Dark soliton microcomb with high conversion efficiency in a 400-nm-thick Si_3N_4 microring for WDM light sources

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Abstract: We generate a dark soliton microcomb with a conversion efficiency of 49% and -10 dBm spectral bandwidth of 28 nm in a single 400-nm-thick Si_3N_4 microring fabricated by a commercial foundry, which supports high-performance WDM light sources.

1. Introduction

Soliton microcombs, which are composed of phase-coherent and equidistant optical comb lines with low noise characteristics, can find various potential applications including coherent communications, ranging, spectroscopy, etc. Among multiple nonlinear materials, silicon nitride (Si_3N_4), due to its low loss and CMOS compatibility, has been widely used for generating on-chip soliton microcombs. Although dissipative Kerr soliton (bright soliton) has a smooth $Sech^2$ spectrum, its low conversion efficiency and low comb line power restrict the applications for WDM light sources. More complex structures are required to achieve relatively higher conversion efficiency, like photonic molecules [1]. Besides, a thick Si_3N_4 waveguide (~ 800 nm) is essential to form the anomalous dispersion. On the contrary, dark solitons can be generated in a thinner Si_3N_4 microring with normal dispersion [2]. Compared with the bright soliton microcombs, the dark soliton combs have higher conversion efficiency, thereby supporting higher power of the frequency lines. There are many methods to generate dark solitons, such as avoided mode crossing (AMX) [2, 3], self-injection locking [4], pump intensity modulation [5], etc. In the previous studies, the thickness of Si_3N_4 waveguides used to produce normal dispersion typically ranges between 500 nm and 800 nm, because it is easier to form local anomalous dispersion required for dark soliton generation with the normal dispersion S_3N_4 waveguides [2, 4, 6]. However, the high stress of the thick Si_3N_4 film hinders the monolithic integration with silicon photonic devices. For most commercial silicon photonics foundries, like AMF, SITRI, etc., the supported Si_3N_4 layer thickness that can be integrated with silicon photonic devices is less than 400 nm. Although dark soliton microcombs have been generated in 100-nm-thick Si_3N_4 microrings [7], the large bending radii of the low confinement waveguides result in small free spectral range (FSR) of several GHz, which are not suitable for WDM light sources.

Here, we demonstrate the generation of dark soliton microcombs with the assistance of AMXs in a single 400-nm-thick Si_3N_4 microring, which was fabricated by a commercial foundry. We achieve a high conversion efficiency of 49% with a comb spacing of 96.2 GHz. The generated dark soliton has 36 lines with an output power greater than -10 dBm in a bandwidth of 28 nm, and nearly 88.9% of them range from -10 dBm to -2 dBm. Further, the microcomb is reshaped to support flat and long-term stable 36 carriers, which is promising for high-performance and reliable WDM light sources [8].

2. Device design and implementation

We implement a single Si_3N_4 ring for high-efficiency dark soliton microcomb generation. The conversion efficiency of the dark soliton is related to the coupling ratio of the microring. It has been demonstrated that over-coupling is beneficial for high conversion efficiency [9]. Figure 1 (a) shows the simulated conversion efficiency by varying the power coupling ratio from 0.002 to 0.03. In the simulation, the cavity decay rate is assumed to be 0.0013, β_2 is 608.6 ps^2 /km and the radius of the ring is 246 μm. It can be seen that when the power coupling ratio is in the range of 0.012 to 0.026, the conversion efficiency is higher than 50%. The conversion efficiency and the spectral shape are also related to the dispersion of the microring. Figure 1 (b) shows the simulated spectra when the second-order dispersion β_2 are 100, 500, and 1000 $ps^2\ km^{-1}$. The conversion efficiencies are 40%, 45.2%, and 50.2%, and the numbers of comb lines over -5 dBm are 23, 46, and 33, respectively. Therefore, although a larger dispersion can increase the conversion efficiency, excessive dispersion in turn reduces the comb spectral bandwidth. To get a flat spectrum, the waveguide dimensions of the Si_3N_4 microring are designed to be 0.4 μm (height) × 2 μm (width), and the corresponding β_2 for the TE_0 mode is 560.6 $ps^2\,km^{-1}$. Since the Si_3N_4 waveguide supports multiple modes, the width of the straight bus waveguide is designed to be 1.5 μm to realize mode coupling between the TE_0 and TE_1 modes for dark soliton generation. Meanwhile, the gap between the straight bus waveguide and the microring is 0.5 μm to promote the conversion efficiency. The designed FSR of the microring is 96.2 GHz.

The Si_3N_4 chip was fabricated by SITRI using an 8-inch wafer. Figure 1 (c) shows the packaged chip with a pair of fiber arrays to support stable coupling in the experiment and the coupling loss is ~3.5 dB/facet. The right of Fig. 1 (c) shows the microscope image of the fabricated ring. Figure 1 (d) shows the measured transmission spectrum. By extracting the resonance frequency of each longitudinal mode (ω_μ), we calculated the integrated dispersion curve ($D_{int} = \omega_\mu - \omega_o - D_1\mu$) which is shown in Fig. 1 (e). The second-order group-velocity dispersion ($D_2/2\pi$) is -5.2 MHz, corresponding to the β_2 of 608.6 ps^2 /km. Figure 1 (f) shows the adopted resonance in the over-coupling regime. With curve fitting of the resonance lineshape, the power coupling ratio is extracted to be 0.01 and the loaded Q is 8×10^5.

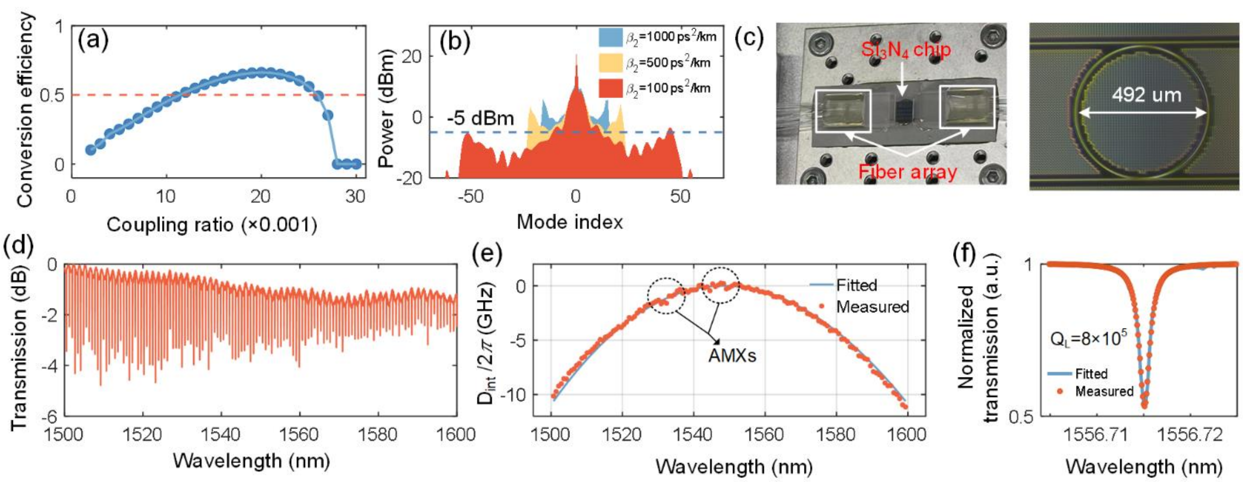

Fig. 1. (a) Simulated conversion efficiency changing with the power coupling ratio at a fixed pump detuning. (b) Simulated spectra under various β_2. (c) Left is the photograph of the packaged Si_3N_4 chip and right is the microscope image of the fabricated ring. (d) Measured TE_0 mode transmission spectrum of the microring. (e) Integrated dispersion of the TE_0 mode. (f) Measured and fitted resonance trace at around 1556.715 nm

3. Dark soliton generation

We used a continuous wave (C.W.) laser to pump the Si_3N_4 microring, which was first amplified to 29 dBm by an erbium-doped fiber amplifier (EDFA). The pump wavelength was set to 1556.9 nm and scanned across the adopted TE_0 resonance. Figure 2 (a) shows the recorded comb power trace after filtering out the pump with a waveshaper. It is noted that the waveshaper has an insertion loss of about 6 dB. During the wavelength scanning, there exists a smooth comb power trace ranging about 3.75 GHz, which is the mode-locked state. Figures 2 (b) and (c) show the measured optical spectra and the low-frequency RF spectra by filtering out one of the comb lines and feeding it into a photodetector when the pump light is located at points 1 and 2 of Fig. 2 (a), respectively. The conversion from stage 1 to stage 2 is accompanied by a significant reduction of noise in the low-frequency range, which verifies the mode-locked state of stage 2. We further explored the characteristics of the generated dark soliton. The pump-to-comb conversion efficiency reaches 49% and there are 36 comb lines with optical power larger than -10 dBm. Among the 36 comb lines, 88.9 % of them have a power variation of less than 8 dB (-10 dBm to -2 dBm), and the average power is -4.3 dBm, indicating the flatness of the dark soliton spectrum.

We then used the waveshaper to reshape the spectrum to construct high-performance WDM light sources. As shown in Fig. 2 (d), the comb lines range from 1545 to 1573 nm with an average line power of -18 dBm and power variation of less than 0.4 dB. It is noted that the additional loss is from the waveshaper. The optical signal-to-noise ratio (OSNR) of all 36 comb lines is larger than 35 dB. The flat comb can exist for more than 7 hours without any feedback. Figure 2 (e) shows the recorded power dither for each line over the 7 hours. Most comb lines have a power variation of less than 0.3 dB while the maximum is 0.6 dB, which shows the high stability of the generated dark soliton. We also measured the single sideband (SSB) frequency noise of the comb lines, which are symmetrically located at 12 and 6 spacings from the pump laser, as shown in Fig. 2 (f). Compared with the pump mode, the frequency noises of other comb lines are almost the same at the low frequency offset, but increase when the frequency offset is larger than ~ 2 kHz. Besides, these symmetrically distributed comb lines have similar noise properties. The intrinsic linewidth of the comb line increases two and four times when located at 6 and 12 spacings from the pump laser due to the repetition rate instability caused by the thermal noise. However, due to the narrow line width of the pump laser, all the comb lines still have low-frequency noises (intrinsic linewidth ~ kHz), indicating the microcomb can work as a high-performance on-chip WDM source.

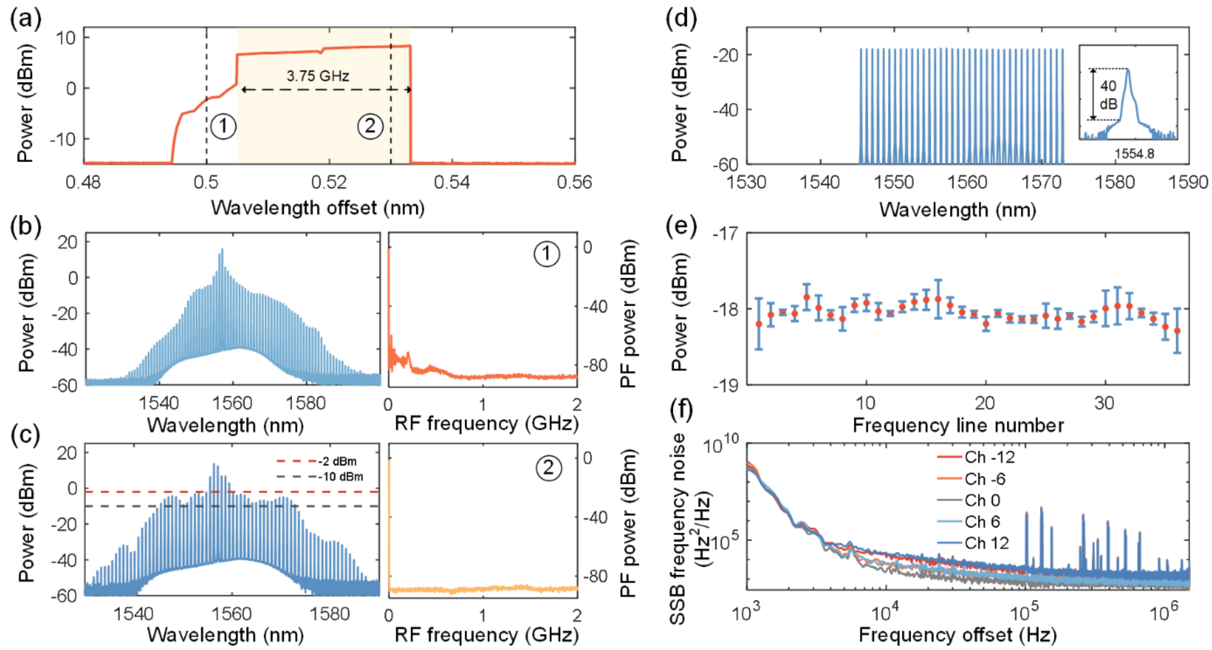

Figure 2. (a) Recorded comb power trace during the pump tuning process. The shaded region marks the mode-locked state. (b, d) Recorded spectrum and corresponding single-line RF spectrum at (b) stage 1 and (c) stage 2 in (a). (d) Optical spectrum of the microcomb after being reconstructed by a waveshaper. The inset shows that the frequency line at 1554.8 nm with an OSNR of 40 dB. (e) Optical power fluctuation statistics of the 36 comb lines in 7 hours. (f) Single-sideband frequency noise of five comb lines with Ch 0 corresponding to the pump mode. It is noted that several peaks between the frequency offset from 100 kHz to 1 MHz are introduced by the commercial tunable laser.

4. Conclusion

In this work, we have realized a flat dark soliton microcomb with a comb spacing of 96.2 GHz and near 50% conversion efficiency using a single 400-nm-thick Si_3N_4 microring for the first time. The dark soliton has 36 comb lines with an optical power of larger than -10 dBm over a wavelength range of 28 nm. We characterized the OSNR, the long-term stability, and the phase noise of the comb lines after being reconstructed by a waveshaper. The results indicate the fulfillment of the microcomb for WDM light sources and it can be monolithically integrated with silicon photonic chips in the future.

References

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