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720 Million Quality Factor Integrated All-Waveguide Photonic Resonator

Kaikai Liu[1], Naijun Jin[2], Haotian Cheng[2], Matthew W. Puckett[3], Ryan O. Behunin[4,5], Karl D. Nelson[3], Peter T. Rakich[2] and Daniel J. Blumenthal[1,*]
[1]*University of California at Santa Barbara, Department of ECE, Santa Barbara, CA 93016 USA*
[2]*Department of Applied Physics, Yale University, New Haven, CT, USA*
[3]*Honeywell International, Phoenix, AZ, USA*
[4]*Department of Applied Physics and Materials Science, Northern Arizona University, Flagstaff, AZ, USA*
[5]*Center for Materials Interfaces in Research and Applications, Northern Arizona University, Flagstaff, AZ, USA*
Email: danb@ucsb.edu

Introduction: Ultra-high Q optical resonators are an essential component for a wide range of applications such as ultra-narrow linewidth lasers, optical gyroscopes, optical atomic clocks and quantum communications and computation [1–3]. Efforts have been made towards miniaturizing bulk-optical resonators with Qs of tens of Billions [4] such as the whispering gallery mode resonator with 63 Billion Q [5] and the microrod resonator with 1 Billion Q [6]. Progress has been made with on-chip etched silica disk resonators reaching 1.1 Billion Q, however, these designs are not compatible with wafer-scale photonic waveguide fabrication [7]. Recently, we reported a 422 Million intrinsic Q Si_3N_4 integrated all-waveguide resonator with a 453 kHz intrinsic linewidth and 0.060 dB/m loss [8]. Moving these all-waveguide designs towards 1 Billion Q for integrated all-waveguide resonators is a key milestone towards fully integrated ultra-narrow linewidth, ultra-stable lasers.

In this paper we report a record high 720 Million intrinsic Q integrated all-waveguide resonator with an intrinsic linewidth of 258 kHz and loaded linewidth of 386 kHz with corresponding record low loss of 0.034 dB/m. These results are the highest Q reported to date for all-waveguide integrated resonators and lowest waveguide losses for a non-bonded structure, a factor of 70% increase in Q, and a factor of ~2X reduction in intrinsic linewidth and loss.

Resonator Design and Q and Linewidth Measurements: The Si_3N_4 resonator is based on a TM guided mode bus-coupled resonator with high-aspect ratio waveguide core geometry (11 µm by 80 nm), a radius of 11.787 mm, and a bus-ring coupling gap of 6.898 µm. The fabrication processes is the same as described in [8]. Our prior design supported the fundamental TE mode, with a propagation loss dominated by top or bottom surface roughness scattering loss [8]. Since TM modes are less susceptible to the top and bottom roughness scattering losses, we increased the TE design nitride thickness to 80 nm to support ™ guiding. As shown in Fig. 1, the 11 µm by 80 nm waveguide is a multi-mode waveguide, with TE modes more confined than TM modes. Simulations show that the TE modes are extremely weakly coupled. As a result, in the spectral scan shown in Fig. 2(a), there are only two TM modes observed.

The Q is measured using both the radio frequency (RF) calibrated fiber Mach-Zehnder interferometer (MZI) and ring-down techniques [8] with a calibrated free spectral range (FSR) of 1.026 MHz. A Velocity™ TLB-6700 widely tunable laser (1550 nm to 1630 nm) is used as the probe laser with the calibrated MZI. The measurements are fit to a Lorentzian lineshape to extract the loaded, intrinsic and coupling linewidths. Fig. 2(d) and 2(e) shows the measured Qs and linewidths for the fundamental TM mode from 1550 nm and 1630 nm. The highest intrinsic Q is 720 Million at 1615 nm and intrinsic linewidth of 258 kHz. We average the fitted Qs from 10 ringdown measurements for the fundamental TM mode at 1615 nm, with a measured loaded Q of 518 Million and the intrinsic Q of 775 Million. These results are in good agreement with the RF-MZI measurements.

Conclusion: We report the highest demonstrated Q to date, 720 Million, for an integrated all-waveguide resonator, exceeding our prior results, 422 Million [8], by around 70% improvement and the lowest loss waveguide reported to date for a non-wafer bonded silicon nitride waveguide. The waveguide is a silicon nitride TM mode design that minimizes top and bottom surface roughness scattering, enabling a 386 kHz loaded linewidth, 258 kHz intrinsic linewidth, and a waveguide loss of 0.034 dB/m. Photonic integrated resonators, with linewidths on the order of several kHz, and Qs approaching 1 Billion, that are compatible with planar wafer scale fabrication [9], show promise towards precision spectroscopy, metrology, timekeeping and quantum applications integrated on-chip.

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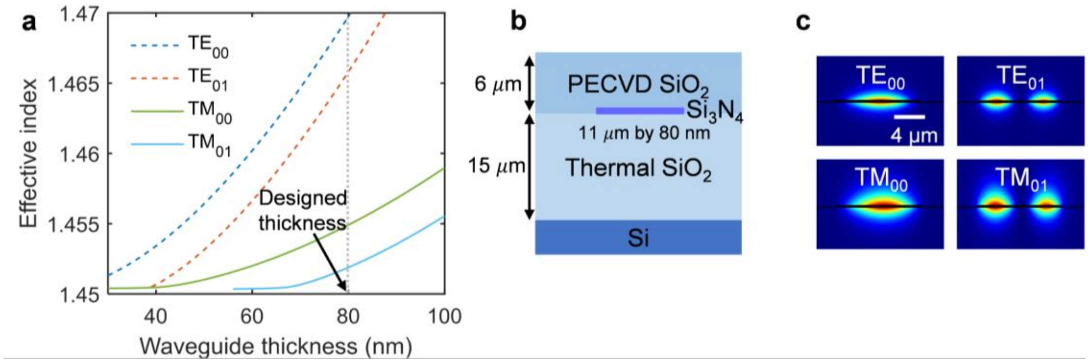

Fig. 1. (a) Effective index simulation for the 11 μm wide waveguide with different thicknesses. (b) Cross-section diagram of the waveguide. (c) TE and TM mode profiles for the11 μm by 80 nm waveguide.

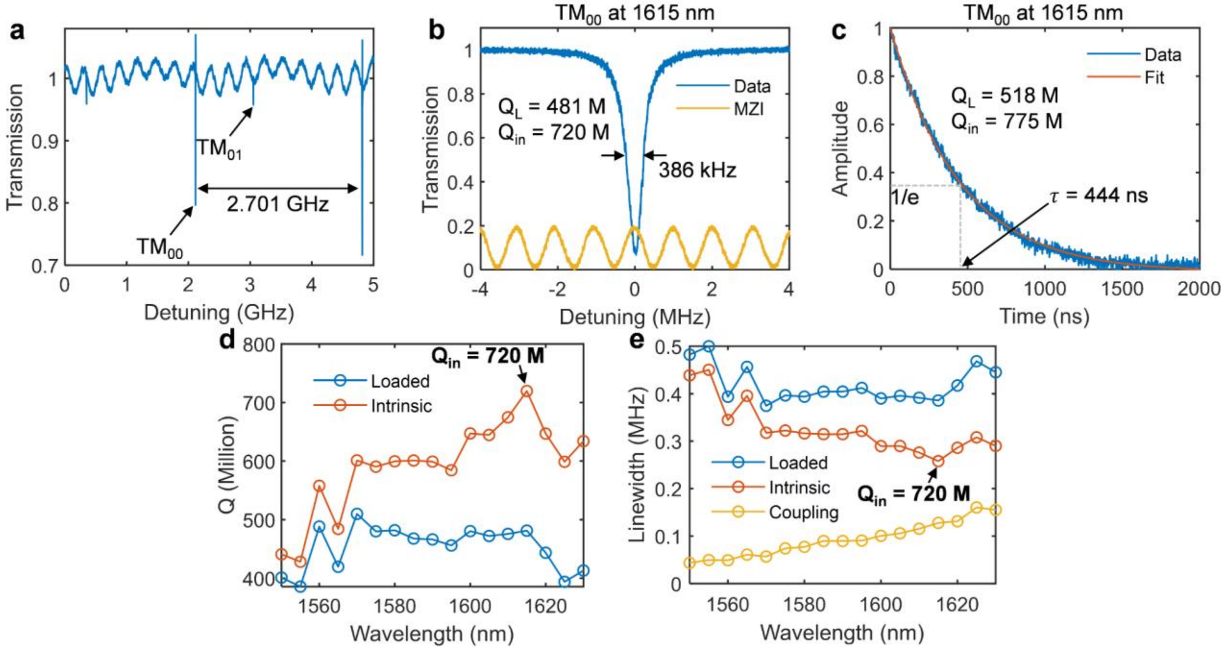

Fig. 2. (a) Spectral scan across two FSRs, where the TM$_{00}$ and TM$_{01}$ modes are observed. (b) Spectral scan of the TM$_{00}$ mode at 1615 nm with the 1.026 MHz FSR MZI as the optical frequency calibration. (c) Ringdown time measurement for the TM$_{00}$ mode at 1615 nm. Summary of (d) the loaded and intrinsic Qs and (e) the loaded, intrinsic and coupling linewidths for the TM$_{00}$ mode from 1550 nm to 1630 nm.

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