

Near-Visible Microresonator-Based Soliton Combs

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Abstract: We experimentally demonstrate soliton mode-locked Kerr comb generation at near-visible wavelengths in a silicon nitride microresonator. We achieve the shortest wavelength to-date for mode-locked Kerr combs through dispersion engineering of a higher-order mode.

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Soliton mode-locked microresonator combs provide a pathway towards fully integrated comb sources that can find applications across numerous areas of science and engineering [1]. Since its first demonstration, most of the work on Kerr comb generation (KCG) has focused on near-infrared (NIR) wavelengths, particularly telecom wavelengths. One important parameter for KCG is the group velocity dispersion (GVD) where a negative β_2 is prerequisite. In the NIR, most of the chip-integrable optical materials (silicon nitride, silica, etc.) exhibit small material GVD, which enables flexible dispersion engineering through waveguide dispersion. The extension to shorter wavelengths has been largely impeded by the strong normal material GVD in almost all of the chip-integrable materials. Lee *et al.* [2] achieved anomalous GVD and subsequent soliton generation near 778 nm using a silica whispering gallery mode resonator (WGMR). Compared to silica, silicon nitride (Si_3N_4) is a more preferred material for chip integration but it has a material dispersion that is an order of magnitude higher. Yu *et al.* [3] extended Si_3N_4 based Kerr combs down to 770 nm through dispersive wave formation. To date, most studies of KCG utilized the fundamental mode of the microresonators due to the cavity Q's and ease of mode excitation, with the exception of Lucas *et al.* [4] which simultaneously excited the fundamental and a higher order mode in a WGMR. Savchenkov *et al.* [5] explored the use of higher-order modes in WGMRs but mode-locking was not achieved.

In this work, we apply techniques of higher-order dispersion engineering on the bus and microresonator waveguides to obtain broadband KCG in the near visible regime and achieve the shortest wavelength (710 nm) in a mode-locked microresonator. We show that by exciting the higher-order mode in a Si_3N_4 microring resonator, anomalous GVD can be realized across a broad range of wavelengths in this regime, which is not possible for the fundamental modes. We believe this technique can be scaled to achieve KCG pumping at visible wavelength. Our approach to visible and near-visible KCG creates new potential applications for optical clockwork, spectroscopy, and bio-imaging.

We numerically simulate the device dispersion with a finite element mode solver. We choose a ring size of 730×1330 nm and a radius of $22 \mu\text{m}$, whose GVD is shown in Fig. 1(a). We design our microresonator to have anomalous GVD for the TE_{10} mode. Since most lasers operate in the fundamental mode, we excite the TE_{10} mode in the ring through evanescent-coupling mode conversion from the fundamental mode in the bus waveguide. This is achieved by matching the effective index of the TE_{00} mode of the bus to the TE_{10} mode of the ring. In our design, index matching is achieved for a bus size of 730×568 nm. The final structure is shown in Fig. 1(b). In addition, we include drop ports (same dimension as the ring) for selected devices to monitor the mode profile in the ring [inset, Fig 1(b)]. The drop port devices are not used for comb generation in this work since the extra coupling loss lowers the Q. We measure a loaded Q of our devices to be 7.7×10^5 which corresponds to a power enhancement factor of 333 with respect to the pump power in the bus. The devices also have integrated platinum heaters that are used for KCG, as described in Joshi, *et al.* [6].

In our experiment, a continuous laser at 784 nm is coupled into the bus waveguide. The power is measured to be 220 mW on chip. We generate the soliton using thermal tuning [6] and observe the signature soliton step after the high noise state [Fig. 1(c)]. We achieve a 4-soliton state [Fig. 1(d)] where the solitons are equally spaced inside the ring. This is the preferred state because it has an intracavity energy which is close to that of the chaotic state, making it experience the least amount of thermal backlash after the soliton jump. In addition, this state is formed due to self-organized soliton patterns assisted by mode interactions [7]. We show the simulated single soliton spectrum in Fig. 1(e). The lower wavelength part of the experiment spectrum [Fig. 1(d), red] is measured with a different optical spectrum analyzer (OSA) and rescaled due to equipment limitations. A dispersive wave at 710 nm is observed. We also note that the bus-ring coupling coefficient rapidly decreases for frequencies away from the pump, which can be attributed to the mode converting scheme we used for the pump. This results in spectral narrowing of the generated

comb and a potential shift of center wavelength. This issue can be overcome by extracting the comb output from the drop port. The frequency dependence of output coupling is not included in the simulation [Fig 1(e)], which leads to the mismatch between the experiment and simulated spectra.

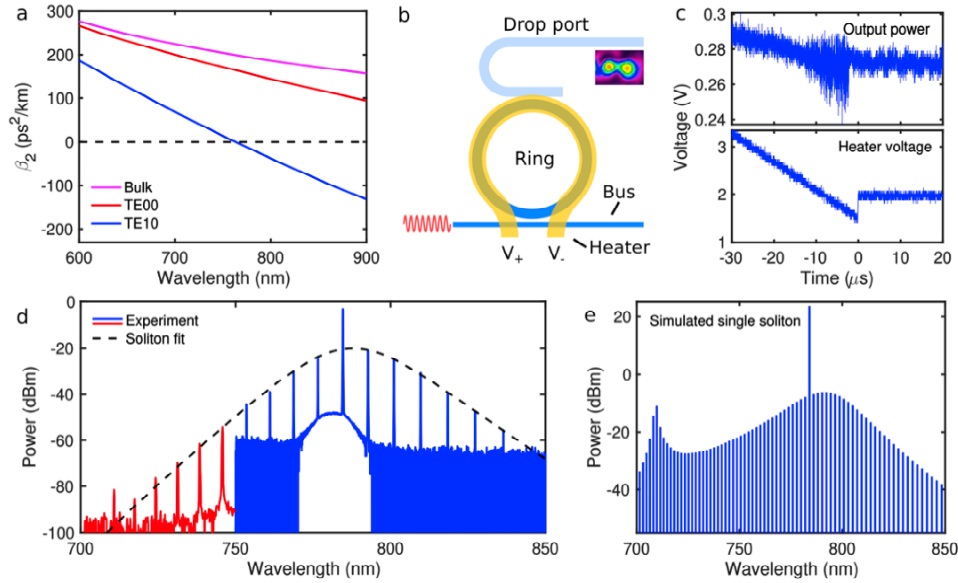


Fig. 1. (a) Simulated GVD for 730×1330 nm Si_3N_4 waveguides. (b) The schematic of chip design. Drop-port devices used for mode characterization. Inset: mode profile observed from the drop port. (c) Measured soliton step and the corresponding heater voltage. (d) Measured soliton spectrum. The red and blue curves are measured with different optical filtering under the same experiment condition. (e) Simulated single soliton for the same device parameters.

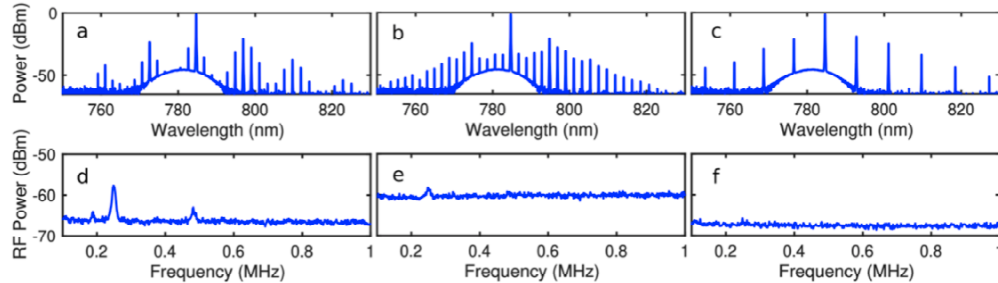


Fig. 2. Optical spectra for (a) micro-comb formation, (b) chaotic evolution, and (c) 4-soliton generation. (d) ~ (f) Corresponding RF noise spectra.

We next characterize noise performance of the comb. We use a long pass filter (>800 nm) to pick up part of the spectrum which is then detected by an amplified photodiode and sent to a radio frequency spectrum analyzer. As shown in Fig. 2, we verify that the soliton state 2(f) has significantly lower noise than the parametric oscillation regime 2(d) or the chaotic regime 2(e).

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