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Kerr frequency comb with varying FSR spacing based on Si_3N_4 micro-resonator

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Abstract In this paper, we experimentally investigate a novel feedback loop scheme to generate optical frequency comb with varying free spectral range (FSR) spacing in a high-Q silicon nitride (Si_3N_4) micro-ring resonator. By selecting and amplifying different feedback sidebands, comb line spacing varying from 1-fold to 6-fold FSRs is successfully achieved. This approach could be beneficial to tune the comb repetition rate which is an important parameter for many applications, such as optical coherent communications, optical metrology and arbitrary waveform generation.

Keywords feedback loop, free spectral range, silicon nitride, Kerr frequency combs, micro-ring resonator

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1 Introduction

Optical frequency combs [1, 2] characterized by discrete and equally spaced frequencies are widely used in the fields such as high-speed optical communication [3, 4], spectroscopy [5], optical metrology [6], arbitrary optical waveform generation [7], astrocomb [8], and sources for quantum entanglement [9]. Most of these applications have been realized based on mode-locked lasers with stabilized repetition rate and carrier envelope phase [10, 11], such as Ti: sapphire laser, Er-doped fiber laser, and Yb: fiber laser. However, it would be more attractive to further reduce the footprint and increase the repetition rate over 10 GHz. The bandwidth of generated combs based on phase modulation [12] or intensity modulation [13] is restricted by the achievable modulation depth. Recently, micro-resonator-based Kerr frequency combs have been demonstrated on a variety of platforms, including calcium fluoride (CaF_2) [14], silicon nitride (Si_3N_4) [3, 4], high-index doped silica glass [15], diamond [16], lithium niobate [17] as well as Gallium phosphide (GaP) [18]. An important category of optical microresonators is whispering gallery mode (WGM) resonators, such as microdisks, microspheres, microtoroids, or microrings [2]. Owing to the long photon life (high-Q) and strong light confinement, a high-repetition rate comb with broad bandwidth is achieved via Kerr nonlinearity. Recently, significant progress has been made in ultrahigh-Q WGM microcavities, which have triggered emerging opportunities in practical applications [19, 20].

Using Si_3N_4 as a nonlinear optical material has attracted great attention in the past decade because of its significant third-order nonlinearity of 2.5×10^{-15} cm^2W^{-1}, about an order of magnitude larger than silica and CaF_2 [21]. Besides, as a CMOS-compatible material, Si_3N_4-based structures can be integrated

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with the mature Si photonics platform. In addition, Si_3N_4 resonators can be cladded with SiO_2 for long-term operation, thereby offer stable and tunable coupling between the resonators and bus waveguides with robustness to external disturbances such as mechanical instability, and allow for integration of other photonic components, including drop ports, heaters [22], and multiple coupled resonators [23].

In many cases, the frequency spacing of these optical frequency combs is equal to the FSR of the micro-ring resonator. Generally, it cannot be changed randomly. Thus, efforts have been made to get varying FSR controllably. For instance, the frequency spacing is changed from 1-FSR to 3-FSRs by selecting the proper detuning of the carrier frequency of the pump laser with respect to a selected WGM frequency in CaF_2 resonators [14]. Under different detuning conditions of the pump laser from the resonance, 1-fold FSR, 2-fold FSRs and 6-fold FSRs frequency spacing are obtained with an aluminum nitride micro-ring resonator [24]. However, these methods are vulnerable to the change of intracavity power, tuning speed and environment temperature. In 2013, it was demonstrated that the injection of EO-modulated sidebands of the pump besides the pump itself led to the generation of a strictly equidistant microcomb spectrum [25]. Later, another method was proposed to produce broadband parametric frequency comb generation spanning 90 THz without the need of an external pump laser [26]. Wang et al. [27] has successfully achieved combs with frequency spacing varying from 6 to 46-fold FSRs by employing dual-pump which is self-oscillated in the laser cavity loop. They have also realized repetition rate multiplication of laser pulse by time division multiplexing multiple pulses in the micro-ring resonators through tuning of the fiber cavity length [28]. To obtain stable mode-locked pulse output, it is a challenge to precisely control the length of the laser cavity [28].

With methods mentioned above, it can be seen that additional power apart from pump can change comb generation process. Approaches with a high power feedback loop put strict requirements on experimental conditions and device performance. Here, we demonstrate that, by selectively seeding the microresonator with the comb lines at a distance of nFSR (n is an integer number) away from the pump, the generation of optical frequency combs varing from 1-fold to 6-fold FSRs is available (1-fold, 3-fold and 5-fold are not shown). This scheme is relatively simple and cost-effective.

2 Dispersion simulations and discussion

High Q-factor optical micro-cavities can effectively enhance nonlinear optical processes such as four-wave mixing (FWM). When a micro-resonator based on a third-order nonlinearity material is pumped with a laser, there is a chance that two pump photons annihilate to produce a new photon pair consisted with a frequency up-shifted signal and a frequency down-shifted idler. The signal and the idler are symmetric about the pump frequency [2]. Achieving phase matching of the three interacting waves is essential for efficient FWM process. In the micro-resonator, FWM and parametric oscillation are enabled by the interplay between the nonlinearity and the group-velocity dispersion (GVD). The frequency of the pump laser is tuned to the anomalous-GVD regime of the micro-resonator to compensate for the nonlinear phase mismatch [29]. Once oscillation has been achieved by degenerate FWM, cascaded FWM among different cavity modes takes over, enabling the generation of a frequency comb.

The Si_3N_4 micro-ring resonators are fabricated on a silicon wafer and sit on top of a 4-μm-thick silicon oxide layer. Then Si_3N_4 film is deposited on the substrate, and the devices are patterned and etched on the 800-nm-thick Si_3N_4 film. Finally, the micro-ring resonators are cladded with 2.7-μm-thick silicon oxide layer. The relatively high-index contrast between the Si_3N_4 core and the silicon oxide cladding allows for dispersion engineering by modifying the structure of the waveguides [30]. To observe the frequency comb generation, near-zero anomalous GVD is required in the waveguide to satisfy the phase matching condition. We numerically calculate the dispersion relations of different waveguides using a finite-difference eigenmode solver. Figure 1 shows the simulated dispersion for Si_3N_4 waveguides with a height of 800 nm, and widths of 1500 and 2000 nm. The insets show modal power profiles of these waveguides at a wavelength of 1500 nm. Owing to the sidewall angle, the waveguide has a trapezium shape. It can be seen that the wider waveguides have a flatter dispersion curve, which is beneficial to

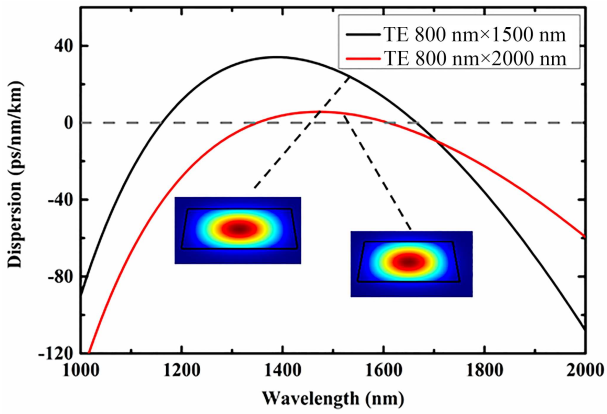

Figure 1 (Color online) Dispersion simulations for the fundamental TE mode of a Si_3N_4 waveguide with a height of 800 nm and widths of 1500 and 2000 nm. Insets are the modal power profiles at 1550 nm wavelength.

generate a wider range of optical frequency comb according to the previous experimental results and theoretical analysis [31].

3 Experiment and discussion

Figure 2(a) illustrates the experimental setup for combs generation. The light from the tunable laser is amplified by a high power erbium-doped fiber amplifier (EDFA) as pump light. After going through an isolator (ISO) and a polarization controller (PC), the pump light is coupled into the chip using a lensed fiber. One portion of the coupled output light is sent to power meter (PM) for fiber-to-chip feedback alignment and another portion is for comb monitoring by using an optical spectrum analyzer (OSA). The measured coupling loss at each facet is approximately 1.8 dB at 1550 nm. The transmission spectrum of the resonances and the Lorentz fitting results of the micro-resonator are shown in Figure 2(b) and (c). There are four modes within every 0.808 nm wavelength range, approximately corresponding to an FSR of 99 GHz. To obtain the Kerr frequency comb, the mode with highest quality factor is selected and the pump wavelength is tuned into the resonance from the blue-detuning at a step of 1 pm. Figure 2(d) shows generated frequency combs from a micro-ring resonator with a cross section of 800 nm$\times$2000 nm. The maximum loaded optical Q factor is 1.64×10^5. The pump power in the coupling waveguide is about 800 mW. Broadband optical frequency combs are observed with a spanning over half an octave (75 THz, spanning 1100 nm to 1700 nm).

Besides, we pump another microring resonator with a cross section of 800 nm$\times$1500 nm. This resonator supports single mode transmission with a loaded Q factor of 8.24×10^5 as shown in Figure 3(a) and (b). The initial sidebands are located at a distance of multiple FSRs away from the pump, which is the characteristic of Type II comb [32]. Figures 3(c)–(f) illustrate the formation process of this kind of comb. According to [30], when the parametric gain overcomes the loss in the Si_3N_4 micro-ring resonator, the degenerate FWM process occurs and the primary comb lines are generated spaced by multiple FSRs from the pump. The spacing of the primary comb lines to the pump wavelength relies on the pump power and the dispersion of the microresonator. By reducing the laser-cavity detuning, aditional lines are excited around the primary combs with single FSR spacing. Finally we can obtain frequency combs with single FSR spacing. As shown in Figure 3(f), we get a narrower comb bandwidth compared to comb bandwidth shown in Figure 2(d). The result agrees very well with the dispersion simulations, which indicates that the wider waveguides hold the potential to generate boarder combs.

Figure 4(a) illustrates the experimental setup including the feedback loop for combs generation with varing FSR. The feedback loop includes an isolator, a tunable filter, a lower power EDFA, and a polarization controller. The bandwidth of tunable is set at 0.5 nm and central wavelength is moved to select different sidebands. The pump light is combined with the light in the feedback loop by a 90/10 coupler

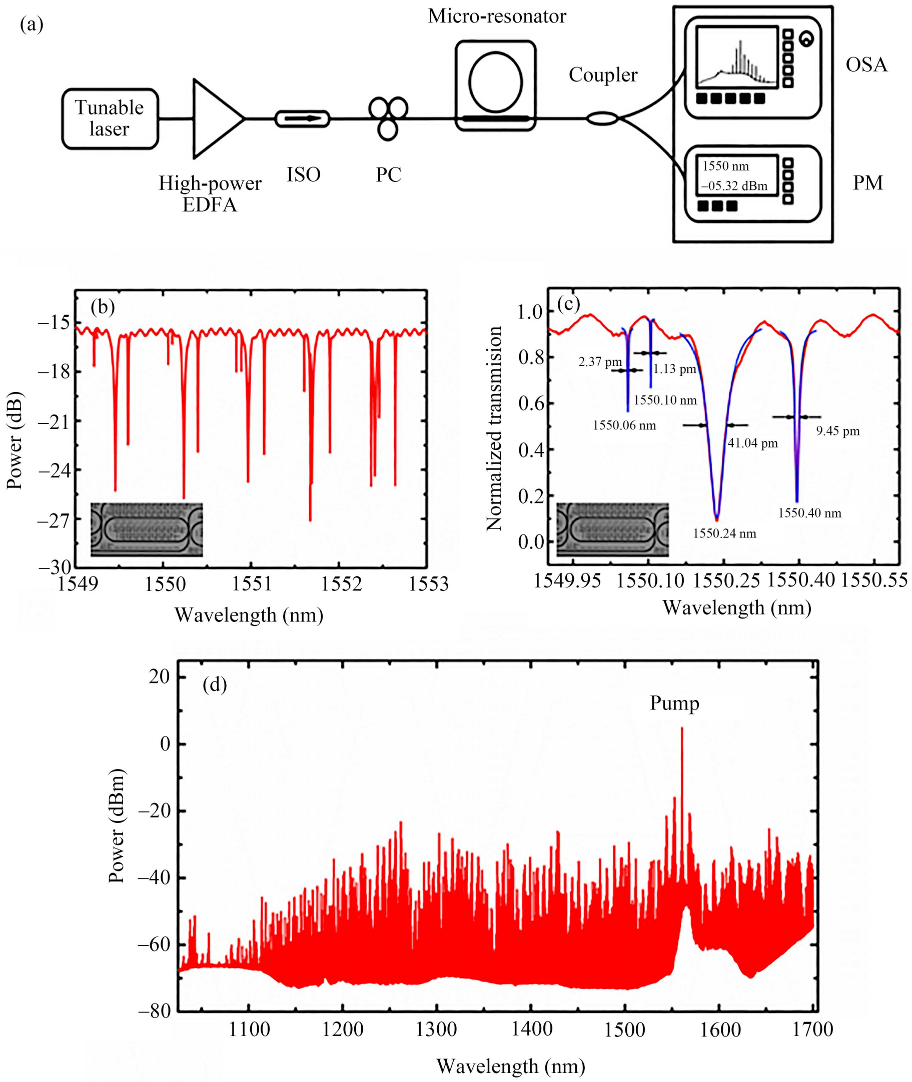

Figure 2 (Color online) (a) The experimental setup for combs generation. (b) The transmission spectrum of the Si_3N_4 micro-resonator with a cross section of 800–2000 nm. (c) The quality factor of the micro-resonator. (d) Optical frequency combs spectra generated in the Si_3N_4 micro-resonator. The inset shows the top view of the Si_3N_4 micro-ring resonator with a height of 800 nm and a width of 2000 nm.

and then coupled into the chip. The light coupled out of the chip is divided into two parts. 10% of coupled output light is used for comb recording and power alignment. 90% of coupled output light is coupled into the feedback loop. Figures 4(b)–(d) present partial experimental results. To be specific, the micro-resonator is pumped at 1560.92 nm and 27.5 dBm (the output power of the high-power EDFA, power on chip is approximately 251 mW), then we carfully tune the detuning between laser and cavity. Meanwhile, we observe that the optical power measured by the power meter shows a significant decrease, indicating that the pump light is coupled into the cavity. Then we turn on the EDFA in the feedback loop whose output power is set to 26 dBm. When the central wavelength of the tunable filter locates at 1559.34 nm (corresponding to 2-FSRs), multiple comb lines with two FSRs spacing are observed as shown in Figure 4(b). Figures 4(c) and (d) show the spectra when the central wavelength of tunable filter is moved to 1557.75 and 1556.17 nm, corresponding to 4-fold and 6-fold FSRs of the micro-ring resonator, respectively. These experimental results show that the spacing of comb lines is determined by the filtering position of the feedback light, that is, the wavelength difference beteween the feedback light and the pump light is equal to the spacing of generated comb lines. We suggest the physical mechanism of this phenomenon is that the feedback loop introduces an additional gain which can significantly alter

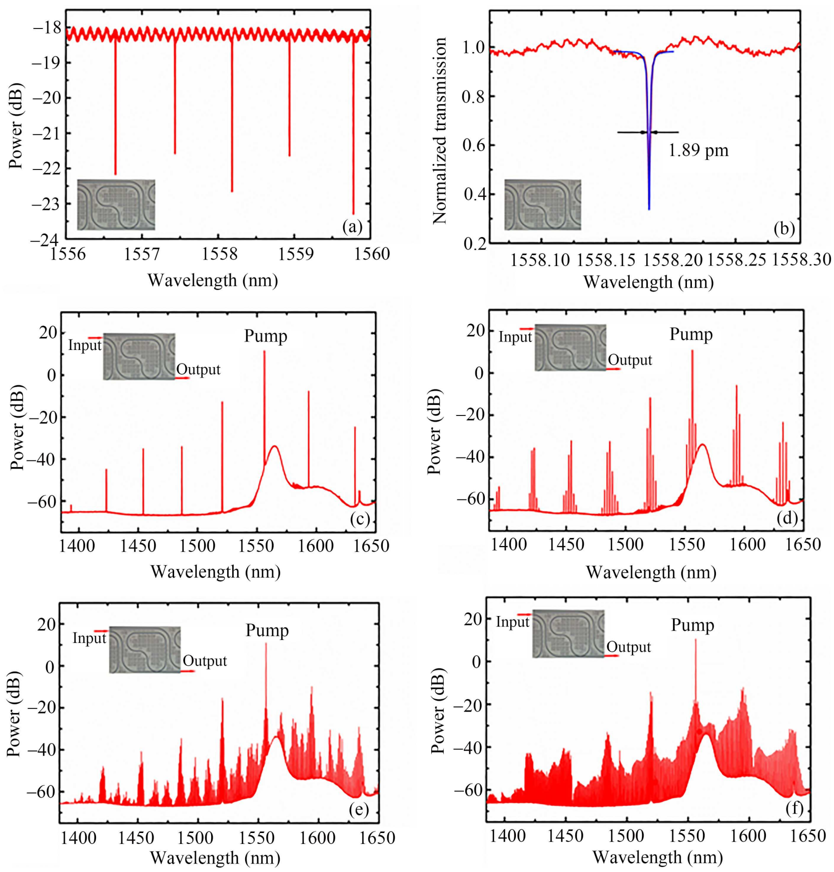

Figure 3 (Color online) (a) The transmission spectrum of the Si_3N_4 micro-resonator with a cross section of 800 nm×1500 nm. (b) The quality factor of the micro-resonator is 8.24×10^5. (c)–(f) Evolution of the frequency comb as the wavelength is gradually tuned to the resonant wavelength from a micro-ring with a cross section of 800 nm× 1500 nm. When the wavelength approaches the resonance, peaks start to appear with fourteen FSRs spacing, as shown in (c). Secondary lines gradually fill in the spectral gaps when the wavelength becomes closer to the resonance and FSRs spacing decreases to one FSR as observed in (d)–(f).

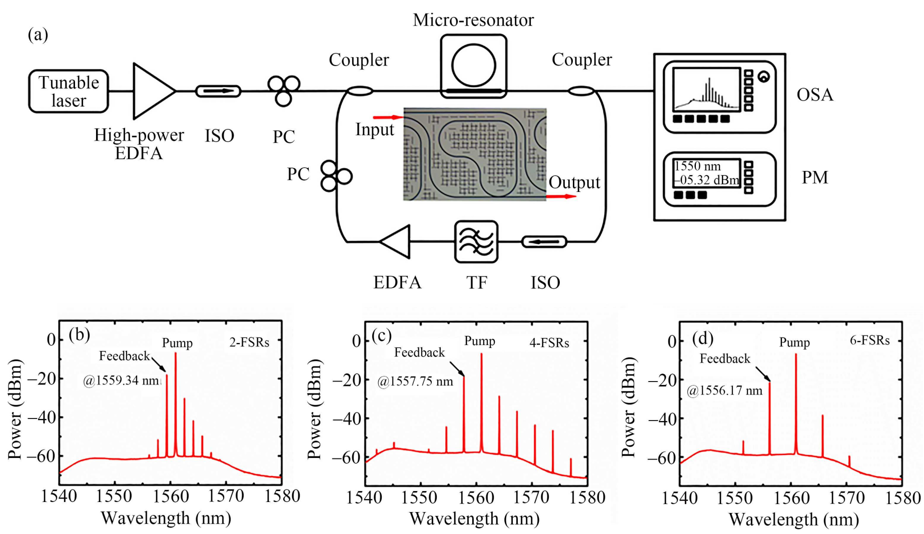

Figure 4 (Color online) (a) Experimental setup for combs generation with feedback loop. The inset shows the micro-resonator formed by 800 nm×1500 nm Si_3N_4 waveguides. (b)–(d) Spectra of the combs with flexible FSR spacing. (b) 2-FSRs, (c) 4-FSRs, (d) 6-FSRs.

the dynamics of optical frequency combs generation.

4 Conclusion

In conclusion, we experimentally demonstrate optical frequency comb generation with a span over 600 nm in a high-Q Si_3N_4 micro-ring resonator via proper dispersion engineering. Simulations and experiments both suggest that wider waveguides hold the potential to generate boarder combs. We show that, by selectively seeding the microresonator at a distance of multiple FSRs away from the pumping wavelength with an amplified fiber feedback loop, combs with varying FSR spacing are experimentally achieved. As this approach is easy to operate and low in cost, it will offer potential for on-chip tunable multiple wavelength source and other appilcations such as spectroscopy, metrology, high-speed communications. Future studys will focus on probing the coherence of these combs and realizing mode-locked frequency combs.

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References

1 Pasquazi A, Peccianti M, Razzari L, et al. Micro-combs: a novel generation of optical sources. Phys Rep, 2018, 729: 1–81
2 Kippenberg T J, Holzwarth R, Diddams S A. Microresonator-based optical frequency combs. Science, 2011, 332: 555–559
3 Pfeifle J, Brasch V, Lauermann M, et al. Coherent terabit communications with microresonator Kerr frequency combs. Nat Photon, 2014, 8: 375–380
4 Marin-Palomo P, Kemal J N, Karpov M, et al. Microresonator-based solitons for massively parallel coherent optical communications. Nature, 2017, 546: 274–279
5 Suh M G, Yang Q F, Yang K Y, et al. Microresonator soliton dual-comb spectroscopy. Science, 2016, 354: 600–603
6 Papp S B, Beha K, Del'Haye P, et al. Microresonator frequency comb optical clock. Optica, 2014, 1: 10–14
7 Ferdous F, Miao H, Leaird D E, et al. Spectral line-by-line pulse shaping of on-chip microresonator frequency combs. Nat Photon, 2011, 5: 770–776
8 Obrzud E, Rainer M, Harutyunyan A, et al. A microphotonic astrocomb. Nat Photon, 2019, 13: 31–35
9 Kues M, Reimer C, Roztocki P, et al. On-chip generation of high-dimensional entangled quantum states and their coherent control. Nature, 2017, 546: 622–626
10 Gohle C, Udem T, Herrmann M, et al. A frequency comb in the extreme ultraviolet. Nature, 2005, 436: 234–237
11 Gambetta A, Ramponi R, Marangoni M. Mid-infrared optical combs from a compact amplified Er-doped fiber oscillator. Opt Lett, 2008, 33: 2671–2673
12 Ozharar S, Quinlan F, Ozdur I, et al. Ultraflat optical comb generation by phase-only modulation of continuous-wave light. IEEE Photon Technol Lett, 2008, 20: 36–38
13 Zhou X, Zheng X P, Wen H, et al. All optical arbitrary waveform generation by optical frequency comb based on cascading intensity modulation. Opt Commun, 2011, 284: 3706–3710
14 Savchenkov A A, Matsko A B, Ilchenko V S, et al. Tunable optical frequency comb with a crystalline whispering gallery mode resonator. Phys Rev Lett, 2008, 101: 093902
15 Pasquazi A, Caspani L, Peccianti M, et al. Self-locked optical parametric oscillation in a CMOS compatible microring resonator: a route to robust optical frequency comb generation on a chip. Opt Express, 2013, 21: 13333–13341
16 Hausmann B J M, Bulu I, Venkataraman V, et al. Diamond nonlinear photonics. Nat Photon, 2014, 8: 369–374
17 Wang C, Zhu R R, Hu H, et al. Monolithic photonic circuits for Kerr frequency comb generation, filtering and modulation. 2018. ArXiv: 1809.08637v1
18 Wilson D J, Schneider K, Hoenl S, et al. Gallium phosphide nonlinear photonics. 2018. ArXiv: 1808.03554
19 Song Q H. Emerging opportunities for ultra-high Q whispering gallery mode microcavities. Sci China-Phys Mech Astron, 2019, 62: 074231
20 Hao Z Z, Zhang L, Gao A, et al. Periodically poled lithium niobate whispering gallery mode microcavities on a chip. Sci China-Phys Mech Astron, 2018, 61: 114211
21 Ikeda K, Saperstein R E, Alic N, et al. Thermal and Kerr nonlinear properties of plasma-deposited silicon nitride/silicon dioxide waveguides. Opt Express, 2008, 16: 12987–12994
22 Xue X X, Xuan Y, Liu Y, et al. Mode-locked dark pulse Kerr combs in normal-dispersion microresonators. Nat Photon, 2015, 9: 594–600
23 Miller S A, Okawachi Y, Ramelow S, et al. Tunable frequency combs based on dual microring resonators. Opt Express, 2015, 23: 21527–21540

24 Jung H, Xiong C, Fong K Y, et al. Optical frequency comb generation from aluminum nitride microring resonator. Opt Lett, 2013, 38: 2810–2813
25 Papp S B, Del'Haye P, Diddams S A. Parametric seeding of a microresonator optical frequency comb. Opt Express, 2013, 21: 17615
26 Johnson A R, Okawachi Y, Lamont M R E, et al. Microresonator-based comb generation without an external laser source. Opt Express, 2014, 22: 1394
27 Wang W Q, Chu S T, Little B E, et al. Dual-pump Kerr micro-cavity optical frequency comb with varying FSR spacing. Sci Rep, 2016, 6: 28501
28 Wang W Q, Zhang W F, Chu S T, et al. Repetition rate multiplication pulsed laser source based on a microring resonator. ACS Photonic, 2017, 4: 1677–1683
29 Okawachi Y, Saha K, Levy J S, et al. Octave-spanning frequency comb generation in a silicon nitride chip. Opt Lett, 2011, 36: 3398–3400
30 Tan D T H, Ikeda K, Sun P C, et al. Group velocity dispersion and self phase modulation in silicon nitride waveguides. Appl Phys Lett, 2010, 96: 061101
31 Okawachi Y, Lamont M R E, Luke K, et al. Bandwidth shaping of microresonator-based frequency combs via dispersion engineering. Opt Let, 2014, 39: 3535–3538
32 Ferdous F, Miao H X, Wang P H, et al. Probing coherence in microcavity frequency combs via optical pulse shaping. Opt Express, 2012, 20: 21033–21043