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

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Abstract: A 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 consumption and 20 MHz bandwidth, is used to track a laser in real time.

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. These functions include 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 platform has been demonstrated using the Pockels effect in lithium niobate [10], ferroelectric material [11] and zinc oxide [12] for modulation bandwidth greater than 1 GHz, however, these methods introduce large optical losses and have high power consumption. Integration of the stress-optic effect, using aluminum nitride (AlN) [13] and lead zirconate titanate (PZT) [14,15] actuation with silicon nitride waveguides is used to modulate index changes in the waveguides, however these approaches either depend on the low induced strain of AlN and need to use acoustic resonance modes (leading to narrow band modulation), or through 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 better responsivity [13], the fabrication complexity significantly increases. The wafer-scale approach in [14] demonstrates a PZT stress-optic MZI phase modulator with modulation bandwidth of 629 kHz. The under-etched approach in [15] allows for a larger tuning range, but greatly increases the fabrication complexity and is not wafer-scale CMOS compatible, which has a PZT tuned resonator with 86,000 Q, 0.65 dB/cm loss, and is limited to low bandwidth modulation (1 MHz). New wafer-scale and CMOS compatible PZT actuation approaches, that preserve the ultra-low loss properties of silicon nitride (and other) waveguides and have low power dissipation 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 um diameter ring modulator, with 20 MHz 3-dB and 25 MHz 6-dB modulation bandwidth, 14 dB extinction ratio (ER) across the tuning range, and 7 million intrinsic Q, and demonstrate its use in real time locking to a laser output. Prior static tuning of these resonators is presented in [16]. 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 created in the PZT film by applying a voltage across the top and bottom electrodes, the PZT film will strain due to the piezoelectric effect. Thus, the effective refractive index of the waveguide is changed due to the stress-optic effect. The ring resonance, with an ER over 14 dB, can be detuned by over 4 GHz at 20 V bias voltage, as shown in Fig. 1(b), with a low power consumption of 20 nW due to the extremely low leakage current of PZT measured 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 WDM filters with add/drop multiplexer design for tuning and laser signal tracking on a specified channel in a fiber communications link and the bandwidth of the modulator is suitable for close loop PDH locking applications such as laser stabilization [5].

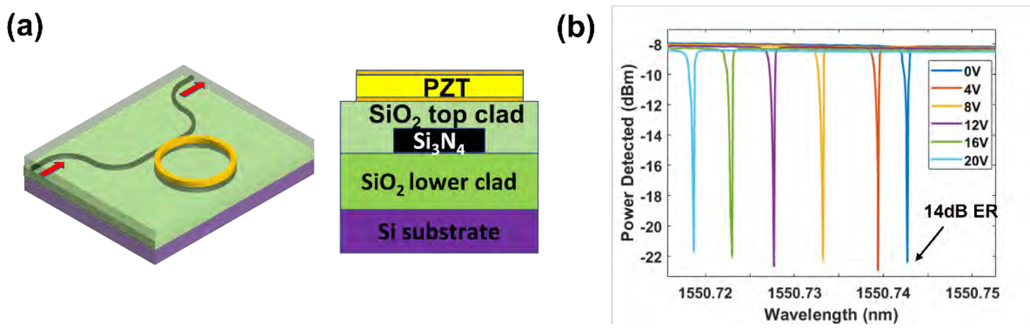

Fig. 1 (a) 3D schematic and the cross-section of the silicon nitride ring modulator with PZT actuator on top. (b) The PZT static tuning of the 1250 um diameter ring-bus resonator, the 14 dB ER resonance can be tuned by 32 pm with a change of 20 V.

2. Experimental results

The modulation bandwidth is measured using the configuration shown in Fig. 2(a) with the electrical-to-optical small-signal 3-dB response up to 20 MHz and 6-dB response up to 25 MHz, as shown in Fig. 2(b). The tunable laser is biased at the half-point 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 can be calculated by $\tau_{ph} = \lambda Q/2\pi c$ 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 cavity and coupler designs increase the RC and cavity photon lifetime limited cutoff frequencies, as well as by roughening the Si substrate to damp the vertical propagating acoustic modes.

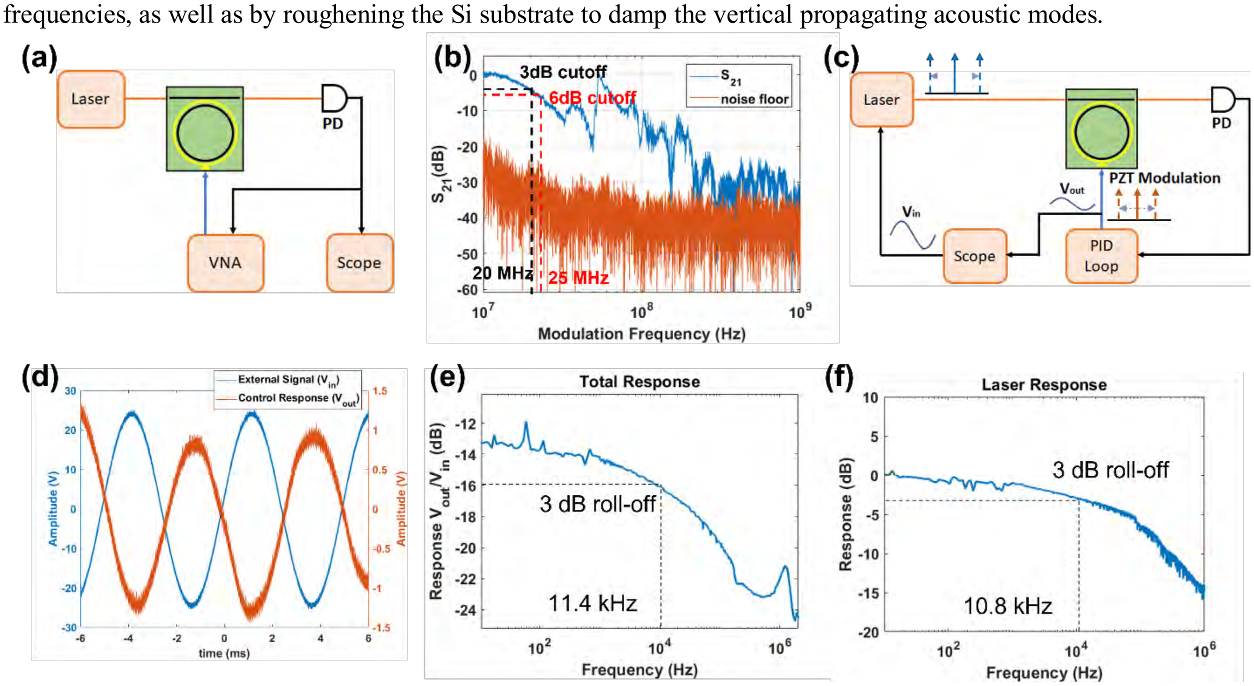

Fig. 2 (a) Experiment diagram for small-signal frequency response measurements of the stress-optic modulator at telecom wavelengths. (b) The 3-dB and 6-dB modulation bandwidth is about 20 MHz and 25 MHz. (c) Experiment diagram of a control loop measurement where the PZT modulated resonator is locked to the laser. An external signal is given to the laser via the current modulation, the PZT modulation will track the variance in the laser optical signal and is measured at the servo output at 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 as a current modulation, and the PZT modulation tracking signal (orange) measured as the servo control response is observed in real time on a scope. (e) The total response of the whole control loop, indicated as V_{out}/V_{in}, shows the 3-dB bandwidth is 11.4 kHz. (f) The laser response shows the 3-dB bandwidth is 10.8 kHz, which is the limiting factor of the whole loop bandwidth.

Demonstration of the PZT actuation for tracking a laser signal 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 [12] so that the resonator resonance stays aligned with the laser tone, where the PDH error signal and a proportional–integral–derivative (PID) servo is used for the control and tracking loop. To demonstrate the tracking performance, an external signal V_{in} (sinusoidal wave at 200 Hz in this case, 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)), monitored in real time on the oscilloscope, tracks the laser. Because the resonator resonance is tightly aligned to the laser tone, the modulation tracks the signal closely using the piezoelectric actuator. The total response, including the individual response of 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 cut-off bandwidth, shown in Fig. 2(e), is 11.4 kHz. As Fig. 2(f) shows, the external laser has a 3-dB bandwidth about 10.8 kHz which is the limiting factor of the feedback loop.

3. Discussion

We have demonstrated a silicon nitride stress-optic ring modulator with 20 MHz modulation bandwidth. The planar processed PZT actuator does not compromise the low optical loss of 0.03 dB/cm, while maintaining a relatively large tuning efficiency of 1.6 pm/V. The modulation of the PZT controlled resonator used to track the variance in the external laser signal demonstrates the control function of the modulator, which can be used in a WDM system as filters with add/drop designs to track the wavelengths of the laser source. Compared to other electro-optic modulation techniques where the optical losses are compromised and power consumption is high, the 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. For instance, the PZT actuator can be integrated on a stimulated Brillouin scattering (SBS) resonator [17] to make a tunable SBS laser that is external pumped without affecting its Q and losses and be modulated to PDH lock the SBS cavity to external reference cavity for laser stabilization and noise reduction.

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