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Sub-dB/m loss integrated 103 and 90 million Q resonators for laser stabilization at rubidium and strontium wavelengths

Nitesh Chauhan
Department of Electrical and Computer Engineering
University of California Santa Barbara
Santa Barbara, CA, USA
niteshchauhan@ucsb.edu

Andrei Isichenko
Department of Electrical and Computer Engineering
University of California Santa Barbara
Santa Barbara, CA, USA
aisichenko@ucsb.edu

Jiawei Wang
Department of Electrical and Computer Engineering
University of California Santa Barbara
Santa Barbara, CA, USA
jiawei_wang@ece.ucsb.edu

Daniel J. Blumenthal
Department of Electrical and Computer Engineering
University of California Santa Barbara
Santa Barbara, CA, USA
danb@ucsb.edu

***Abstract*— We report integrated silicon nitride resonators with 0.65 dB/m loss and 90x10^6 intrinsic Q at 674 nm and 0.5 dB/m loss with 103x10^6 intrinsic Q at 780 nm. We demonstrate laser stabilization with over two orders magnitude frequency noise reduction.**

***Keywords*— photonic integrated circuits, low loss waveguides, visible waveguides, high Q integrated resonator**

I. INTRODUCTION

Integrated ultra-low loss waveguides and high quality factor (Q) resonators are critical for the miniaturization and scalability of atomic, molecular and optical (AMO) systems like quantum computing, atomic clocks, precision spectroscopy. Such systems traditionally use free space optics for beam routing and delivery and lasers are stabilized using Pound-Drever-Hall (PDH) locks to bulky table top cavities to provide a highly coherent laser required for interacting with AMO systems [1]. Low loss waveguides have been demonstrated with grating couplers for beam delivery in visible wavelengths [2] and miniature free space high Q resonators have shown to provide linewidth narrowing through PDH [3] or injection locking [4]. Previously, the lowest reported losses in visible wavelengths are ~ 1 dB/m [5] and SBS lasing in resonators with 1.1 dB/m loss and loaded Q (Q_L) of 28 million and intrinsic Q (Q_i) of 54 million resonator using dilute mode TE waveguides in Si_3N_4 [6] for far-from-carrier linewidth noise reduction.

Here we demonstrate the first waveguides at visible (674 nm and near visible 780 nm) with < 1 dB/m losses. We demonstrate resonators with propagation loss 0.65 dB/m, Q_i = 90 million (M), Q_L = 51 M at λ = 674 nm which was chosen for Sr^+ clock transition. At λ = 780 nm, chosen for probing the rubidium D_2 transition, we measure a propagation loss of 0.5 dB/m, Q_i = 103 M, Q_L = 37 M. These resonators are then used to stabilize lasers, achieving reduction in integral linewidth from 100s of kHz to a few kHz. The waveguides are fundamental TM mode in the Si_3N_4 CMOS foundry compatible process [5], [7]. We lock commercial diode lasers using the PDH technique to show linewidth narrowing, limited by the fundamental thermo-refractive noise (TRN) of the resonator. At 674 nm, the lock achieves ~2 orders of magnitude frequency noise (FN) reduction with lowest FN of ~ 2×10^3 Hz^2/Hz for ~1 - 10 kHz frequency offsets with an integral linewidth of 4 kHz ($1/\pi$ integral [8]) of locked, which is ~ 30x reduction from 112 kHz integral linewidth of free running laser. At 780 nm, the lock frequency noise reaches ~2×10^2 Hz^2/Hz at 10 kHz frequency offset.

II. RESULTS

A. High-Q Resonator Devices

The waveguide geometry consists of 15 µm SiO_2 lower cladding, a 40 nm thick 2.3 µm wide Si_3N_4 core and 6 µm SiO_2 upper cladding shown in Fig. 1(a) and supports fundamental TE and TM modes. Fundamental TM mode is selected for resonator as it has been demonstrated to have lowest waveguide loss at telecom [7]. The resonator is 8.9 mm radius for 674 nm and 9.4 mm for 780 nm, with coupling gap 2.5 um, power coupling coefficient κ^2 0.4% (under-coupled) at 674 nm and coupling gap 3.4 um, κ^2 1.2% (over-coupled) at 780 nm. The fundamental TE is not coupled into the resonator at these gaps. The Q was measured using a 20 MHz unbalanced Mach-Zehnder interferometer (MZI) with 20 MHz FSR for 674 nm and 4 MHz FSR for 780 nm to calibrate the laser frequency detuning. The measured Q_L = 51 M at 674 nm is shown in Fig. 1(b) Q_L = 37 M at 780 nm is shown in Fig. 1(c). The coupling is extracted from a Lorentzian fit and independent test structures are used to extract the Q_i = 90 M at 674 nm and 103 M at 780 nm. The propagation losses are 0.65 dB/m and 0.5 dB/m at 674 nm and 780 nm, respectively.

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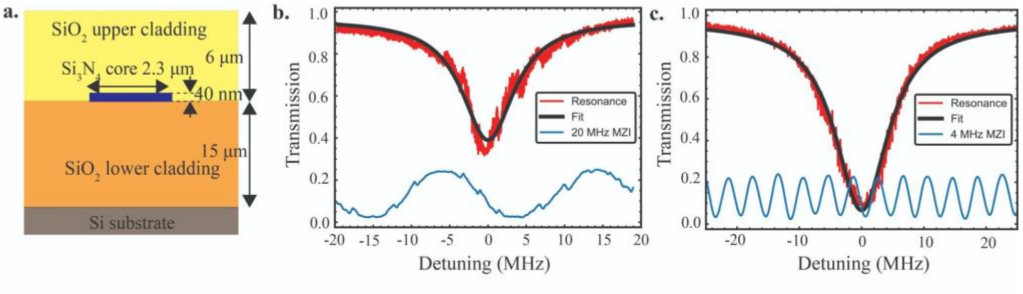

Fig. 1. (a) Waveguide cross section. (b) Q measurement of resonator at λ = 674 nm yielding loaded Q = 51 × 10^6, the extracted Q_i = 90 × 10^6 and 0.65 dB/m loss. (c) Q measurement of resonator at λ = 780 nm yielding Q_L = 37 × 10^6, the extracted Q_i = 130 × 10^6 and 0.5 dB/m loss.

B. *Laser Stabilization*

The high Q enables tight locking to the resonators resulting in reduction of linewidth in the PDH locking bandwidth. We use commercial diode lasers with free-running linewidths of 100s of kHz and a commercial PDH servo to lock the laser to the resonator with locking bandwidth of ~1 MHz. The FN is measured using an optical frequency discriminator (OFD) [6] (Fig. 2(a).) and the FN of free running and locked lasers are shown in Fig. 2(b). The noise below 2 kHz offset is dominated by OFD system noise. At ~2 kHz the FN reaches the TRN floor which depends on thermo-refractive properties of mode and the mode volume.

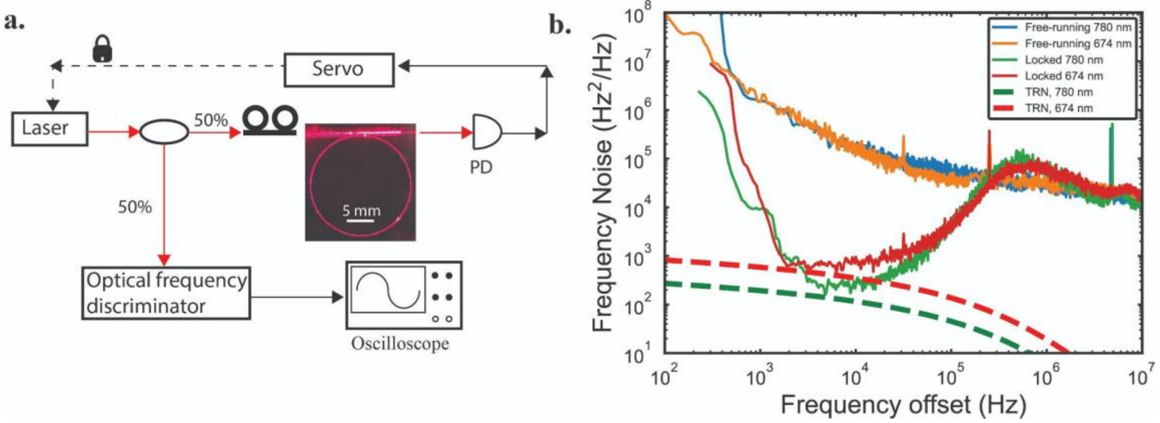

Fig. 2. (a) Setup schematic for PDH locking to resonator with actual resonator shown at 674 nm. (b) OFD frequency noise data of 674 nm and 780 nm laser locked to the low loss resonator. The 1/π integral linewidth of free running laser = 112 kHz and the locked laser is 4 kHz, a factor of ~ 30 decrease at 674 nm. At 780 nm the laser frequency noise is reduced to 2x10^2 Hz^2/Hz at 10 kHz frequency offset, with the performance limited by the TRN of the resonator for both wavelengths.

III. CONCLUSION

We report the first sub-dB/m loss waveguides in visible, with propagation loss at Sr$^+$ clock λ = 674 nm of 0.65 dB/m, Q_i = 90 M. At the Rb D_2 wavelength λ = 780 nm we demonstrate propagation loss of 0.5 dB/m, and the first >100 million Q near visible in integrated waveguide resonator with Q_i = 103 M. We demonstrate the use of these high Q resonators as stabilization cavities to reduce linewidth from 100s of kHz to few kHz, with the reduction in FN around two orders of magnitude, limited by the TRN floor of resonator. This limit can be further reduced to provide <100 Hz integral linewidth [9]. These advances can enable on-chip stabilized laser systems for compact and scalable AMO applications.

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