A low-power PZT stress-optic Si_3N_4 micro-ring modulator for PDH locking applications

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Abstract: A low power, PZT stress-optic Si_3N_4 micro-ring modulator, with Q = 7 million and a 20 MHz 3-dB bandwidth is demonstrated as an amplitude modulator in a PDH laser stabilization lock loop.
OCIS codes: (130.4110) Modulators; (230.1040) Acousto-optical devices; (140.4780) Optical resonators.

1. Introduction

Photonic-integrated circuits (PICs) based on the wafer-scale, CMOS-compatible silicon nitride (Si_3N_4) waveguide platform have the potential for use in a wide range of applications including precision metrology [1], microwave photonics [2], quantum communications [3] and optical atomic clocks [4]. Compared to other platforms like silicon-on-insulator (SOI) and indium phosphide (InP), Si_3N_4 offers low optical loss (< 1 dB/m) across the visible (VIS) to the infrared (IR) [5,6]. While ultra-low loss waveguides and other components have been successfully developed, modulation and tuning functions are the next step to be realized in the ultra-low loss Si_3N_4 platform and can be used to realize functions such as sideband and sweep modulators, phase shifters, and switches. Specifically, actuation and dithering of laser frequencies is essential to tune, phase-lock and stabilize lasers [7]. However, due to the dielectric and symmetry properties of Si_3N_4, it is challenging to directly modulate using the electro-optic (EO) effect. Heterogenous integration of EO material [8] with the Si_3N_4 waveguides can provide GHz bandwidth modulators, but comes with serious tradeoffs in optical loss, limited optical transparency and complex fabrication process. The piezoelectric effect has been utilized to make stress-optic modulators [9,10] with higher loss, limited modulation bandwidth, and requiring under-etching and waveguide release structures that reduce device robustness, introduce points of failure, and integration limitations.

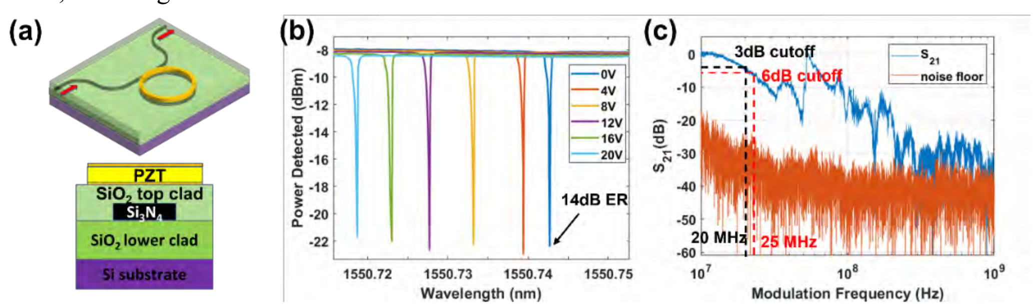

Fig. 1 (a) Illustration and cross-section of the PZT-actuated silicon nitride micro-ring stress-optic modulator, the PZT actuator is monolithically integrated on top of the resonator without complex under-cutting process. (b) Static tuning of the PZT actuator resonator with a 14 dB ER across the voltage range, the measured tuning coefficient is -1.6 pm/V or -200 MHz/V. (c) Small signal frequency response of the modulator showing the 3-dB and 6-dB modulation bandwidth is 20 MHz and 25 MHz.

We report fabrication of a planar-processed PZT-actuated micro-ring stress-optic modulator and show its application as an amplitude modulator in a Pound-Drever-Hall (PDH) [11] feedback circuit that stabilizes a laser to an ultra-high Q silicon nitride resonator. The PZT modulator generated sidebands have a modulation depth of 0.48 and a sideband-to-carrier power ratio of 0.115. The cavity stabilized laser frequency noise is reduced by a factor of 10^4 over the free-running laser noise and is close to the thermo-refractive noise (TRN) limit of the reference cavity. As shown in Fig. 1(a), the modulator consists of a silicon nitride ring resonator with 625 µm radius and an intrinsic quality factor of 7 million measured at 1550 nm with 14 dB extinction ratio (ER), as reported in [12]. The propagation loss is extracted to be 0.03 dB/cm, corresponding to a half-wave voltage-length product $V_\pi L$ of 43.4 V·cm and $V_\pi L\alpha$ of 1.3 V·dB. The PZT actuator is monolithically integrated on top of the waveguide with planar wafer-scale processing. As shown in Fig. 1(b), the static tuning of the modulator is measured with a tuning coefficient of -200 MHz/V. The ultra-low power consumption is measured to be 20 nW at 20 V bias voltage due to the low leakage current of the PZT material. The small signal frequency response of the PZT modulator is measured and the S_{21} is plotted as shown in Fig. 1(c). The 3-dB and 6-dB modulation bandwidth is 20 MHz and 25 MHz, respectively.

2. Experimental Results

We demonstrate the PZT-actuated resonator used as an amplitude modulator in a PDH feedback loop to stabilize a laser to an ultra-high Q Si_3N_4 waveguide resonator, as shown in Fig. 2(a). Sidebands are generated by applying a ±20 MHz signal with an 8 V_{pp} to the PZT modulator in the form similar to amplitude modulation, as illustrated in Fig. 2(b, c), which can be expressed as $A(t) = [1 + m_0 \cos(\Omega t)]A_0 e^{i\omega t} = A_0 e^{i\omega t} + \frac{m_0 A_0}{2} e^{i(\omega+\Omega)t} + \frac{m_0 A_0}{2} e^{i(\omega-\Omega)t}$. The modulation depth m_0 is extracted to be 0.48 and the sideband-to-carrier power ratio $m_0^2/2$ is calculated to be 0.115. The laser signal is steered using an acousto-optic modulator (AOM) driven by a voltage-controlled oscillator (VCO) whose output is PDH locked to an ultra-high Q ~10^8 reference cavity. The frequency noise of the stabilized signal is measured with an optical frequency discriminator (OFD) made of an unbalanced fiber Mach-Zehnder interferometer (MZI) [13]. As shown in Fig. 2(d), the frequency noise of the stabilized laser compared to the free-running laser is reduced by a factor of 10^4 and is close to the simulated TRN limit of the ultra-high Q reference cavity.

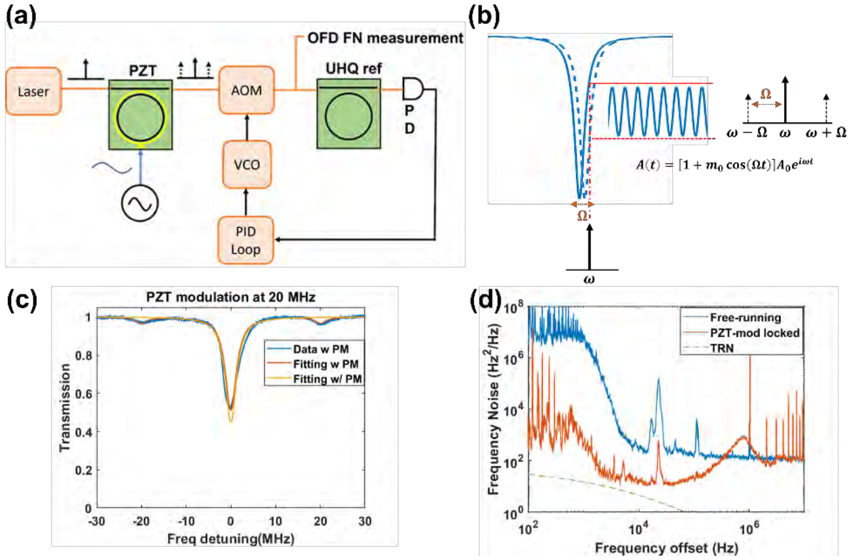

Fig. 2 (a) Experimental diagram of laser stabilization using PZT to PDH lock a semiconductor laser to the ultra-high Q (UHQ) resonator. (b) Illustration of PZT modulator generated sidebands. (c) Optical spectrum of the laser signal with and without the 40 MHz sidebands. (d) Optical frequency noise for the free-running and stabilized laser and thermo-refractive noise (TRN) of the ultra-high Q reference cavity.

3. Conclusion

A planar processed, wafer-scale PZT-actuated stress-optic modulator with 20 MHz 3-dB modulation bandwidth, 0.03 dB/cm propagation loss, 14 dB extinction ratio and 200 MHz/V tuning efficiency is demonstrated as an amplitude modulator in a PDH locking loop to stabilize a semiconductor laser to an ultra-high Q reference cavity, reaching close to the reference cavity TRN limit. The bandwidth is limited by the cavity photon lifetime limited cut-off frequency of 26 MHz, which can be improved by adjusting the cavity resonator and coupler and the PZT actuator design. Future improvement includes scattering the vertically propagating acoustic modes to flatten the system response at higher frequencies by roughening the substrate backside. Integration of Si_3N_4 waveguide and PZT modulation can further lead to photonic control applications in atom cooling and clocks, quantum applications, and ultra-low linewidth lasers.

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