Laser Frequency Drift Stabilization using an Integrated Dual-Mode Locking Si_3N_4 Waveguide Reference Cavity

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Abstract: We demonstrate an integrated Si_3N_4 waveguide resonator designed as a dual-mode locking (DML) cavity that stabilizes laser frequency to 1.7×10^{-10} Allan deviation in a 1000-second average measurement with a temperature sensitivity of 187.56 MHz/K. © 2021 The Author(s)

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1. Introduction

Optical reference cavities are widely used for laser linewidth reduction and frequency stabilization applications such as optical atomic clocks [1]. For reduced cost and portability, it is desirable to miniaturize traditional bench-top reference cavities into photonic integrated resonators [2]. Dual-mode thermometry is a powerful technique that has been used to precisely probe a cavity temperature by utilizing the difference in thermal responses between two polarization modes [3] or two frequencies [4]. This sensitive intra-cavity temperature measurement can be used in a feedback control circuit to stabilize cavity temperature or a feedforward circuit to regulate laser frequency drift [5]. Advances in miniaturizing the dual-mode locking (DML) temperature stabilization technique include crystalline whispering-gallery-mode resonators [6] and fiber resonators [7]. However, to date, DML temperature stabilization for laser frequency stabilization has not been realized in an integrated waveguide photonic resonator.

We show, for the first time, long-term laser frequency stabilization using a DML photonic integrated Si_3N_4 reference cavity. The resonant frequency difference has a temperature sensitivity of 187.56 MHz/K. Using this technique, we are able to improve the laser stability to a measured 1.7×10^{-10} Allan deviation (ADEV) at 945 seconds, 30 times better than when the laser is stabilized to the resonator without the DML control engaged. These results represent a promising step towards photonic integrated reference cavities and ultra-stable integrated lasers.

2. Resonator characterization

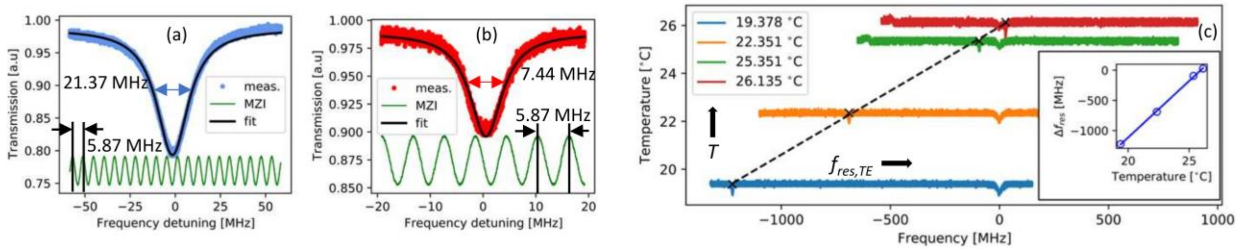

Fig. 1 The transmission spectra of (a) the TM mode and (b) the TE mode with the MZI fringe pattern as a frequency ruler. (c) The transmission spectra of the TE and TM modes at different temperatures. The inset shows the resonance difference vs. temperature.

Our reference cavity is an all-pass Si_3N_4 ring resonator with a core dimension of 6 μm × 80 nm fabricated by an ultra-low-loss process [8]. The measured transmission spectra of the fundamental TM and fundamental TE modes are shown in Fig. 1(a) and (b). The resonances are characterized using a calibrated Mach-Zehnder interferometer (MZI) method [9]. The loaded Q factor of the TM mode is 9.05×10^6 with a full width at half maximum (FWHM) of 21.37 MHz at 1550 nm. The ring-bus coupling coefficient is measured to be -14.3 dB with a resulting TM mode propagation loss of 0.15 dB/m and a 179.87×10^6 intrinsic Q. The loaded Q of the TE mode is 25.99×10^6 with a FWHM of 7.44 MHz, a -32.9 dB ring-bus coupling coefficient, a propagation loss of 1.02 dB/m, and a 26.61×10^6 intrinsic Q factor. The TE and TM mode transmission spectra at different temperatures are shown in Fig. 1(c). These spectra are centered on the TM resonances, and the TE resonances move linearly with the temperature change, with the frequency difference between the two orthogonal modes plotted as a function of the temperature in the inset. The temperature sensitivity of the resonance difference is 187.56 MHz/K, which matches well with our simulation.

3. Dual-mode thermometry temperature stabilization

A semiconductor diode laser (L) is frequency-locked to one of the cavity TM resonances (blue path in Fig. 2(a)) using a Pound-Drever-Hall (PDH) technique. To probe the TE/TM resonance difference, the voltage-controlled oscillator (VCO) that drives the electro-optic modulator (EOM) is tuned to the TE/TM frequency difference and locked such that the generated laser sideband aligns with the TE resonance. While dual-mode locking (DML) is engaged [6], the VCO frequency tracks the TE/TM resonance difference which is cavity temperature dependent. The VCO frequency is actively monitored by a frequency counter (FC2) serving as an error signal to adjust the current of a laser diode illuminating the cavity surface, creating a photothermal temperature correction. The DML stabilized laser is beat with a lab reference stabilized laser (SL) that uses a Stable Laser Systems (SLS) Fabry-Perot cavity [10] to characterize its frequency stability. Fig. 2(b), (c) and (d) show the VCO frequencies, beat note frequencies, and ADEVs of the beat notes with and without DML temperature stabilization engaged, respectively.

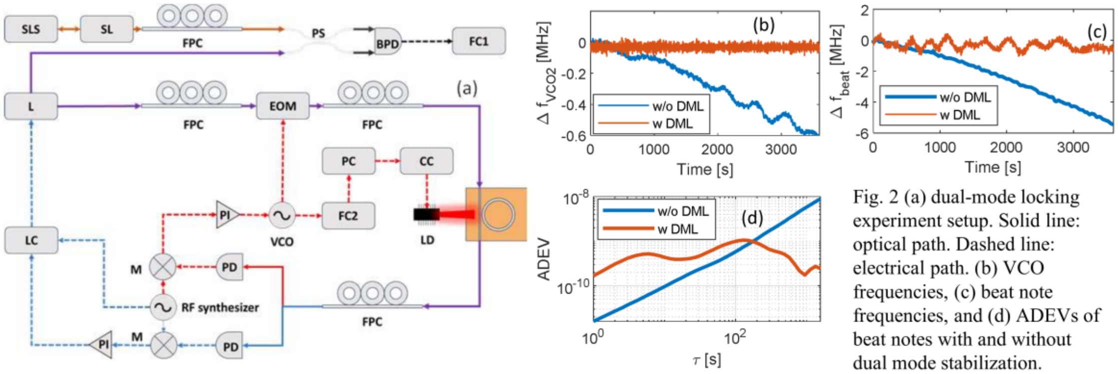

Fig. 2 (a) dual-mode locking experiment setup. Solid line: optical path. Dashed line: electrical path. (b) VCO frequencies, (c) beat note frequencies, and (d) ADEVs of beat notes with and without dual mode stabilization.

SLS: Stable Laser Systems reference cavity, **SL**: stabilized laser, **PS**: power splitter, **BPD**: balanced photodetector, **FC**: frequency counter, **L**: laser, **FPC**: fiber polarization controller, **EOM**: electro-optic modulator, **LC**: laser controller, **M**: mixer, **PI**: proportional-integral gain controller, **VCO**: voltage-controlled oscillator, **PC**: personal computer, **CC**: current controller, **LD**: laser diode, **PD**: photodetector.

With DML temperature stabilization engaged, the servo-controlled VCO frequency stays within ± 58.3 kHz for one hour, whereas it can drift by more than 0.6 MHz while free running as shown in Fig. 2(b). The standard deviation of the VCO frequency is 17.1 kHz, corresponding to a temperature variation of 91 μK in a room-temperature non-vacuum environment. The drift of the beat note is suppressed by a factor of 30X, from 1.54 kHz/s without DML to 51 Hz/s with DML as illustrated in Fig. 2(c). We attribute the fluctuation of the beat note (period ~ 250 s) to the environment variations that affect the TE sideband lock loop. This effect can be mitigated by temperature-stabilizing the electronic components. The resulting ADEV curve shows a peak at 127 s, corresponding to a half period of the fluctuation. The ADEV is measured to be 1.7×10^{-10} at 945 s and has more than 30X reduction compared to that without DML temperature stabilization. The fractional stability of 10^{-10} in the thousands of seconds timescale is useful to space-based applications such as laser interferometry [11]. Our future experiments intend to improve ADEV further to the 10^{-13} level at 1 s by eliminating the oscillations from the feedback loop (peak at 6 s) and environmental variations (peak at 127 s) shown in Fig. 2(d). To further improve the stability of the system, the resonance extinction ratios and Q factors will be increased to improve the SNR of the PDH error signal. Reducing residual amplitude modulation (RAM) will mitigate unwanted PDH error signal DC level shift. A feedforward configuration is currently under investigation to suppress high frequency noises.

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