IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 6, December 2018

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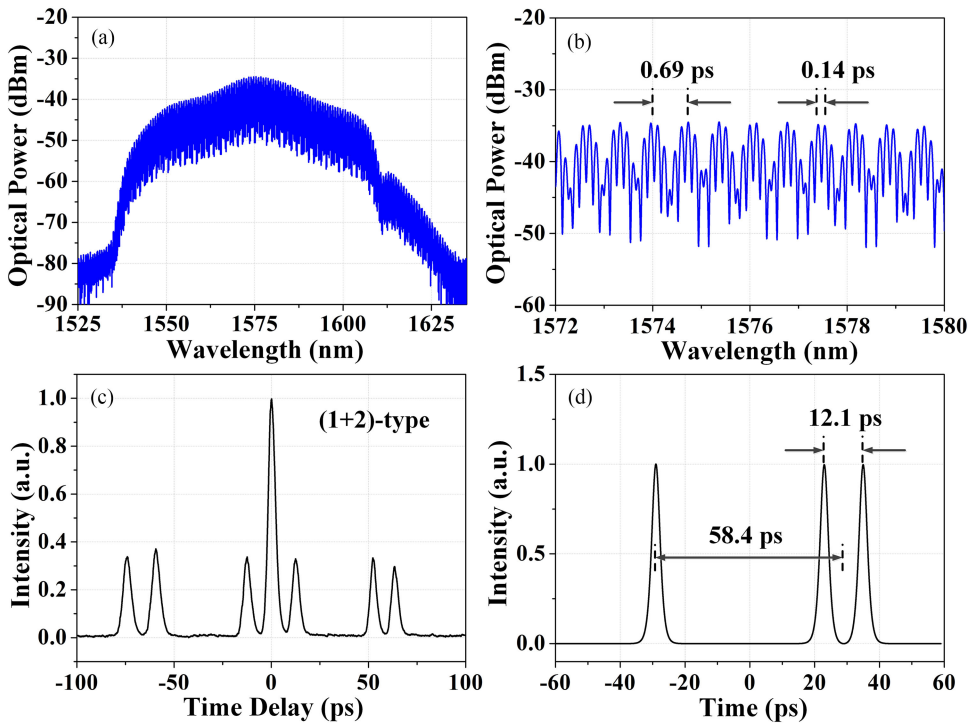

DOI: 10.1109/JPHOT.2018.2874949

Dispersion-Managed Soliton Molecules in a Near Zero-Dispersion Fiber Laser

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DOI:10.1109/JPHOT.2018.2874949

Manuscript received September 19, 2018; accepted October 5, 2018. Date of publication October 9, 2018; date of current version October 19, 2018. This work was supported in part by the National Natural Science Foundation of China under Grants 61775072 and 61575072, in part by the China Postdoctoral Science Foundation funded Project under Grant 2018M630853, in part by the Science and Technology Program of Shenzhen, China under Grant JCYJ20160531194407693, in part by the National Key Research and Development Project under Grant 2016YFB1100302, in part by the Science Fund for Creative Research Groups of the Natural Science Foundation of Hubei under Grant 2018CFA004, and in part by the Major Projects of Technical Innovation of Hubei under Grant 2018AAA040. Corresponding author: Qizhen Sun (e-mail: qzsun@mail.hust.edu.cn).

Abstract: Physics phenomena of multipulse compounds have enriched the life of ultrashort pulses beyond traditional pulse singlets in passively mode-locked fiber lasers. By developing a near zero-dispersion fiber laser, we report on the generation of dispersion-managed soliton (DMS) molecules. During propagation in the laser cavity, the broadband DMSs experience a breathing process (i.e., periodic compression and stretch of the pulse width), which facilitates various molecule evolutions from pulse singlets. In particular, tightly bound DMS pairs, loosely bound DMS pairs and three-pulse to eleven-pulse molecules are respectively observed. Apart from the aforementioned DMS molecules with equal pulse separations, unequally spaced DMS molecules with different multipulse structures are also obtained, typically including the (2 + 1)-type molecule and the (2 + 3 + 1)-type molecule. The investigation of DMS molecules characterized by versatile multipulse structures is of both fundamental scientific interests in soliton dynamics and potential applications of ultrahigh-capacity optics communications based on advanced modulation formats.

Index Terms: Fiber, diode-pumped and mode-locked lasers.

1. Introduction

Passively mode-locked fiber lasers have attracted intensive research for implementing considerable applications in fiber communications, material processing and all-optical sampling, as well as serving as an ideal playground for the exploration of complex pulse dynamics [1]–[3]. Conventional pulse singlets have been thoroughly studied in fiber lasers, and the pulse formation mechanisms at different dispersion regimes spread the concept of conventional solitons (CSs) [4], dispersion-managed solitons (DMSs, i.e., stretch pulses) [5]–[7] and dissipative solitons (DSs) [8]. Recently, the limitation of soliton singlets inspires an extended investigation of soliton compounds which are characterized by multi-pulse structures. They have been manifested in both time domain and

polarization directions, respectively corresponding to the bound state and the vectorial nature of ultrashort pulses [9]–[11]. These multi-pulse compounds possess much more complex behaviors than their singlet counterparts. As expected, the investigation of soliton compounds is motivated for both shedding new light on the detailed nature of fundamental physics towards the ultrafast nonlinear optics, and extending much more potential applications of the pulsed light sources.

Stemming from the interaction of repulsive and attractive forces in time domain, these particle-like soliton singlets can be bound together to form a kind of soliton compound, namely the aforementioned bound state. All these behaviors induced by the multi-pulse structure make it akin to 'molecule' [12]–[14]. According to the strength of the interaction forces, the soliton molecules can be divided into two types: the tightly bound state with a strong soliton interaction force and the loosely bound state with a weak soliton interaction force [15]. The formation process of soliton molecules is inherently dissipative and requires the supply of binding energy [1]. In addition, different from the high-order solitons, the soliton molecules are robustness, thus ensuring their potential applications in optics communications for coding and transmission of information in high-level modulation formats, and increasing capacity of communication channels beyond binary coding limits [16]–[19]. Originally, soliton molecules were theoretically predicted by Malomed and Akhimediev [20], [21]. Until 2001, Tang *et al.* experimentally demonstrated the existence of soliton molecules for the first time [22]. Subsequently, soliton molecules have been respectively reported in passively mode-locked fiber lasers based on various mode-locking mechanisms, such as nonlinear polarization rotation (NPR) [23]–[25], and the real saturable absorber. The real saturable absorber mainly includes the semiconductor saturable absorber mirror (SESAM) [11], molybdenum disulfide [26], [27], carbon nanotube [28], [29], and graphene [30]. In latest research, it is found that soliton molecule could also behave rich phase evolution [31]–[33]. Moreover, apart from the CS molecules [34] and the DS molecules [35] respectively formed in the anomalous-dispersion regime and the normal-dispersion regime, the generation of DMS molecules has been also validated in the near zero-dispersion regime [36]–[38]. Particularly, DMSs formed in the near zero-dispersion regime are generally characterized by a fairly broad spectral bandwidth, which paves a promising way for the generation of hundreds even tens of femtoseconds pulses [39], [40]. Meanwhile, the breathing process (i.e., periodic compression and stretch of the pulse width) of the DMSs during propagating in the laser cavity will cause the overlap of pulses, which will enhance the pulse-pulse interaction forces. Hereby, the DMSs are susceptible to the formation of bound states. Overall, the study of DMS molecules is twofold desirable. On one hand, an optimal dispersion-managed fiber laser provides an experimental testbed for manipulating the DMSs into various molecule evolutions, further unveiling the detailed dynamics of the pulse-pulse interaction. On the other hand, the generation of different types of pulse compounds is potentially set for increasing the communication capacity based on advanced modulation formats.

In this paper, we develop a dispersion-managed fiber laser mode-locked by the NPR technique. By finely managing the net dispersion into near zero-dispersion regime, the proposed fiber laser can not only support the DMS emission, but also serve as an optimal testbed for revealing the dynamics of the DMS molecules. With appropriate settings, various molecule evolutions are experimentally observed, which can be further verified by the modulated spectra and the distinct autocorrelation traces. In particular, DMS molecules with equal separations are obtained, respectively including tightly bound DMS pairs, loosely bound DMS pairs and three-pulse to eleven-pulse bound states. Furthermore, the breathing process induced complex molecule evolutions result in the formation of unequally spaced DMS molecules with different multi-pulse structures. Additionally, numerical simulations are also implemented to confirm the pulse distributions of the molecules in time domain. All these observations will enrich the life of multi-pulse compounds and extend more potential applications.

2. Experimental Setup

The dispersion-managed fiber laser is schematically depicted in Fig. 1. In the ring cavity configuration, a 1.5 m erbium-doped fiber (EDF, OFS EDF80) with group-velocity dispersion (GVD) of about

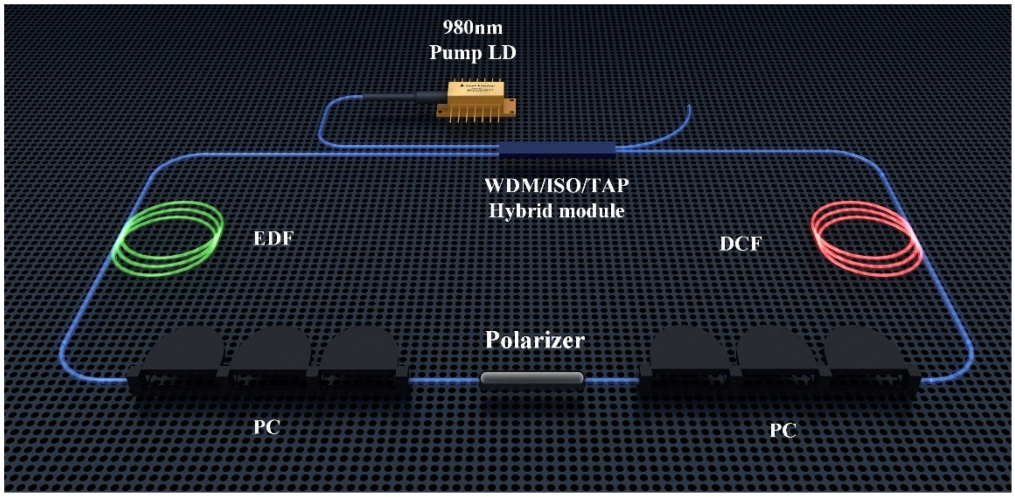

Fig. 1. Schematic diagram of the NPR based near zero-dispersion fiber laser.

−48 (ps/nm)/km is used as the gain medium and pumped by a 980 nm laser diode (980 nm LD). A wavelength division multiplexer/isolator/tap (WDM/Isolator/Tap) hybrid module is utilized to simplify the laser configuration. An in-line polarizer sandwiched between two polarization controllers (PC) is exploited to initialize the NPR based mode-locking. A section of dispersion compensation fiber (DCF) with GVD of −138 (ps/nm)/km is utilized to manage the net dispersion of the fiber laser. In particular, the dispersion management is realized by finely adjusting the pigtail length of the SMF with GVD of 17 (ps/nm)/km. Consequently, the overall length of the fiber laser is about 14.8 m, including 1.5 m EDF, 1 m DCF and 12.3 m SMF. The net dispersion is calculated to be ∼0.0011 ps^2. Thus it can be seen that this dispersion-managed fiber laser approaches into the near zero-dispersion regime. Additionally, an optical spectrum analyzer (OSA, Yokogawa AQ6370C-20) with a resolution of 0.02 nm and a 4 GHz real-time oscilloscope (OSC, Tektronix CSA7404B, 20GS/s) together with a 25 GHz photodetector (PD, Newport1414) are respectively employed to monitor the optical spectrum and the pulse train. The radio frequency (RF) spectrum is analyzed by an electrical spectrum analyzer (ESA, Agilent N9320B), and the pulse width is measured by a commercial autocorrelator (Femtochrome FR-103XL).

3. Experimental Result and Discussion

3.1 DMS Singlet Operation

To start with, self-started mode-locking of the dispersion-managed fiber laser can be easily obtained through increasing the pump power above the mode-locking threshold of 54.0 mW and adjusting the PCs. The mode-locked pulses automatically evolve into DMSs because the proposed fiber laser operates in near zero-dispersion regime. Fig. 2(a) presents the typical optical spectrum of the output DMSs. Different from the CSs formed in anomalous-dispersion regime, the DMSs are characterized by a broadband and smooth spectrum, where no Kelly sidebands are observed. The optical spectrum centers at 1580 nm and the 3-dB bandwidth is around 45 nm. The corresponding autocorrelation trace depicted in Fig. 2(b) declares a pulse width of 3.5 ps with the assumption of a Gaussian pulse shape. The time-bandwidth product is about 18.9, indicating that the output pulses are strongly chirped. It is well known that SMF with anomalous dispersion at 1550 nm can be used to dechirp the DMSs for pulse-width compression. According to the transformed limit of the Gaussian pulse, it is deduced that the pulse width of the chirped DMSs could be compressed to less than 100 fs. Thus, the fiber pigtail between the output of the fiber laser and the measurement setup will compress the pulse width of the DMSs. The measured pulse width of 3.5 ps is essentially narrower

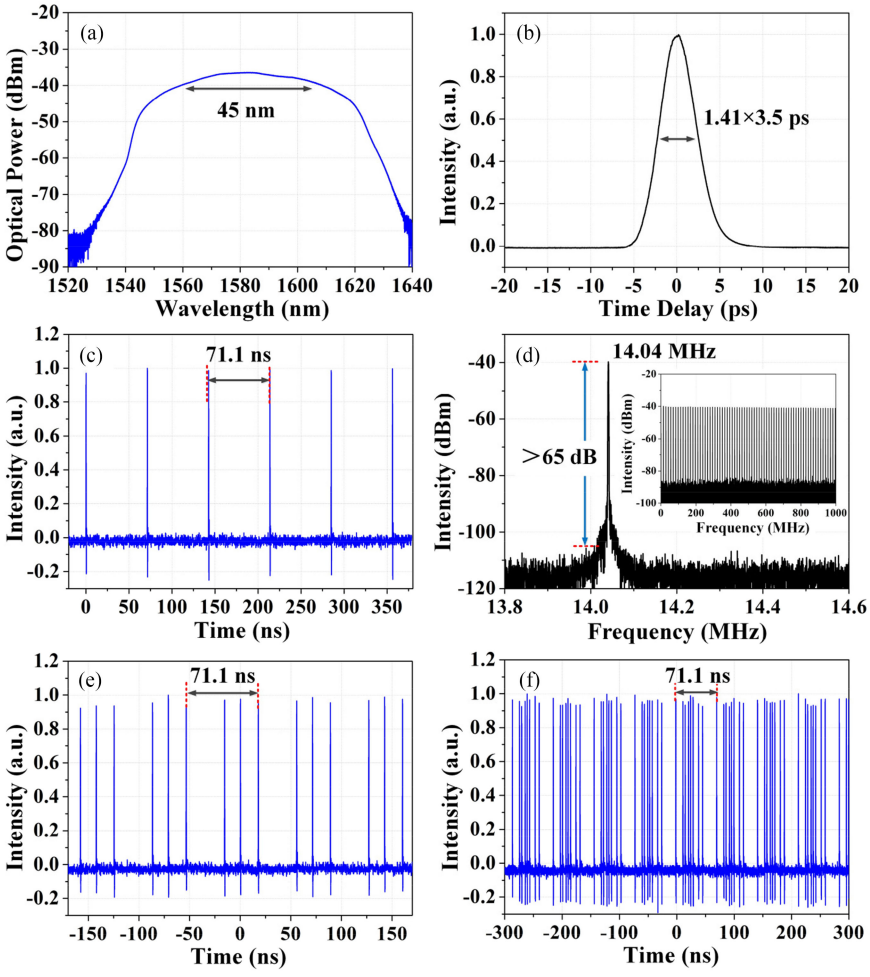

Fig. 2. Generation of DMS singlets: (a) optical spectrum and (b) autocorrelation trace of the DMS singlets; (c) oscilloscope trace and (d) RF spectrum (Inset: RF spectrum in 1 GHz span) of the fundamental mode-locked DMS singlets; (e) three-pulse state and (f) eight-pulse state.

than that of the direct output pulses. By adjusting the pump power to the level slightly lower than the mode-locking threshold, fundamental mode-locking state is obtained due to the hysteresis effect. Fig. 2(c) and (d) respectively show the oscilloscope trace and radio frequency (RF) spectrum of the fundamental mode-locked DMSs. The pulse interval is 71.1 ns, which agrees with the fundamental repetition rate of 14.04 MHz. The RF signal-to-noise ratio is beyond 65 dB, and the inset of Fig. 2(d) illustrates the broadband RF spectrum. It should be noted that the noisy pedestal observed in the RF spectrum is most likely ascribed to the background noise accompanying with the DMSs. Another possibility is that the bandwidth of the Photon detector (PD) and the resolution of the electrical spectrum analyzer (ESA) may also bring about this kind of pedestal in RF spectrum. By increasing the pump power, multiple DMSs are also obtained. Fig. 2(e) and (f) present the three-pulse and eight-pulse states. These DMS singlets provide the possibility for various molecule evolutions in this near zero-dispersion fiber laser.

3.2 DMS Molecules With Equal Pulse Separations

Through finely manipulating the operation parameters of the fiber laser (including the pump strength and the intra-cavity polarization states), various molecule evolutions originating from these DMS

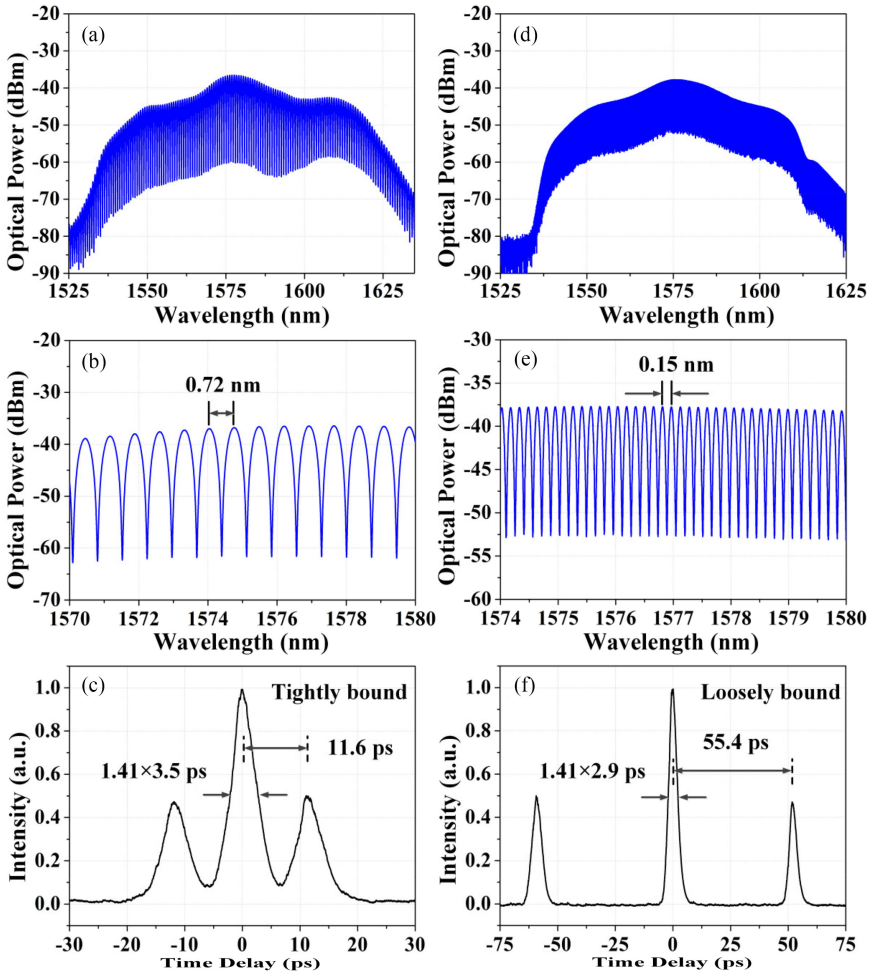

Fig. 3. Generation of DMS pairs: (a) optical spectrum, (b) enlarged optical spectrum, (c) autocorrelation trace of the tightly bound DMS pair; (d) optical spectrum, (e) enlarged optical spectrum, (f) autocorrelation trace of the loosely bound DMS pair.

singlets are obtained. Particularly, with a pump power of 110 mW, two-pulse DMS molecules, namely DMS pairs, are experimentally observed as shown in Fig. 3. The optical spectrum depicted in Fig. 3(a) is characterized by obvious modulated spectral fringes, implying the formation of 'molecules'. Fig. 3(b) presents the enlarged spectrum, where the spectral modulation period is about 0.72 nm. The DMS pair can be further validated by the distinct autocorrelation trace as shown in Fig. 3(c). The pulse width of the individual DMS is 3.5 ps, and the pulse separation is 11.6 ps, which is in accordance with the spectral modulated period of 0.72 nm. The pulse separation is around 3.3 times (less than 5 times) of the pulse width. Thus it can be seen that two DMS singlets are tightly bound together to form the pair [29]. In addition to the tightly bound state, loosely bound DMS pair is also obtained as presented in Fig. 3(d)–(f). The optical spectrum is strongly modulated as well. The spectral modulation period of 0.15 nm agrees with the pulse separation of 55.4 ps, which is about 19.1 times (more than 5 times) of the pulse width of 2.9 ps. Therefore, this DMS pair is loosely bound [29]. Moreover, the autocorrelation traces shown in Fig. 3(c) and (f) possess the same peak-to-peak ratio of 1:2:1. Thus it can be seen that the both the tightly and loosely bound pairs compose of two DMSs with an identical pulse intensity.

Apart from the DMS pairs, multi-pulse DMS molecules can be delivered from this near zero-dispersion fiber laser as well. Fig. 4(a)–(c) present the generation of three-pulse molecule, namely

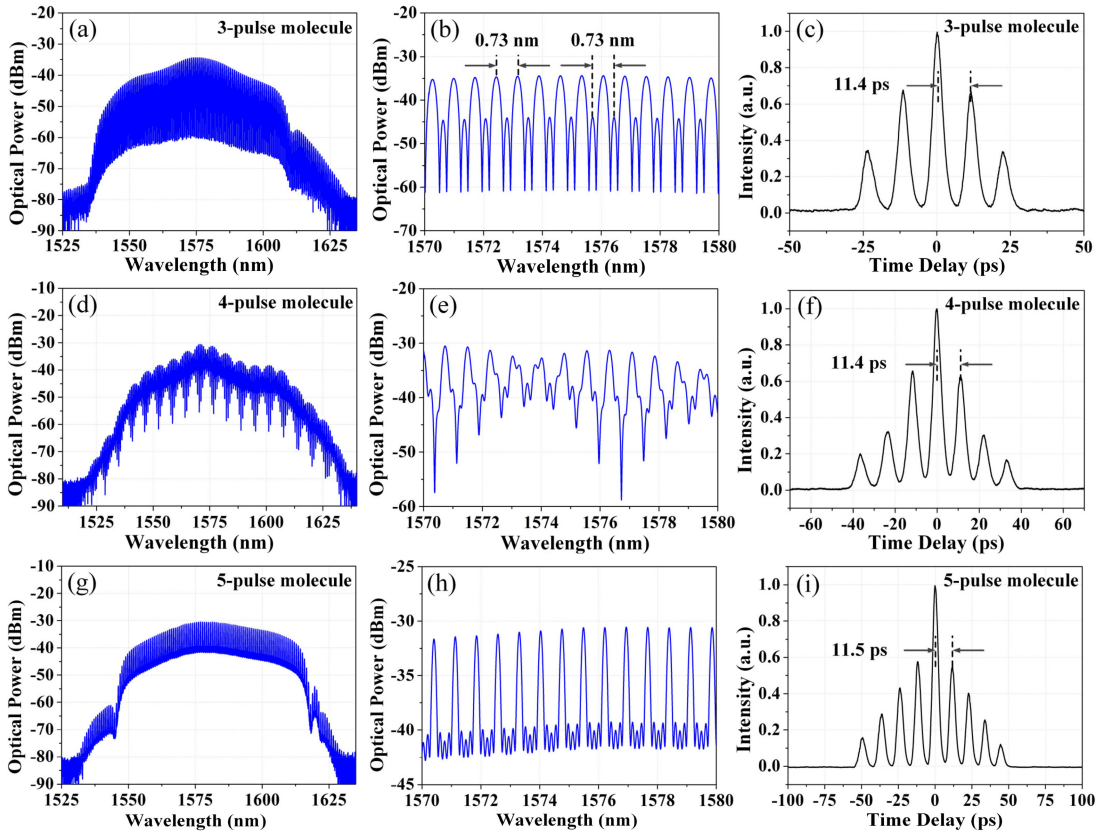

Fig. 4. Generation of multi-pulse DMS molecules: (a) optical spectrum, (b) enlarged optical spectrum, and (c) autocorrelation trace of the DMS triplet; (d) optical spectrum, (e) enlarged optical spectrum, and (f) autocorrelation trace of the four-pulse DMS molecule; (g) optical spectrum, (h) enlarged optical spectrum, and (i) autocorrelation trace of the five-pulse DMS molecule.

a DMS triplet, with the pump power of 160.3 mW. Compare to the spectrum of the DMS pair, the spectrum of the DMS triplet, as shown in Fig. 4(a) and (b), becomes relatively complicated. The modulated spectrum exhibits that a sub-maximum peak centers at the two adjacent maximum peaks. Wavelength differences of the adjacent maximum peaks and sub-maximum peaks are both 0.73 nm. Notably, five peaks exist on the autocorrelation trace of the DMS triplet. The peak-to-peak ratio is 1:2:3:2:1 and the separations of the adjacent peaks are 11.4 ps, which manifests that the molecule is formed by three identical DMSs with the same pulse separation of 11.4 ps. Through increasing the pump power to 187.1 mW, four-pulse DMS molecule is also obtained with appropriate PC settings as recorded in Fig. 4(d)–(f). Surprisingly, twofold spectral modulation and blurred interference fringes are observed on the optical spectrum. Meanwhile, the peak-to-peak ratio of the correlation trace is no longer 1:2:3:4:3:2:1. These unexpected phenomena are most likely attributed to the slight fluctuation of the pulse separation inside the molecule. The optical spectra and the autocorrelation traces are actually the average-recorded results. The pulse separation is estimated to be 11.4 ps. In addition, a five-pulse DMS molecule is generated with the pump power of 198.5 mW as illustrated in Fig. 4(g)–(i). Three sub-maximum peaks can be clearly observed and nine peaks exist on the autocorrelation trace. Since no twofold modulation is observed on the spectrum, the reduction of the peak-to-peak ratio might be ascribed to the unequal intensity of the bound pulses inside the molecule. The pulse separation is around 11.5 ps. From the experimental results, we can conclude that the sub-maximum peaks on the optical spectrum can be a visualized indicator for the multi-pulse molecules.

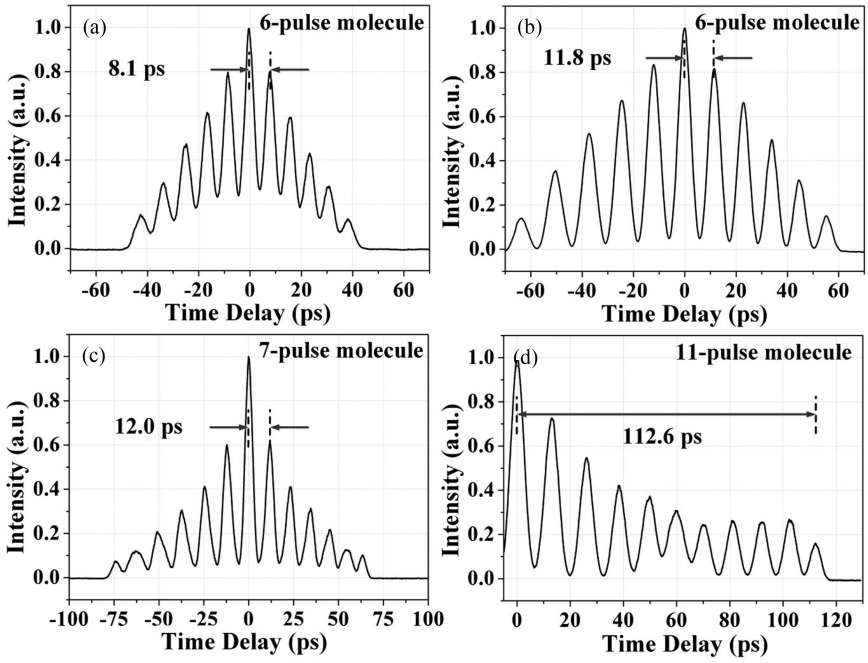

Fig. 5. Autocorrelation traces of (a) and (b) 6-pulse molecules, (c) 7-pulse molecule, and (d) 11-pulse molecule.

Furthermore, it is generally find that the number of pulses inside the molecules can be increased by increasing the pump strength and the intra-cavity polarization state. Particularly, six-pulse DMS molecules with different pulse separations are observed as presented in Fig. 5(a) and (b). Eleven peaks exist on the autocorrelation traces and both of these two types of molecules possess a peak-to-peak ration of 1:2:3:4:5:6:5:4:3:2:1. The pulse separations are respectively 8.1 ps and 11.8 ps. Fig. 5(c) shows the autocorrelation trace of the seven-pulse molecule, where thirteen peaks exist with a pulse separation of 12.0 ps. Moreover, eleven-pulse DMS molecule is the largest molecule observed here with the pump power of 287.7 mW. Limited by the measurement range of the autocorrelator, Fig. 5(d) only displays the one-side autocorrelation trace of the eleven-pulse molecule. The pulse envelope width of the molecule exceeds 100 ps, which requires a relatively strong binding force. As a result, the eleven-pulse DMS molecule is susceptible to dissociation and further evolve into smaller DMS molecules or bunch of molecules.

3.3 DMS Molecules With Unequal Pulse Separations

The aforementioned DMS molecules are assembled with an equal pulse separation, which paves a potential way to the (1010) type of coding. However, more flexible types of coding are needed for practical applications, straightforwardly calling for the irregularly spaced molecules. By carefully manipulating the parameters of the dispersion-managed fiber laser, DMS molecules with unequal separations is obtained. Different from the equally spaced molecules characterized by regular autocorrelation traces, the unequally spaced molecules possess relatively complicated autocorrelation traces due to their complex multi-pulse structures, thus impeding the direct insight into the pulse distribution in time domain. Fig. 6 illustrates one kind of the unequally spaced DMS molecule. The optical spectra of this DMS molecule depicted in Fig. 6(a) and (b) are twofold modulated. The spectral modulation periods are respectively 0.69 nm and 0.14 nm. Fig. 6(c) presents the corresponding autocorrelation trace, where seven peaks exist with different pulse separations. Here, by conducting the numerical simulation [41], the pulse distribution of this molecule can be resolved as shown in

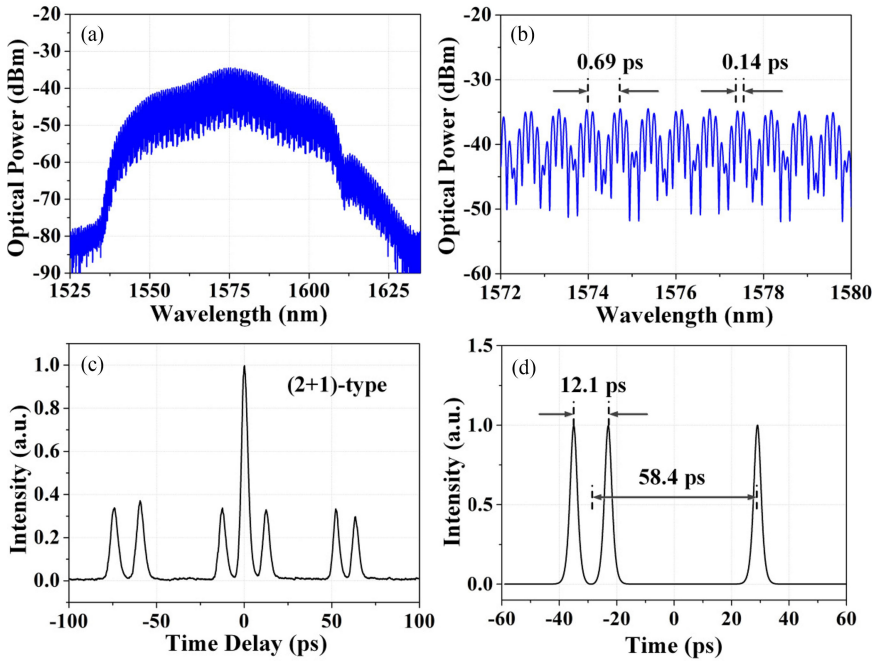

Fig. 6. Generation of (2 + 1)-type molecule: (a) optical spectrum, (b) enlarged optical spectrum, (c) autocorrelation trace, (d) pulse distribution.

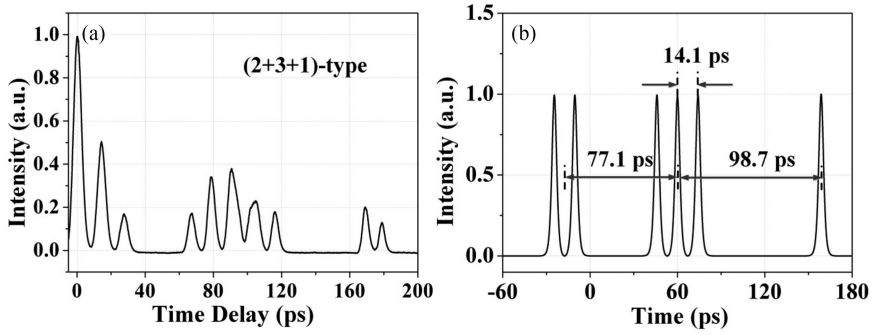

Fig. 7. Generation of (2 + 3 + 1)-type molecule: (a) autocorrelation trace, (b) pulse distribution.

Fig. 6(d). It should be noted that for a given autocorrelation trace, we may find two or more possible pulse distributions through using the solving method of the dispersive signal. Indeed, the actual pulse distribution also needs to obey another role that the multi-pulse molecule is usually dense in the front part and spares in the end part. We find that three DMSs are bound with different pulse separations to form the so-called (2 + 1)-type molecule, which can be also interpreted as a molecule assembled by a DMS pair and a DMS singlet. Particularly, the pulse separation of the DMS pair is 12.1 ps, agreeing with the spectral modulation period of 0.69 nm. The pulse separation between the DMS singlet and the pair is 58.4 ps, which is in accordance with the spectral modulation period of 0.14 nm.

Moreover, another kind of unequally spaced DMS molecule can be also delivered. The one-side autocorrelation trace presented in Fig. 7(a) is much more complicated than the (2 + 1)-type counterpart. The simulated pulse distribution depicted in Fig. 7(b) declares that this is a (2 + 3 + 1)-type molecule formed by a DMS triplet, a DMS pair and a DMS singlet. It is found that

broadened pulse profile can be observed in the autocorrelation trace, which is most likely ascribed to the slight fluctuation of the pulse separation induced by soliton molecules vibration inside the multi-pulse molecules. Meanwhile, the resulted reduction of the peak-to-peak ratio is neglected in the simulation. The pulse separations are respectively illustrated in Fig. 7(b). Thus it can be seen that both the strong soliton interaction force and the weak soliton interaction force play crucial roles in the formation of this unequally spaced DMS molecules. In addition, both the DMS singlets and the DMS molecules can act as a unit and interact with each other to approach a more complex molecule evolution. These multi-pulse molecules are highly desirable for the potential applications of ultra-high-capacity optical communications based on advanced modulation formats.

4. Conclusion

In conclusion, we report on the observation of DMS molecules in a near zero-dispersion fiber laser. The experimental results reveal that by appropriately setting the laser parameters, these DMS singlets can be flexibly assembled to approach various molecule evolutions. Particularly, tightly/loosely bound DMS pairs and three-pulse to eleven-pulse DMS molecules are observed. It is found that the sub-maximum peaks can be a visualized indicator of the multi-pulse molecules. Apart from the equally spaced molecules, unequally spaced molecules are also obtained, respectively including the $(2 + 1)$-type molecule and the $(2 + 3 + 1)$-type molecule. The strong and weak soliton interaction forces jointly play crucial roles in the formation of these more complex molecules. Additionally, numerical simulations are carried out to confirm the pulse distributions in time domain. Overall, the investigation of multi-pulse molecules enriches the life of ultrashort pulses beyond traditional pulse singlets, as well as provides a fascinating conceptual route to the potential applications of ultra-high-capacity optical communications based on advanced modulation format.

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