Silicon Carbide Soliton Microcomb Generation for Narrow-grid Optical Communications

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Abstract: We demonstrate efficient soliton microcomb generation in silicon carbide microresonators with a record-low on-chip pump power of 6.5 mW. The microcomb exhibits a near 100 GHz free spectral range, enabling its application in optical communications.

1. Introduction

An optical frequency comb is a coherent light source consisting of multiple comb lines that are equally spaced and phase coherent with each other. This unique property makes it a versatile tool for a wealth of applications including metrology, sensing, computation, and optical communication [1]. Taking optical communication as an example, the utilization of an optical frequency comb in network facilities such as central offices or hubs offers an attractive solution for replacing many independently operated lasers in wavelength-division multiplexing (WDM) systems, thereby significantly reducing the overall cost and power consumption of optical hardware. In the past decade, significant efforts were devoted to the development of chip-scale comb sources based on micro-resonators (i.e., microcombs), which have the potential to revolutionize the field by reducing the device's SWaP (size, weight, and power) while enabling system-level integration [2]. So far, microcombs have been realized in several integrated photonic platforms such as silicon and silicon nitride (SiN) [3]. Recently, silicon carbide (SiC) emerged as a promising candidate for microcomb generation due to its strong Kerr nonlinearity, which is estimated to be four times of that of SiN and thus allows a reduction of optical power by more than one order of magnitude (assuming other factors are the same) [4]. This, coupled with the demonstration of low-loss SiC-on-insulator (SiCOI) device platforms, has enabled the realization of single solitons and octave-spanning microcombs [5, 6].

In this work, we delve into the design and optimization of microcomb in a low-loss 4H-SiCOI integrated platform (4H-SiC is a polytype of SiC) with its properties tailored for narrow-grid optical communication. Specifically, we demonstrated SiC microcombs with free spectral range (FSR) around 100 GHz for the first time (to the best of our knowledge), which allows the produced comb lines to be aligned to the dense-WDM (DWDM) ITU grid. In addition, we accessed the single-soliton state to enable phase locking across the comb spectrum. Finally, the optical pump power was reduced to <10 mW level, a desired feature for direct on-chip laser integration without the need of optical amplification.

2. Device design and fabrication

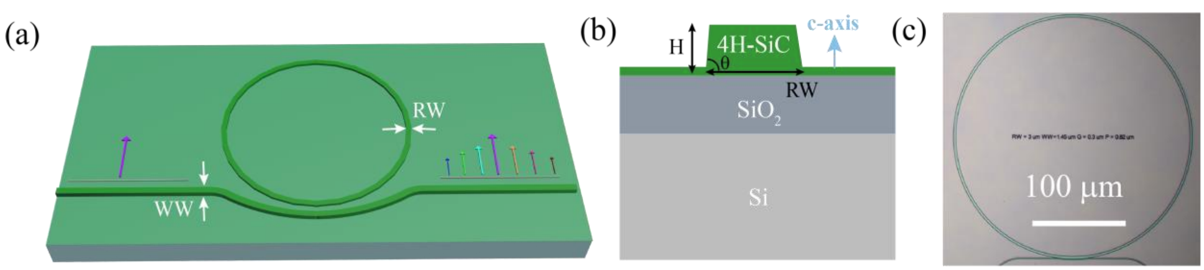

Figure 1: (a) Schematic of microcomb generation in a microresonator with strong Kerr nonlinearity; (b) the material platform consists of a thin layer of 4H-silicon carbide (SiC) on 2-μm-thick oxide. The optical axis (c-axis) of the semi-insulating 4H-SiC layer is normal to the wafer surface; and (c) optical micrograph of a 169-μm-radius SiC microring with ring width of 3 μm.

The key concepts of this work are explained in Fig. 1: the frequency comb was generated by sending a continuous-wave optical pump to a high-quality-factor (high-*Q*) SiC microresonator, where the strong Kerr nonlinear interaction (four-wave mixing) results in a broad spectral output (Fig. 1(a)). The SiCOI wafer was fabricated using a bonding and polishing method, which consists of a 700-nm-thick 4H-SiC on top of a 2-μm-thick oxide layer for devices made in this work (Fig. 1(b)). Using optimized nanofabrication based on electron-beam lithography and plasma etching, we can accurately define low-loss photonic components such as waveguides and microresonators [6]. Figure 1(c) shows an example of fabricated SiC microrings. The ring radius is chosen to be 169 μm so that the corresponding FSR of the fundamental transverse-magnetic (TM_{00}) mode is close to 100 GHz, which allows the produced comb lines to be aligned to the DWDM ITU grid.

3. Experimental setup

After fabricating the SiC microresonators, we test their performance and generate phase-coherent soliton states using the experimental setup in Fig. 2(a). For characterizing linear performance, only a single tunable pump laser is needed. However, soliton generation typically requires an auxiliary laser to overcome thermo-optic bistability caused by pump-induced heating, as explained further in Ref. 7. This auxiliary laser is a key element of the nonlinear soliton generation setup. To achieve efficient fiber to chip coupling, we employ lensed fibers to couple to the SiC waveguides, which have a reduced mode diameter of 2.5 μm (Fig. 2(b)). Furthermore, inverse tapers, whose mode profile can be matched to that of the lensed fiber, are implemented on the facets of the SiC chip (Fig. 2(c)). Optimized simulation pointed to a coupling loss of 2 dB per facet using a taper width of 250 nm. In practice, the fiber to chip coupling loss is estimated to be around 3 dB, with the additional loss attributed to the taper size mismatch and additional propagation loss in the taper region.

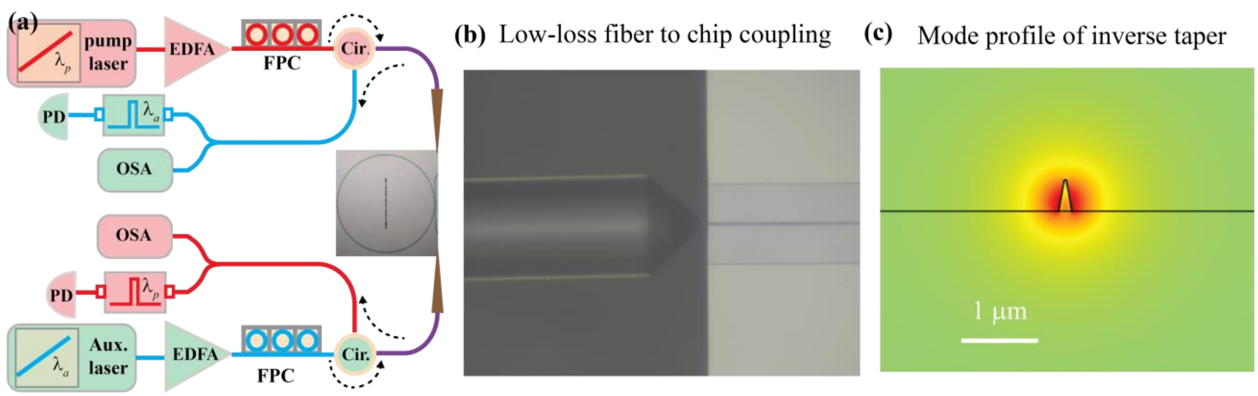

Figure 2: (a) Experimental schematic for the soliton microcomb generation: both the pump laser and the auxiliary laser are coupled to the on-chip waveguide using lensed fibers. The pump laser is to generate the Kerr soliton microcomb while the auxiliary laser is to overcome the thermal effect induced by the pump laser. EDFA: erbium-doped fiber amplifier; FPC: fiber polarization controller; Cir.: circulator; and OSA: optical spectrum analyzer; (b) image of a lensed fiber aligned to the inverse taper implemented on the SiC chip; and (c) mode profile of the SiC inverse taper, with a simulated coupling loss of 2 dB for a lensed fiber with mode diameter of 2.5 μm.

3. Results and discussions

We summarize the major experimental results in Fig. 3: For the microcomb generation, we couple the pump laser to the fundamental TM_{00} mode near 1546 nm, which exhibited an intrinsic Q of 5.0 million (Fig. 3(a)). Such high optical Qs allows the observation of optical parametric oscillation at a pump power of only 2.5 mW (Fig. 3(b)). For the soliton generation, we couple another auxiliary laser to the TM_{00} resonance near 1556 nm, whose Kerr comb generation was inhibited by the Raman effect (details will be explained in presentation). After tuning the auxiliary laser to the cavity resonance, we begin to observe the characteristic soliton steps in the pump laser transmission when the pump power is more than 3 mW (Fig. 3(c)). Such abrupt changes in the pump transmission ("steps") are indicative of different comb dynamics as we vary the pump wavelength, typically evolving from multi-soliton to a single-soliton state in the end. Landing on the single-soliton state, however, turns out to be more challenging compared to smaller-sized microresonators [3]. This is because the soliton step has a narrow frequency span of only tens of MHz, similar to free-running laser fluctuations. Nevertheless, we succeeded in generating single solitons with an on-chip power near 6.5 mW, as shown in Fig. 3(d). The microcomb has a measured free spectral range around 100.1 GHz and an estimated bandwidth exceeding 60 nm.

Our low power threshold around 6.5 mW for the 100-GHz-FSR soliton microcombs represents one of the lowest powers ever recorded for microcombs with electronically detectable FSRs. For example, the current record was held by a SiN microresonator with an intrinsic Q of 15 million, which generated a 99-GHz-FSR single soliton at an on-chip power of 6.2 mW [8]. However, the power of the produced comb lines in our device (>-20 dBm) is significantly higher than what's observed in Ref. 8. Hence, our results compare favorably to the state of the art in terms of the pump threshold and average power per comb line, suggesting that the 4H-SiCOI platform is promising for the generation of low-power-threshold soliton microcombs.

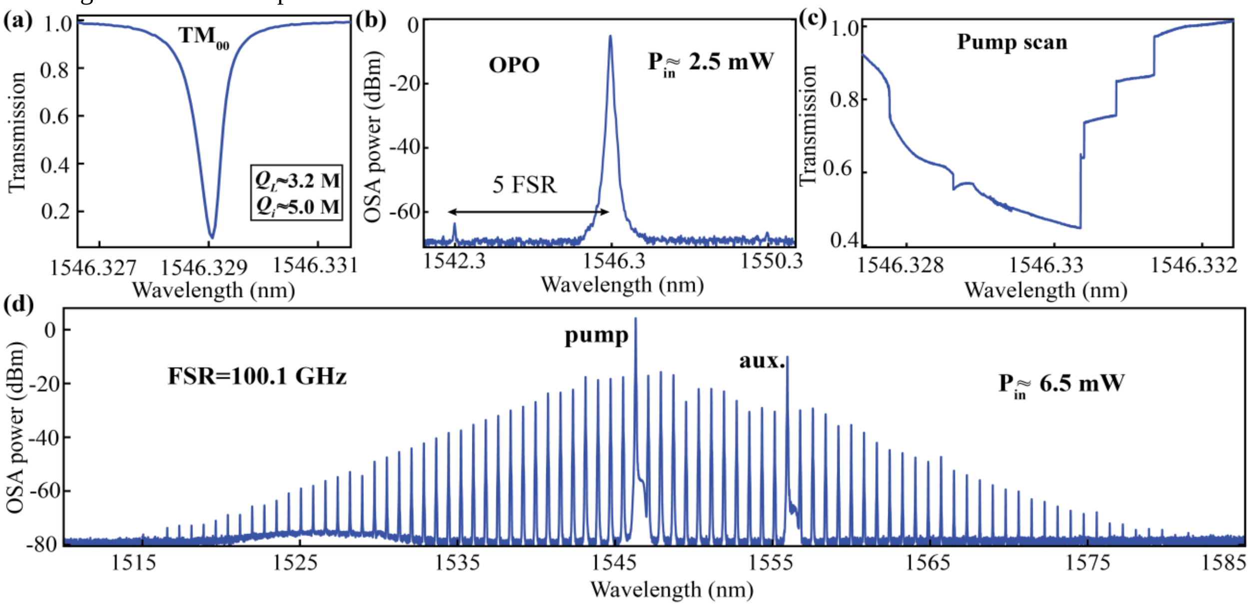

Figure 3: (a) Linear transmission of the pump resonance which is TM polarized, showing an intrinsic *Q* around 5.0 million; (b) Optical parametric oscillation (OPO) was observed for an input pump power of 2.5 mW, generating signal-idler pairs that are 5 FSR away from the pump; (c) nonlinear transmission scan of the pump mode when the auxiliary laser is tuned to TM00 resonance around 1556 nm, displaying various soliton steps; and (d) optical spectrum of the single soliton by tuning the pump laser to the single-soliton step at an approximated on-chip power of 6.5 mW. The on-chip power is approximately 3 dB higher the recorded OSA power due to the fiber-chip coupling loss.

4. Conclusion

In summary, we have designed and fabricated a soliton microcomb on a low-loss 4H-SiCOI integrated platform with 100-GHz-FSR for the first time (to the best of our knowledge). As such, the comb lines can be easily aligned with the DWDM ITU grid spacing. In addition, a single-soliton state that enables phase synchronization across the entire comb spectrum has been demonstrated experimentally. Notably, the optical pump power is reduced to a record-low level of 6.5 mW, enabling direct on-chip laser integration without necessitating optical amplification. Future efforts will focus on enhancing comb efficiency to further increase the average power per comb line.

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