High-efficiency Microcombs Aligned with ITU-T Grid for WDM Optical Interconnects

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Abstract: We report generation of flat soliton microcombs aligned with ITU-T grid. We demonstrate close to 70% pump-to-comb conversion efficiency and the required on-chip pump power is below 40 mW. © 2022 The Author(s)

1. Introduction

The rapid growth of data traffic in optical communication networks requires more compact and more power-efficient wavelength-division multiplexing (WDM) transceivers with larger data capacity. Microresonator-based optical frequency combs, or microcombs, have merged as a promising candidate for chip-scale light sources in WDM systems [1]. Compared with conventional laser array solutions, microcombs offer revolutionary advantages, such as small footprint, low power consumption and high power efficiency. A soliton-microcomb-based WDM communication system at tens of Terabit/s has been demonstrated [2]. For integrated WDM transceivers, the pump-to-comb conversion efficiency (CE) is a crucial parameter because the available pump power is usually limited to tens of milliwatt. The CE should be as high as possible to maximize the comb power for longer transmission distance or higher date rate. Beyond that, precise management of the comb line frequency is needed because the WDM frequency channels are defined by the International Telecommunication Union Telecommunication (ITU-T). The comb lines should be exactly aligned with the ITU-T grid for compatibility with other standardized components, especially WDM multiplexer and demultiplexers.

Here we report the generation of flat dark soliton microcombs with good alignment to the ITU-T grid, low pump power and high pump-to-comb conversion efficiency. We experimentally demonstrate a 200 GHz soliton microcomb spanning from L-band to S-band and the mismatch (distance between each comb line and the closet ITU-T channel) is below 4.6 GHz. In narrower-band microcombs, we achieve close to 70% pump-to-comb conversion efficiency with 40 mW on-chip pump power. Our approach opens a path towards practical application of microcombs in high-speed optical interconnects.

2. 200 GHz soliton microcombs aligned with ITU-T grid

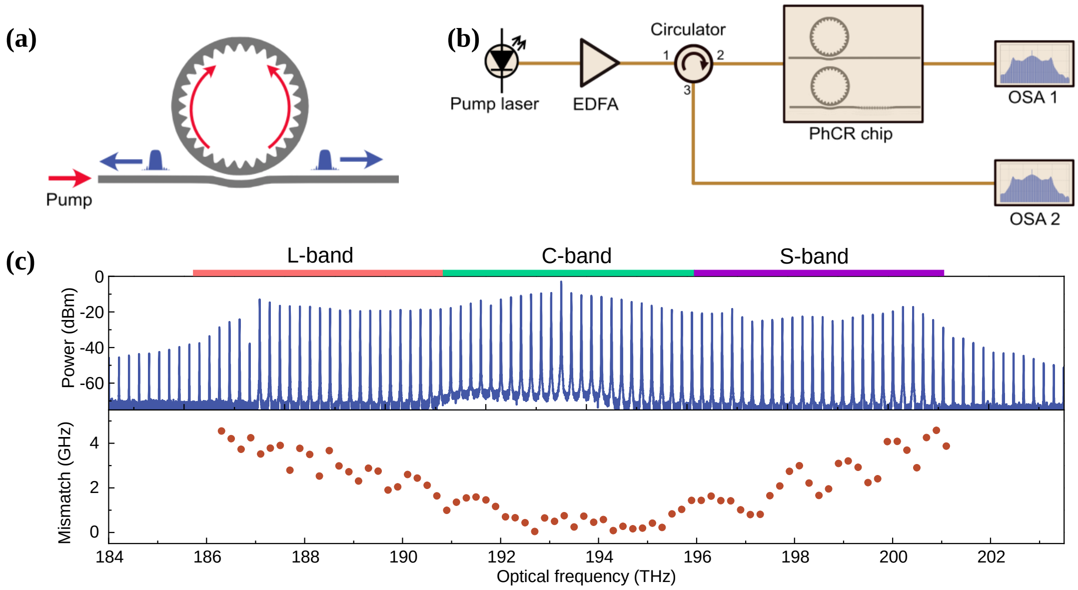

Fig. 1: (a) A schematic diagram of the photonic crystal ring resonator; (b) Experimental setup for comb generation and characterization; (c) Optical spectrum (upper panel) of the 200 GHz soliton microcomb and its mismatch compared with the ITU-T grid (lower panel).

We fabricate our air-clad devices with tantalum pentoxide (Ta_2O_5, hereafter tantala) based platform. Compared with silicon nitride, tantala offer several advantages in material properties, such as lower residual stress, higher nonlinear index and smaller thermo-optic coefficient [3]. Fig. 1 (a) shows the structure of our photonic crystal ring resonator (PhCR). We design microresonators with normal group-velocity dispersion (GVD) because dark soliton combs formed in normal GVD regime usually provide better flatness than those in anomalous GVD regime [4]. To fulfill the phase matching condition for four-wave mixing, we inscribe oscillatory nanopattern on the innner wall of the microresonator, which creates a photonic bandgap at the desired resonant mode and results as two split modes [5]. Dark soliton pulses can be excited by pumping the red-shifted mode. Both clockwise and counterclockwise propagating pulses can exist simultaneously in the PhCRs. The bi-directional pulse dynamics are still mysterious and need further investigation.

Our experimental setup is depicted in Fig. 1 (b). We use a tunable external cavity laser at 1550 nm to pump the PhCR. The pump signal is amplified by an EDFA and coupled to the microresonator chip by a lensed fiber. Since the soliton pulses can propagate in the clockwise and counterclockwise direction in the ring, we employ a circulator before the input lensed fiber. The counterclockwise and clockwise propagating pulses are monitored by optical spectrum analyzer (OSA) 1 and OSA 2, respectively. Unless otherwise stated, the comb we present in this paper is the counterclockwise propagating pulses (measured by OSA 2) because pulses in this direction usually have much higher power than those in another direction.

In the first experiment, we design microresonators with free spectral range (FSR) of 200 GHz and ring width (RW) of 2210 nm, corresponding to a GVD parameter D2/2π=-3 MHz. Both the comb line frequencies and their spacing can be tuned by ring radius (RR). Our calculation indicates that the tuning rate of the pump mode (1.5 GHz/nm) is much larger than that of the comb spacing (1.82 MHz/nm). Therefore, it is possible to move the pump mode with little influence on the comb spacing. To align our microcombs with the ITU-T grid, we first coarsely adjust the RR to generate solitons with repetition rate of exact 200 GHz, and then anchor the pump mode at one of the ITU-T frequency channels by finely tuning RR and device temperature (tuning rate: 1 GHz/$^\circ C$). Using this approach, we successfully generate a 200 GHz soliton microcomb (upper panel of Fig. 1 (c)) precisely aligned with the ITU-T grid (RR=109.12 μm, device temperature =27.7 $^\circ C$). This PhCR's intrinsic quality factor (Q) is 2 million and it is critically coupled (coupling factor $K = \kappa_c/\kappa_i = 1$). At on-chip pump power of 100 mW, the generated 200 GHz microcomb nearly covers all the ITU-T channels from L-band to S-band. The lower panel of Fig. 1 (c) shows the mismatch between the comb lines and ITU-T grid. From L-band to S-band, this mismatch is below 4.6 GHz and it is below 1.6 GHz for all the comb lines in C-band. The good alignment between our microcomb and the ITU-T grid is beneficial in reducing the insertion loss of WDM multiplexers and improving the received optical power at the receiver.

3. High-efficiency microcomb generation with reflector-assisted PhCRs

For some specific applications, a narrower-band microcomb with higher comb line power may be advantageous if the WDM communication links need < 30 optical frequency channels. In the second experiment, we design PhCRs with RW of 4000 nm and GVD parameter D2/2π of -8.5 MHz to reduce the comb spectral width. Simulation shows that the soliton combs are narrower but the comb line power is much higher than that in Fig. 1 (c). Again, by tuning RR and device temperature, we generate a narrower-band soliton microcomb aligned with the ITU-T grid. Fig. 2 (a) shows the comb spectrum (upper panel) and its mismatch with the ITU-T grid (lower panel). The PhCR's intrinsic Q is 2.6 million and the on-chip pump power is 68 mW. From 191 to 197 THz, all the comb lines are above -10 dBm and their mismatch is below 2.3 GHz.

Although the microcombs in Fig. 1 (c) and Fig. 2 (a) are well aligned with the ITU-T grid, their pump-to-comb conversion efficiency is still low ($< 25\%$). As suggested in the literature, we can improve the CE by operating the PhCRs in the over-coupling regime. However, our simulation shows that at least 50% pump power is wasted in strongly over-coupled PhCRs. To solve this problem and further improve the CE, we design a photonic crystal reflector [6] in the downstream side of the bus waveguide (Fig. 2 (b)). This reflector, with reflectivity of 90% and 3-dB bandwidth of 5 THz, modifies the pump power distribution and makes close to 100% CE possible. In addition to that, the reflector also reduces the threshold power for Kerr comb generation, which may results from the enhanced cavity field intensity with the reflector. Since the CE highly depends on the the phase delay (ϕ) between the reflected pump and optical field in the ring, we optimize ϕ by tuning the ring-reflector distance or simply rotating the ring. Fig. 2 (c) illustrates the reflection spectra when ϕ is tuned with a step of 0.3 π. We can selectively couple the blue-shifted mode or red-shifted mode by tuning ϕ and the highest CE is achieved when the blue-shifted mode is strongly under-coupled.

Using the reflector, we achieve 65% conversion efficiency in a PhCR which has the same RW and GVD as that of Fig. 2 (a). The coupling factor K=4 and the on-chip pump power is only 40 mW. Fig. 2 (d) shows the comb spectrum. The residual pump, indicated by the red arrow, is lower than other comb lines. Although this high-efficiency microcomb is not aligned with the ITU-T grid, we can modify the RR and tune the device temperature to get similar aligning performance as that in Fig. 2 (a). Finally, we investigate the influence of ring–bus coupling

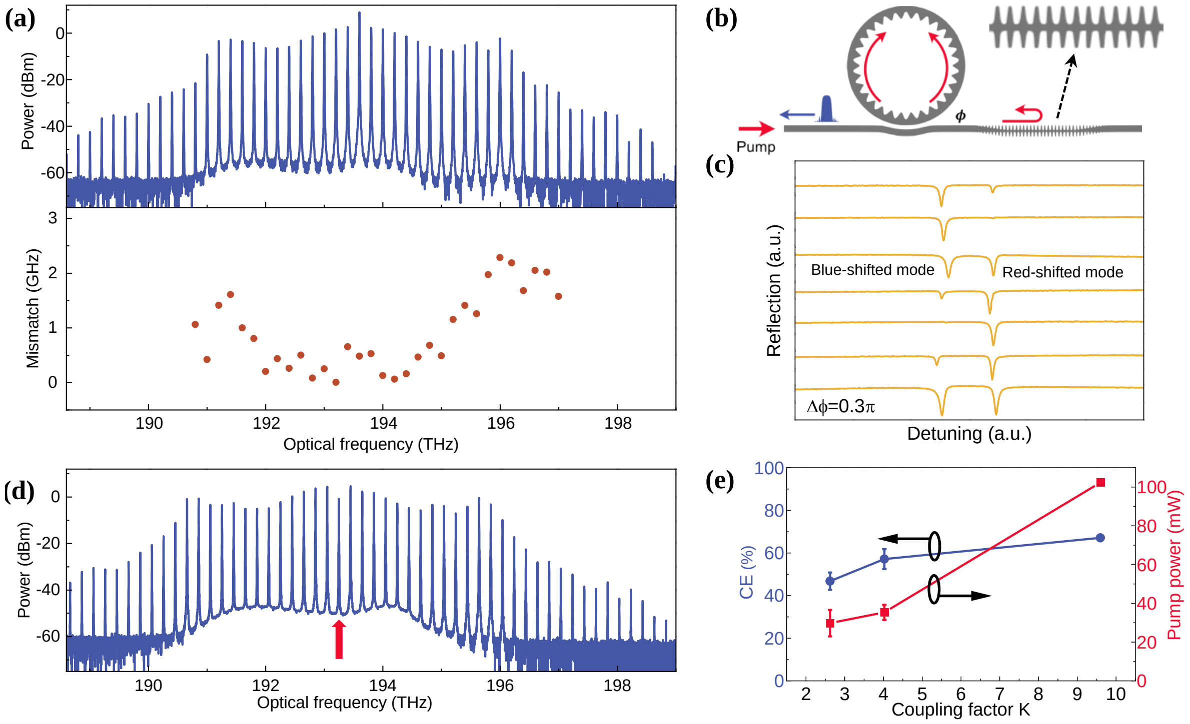

Fig. 2: (a) Optical spectrum (upper panel) of the soliton microcomb and its mismatch with the ITU-T grid (lower panel); (b) A schematic diagram of the PhCR with a photonic crystal reflector, we tune the phase delay(ϕ) by changing the ring-reflector distance or rotating the ring; (c) The reflection spectra of the reflector-assisted PhCRs when ϕ is tuned with a step of 0.3 π; (d) The optical spectrum of the microcombs with CE of 65%, the residual pump is indicated by the red arrow; (e) CE versus coupling factor K, the right y-axis shows the corresponding required on-chip pump power for soliton generation.

on the conversion efficiency and required pump power for soliton generation. Fig. 2 (e) shows the CE and pump power at different coupling factor K. The highest CE is 67.1% for the 200 GHz PhCRs. Although we can achieve higher CE by operating our device in more over-coupled regime, the required pump power also increases sharply with the coupling factor.

4. Conclusions

In summary, we demonstrate flat dark soliton microcombs generated by the PhCRs and the comb lines are precisely aligned with ITU-T grid. We also propose a reflector-assisted PhCR scheme to improve the conversion efficiency. We experimentally achieve close to 70% pump-to-comb conversion efficiency and the required pump power is below 40 mW. Our work represents an important step towards low-pump-power and high-efficiency soliton microcombs. This research paves the way for microresonator-based high-speed optical transceivers in WDM optical interconnects.

5. Acknowledgment

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References

[1] T. J. Kippenberg, A. L. Gaeta, M. Lipson, et al. “Dissipative kerr solitons in optical microresonators”. In: *Science* 361.6402 (2018).

[2] Pablo Marin-Palomo, Juned N. Kemal, Maxim Karpov, et al. “Microresonator-based solitons for massively parallel coherent optical communications”. In: *Nature* 546 (June 2017), pp. 274–279.

[3] Hojoong Jung, Su-Peng Yu, David R. Carlson, et al. “Tantala Kerr nonlinear integrated photonics”. In: *Optica* 8.6 (June 2021), pp. 811–817.

[4] Xiaoxiao Xue, Pei-Hsun Wang, Yi Xuan, et al. “Microresonator Kerr frequency combs with high conversion efficiency”. In: *Laser Photonics Rev.* 11.1 (Jan. 2017), p. 1600276.

[5] Su-Peng Yu, Daniel C. Cole, Hojoong Jung, et al. “Spontaneous pulse formation in edgeless photonic crystal resonators”. In: *Nat. Photonics* 15 (Apr. 2021), pp. 461–467.

[6] Su-Peng Yu, Hojoong Jung, Travis C. Briles, et al. “Photonic-crystal-reflector nanoresonators for Kerr-frequency combs”. In: *ACS Photonics* 6.8 (July 2019), pp. 2083–2089.