High Finesse Silicon Ring Resonators for Monolithic Mode-locked Lasers

W. E. Hayenga,[a] M. Akhlaghi-Bouzan,[a] P. J. Delfyett,[a] and M. Khajavikhan,*[a]

[a] CREOL, College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816-2700, USA

*Corresponding author: mercedeh@creol.ucf.edu

ABSTRACT

Low noise mode-locked lasers and stabilized optical frequency combs are receiving considerable attention due to their broad spectrum of applications which ranges from signal processing to communications to metrology. Progress has been made in the realization of ultralow noise pulse trains by using ultralow expansion (ULE) quartz etalons for filtering the axial mode groups. An important step towards miniaturization of these systems is the integration of a high finesse on-chip optical filter that would serve to replace the ULE etalon. In this paper, we report our experimental results towards the realization of such a high finesse cavity based on a silicon microring resonator.

Keywords: Silicon microring resonators, Integrated mode-locked lasers, High Q resonators

1. INTRODUCTION

Low noise mode-locked lasers and stabilized optical frequency combs are receiving considerable attention owing to their broad spectrum of applications which ranges from metrology to signal processing to communications. Progress has been made towards the realization of ultralow noise pulse trains from electrically efficient compact semiconductor gain media that are used as sampling pulses for analog to digital converters. However, these realizations require ultralow expansion (ULE) quartz etalons as an optical element in an extended fiber cavity, making miniaturization difficult. Further advances are needed to reduce the size of these sources so that a chip-scale footprint can be achieved to enable new applications. One key step towards miniaturization is the integration of an optical filter that would serve to replace the ULE etalon in the aforementioned extended mode-locked fiber cavity [1]. In this paper, we fabricate a high finesse ring resonator that acts as an optical filter to select a single mode-locked axial group for the generation of low noise optical pulse trains.

Figure 1(a) shows the schematic of a frequency stabilized harmonically mode locked laser in which an ULE etalon provides the optical filtering to select a single axial mode-locked group of optical frequencies. Figure 1(b) provides a schematic of the proposed miniaturized mode-locked semiconductor laser. The system consists of two coupled ring resonators where the semiconductor amplifier is placed in the longer cavity and provides 35 dB of gain. Meanwhile, the smaller cavity dictates the repetition rate of the mode locked laser system. In this configuration, the smaller ring resonator serves as the replacement of the ULE etalon. A necessary requirement of the ring resonators is that the large ring should be n times longer than the short ring, where n is an integer. In this arrangement, an intensity modulator incorporated in the larger ring that is modulated at the free spectral range of the shorter ring will produce a stabilized mode-locked optical frequency comb.

As a first step towards the miniaturization of such semiconductor-based mode locked lasers the etalon is replaced with a chip-scale micro-resonator. We here choose a Silicon on insulator (SOI) platform because it offers unique capabilities in building versatile photonic components, including filters, splitters, modulators, and photodetectors. We have developed a

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fabrication recipe for a low loss resonator that results in high quality factor silicon rings via reducing the scattering loss at the interfaces.

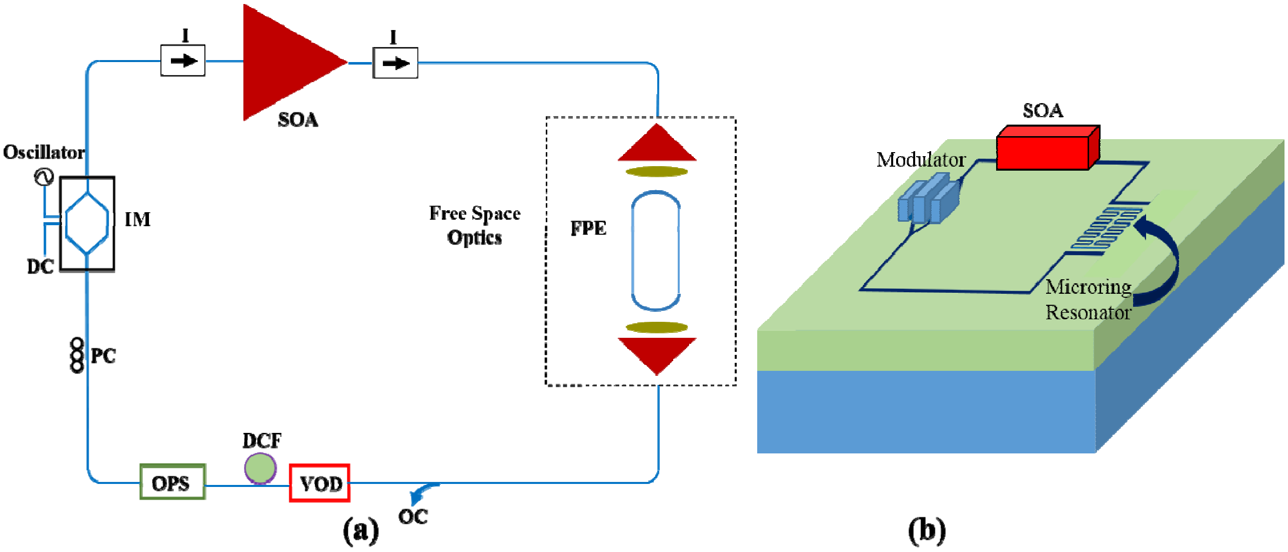

Figure 1 (a) A schematic of a mode locked laser with an intra-cavity etalon. **(b)** A simplified compact cavity for an on-chip mode locked laser in which the etalon is replaced by a silicon ring resonator. I, isolator; SOA, semiconductor optical amplifier; FPE, Fabry Perot Etalon; OC, output coupler; VOD, variable optical delay; DCF, dispersion compensating fiber; OPS, optical phase shift; PC, polarization controller; IM, electro-optic intensity modulator.

2. FABRICATION

The SOI wafer used in this arrangement is composed of a 220 nm thick silicon film and a 2 µm buried SiO_2 buffer oxide layer. To attain the desired FSR values that are dictated by the above design (~30 GHz and less), long resonators with a length on the order of $L = 2500$ µm ($\Delta\upsilon = c/(n_g L)$ where $n_g = 4.10$ for this waveguide) must be fabricated. Even though several approaches exist for realizing low-loss etch-free silicon waveguides, these techniques are not suitable for long and compact resonators. The reason for this is that the etch-free recipes result in modes that are not well confined, thus making them subject to large losses due to the many bends in the long and compact resonator [3]. We developed a new recipe to fabricate long yet compact low loss resonators, by first dry oxidation of the SOI wafer in a furnace at a temperature of 1000 C to form a thin (< 20 nm) SiO_2 film. Then an ~600 nm thick Hydrogen Silsesquioxane (HSQ) resist spun on the wafer was patterned by electron beam (e-beam) lithography. To effectively incorporate the real estate on the chip, a radiator shape ring resonator with bending radii of 20 µm is defined. Figure 2 (a) shows an image of the resonator taken by an optical microscope. The radiator-shaped resonator also ensures that the pattern is written in one write field to avoid stitching errors. After exposure, the HSQ cross links and turns into a film with similar properties to SiO_2. The pattern is then transferred to the silicon layer using dry etching with Cl_2:BCl_3:Ar gas mixture at a 12 mTorr of pressure. Once again the wafer is placed in the oxidation furnace at a temperature of 1000 C to create a thin layer (< 20 nm) of SiO_2 on the walls of the waveguides. This step is employed to reduce the roughness generated by dry etching. Finally, the entire wafer was covered by a 3µm thick SiO_2 film which was deposited by using plasma-enhanced chemical vapor deposition (PECVD). The effective width of the waveguide is 400 nm, this is to reject the propagation of higher order modes. The resonator supports only the fundamental TE_{01} mode. A bus waveguide that is inversely tapered at both ends couples the light into and out of the microring resonator. Figure 2 (b) shows the Finite Element Method (FEM) simulated mode profile supported by the waveguide.

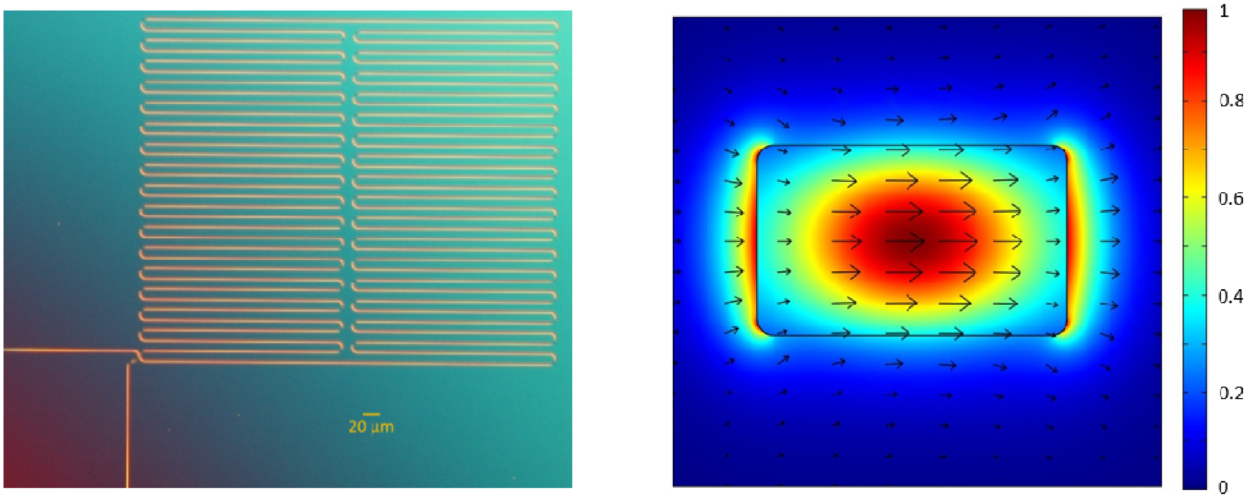

Figure 2 (a) Top view of a microscope image of the silicon based resonator. **(b)** An FEM COMSOL simulation detailing E_{norm}^2 for the fundamental mode. The black arrows indicate the polarization of the electric field. The height and width of the waveguide film is 220 nm and 400 nm, respectively.

3. CHARACTERIZATION

The transmission properties of the ring resonators are interrogated by a tunable laser that is coupled into the waveguide, which in turn is coupled to the ring resonator. The waveguide is then out coupled and measured as a function of wavelength with a power meter to find the transmission, allowing for the determination of the Fieness. Figure 3 (a) is the measured mode profile of this single mode resonator and Figure 3 (b) shows the measured spectral response of the ring resonator. The FSR of the resonator is 32.4 GHz and the Full Width Half Maximum (FWHM) is 0.13 GHz, resulting in a finesse of 250. The resonator has a quality factor (Q) of $1.5\text{x}10^6$, which is comparable to state of the art small ring resonators developed via the etch-free waveguide fabrication recipes [3]. In our current design, fiber epoxy is used to attach the fiber coupled semiconductor optical amplifier to the SOI wafer through the bus waveguide. The polarization of the beam in the large ring is adjusted via manual polarization controllers. The output is collected by a directional coupler incorporated in the larger fiber ring.

CONCLUSION

In summary, we have reported results towards the realization of a fully integrated mode-locked semiconductor laser. We have demonstrated a high finesse and large FSR ring resonator that is coupled to a semiconductor amplifier capable of generating pulses at a repetition rate of ~32 GHz. The performance specifications of this system will be presented and compared with state of the art etalon-based cavities for the realization of on-chip mode-locked lasers.

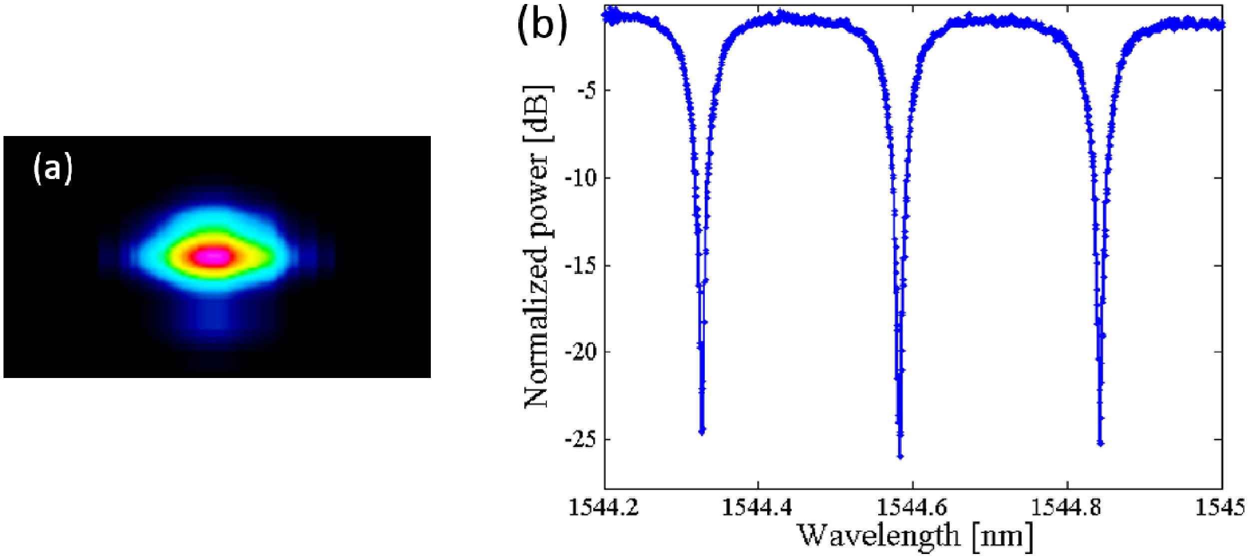

Figure 3 (a) The measured mode profile of this single mode resonator. **(b)** The spectral response of the resonator having a FSR of 32 GHz and a resonance FWHM of 0.13 GHz.

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