On-chip dark pulse frequency combs with modulated pumps in normal-dispersion microresonators

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***Abstract*—We propose an approach to generate robust dark-pulse Kerr combs with the total bandwidth of 200 nm, utilizing modulated continuous waves as driven pumps in normal-dispersion microresonators.**

Keywords—dark pulse, frequency comb, normal-dispersion microresonator

I. INTRODUCTION

Integrated optical frequency comb sources have undergone rapid development in both fundamental research and industrial fabrication for applications, such as coherent optical communications, light detection and ranging (LiDAR) and photonic computing. One of the leading approaches for on-chip comb generation is based on mode-locking the optical wave in microresonators with appropriate pump power and frequency detuning, which is the most common method to generate on-chip bright solitons and a series of frequency combs [1]. Such temporal structure with a series of combs in the frequency domain has been widely generated and observed in anomalous-dispersion microresonators. Compared with the former, the frequency combs generated in the normal-dispersion region were not well understood, as their precise regulation to the pump and the resonator. In 2015, the on-chip dark pulse with a series of combs was successfully generated and observed in normal-dispersion microresonators, which broke the challenges and difficulties of dark-pulse generation and observation by using the mode-interaction-assisted excitation [2]. This method was used to support laser mode-locking and eventually to obtain a 800-fs-wide dark pulse with a broadened comb spectrum from 1450 nm to 1650 nm in the normal-dispersion region. The dark-pulse comb with a line spacing of 100 GHz has been further applied as a multi-wavelength light source in optical fiber communication [3]. Such a light source maintains a laser pump power level compatible with state-of-the-art hybrid silicon lasers, enabling transmitted optical signal-to-noise ratios above 33 dB encoded by 64-quadrature amplitude modulation. Compared to the combs formed in anomalous-dispersion microresonators with conversion efficencies of only a few percent, the mode-locked dark-pulse or platicon combs can achieve the efficiency of about 30% [4], which is also fascinating.

With the rapid development of the integrated frequency comb generation technique, the comb generation in normal-dispersion microresonators was found to be dependent on the pump detuning and the mode coupling of the microrings. In this case, an auxiliary pump with a frequency shift that takes into account the thermal effect has less influence than the pump with a quasi-instantaneous Kerr shift, which normally leads to minor differences in comb generation over a wide range of detuning [5]. The dual-pump approach, however, is mostly used to generate a more stable platicon frequency comb, which is a flat and top pulse with a series of frequency combs generated in the normal-dispersion region. The generation of the dark-pulse comb in the normal-dispersion microring using a frequency-modulated pump, is reported for the first time to the best of our knowledge, providing a stable dark-pulse comb generation with flexible detuning control and low noise sensitivity.

II. THEORETICAL MODEL

The intra-cavity dynamics of the SiN microresonator can be governed by the Ikeda map [3], which is an infinite-dimensional map. The standard Ikeda map, which includes the nonlinear Schrödinger equation with one boundary condition, is written as

$$\frac{\partial E(z,\tau)}{\partial z} = -\frac{\alpha}{2}E + i\frac{\beta_2}{2}\frac{\partial^2}{\partial \tau^2}E + i\gamma|E|^2E, \tag{1}$$

$$E_{n+1}(0,\tau) = \sqrt{\theta}E_{\text{in}} + \sqrt{1-\theta}E_n(L,\tau)e^{-i\delta_0}, \tag{2}$$

is used to model the pulse and the comb generation behavior by injecting the modulated continuous waves into the ring, where $E\ (z, \tau)$, z, t, L represent the slowly varying envelope of the field, the fast time variable, the propagation distance, and the roundtrip length, respectively. α, θ, β_2, γ are the round-trip cavity loss, the bus waveguide coupling coefficient, the group velocity dispersion, and the nonlinear coefficient, respectively. The intracavity field $E_{n+1}\ (0, \tau)$ is the coupled field between the initial pump field E_{in} and the end of the n-th roundtrip field $E_n\ (L, \tau)$. $E_{\text{in}} = \sqrt{P} + \sigma\sqrt{P}e^{-i2\pi\Delta v\tau}$ is the driven pump, which is phase-modulated. For the simulations, $\alpha = 0.0031$, $\theta = 0.00193$, $\gamma = 0.89\ \text{m}^{-1}\text{W}^{-1}$, $L = 0.2\pi$ mm and $\beta_2 = 186.9\ \text{ps}^2/\text{km}$ are taken from Ref. [2].

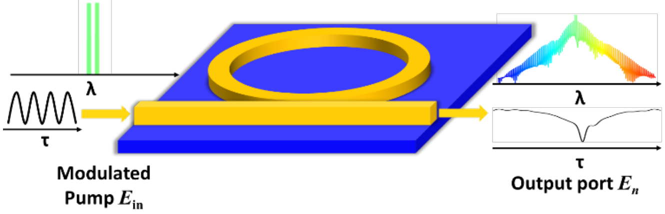

Fig. 1. Schematic diagram of the modulated laser pump injecting into the 0.2π-mm-long normal-dispersion microresonator.

Figure 1 derives the schematic of the dark-pulse comb generation in the proposed on-chip microring with modulated continuous wave (CW) pump. The ring has a radius of 0.1 mm and is coupled to a straight SiN waveguide. The injected pump's parameters are as follow: the injected pump power P = 0.5 W, the cavity noise 0.5 pW, the detuning value δ_0 = 0.015, the modulated coupling coefficient σ = 1.00, the modulated frequency $\Delta v = 2\Delta v_0$ and $\Delta v_0 = 0.1247$ THz corresponding to $\Delta\lambda$ = 1 nm.

III. Simulation Results

We chose the dual pump with equivalent input power as the parametric seeding. With different random noises of 512 simulated results, the intensity distributions at the end of the 5000-th roundtrip in the temporal domain in Fig. 2 (a) and the spectral domain in Fig. 2(b) remain almost in the same position, which represents a very high repeatability. In the nomral dispersion, the amplification of the input shot noise inherent due to the modulation instability (MI) is suppressed, providing a stable formation environment for frequency comb generation. On the contrary, due to the absence of MI, it is difficult to form mode-locked pulses in the cavity, which makes the generation of dark pulses require significant perturbations in the initial temporal domain. The modulated pump are able to solve this problem very well, because its cosine wave based on the beat frequency can inherently produce significant perturbations. In a sense, the modulated pump is equivalent to performing a pre-mode-locking before injecting into the microresonator so that we can reduce the dependence of the frequency comb generation on the MI and the precise regulation of the initial pump. The intensity distribution with a watt unit of the dark pulse is shown in the inset of Fig. 2(a). The dark pulse has a weak side lob with 0.23 ps delay compared to the main lobe. We obtain a stable pulse duration of 79.2 fs, an approximately zero-power-peak dark pulse with the bright-background power of 43.01 W and a series of 2-nm-space-line frequency combs ranged from 1450 nm to 1650 nm, which is equal to the distance between two peaks of the driven pump. The modulated frequency can directly control the output comb-line spacing.

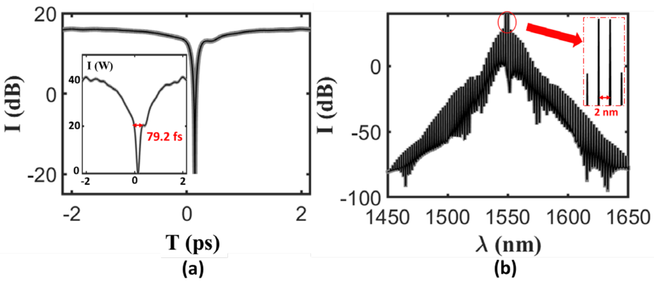

Fig. 2. Output results of (a) temporal field and (b) spectral field at the end of the 5000-th roundtrip. The gray lines are 512 individual results with different random initial noise, and the black line is the calculated average spectrum.

In Fig. 3, the intensity contours demonstrate the average temporal evolution, the average spectral evolution when we inject a modulated pump equivalent to two CW pumps at 1550 nm and 1552 nm, respectively. The modulated pump with an initial power of 0.5 W and the constant detuning δ_0 of 0.0015 is used to drive the microresonator. The cavity acts as a power filter, resulting in high power accumulation and low power dissipation. During the roundtrip goes, the lower intensity part is gradually compressed to a narrow dark pulse with two "weak" side lopes after 1200 roundtrips as shown in Fig. 3(a). From Fig. 2(a), these two side lopes are not symmetrically distributed, where the advanced lope peak is hardly observed on the output field. We also measure the comb generation time as 385 roundtrips, which has a much faster pulse-on stabilization time than that using the mode-interaction method [2]. After 1200 roundtrips, the temporal and the spectral profiles are almost invariant. It is worth mentioning that we keep the detuning value δ_0 as a constant, which shows that our generation method can avoid tuning the detuning phase of the pumps and the thermal effect [6] in the microresonator continuously. Conversely, we can also obtain the dark-pulse comb with desired properties by controlling the pump power P, the detuning value δ_0.

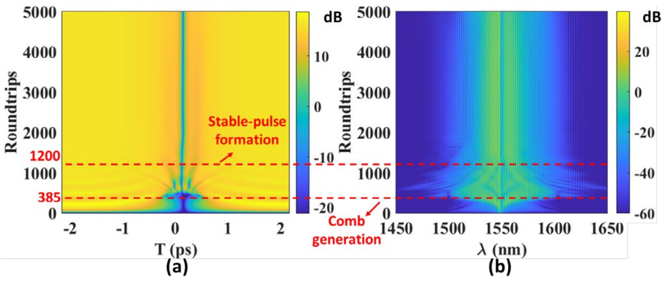

Fig. 3. Average evolutions of (a) temporal field and (b) spectral field in the normal-dispersion mircoresonator with driven modulated pump.

IV. Conclusion

We propose a practical method to generate a robust dark-pulse Kerr combs by using the modulated pump in the SiN microresonator with normal dispersion. The approach can form a stable dark-pulse comb after 1200 roundtrips, with the pulse width of 79.2 fs, the background power of 43.01 W in the temporal domain and the 2-nm-space-line combs in the spectral domain, resulting in a total bandwidth of 200 nm (1450-1650 nm). Our results further our understanding of the on-chip dark-pulse generation in normal-dispersion region, which may improve the performance of on-chip light sources.

Acknowledgment

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