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A Photonic Integrated High-power Soliton Microcomb Generator

(Student paper)

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We demonstrate a compact soliton microcomb light source. The soliton is generated from a Kerr microresonator and amplified by an erbium-implanted gain section integrated on the same photonic chip. We achieved an output power of 7.9 mW at a compact device footprint of 12.5 mm^2.

Keywords: *soliton, Kerr microresonator, erbium ion implantation*

INTRODUCTION

Soliton microcombs in photonic integrated Kerr microresonators are enabling unprecedented measurement precision and novel applications in a variety of fields [1]. The generation of soliton microcombs typically exhibits a low conversion (~1-4 %) efficiency [2], and post-amplification is required in practically all applications [3]. Therefore, large-scale, bench-top, fiber-based amplifiers are usually needed, which however, increases power consumption and impedes the ultimate system miniaturization demanded by emerging applications.

The on-chip amplification of soliton microcombs has been made possible until recently by the demonstration of a high-power, broadband, integrated erbium-implanted Si_3N_4 optical amplifier (EDWA) that can produce 30 dB on-chip net gain with an output power exceeding 100 mW [4]. This EDWA was applied to amplify a 20 GHz free spectral range (FSR) soliton microcomb [5], and performance comparable to commercial erbium-doped fiber amplifiers was achieved.

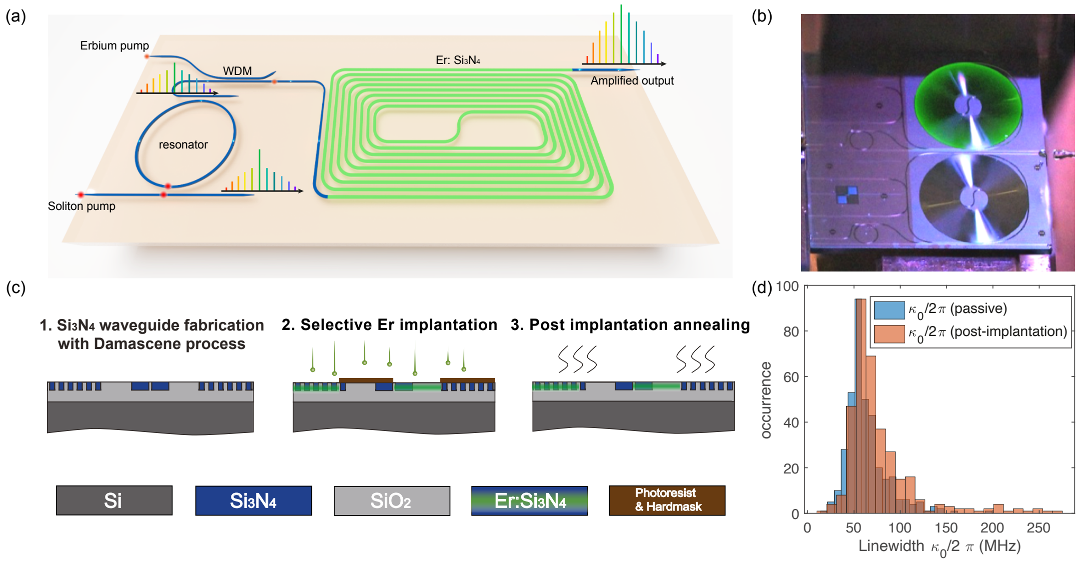

Fig. 1. Integrated high-power soliton microcomb generator. (a) A schematic design of the high-power soliton generator. Soliton is generated in a Kerr microresonator and extracted with a waveguide at the drop port for amplification. The erbium ions are optically excited by a 1480-nm pump laser via an integrated dichroic mirror. (b) A photo of the fabricated device. The dimension of the photonic chip is 5×5 mm^2, with two devices integrated. The footprint of one device is 12.5 mm^2. (c) A simplified process flow for device fabrication. Steps 1 represents the device fabricated with the photonic Damascene process, including DUV stepper lithography, LPCVD Si_3N_4 deposition, high-temperature annealing and top surface planarization. Steps 2-3 depict the selective implantation of erbium ions into the Si_3N_4 waveguide. (d) Histogram of intrinsic linewidth $\kappa_0/2\pi$ of the masked microresonator before and after ion implantation.

Nevertheless, such a demonstration was based on two separate Si_3N_4 chips, which introduced unwanted coupling losses that can degrade the signal-to-noise ratio, and increase the system complexity and required pump power.

RESULTS

Here, we demonstrate a compact high-power soliton generator, by integrating both Kerr microresonators and erbium-implanted gain sections on the same photonic chip, since the passive and active devices inherently share the same Si_3N_4 material and waveguide layers. This allows for advantages such as compactness, reduced insertion loss, cost, power consumption, and optical SNR, as well as low system complexity. The schematic of a photonic integrated high-power soliton generator is depicted in Figure 1(a). The generated soliton is extracted from a drop waveguide coupled to the Kerr resonator for amplification, where a microcomb with a lower carrier-to-sideband ratio is obtained to avoid gain saturation by the excess residual pump carrier.

The passive Si_3N_4 devices were fabricated using the photonic Damascene process [6]. The simplified fabrication process flow is depicted in Figure 1(c). The gain section was realized with three consecutive erbium ion implantations with a beam energy up to 2 MeV, to achieve a large overlap factor between the erbium ions and the waveguide optical mode. The microresonator was selectively masked with photoresist during implantation to preserve its properties such as optical loss and dispersion. The erbium ion concentration for doping the gain spiral is 1.68×10^{20} cm^3. The waveguide dimension is 2.1 µm×0.7 µm, featuring anomalous dispersion and an estimated overlapping factor of 0.5. The fabricated device is shown in Figure 1(b). The microresonator is characterized with scanning laser spectroscopy from 1350 to 1630 nm. From the fitted resonance linewidth, the intrinsic loss rate $\kappa_0/2\pi$ can be extracted. We characterize the microresonator by the most probable value of $\kappa_0/2\pi$ = 50 MHz, corresponding to a quality factor of 3.88×10^6. Figure 1(d) presents the histogram of the intrinsic loss rate distribution before and after erbium ion implantation, from which we confirm that the low loss property of the passive Kerr microresonator was conserved.

We then performed on-chip soliton amplification using the experimental setup shown in Figure 2(a). With an on-chip continuous-wave (CW) pump power of 380 mW at 1556.5 nm, a single soliton of 100 GHz FSR was generated. The loaded resonance linewidth $\kappa/2\pi$ is 60 MHz and the output power was measured as 0.031 mW. Next, we optically pumped the erbium ions using 1480 nm laser diodes in both forward and backward directions. The amplified soliton at the output, along with the input soliton power level, are depicted in Figure 2(c). We achieved an on-chip amplified soliton output power of 7.9 mW, corresponding to a power gain of ~24 dB. The demonstrated output power was limited by the small microcomb power as the amplifier input, stemming from the low external coupling rate $\kappa_{ex}/2\pi$ between the microresonator and the drop waveguide (~10 MHz). When the on-chip gain reached 24 dB, we observed parasitic lasing at unwanted wavelengths that can saturate the gain and power for microcomb amplification. Polishing the chip facet with an angle and utilizing UHNA fibers with matching cleaved facets will further minimize the parasitic lasing and enhance the amplified soliton power.

In conclusion, we demonstrated a compact soliton microcomb generator with an output power of 7.9 mW using on-chip amplification of soliton microcomb. This device will be suitable for applications such as LiDAR, photonic generation of microwaves, and high-power multi-wavelength coherent transceivers for high-speed coherent optical communications.

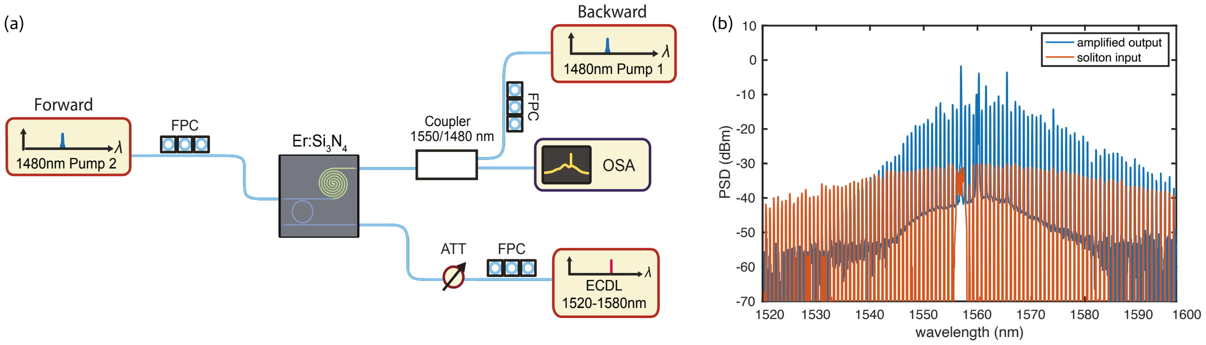

Fig. 2. Experimental results for on-chip soliton amplification. (a) Experimental setup for soliton generation and amplification. ECDL: external cavity diode laser; ATT, tunable optical attenuator; FPC, fiber polarization controller; OSA, optical spectrum analyzer. (b) Amplified soliton spectrum at the output (in blue). The red spectrum plots the generated soliton extracted at the microresonator drop port.

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References

[1] T. Kippenberg et al., *Microresonator-Based Optical Frequency Combs*, Science 332, 555-559 (2011)
[2] C. Bao et al., *Nonlinear conversion efficiency in Kerr frequency comb generation*, Opt. Lett. 39, 6126-6129 (2014)
[3] H. Shu et al., *Microcomb-driven silicon photonic systems*, Nature 605.7910, 457-463 (2022)
[4] Y. Liu, et al., *A photonic integrated circuit-based erbium-doped amplifier*, Science 376, 1309-1313 (2022)
[5] X. Ji et al., *Compact, spatial-mode-interaction-free, ultralow-loss, nonlinear photonic integrated circuits*, Communication Physics 5.1, 1-9 (2022)
[6] J. Liu et al., *High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits*, Nature Communications 12, 2236 (2021)