

Generation of Multi-pulse Dissipative Solitons in a Mode-Locked Yb-Doped Fiber laser

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Abstract. We report on multi-pulse dissipative solitons generation in all-normal-dispersion (ANDi) long cavity Yb-doped fiber laser with a cascaded long-period fiber grating as a spectral filter. The mode-locking is based on nonlinear polarization evolution. It was found that through either changing the pump power or adjusting wave plates in the cavity, several characteristic modes have been experimentally observed, including disordered multi-pulses, bunch of pulses with equal time intervals and non-equal time intervals. The observed results of multi-pulse output suggest a method of multi-pulse generation for potential applications in micromachining, high-resolution ranging-finding and geological exploration.

Introduction

Passive mode-locked fiber lasers have attracted much attention because they are ideal platforms for the investigation of multi-soliton nonlinear dynamics and potential applications in micromachining, high-resolution ranging-finding and geological exploration. In an anomalous dispersion laser cavity, more than one soliton, which is well known as the multi-soliton state, appears and circulates inside the cavity when the pump exceeds a certain value. Various modes of multi-soliton operation have been observed in this type of fiber lasers, such as bound solitons [1, 2], disordered bunched multi-solitons [3, 4], soliton rains [5-7], high-order harmonic mode-locking [8-9]. In principle, the dynamics of soliton formation is dominated by the balance between anomalous group-velocity dispersion (GVD) and Kerr nonlinearity of the fiber, the single pulse energy of such soliton is usually around ~10nJ.

To increase the energy efficiency, a type of dissipative laser has been proposed and demonstrated to generate pulses with high pulse energy [10], in which the pulses can exist in the cavity with all-normal dispersion (ANDi) and rely on the dissipative processes, the pulses from the dissipative processes are considered as dissipative solitons (DSs). In 2007, A. Chong *et al* reported a mode-locked all-normal-dispersion giant chirped passively fiber laser system [11], in which the energy of the DSs is above 20nJ. Various ANDi systems such as switchable dual-wavelength laser system [12], tunable high energy giant chirped passively mode-locked fiber laser [13] have also been reported in recently years. In an ANDi system, multi pulses have been observed in the cavity when the pump power is increased to a certain level. The existence of multiple pulses can lead to harmonically mode-locked (HML) solitons or soliton pairs in the fiber lasers, in which several theoretical and experimental investigations about the HML or twin-pulse solitons generation in the ANDi lasers were reported [14-16]. In 2010, Liu *et al.* reported a low-repetition-rate, passively mode-locked, twin-pulse, ANDi fiber laser [14], in which two pulses separated by 33.4ns with a fundamental repetition rate of 2.54MHz were observed. In 2012, a high-order HML Yb-doped fiber laser with DSs was observed [15] in which as high as 14th harmonic mode-locking was achieved. In

2015, Zhu *et al.* reported a harmonically mode-locked (HML) twin-pulse solitons in all-normal-dispersion (ANDi) Yb-doped fiber laser, in which a maximal third HML twin-pulse solitons fiber laser was achieved for the first time in the ANDi system [16].

In this paper, we report on the generation of more type of multi-pulses DSs in a long-cavity ANDi fiber laser based on nonlinear polarization evolution (NPE) effect, in which a cascaded long-period fiber grating is used as the spectral filter for pulse shaping. By adjusting the pump power and the orientation of the wave plates, it has been found that multi-pulses can be achieved with several distinct features including disordered multi-pulse, bunch of pulses with equal time intervals and non-equal time intervals. The observed results suggest a method of multi-pulse generation for potential applications in optical measurement instruments, high resolution ranging systems and also investigation of multi-soliton nonlinear dynamics.

Experimental Setup

Fig. 1(a) shows the experimental setup of a passively and multi-pulse DSs solutions in an ANDi laser, which was built in a unidirectional cavity for self-starting operation. The total length of the cavity is 1144m, and all components of the laser have normal group velocity dispersion (GVD). A 28cm piece of Yb-doped gain fiber (612dB/m absorption at 976nm) was placed after 1139m of single-mode fiber (SMF). The pump laser (pump diode) was a 976nm grating-stabilized laser diode, which delivers up to 530mW to the gain fiber through a 980/1060 wavelength-division multiplexer (WDM). A cascaded long-period fiber grating (CLPFG) is used as a spectrum filter, the transmission spectrum of which is shown in Fig. 1(b). The CLPFG was fabricated with a CO₂ laser focused on a Corning HI1060 SMF. One of the transmission peak of the CLPFG bandpass filter was at 1034 nm and the full-width at half-maximum (FWHM) was about 7 nm with a near-Gaussian shape. This passband determines and coincides with the central wavelength of our laser output. The multi-pulse solitons was implemented by adjusting quarter-wave plates (QWPS) and a half-wave plate (HWP). The output of the laser was directly from the NPE rejection port of polarization beam splitter (PBS). A high speed photo-detector was connected to a digital oscilloscope (50GHz bandwidth, Tektronix DPO72004C) which is used for the pulses monitoring and the radio-frequency (RF) spectrum measurement. An AQ-6370 spectrum analyzer is used for the optical spectral measurement.

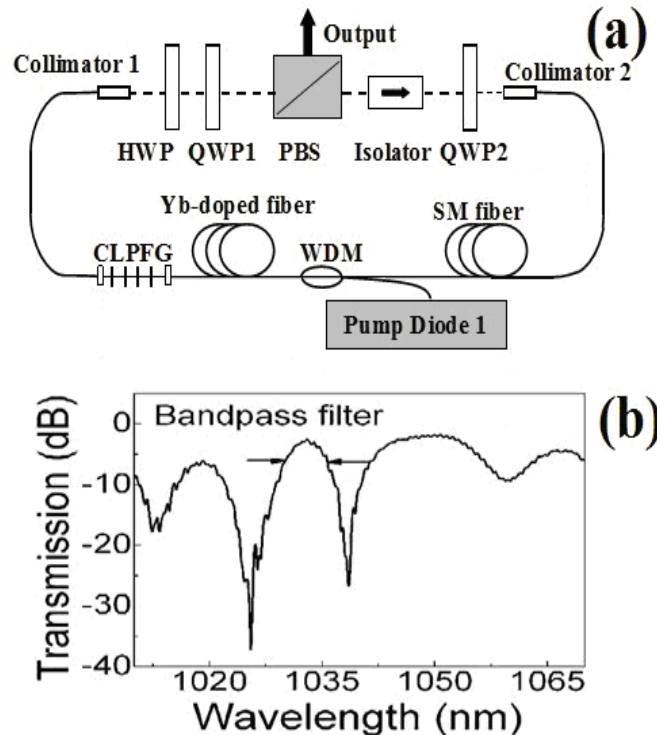


Fig. 1. (a) Schematic diagram of a ring fiber laser setup. (b) The transmission spectrum of a CLPFG.

Experimental results and discussion

Fundamental Mode-locking. The NPE technique was used to achieve the mode-locking state of the fiber laser. A self-starting stable fundamental mode-locked (FML) soliton was achieved, when the pump power is higher than the threshold power of 250mW. As shown in Fig. 2(a), the pulse train had a cavity round-trip time of $\sim 6\mu\text{s}$, corresponding to the fundamental mode-locking repetition rate of $\sim 166\text{kHz}$ and the total cavity length of $\sim 1144\text{m}$. Fig. 2(b) showed that the full width at half maximum (FWHM) of the single pulse profile was $\sim 1.76\text{ns}$. The corresponding optical spectrum was also measured, as shown in Fig. 2(c). It has a central wavelength of $\sim 1034\text{nm}$ and a 3-dB spectral bandwidth $\sim 3.5\text{nm}$, which is determined by the bandpass wavelength of the CLPFG filter as shown in Fig. 1(b). The corresponding ratio frequency (RF) spectrum observed in the ratio frequency spectrum analyzer is shown in Fig. 2(d) with a span of 100kHz. It is revealed that the signal-to-noise ratio (SNR) is $\sim 50\text{dB}$, indicating a high temporal stability.

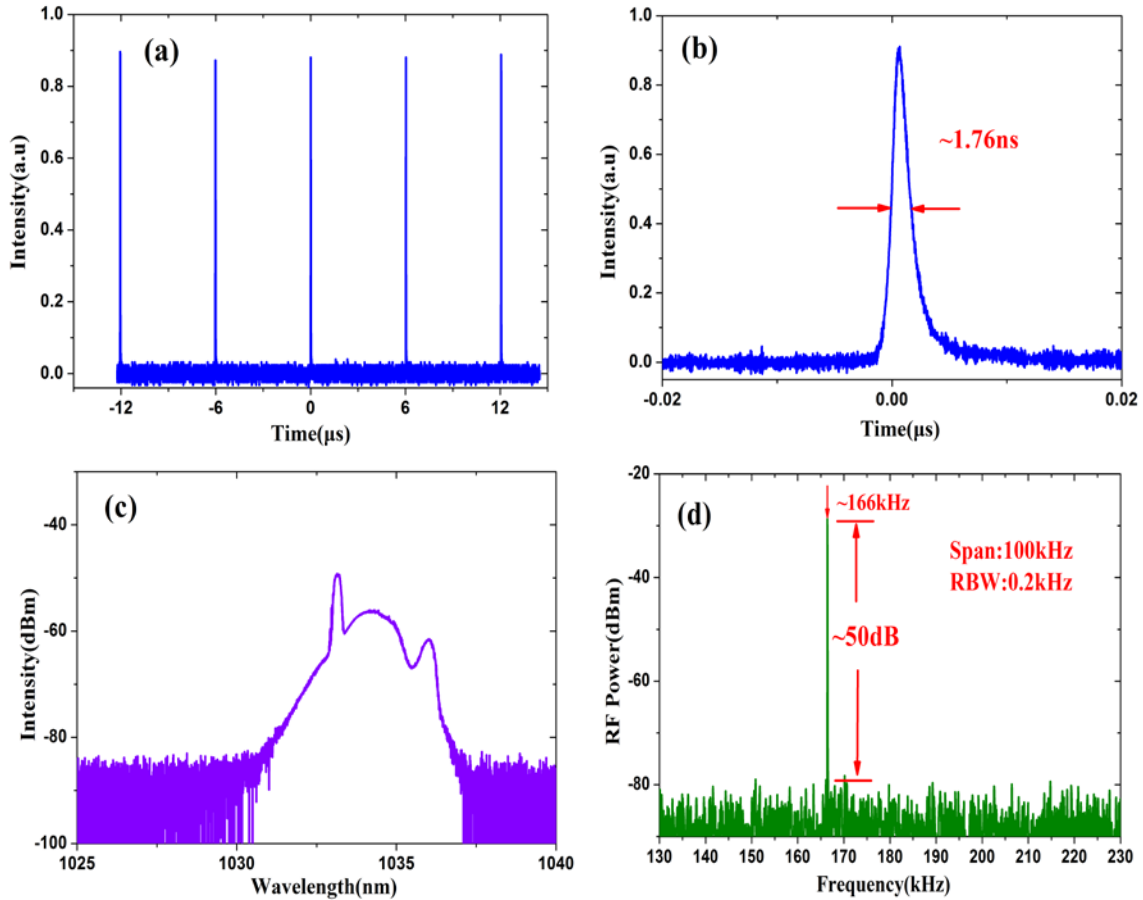


Fig. 2. (a) Fundamental mode-locked pulse train. (b) Single pulse width. (c) Optical spectrum of the output pulse. (d) RF spectrum of the output pulses with a span of 100kHz.

Disordered multi-pulses. By adjusting quarter-wave plates (QWPS) and a half-wave plate (HWP), pulse splitting was found to occur owing to the soliton peak clamping effect. The corresponding pump power and average output power were $\sim 320\text{mW}$ and $\sim 17.6\text{mW}$, respectively. Disordered multi-pulses had been observed at this pump power, in which pulses were randomly distributed in the cavity. Fig. 3(a) showed a typical example, where three individual pulses coexist in the cavity and they were unequally separated. Correspondingly, the measured optical spectrum was shown in Fig. 3(b). It was worth mentioning that this operation was steady. Another type of disordered multi-pulses could also be observed by adjusting the wave plates at the same pump power level, as shown in Fig. 3(c). It was found that many more new pulses appeared, and all the pulses were randomly distributed with respect to each other in the cavity. The corresponding optical spectrum was measured as shown in Fig. 3(d). The multi-pulse operation observed may due to the peak limiting and soliton quantization effect. When the pump power increased to a certain value (320mW in our case), the single soliton pulse breaks up. Also, different pulses were located at different wavelengths, thus

they would have different GVD and round-trip times, which induce the disordered distribution of these pulses along the cavity [17].

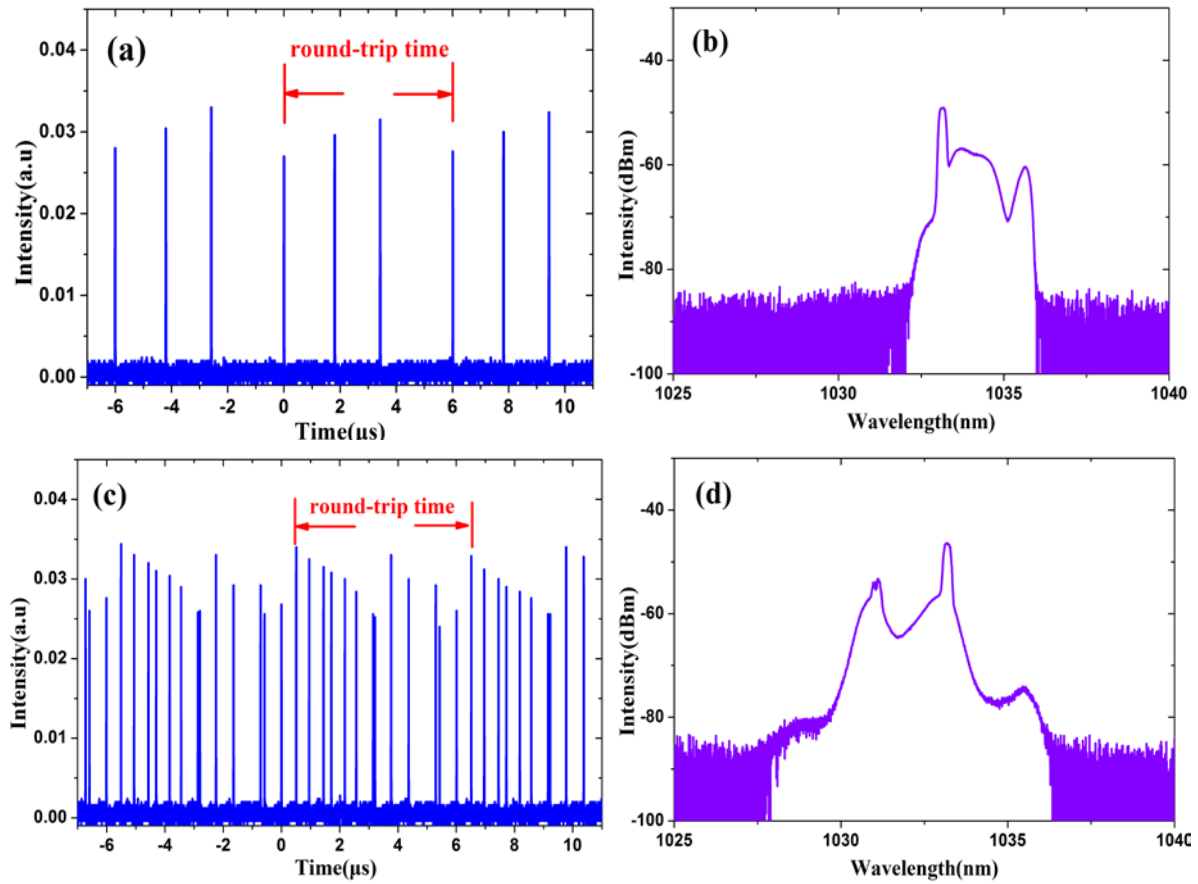


Fig. 3. (a) The oscilloscope trace of disordered multi-pulses and (b) the corresponding optical spectrum; (c) Another type of disordered multi-pulses and (d) the corresponding optical spectrum.

Bunch of pulses. The bunch of pulses occurred when the pump power was increased up to 360mW. By adjusting the QWPs at different polarizing states, twin-pulse solitons can be obtained with the output power of ~ 28.8 mW. Fig. 4(a) showed the oscilloscope trace in which pulse-pulse separation in one twin-pulse solitons was 33.6ns and the bunch repeated with a fundamental repetition of ~ 166 KHz. The corresponding optical spectrum was shown in Fig. 4(b). A noticeable phenomenon was found that the number of pulses in the bunch could be increased to 3 by fixing the polarizing states of QWPs but further increasing the pump power slightly to ~ 420 mW. Fig. 4(c) showed the oscilloscope traces of triple-pulse solitons, the corresponding spectra were shown in Fig. 4(d). From Fig. 4, we can see that pulse-pulse separation is fixed at 33.6ns in time domain in either twin-pulse or triple-pulse solitons. This is similar to that of soliton pairs as discussed in Ref. [14] and [16], in which the solitons pairs are oscillating at fixed positions i.e., the pulse-pulse separation in one twin-pulse solitons is fixed. It is seen from Fig. 4(b) and (d) that the spectra of twin-pulse and three-pulse solitons were similar to each other, which suggests that these multi-pulses are generated in the same cavity mode. When the pump power was increased to 530mW (maximum in our system), more pulses with non-equal intervals can also be obtained by adjusting the QWPs. Fig. 5 (a) showed a typical example of multi-pulse solitons (8 pulses in this case) in which the pulse-pulse separation was not fixed. This type of solitons can be called as non-equal intervals multi-pulse DSs. It is experimentally seen that this operation state was not very steady when compared to that of equal interval multi-pulse operation mode. In order to understand its origin, the corresponding optical spectra were measured as shown in Fig. 5(b). It was clearly seen that the spectrum was different from the spectral of multi-pulse solitons with equal time intervals as shown in Fig. 4, which suggests a possible viewpoint to further explore the physical mechanism of the multi-pulse generation.

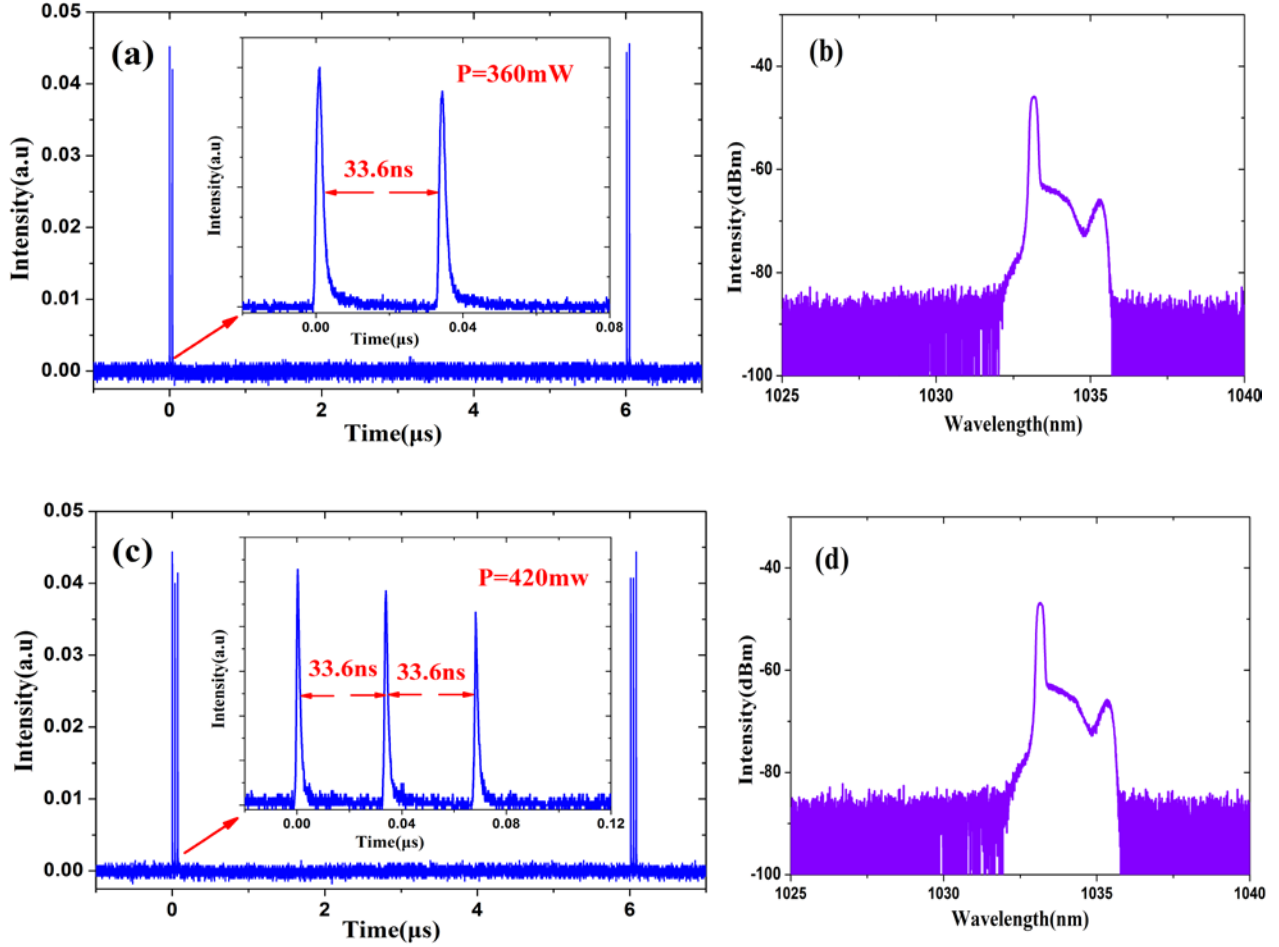


Fig. 4. (a) The oscilloscope trace of twin-pulse solitons and (b) the corresponding optical spectrum. (c) The oscilloscope trace of three-pulse solitons and (d) the corresponding optical spectrum.

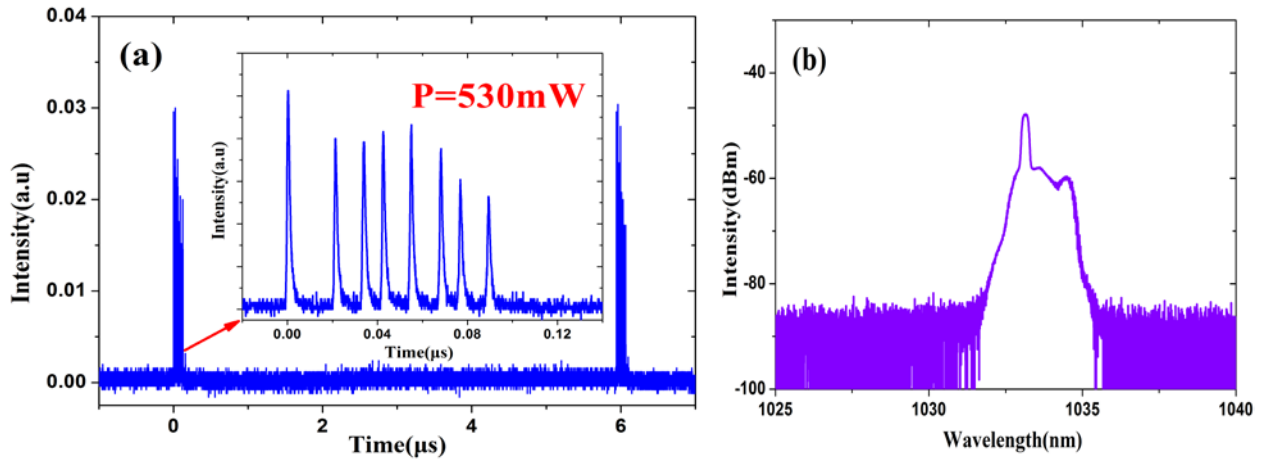


Fig. 5. (a) The oscilloscope traces of multi-pulse solitons with non-equal time intervals, and (b) the corresponding spectrum.

Summary

In conclusion, we reported on the generation of multi-pulse dissipative solitons in a mode-locked Yb-doped long cavity fiber laser. The multi-pulse solitons include disordered multi-pulses, bunch pulses with equal time intervals and non-equal time intervals. In equal time interval multi-pulse solitons, two or three pulses could coexist in the bunch depending on the pump power. The generation

mechanisms of multi-pulse solitons could be attributed to the spectral filter and oversaturation of the NPE characteristic in the ANDi system. It is expected that with the higher pump power and longer cavity, more pulses could be achieved. The observed results of multi-pulse output may provide evidence for understanding multi-soliton nonlinear dynamics and also suggest a method of multi-pulse generation for potential applications in micromachinin, high-resolution ranging-finding and geological exploration.

Acknowledgments

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