3-dB bandwidth, shown in Fig. 2(e), is 11.4 kHz. The external laser has a 3-dB bandwidth ~10.8 kHz which is the limiting factor of the feedback loop.

3. Discussion

We have demonstrated a wafer-scale, photonic integrated silicon nitride waveguide PZT stress-optic ring modulator with 20 MHz 3-dB modulation bandwidth, suitable for control applications. The planar processed PZT actuator design maintains the low optical loss of 0.03 dB/cm, high Q (7 million) and a relatively large tuning efficiency of 1.6 pm/V, and operates with ultra-low 20 nW power consumption. We demonstrate a simple control application with the PZT controlled resonator used to track an input laser carrier. Such a function can be used in a WDM system as an auto-aligning filter or add/drop multiplexer. Compared to other electro-optic modulation techniques where the optical losses are compromised and power consumption is high, the planar integrated PZT stress-optic modulator can provide a versatile modulation method to integrate with ultra-high Q resonators while keeping the power consumption as low as tens of nW. The DC to 20 MHz bandwidth of the modulator is suitable for low-bandwidth feedback techniques such as PDH locking in laser stabilization. Future work involves improving the modulation bandwidth with ring resonator loss and RC time constant optimization. Other applications are envisioned that leverage the DC to medium modulation bandwidths, for example, integrating with a stimulated Brillouin scattering (SBS) resonator [18] to lock the SBS cavity to external reference cavity for laser stabilization and noise reduction, or tuning resonators for a silicon nitride cavity tunable laser.

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