Laser Frequency Stabilization Using Pound-Drever-Hall Technique with an Integrated TiO_2 Athermal Resonator

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Abstract: We demonstrate frequency stabilization of a continuous-wave laser using an integrated TiO_2 athermal cavity as a reference for the first time, and show linewidth improvement by a factor of 6 compared to a SiN cavity.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (140.3425) Laser stabilization.

1. Introduction

Temperature insensitive devices are crucial for robust and efficient photonic systems such as communication links and sensor networks. However, thermal stability remains as one of the most challenging problems in integrated photonics today. In applications with large temperature swings, cavities made from CMOS-compatible materials such as Si, SiN, and SiO_2 tend to drift, resulting in unstable resonances. This is due to their non-zero thermo-optic coefficients (TOC) ($dn_{Si}/dT\sim10^{-4}$ K^{-1}, $dn_{SiN}/dT\sim10^{-5}$ K^{-1}, $dn_{SiO2}/dT\sim10^{-5}$ K^{-1}) that are all positive [1]. Therefore, a CMOS-compatible material with negative TOC such as TiO_2 is required to thermally stabilize these resonances. In compensating for thermal fluctuations, this passive solution is much more efficient than active solutions, i.e. the use of a thermo-electric cooler (TEC). Although athermal TiO_2 cavities with low TOCs have been demonstrated [1-3], so far these cavities have not been used as a reference for frequency stabilization of a laser. Therefore, noise performance of these athermal cavities is not yet well known. However, in applications where low noise oscillators are needed like RADAR, communications, or GPS, athermal resonators can be used for frequency stabilization to suppress thermal noise. For a continuous-wave (CW) laser locked to a cavity, the total phase noise $S_\varphi(f)$ and the corresponding linewidth $\Delta\nu$ are due to the Schawlow-Townes limit and the thermal noise. These can be expressed as

$$S_\varphi(f) = \left[\frac{h\nu_{CW}}{4\pi P_{\text{out}} Q^2} + \frac{4k_B T^2}{G}\left(\frac{1}{n}\frac{dn}{dT} + \frac{1}{L}\frac{dL}{dT}\right)^2\right]\left(\frac{\nu_{CW}}{f}\right)^2 \quad (1)$$

$$\Delta\nu = \left[\frac{\pi h\nu_{CW}}{P_{\text{out}} Q^2} + \frac{16\pi^2 k_B T^2}{G}\left(\frac{1}{n}\frac{dn}{dT} + \frac{1}{L}\frac{dL}{dT}\right)^2\right]\nu_{CW}^2 \quad (2)$$

where ν_{CW} is the frequency of the locked CW laser, P_{out} is power output from the resonator, Q is the quality factor of the resonator, h is Planck's constant, k_B is Boltzmann's constant, T is temperature, G is thermal conductance to the substrate, n is the effective index of the resonator mode, L is the length of the resonator, and f is the offset frequency from ν_{CW} [4]. Here, we first show that an integrated athermal resonator can be fabricated with the desired athermal operation temperature by adjusting the TiO_2 layer thickness on top of an inverted ridge waveguide. Then, using the Pound-Drever-Hall technique [5], we demonstrate that the thermal noise limit of a standard SiN resonator estimated by Eq. (2) can be surpassed by a composite TiO_2 resonator with a similar quality factor, showing the improved linewidth and noise performance of the athermal cavity.

2. Athermal Cavity and Temperature Independent Resonance

A ring resonator with 80 µm radius and the cross section shown in Fig. 1a has been fabricated in a 300 mm CMOS process. The 0.6 µm wide, 0.2 µm thick buried SiN segments, and the surrounding SiO_2 layers have been grown; and a 4 µm trench has been etched. Resonator coupling gap was 0.2 µm. TiO_2 has then been sputtered from a fully oxidized Ti target using an in-house process, similar to the process described here [6]. The deposition temperature was kept relatively low at 100 ºC in order to prevent crystallization of the TiO_2 film [7]. Multiple samples were prepared with TiO_2 thicknesses from 125 nm to 139 nm. The loaded quality factor of the athermal resonance was measured as Q=70,000 with an extinction ratio of r_e=18.4 dB (Fig. 1b). Resulting resonance shifts were measured for each sample with a TEC, showing successful athermal operation at various temperatures, as determined by the TiO_2 thickness (Fig 1c). According to International Telecommunications Union's (ITU) dense wavelength division multiplexing (DWDM) grid [8], the requirement of <2.5 GHz channel frequency shift was achieved over the whole measurement range of 20-45 ºC. More precisely, for a temperature change of ±5 ºC and ±1 ºC, the resonance stays within 140 MHz and 5 MHz of the athermal operation point respectively.

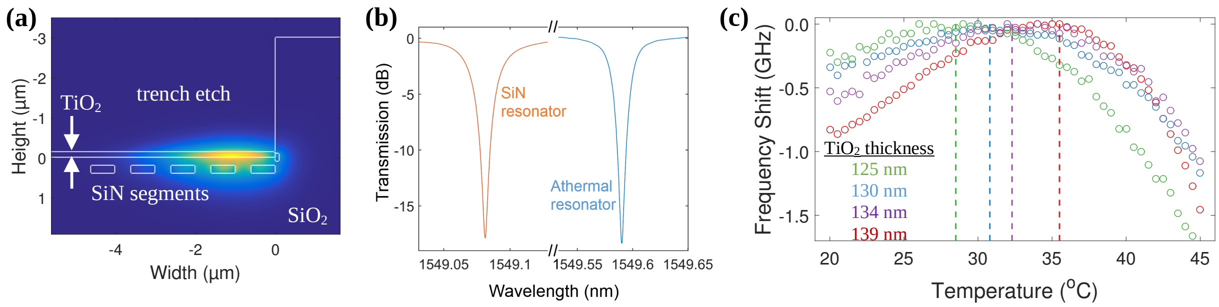

Fig. 1. (a) Fundamental TE mode electric field profile and cross-section of 80 µm radius athermal ring resonator showing buried SiN segments, SiO_2 cladding, and deposited TiO_2 in the trench. (b) Transmission spectra of SiN and athermal resonators. (c) Resonance frequency shift of the fabricated athermal resonator. With increasing TiO_2 thickness, the athermal operation can be shifted to longer wavelengths.

3. Noise Characterization and Linewidth Measurement

First, to see thermal effects, a conventional, 80 µm radius, 200 nm thick SiN cavity with 1.5 µm wide ring and 1.2 µm wide bus was characterized. With a coupling gap of 1 µm, Q=67,000 and extinction ratio r_e=17.9 dB were obtained, similar to the athermal cavity above (Fig. 1b). For this SiN resonator at room temperature, with P_{out}=5 mW, n_{eff}=1.52, dn/dT≈3x10^{-5}, dL/(LdT)≈1.5x10^{-6} and G=0.002 W/K, the Schawlow-Townes limit is $\Delta\nu_{ST} \approx$ 660 Hz whereas the total linewidth due to the combined Schawlow-Townes limit and thermal noise is $\Delta\nu_{SiN} \approx$ 1.6 MHz. Therefore, the linewidth of a laser locked to this SiN cavity is thermally limited. As a result, significant linewidth improvement would be expected upon locking to the athermal cavity described above. This is achieved by the Pound-Drever-Hall technique, where the CW laser is modulated with a 10 GHz phase modulator, and the resulting signal is fed into the resonator under test. The error signal at the thru port is detected, mixed down to base-band, and used as an input to a servo controller for modulating the CW input. The resulting linewidth is measured by the beat signal between the CW laser and a mode-locked laser whose repetition rate and carrier envelope offset have been stabilized by a 1f-2f lock and external RF sources (Fig. 2a). The linewidths for the free-running and SiN cavity locked CW laser are 4.79 MHz and 1.91 MHz respectively (Fig. 2b). This linewidth when the laser is locked to the SiN cavity is similar to the thermal limitation of $\Delta\nu_{SiN} \approx$ 1.6 MHz above. After locking to the athermal cavity, the linewidth is reduced by an additional factor of 6 to 0.34 MHz, demonstrating the performance of the athermal cavity in reducing thermal noise.

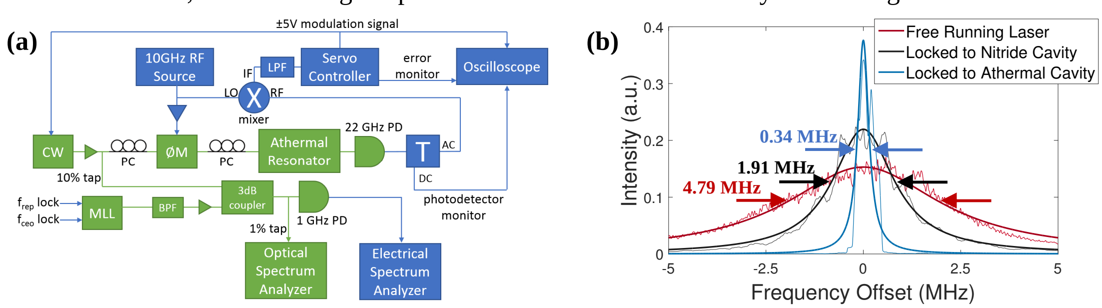

Fig. 2. (a) Pound-Drever-Hall lock and characterization setup (b) Beat notes between the stabilized mode-locked laser and the CW laser in its free-running state, when locked to the SiN cavity, and when locked to the athermal cavity. Lorentzian fits show supressed thermal noise in the athermal cavity.

In conclusion, by making use of the negative TOC of TiO_2, we demonstrated high-Q athermal resonators. The athermal operating temperature can be controlled by the TiO_2 thickness. By locking a CW laser to this athermal cavity, we showed suppressed thermal noise compared to a conventional SiN cavity. This marks an important step towards creating integrated low-noise oscillators. *This work was supported by DARPA under the E-PHI projects, grant no. HR0011-12-2-0007.*

4. References

[1] B. Guha, et al., "Athermal silicon microring resonators with titanium oxide cladding," Optics express 21.22 (2013), pp. 26557-26563.
[2] S.S. Djordjevic, et al., "CMOS-compatible, athermal silicon ring modulators clad with titanium dioxide," Optics Express 21.12 (2013): pp. 13958-13968.
[3] J.Bovington, et al., "Thermal stress implications in athermal TiO_2 waveguides on a silicon substrate," Optics Express 22.1(2014), pp.661-666.
[4] K. Numata, et al,"Thermal-noise limit in the frequency stabilization of lasers with rigid cavities," Phys. Rev. Lett. 93.25(2004), 250602.
[5] R.W.P. Drever, et al., "Laser phase and frequency stabilization using an optical resonator," Applied Physics B 31.2 (1983), pp. 97-105.
[6] E.S. Magden, "Rare-earth doped aluminum oxide lasers for silicon photonics." MS Thesis, Massachusetts Institute of Technology, 2014.
[7] J.D.B. Bradley, et al., "Submicrometer-wide amorphous and polycrystalline anatase TiO_2 waveguides for microphotonic devices," Optics Express 20.21 (2012), pp. 23821-23831.
[8] International Telecom. Union, "Spectral grids for WDM applications (Series G.694.1)," 2012.