Photonic Integrated Microwave Oscillator Based on Silicon Nitride Soliton Microcomb

(Student Paper)

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ABSTRACT

Soliton microcomb devices based on integrated waveguides are miniaturized optical frequency combs, which are ideal for portable applications for timing, spectroscopy and metrology. A particularly promising application is to build soliton-microcomb-based photonic integrated microwave oscillators. Yet, so far, soliton microcombs at microwave repetition rate have not been reported on integrated material platform, such as silicon nitride (Si_3N_4), mainly due to high optical losses in waveguides caused by the fabrication process. Here, by improving the photonic Damascene reflow process to fabricate integrated Si_3N_4 microresonators with quality factor exceeding 22×10^6, we demonstrate, not only for the first time but also with an ultralow power of 35 mW, the single soliton formation at 19.6 GHz repetition rate, in the microwave K-band. We characterize the phase noise of the soliton repetition rate, and reveal that the main issue limiting the phase noise performance is the chip input coupling. Furthermore, we demonstrate single soliton at a repetition rate as low as 9.77 GHz. Our results pave the way to low-noise, cost-effective, small-footprint, soliton-microcomb-based integrated microwave oscillator using low-loss Si_3N_4 waveguides, promising for chip-based communication, radar, high-frequency arbitrary waveform generation and spectroscopy.

Keywords: Microwave photonics, frequency comb, integrated photonics, microresonator, silicon nitride, nonlinear optics.

1 INTRODUCTION

Microresonator-based Kerr frequency combs ("microcomb") [1] enable chip-scale optical frequency combs with broad bandwidth and repetition rates in the GHz to THz domain. Operating such microcombs in the dissipative Kerr soliton (DKS) regime [2] is center to applications of timing, metrology and spectroscopy. Silicon nitride [3] is particularly promising to realize photonic integrated soliton microcombs, due to its wide transparency window from visible to mid-infrared, absence of two-photon absorption, relatively high material Kerr nonlinearity, and fabrication process is CMOS-compatible. Soliton microcombs have already been used for low-noise microwave generation, coherent communication, astronomical spectrometer calibration, and to build photonic integrated frequency synthesizers and atomic clocks.

A particularly promising application using soliton microcombs at microwave repetition rates is to build microwave oscillators based on integrated photonics, whose centre frequency is determined by the microresonator free spectral range (FSR) and thus can be freely designed by users and actively tuned using e.g. heaters [4], in contrast to conventional electronics-based microwave oscillators that have fixed center frequency and limited tunability. So far, soliton microcombs at microwave repetition rates, e.g. $f_{\text{rep}} < 20$ GHz in the microwave K-band, have been demonstrated only in silica and crystalline microresonators [5], [6]. In integrated waveguide platform such as Si_3N_4, only chaotic comb states have been observed. The crucial challenges hindering the generation of single soliton states in integrated Si_3N_4 microresonators at microwave repetition rates are related to the comparatively low quality (Q) factor, and the thermal effect in Si_3N_4 which leads to difficulty in accessing the soliton state via only laser frequency tuning.

2 RESULTS

Here, we report the single soliton formation of 19.6 GHz repetition rate in integrated Si_3N_4 microresonators, with a record-low laser power of 35 mW on the chip device (70 mW in the input fiber coupled to the chip), using an optimized photonic Damascene reflow fabrication process [7], [8], [9]. The integrated Si_3N_4 microresonator exhibits a statistical intrinsic Q factor of $Q_0 > 22 \times 10^6$ (shown in Fig. 1(a)), and a strong anomalous GVD $D_2/2\pi \sim 64.0$ kHz (shown in Fig. 1(b)), based on low-loss (linear propagation loss $\alpha < 1$ dB/m), thick (950 nm in height) Si_3N_4 waveguides. We generate the single soliton state via simple laser frequency tuning, which significantly simplifies the experimental setup. Figure 1(c) shows two single soliton spectra generated from two different samples, A and B. Sample A is undercoupled, with a loaded linewidth $\kappa/2\pi = (\kappa_0 + \kappa_{\text{ex}})/2\pi \sim 18$ MHz and coupling coefficient $\eta = \kappa_{\text{ex}}/\kappa \sim 1/3$; Sample B is overcoupled, with a loaded linewidth $\kappa/2\pi = (\kappa_0 + \kappa_{\text{ex}})/2\pi \sim 27$ MHz and coupling coefficient $\eta = \kappa_{\text{ex}}/\kappa \sim 2/3$. In sample A, a single soliton state is

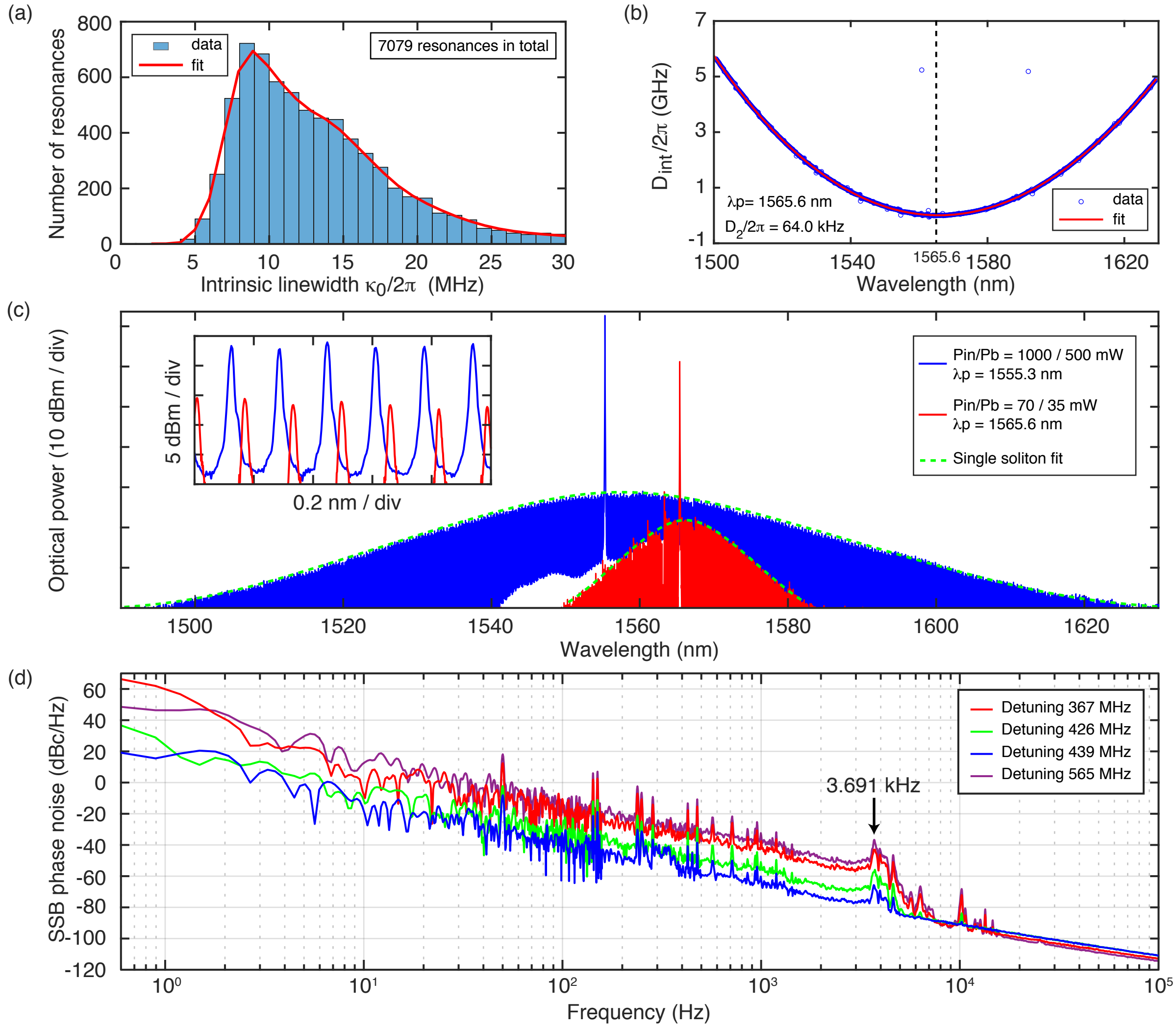

Figure 1. (a) The histogram of the intrinsic loss $\kappa_0/2\pi$ of 7079 fitted resonances, from nine characterized samples. The most probable value is $\kappa_0/2\pi = 8.5$ MHz, corresponding to statistical intrinsic $Q_0 > 22 \times 10^6$. The histogram is fitted with a non-parametric, normal Kernel distribution. (d) The fitted microresonator GVD $D_{\mathrm{int}}/2\pi$, including $D_1/2\pi \sim 19.6$ GHz, $D_2/2\pi \sim 64.0$ kHz, and $D_3/2\pi \sim \mathcal{O}(1)$ Hz, with respect to the pump resonance $\lambda_{\mathrm{p}} = 1565.6$ nm. (c) Single soliton spectra of 19.6 GHz repetition rate with 35 mW power in sample A (in red), and with 500 mW power in sample B (in blue), and their spectrum fit (in green) to extract the 3-dB-bandwidth and pulse duration. Inset: Spectrum zoom-in showing 19.6 GHz mode spacing. (d) SSB phase noise measurement at different pump-to-cavity detuning values, when the soliton repetition rate is stabilized. A quiet point is observed at the detuning of 439 MHz.

generated with 35 mW in the bus waveguide on the chip (70 mW power in the input lensed fiber), as shown in Fig. 1(c), while parametric oscillation for sideband generation is observed with 7 mW power. The single soliton spectrum fit shows 3-dB-bandwidth of 8.53 nm, corresponding to a pulse duration of 302 fs. This is not only the first Si_3N_4 single soliton at microwave K-band repetition rate, but also represents an extremely low threshold power for soliton formation, on a par with the power values in silica and crystalline microresonators [5], [6]. This power level is compatible with state-of-art silicon-based laser, thus full integration, heterogeneous or homogeneous, of on-chip lasers and Si_4N_4 nonlinear microresonators for soliton-microcomb-based microwave synthesis becomes realistic. In sample B, the input laser power is increased to 1 Watt, and a single soliton state of a bandwidth exceeding 120 nm, consisting of more than 800 comb lines, is achieved with a smooth spectral envelope. The single soliton spectrum fit shows 3-dB-bandwidth of 25.8 nm, corresponding to a pulse duration of 98.4 fs. The estimated power conversion efficiency from the continuous-wave pump to the soliton pulse is around 0.3%.

We further characterize the phase noise of repetition rate of this soliton state. The soliton repetition rate is detected on a fast InGaAs photodetector whose output electrical signal at 19.6 GHz is amplified and fed to a cross-correlator-based phase noise analyzer. We lock the driven laser's frequency and power, in order to stabilize the soliton repetition rate, and perform the single sideband (SSB) phase noise measurement using the phase noise analyzer. We perform the phase noise measurement at different detuning values as shown in Fig. 1(d). A "quiet" point [10], caused by mode crossings, is observed at the detuning of 439 MHz, which gives the best phase noise performance compared with other detuning values. Operated at this quiet point, the absolute phase noise power spectral density of the microwave carrier exhibits levels of $\sim$ 20 dBc/Hz at 1 Hz offset Fourier frequency, $\sim$ –65 dBc/Hz at 1 kHz, and $\sim$ –120 dBc/Hz at 1 MHz. A noise floor at –120 dBc/Hz is reached above 1 MHz Fourier frequency, which is mainly caused by the low electrical signal-to-noise ratio obtained after photodetection of the soliton pulse rate due to the low soliton optical power available.

In addition, we also generate single soliton at 9.77 GHz repetition rate, in the microwave X-band, accessed via only laser frequency forward tuning and with approximately 800 mW power on the chip (spectrum not shown here).

CONCLUSION

In conclusion, we demonstrate, for the first time, the single soliton formation of 19.6 GHz repetition rate in the microwave K-band, in integrated Si_3N_4 microresonators. The high microresonator Q factor ($Q_0 > 22 \times 10^6$), enabled by the photonic Damascene reflow process, allows the single soliton formation with only 35 mW laser power on the chip device and easy access with simple laser frequency tuning. The phase noise of soliton repetition rate is characterized at different detunings, showing the approach for phase noise improvement through operation at a quiet point, and input power stabilization. The phase noise measured in our work is still 40 dBc/Hz higher than the thermo-refractive noise characterized in Si_3N_4 microresonator recently [11], revealing the considerable potential for further phase noise improvement, using better device input coupling, a pump laser with lower noise, and better fabrication process for higher Q. Nevertheless, our work represents a significant milestone on the path towards using integrated soliton microcombs for low-noise, low-power-consumption, cost-effective, customized, chip-based photonic microwave oscillators, promising for portable applications such as radar, telecommunication, spectroscopy, arbitrary waveform generation, remote sensing and wireless networks.

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REFERENCES

[1] T. J. Kippenberg, R. Holzwarth, and S. A. Diddams, "Microresonator-based optical frequency combs", Science 332, 555 (2011).

[2] T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, "Dissipative Kerr solitons in optical microresonators", Science 361, 0036-8075 (2018)

[3] D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, "New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics", Nature Photonics 7, 597 (2013).

[4] C. Joshi *et al*, "Thermally controlled comb generation and soliton modelocking in microresonators", Opt. Lett. 41, 2565 (2016).

[5] X. Yi, Q.-F. Yang, K. Y. Yang, M.-G. Suh, and K. Vahala, "Soliton frequency comb at microwave rates in a high-Q silica microresonator", Optica 2, 1078 (2015)

[6] W. Liang, D. Eliyahu, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, "High spectral purity Kerr frequency comb radio frequency photonic oscillator", Nature Communications 6, 7957 (2015)

[7] J. Liu *et al*, "Ultralow-power chip-based soliton microcombs for photonic integration", Optica 5, 1347 (2018)

[8] M. H. P. Pfeiffer, J. Liu, A. S. Raja, T. Morais, B. Ghadiani, and T. J. Kippenberg, "Ultra-smooth silicon nitride waveguides based on the Damascene reflow process: fabrication and loss origins", Optica 5, 885 (2018).

[9] M. H. P. Pfeiffer *et al*, "Photonic Damascene process for low-loss, high-confinement silicon nitride waveguides", IEEE Journal of Selected Topics in Quantum Electronics 24, 1 (2018).

[10] X. Yi, Q.-F. Yang, X. Zhang, K. Y. Yang, X. Li, and K. Vahala, "Single-mode dispersive waves and soliton microcomb dynamics", Nature Communications 8, 14869 (2017)

[11] G. Huang *et al*, "Thermo-refractive noise in silicon nitride based microresonators", arXiv: 1901.07112v1 (2019).