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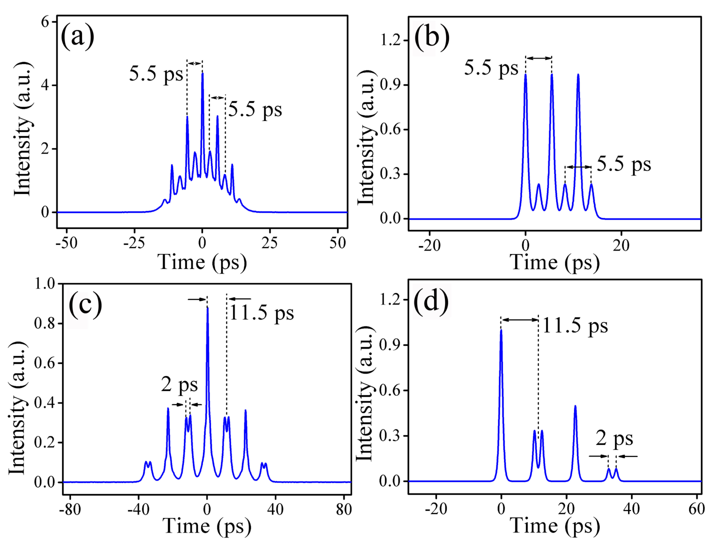

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Broadband Dispersion-Managed Dissipative Soliton and Structural Soliton Molecules in a Slight-Normal Dispersion Fiber Laser

Xu-De Wang[1], **Meng-Qiu Sun**[1], **Si-Min Yang**[1], **Jie-Yu Pan**[1], **and Su-Wen Li**[1,2]

[1]School of Physics and Electronic Information, Huaibei Normal University, Huaibei 235000, China
[2]Anhui Province Key Laboratory of Pollutant Sensitive Materials and Environmental Remediation, Huaibei Normal University, Huaibei 235000, China

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Abstract: We report on the generation of dispersion-managed dissipative soliton and various structural soliton molecules from a slight-normal dispersion fiber laser. The laser was capable of generating 56.5 nm broad dissipative solitons with quasi-rectangular spectral profile. Furthermore, the broadest top-flat spectrum with up to 71.4 nm bandwidth was achieved in the noise-like pulse regime, operating in the 1542–1613.4 nm. More importantly, by manipulating the laser cavity parameters, various types of soliton molecules, including conventional and unusual structural soliton molecules, were observed in fiber laser. The soliton molecules exhibit different features in autocorrelation traces, which are found to be related to soliton number, soliton intensity and soliton separation within the soliton molecules. The results contribute to enriching the soliton dynamics in the fiber lasers in the slight-normal dispersion regime.

Index Terms: Fiber lasers, mode-locked lasers, dissipative soliton, soliton molecules.

1. Introduction

Passively mode-locked fiber lasers, which have the capacity for generating ultrashort pulses, have been extensively investigated owing to their potential applications in optical communication, nonlinear optics, optical sensing, and micromachining [1], [2]. Until now, various techniques have been proposed to realize reliable mode locking operation, including real material saturable absorber such as semiconductor saturable absorber mirror (SESAM), carbon nanotube (CNT), graphene, topological insulator (TI), and transition metal dichalcogenides [3]–[7], and artificial saturable absorber including nonlinear polarization rotation (NPR), nonlinear optical loop mirror (NOLM) [8]–[9]. Among them, NPR technique, as a mature cavity design method, exhibits merits of simple construction, easy implementation and high damage threshold and has been widely used for initiating mode locking operation.

It is well known that the fiber laser can realize mode locking in anomalous dispersion, normal dispersion, and near-zero dispersion regimes. In different dispersion regimes, various kinds of solitons have been achieved in the past few years, such as conventional soliton, dissipative soliton, self-similar pulse and dispersion-managed soliton (DMS) [10]–[13]. Among them, DMS around zero-dispersion region has drawn massive attention for the capability of generation of ultrashort pulse with broadband spectrum [14]. If the cavity dispersion is tailored properly (i.e., near zero but net-normal dispersion regime), the broadband mode-locking rectangular spectrum with several tens of nanometers would be achieved [15], [16]. In addition, due to arranging alternately positive and negative dispersion fiber in the fiber laser, the DMSs will be periodically stretched and compressed during propagating in the laser cavity, which could result in the partial overlap of pulses [17]. Hence, it is expected that the DMSs are susceptible to the formation of soliton molecules.

Soliton molecule, also termed as soliton bound state, is comprised of several individual solitons with constant temporal separation and invariant phase difference, which was firstly predicted theoretically by Malomed et al in 1991[18]. Soliton molecule is formed due to the balance of repulsive and attraction forces between solitons by nonlinear and dispersive effects [19]. Their spectra are usually characterized by periodic modulation [20]. So far soliton molecules have been investigated by simulated and experimental methods in types of fiber laser cavities [21]–[24]. Due to the strong interaction via soliton overlapping, soliton molecules have also been observed in dispersion-managed fiber lasers [25]–[29]. As early as 2007, Zhao et al have investigated various bound states in the dispersion-managed fiber laser [27]. Utilizing grating pairs as dispersion compensation element, Lin et al have reported the multiple bound solitons and bound states of multiple solitons in Yb-doped fiber laser around zero dispersion regime [28]. Employing dispersion compensation fiber to manage the cavity dispersion, Luo et al observed equally spaced molecules and unequally spaced molecules in the fiber laser [29]. To date, most studies are mainly focused on large-normal/anomalous dispersion regimes, and the investigation of soliton molecules is relatively fewer in dispersion-managed fiber laser, especially in a slight-normal-dispersion fiber laser. The researches mainly concentrated on formation mechanism, harmonic property, vector feature, number of bound solitons, phase relation, dynamic evolution, and so on. However, the investigations on more complicated soliton compounds are still insufficient. Therefore, an extended investigation of soliton molecular complexes with multi-pulse structures would be undoubtedly significant. Considering complex evolutions of soliton molecules in formation process, it would be interesting to know whether soltion molecules with special soliton structure could be observed in the slight-normal dispersion fiber laser.

In this paper, dispersion-managed soliton and various structural soliton molecules are observed from a slight-normal dispersion fiber laser. Relying on NPR technology, dispersion-managed soliton with the ultra-broadband spectrum of 56.5 nm is generated from the slight-normal dispersion fiber laser. By regulating cavity parameters, a broader output spectrum can be obtained in the noise-like pulse (NLP) regime, which could be up to 71.4 nm bandwidth. More importantly, in our experiment, various types of soliton molecules, including conventional molecules and structural molecules, were observed in fiber laser. The soliton molecules exhibit different features in ACs, which are found to be caused by the different peak intensities and pulse separations between pulses within the soliton molecules.

2. Experimental Setup

The laser cavity in experiment is shown in Fig. 1. It consists of a wavelength division multiplexed (WDM) coupler, a 7 m long erbium doped fiber (EDF) with a dispersion coefficient of -18.5 ps/nm/km, a polarization dependent isolator (PI-ISO), an optical coupler (OC) with 20% output, and two set of PCs. Here, the PD-ISO is used to guarantee the light propagate unidirectionally in the resonant cavity. The PCs are used to change the polarization state of pulse transmission in the fiber laser. Meanwhile, the NPR structure constituted by the PD-ISO and two PCs is used

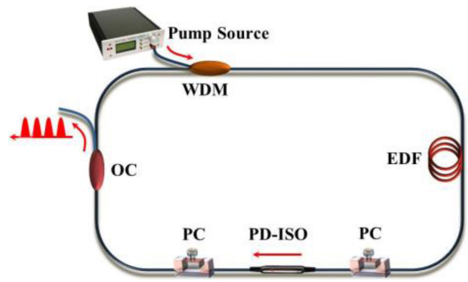

Fig. 1. Experimental setup of the ring fiber laser with slight-normal cavity dispersion.

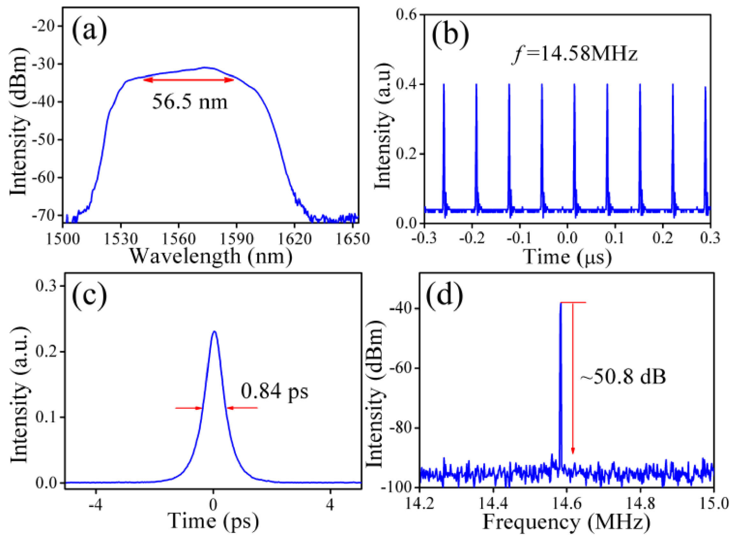

Fig. 2. Dissipative soliton operation. (a) Spectrum. (b) Oscilloscope trace. (c) AC. (d) RF spectrum.

to realize artificial saturable absorber to promote the pulse formation. The residual fiber is the fiber pigtail of optical devices, which is single mode fiber (SMF) with a length of 7.2 m and a dispersion coefficient of 17 ps/nm/km. The anomalous dispersion of SMF is compensated by the normal dispersion of EDF. Therefore, the estimated net cavity dispersion is at the level of ~0.0077 ps^2, which exhibits slight normal net dispersion. The total cavity length is 14.2 m, resulting in the fundamental repetition frequency of 14.58 MHz. The pulse train and spectrum are simultaneously monitored by a digital oscilloscope and optical spectrum analyzer. Moreover, the pulse profile is measured by an autocorrelator and the stability of the mode locking is measured by a radio frequency spectrum analyzer.

3. Experimental Results and Discussions

3.1. Fundamental Mode-Locking and Noise-Like Pulse Operation

At pump power of 160 mW, the robust and stable single-pulse operation could be generated as shown in Fig. 2. The laser generates a very broad and smooth spectrum as shown in Fig. 2(a). The spectrum exhibits quasi-rectangular profile, which is the typical feature for dissipative soliton in the normal dispersion regime [30]. Here, the 3 dB spectral bandwidth can be up to 56.5 nm and the central wavelength is about 1566 nm. The oscilloscope trace of pulse operation in Fig. 2(b) indicates that the pulse repetition rate is about 14.58 MHz, which corresponds to the time interval between sequential pulses of about 68.6 ns. The AC is shown in Fig. 2(c). Taken on a Gaussian

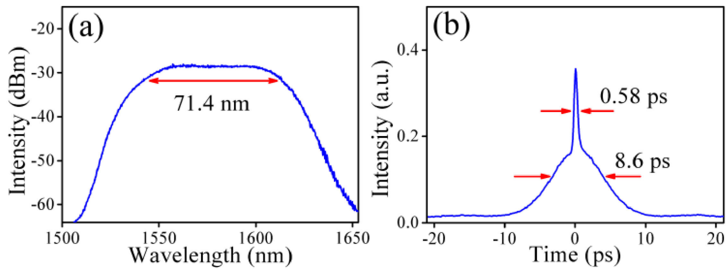

Fig. 3. Noise-like pulse operation. (a) Spectrum. (b) AC.

shape, the width of the single pulse is 0.84 ps. Therefore, the time bandwidth product (TBP) is 5.8, denoting that the pulse is highly chirped. The radio frequency (RF) spectrum exhibited high contrast near 51 dB as shown in Fig. 2(d), indicating low-amplitude fluctuations in the mode-locking state. However, due to operating at near zero dispersion, the laser tends to produce multi-pulse in cavity. By increasing the pump power, multi-soliton operation is also easily obtained in the fiber laser. The emergence of multiple solitons indicates that overdriven nonlinearity exists in this fiber laser, which could be conducive to pulse splitting.

Due to the mode locking state sensitive to the cavity parameter, by adjusting the rotation angle of the PC, the dissipative soliton can evolve into noise-like pulses (NLP) in a fiber laser. When the noise-like mode locking is triggered, the spectrum bandwidth would be further broadened, which is much larger than the one of dissipative soliton. The NLP with ultra-broadband spectrum is shown in Fig. 3(a). The flat-top spectrum centers at 1577.7 nm and the 3-dB bandwidth is 71.4 nm, which covers from 1542 nm to 1613.4 nm. The 10-dB spectral bandwidth can even reach ~100 nm. The AC in Fig. 3(b) shows that a narrow coherent spike locates on top of a smooth pedestal with several picoseconds, which is a typical feature of a broadband NLP operation as observed in the previous results [16]. Assuming Gaussian pulse profiles, the widths of the pedestal and the spike are 8.6 ps and 0.58 ps, respectively. The spike-to-pedestal intensity ratio is about 0.5, indicating that the intensities of the subpulses inside the NLP vary randomly [31].

3.2. Conventional Soliton Molecules

Enlarging pump power and adjusting PCs, soliton molecule operation can be obtained at a pump power of 320 mW. Fig. 4(a) shows the typical spectrum of the two-pulse soliton molecule. The spectrum has quasi-rectangular spectral profile with dense modulation, which exhibits the pronounced feature of the soliton molecule [32], [33]. The enlarged spectrum in the inset of Fig. 4(a) shows that the spectral modulation period is 0.6 nm, implying that the inter-pulse separation is 13.5 ps. Fig. 4(b) shows the AC with three peaks, which clearly indicates the existence of two subpulses with the separation of 13.5 ps. The pulse separation is around 12.3 times of the pulse width (~1.1 ps), indicating the two subpulses are loosely bound [19], [34]. According to the intensity ratio of three peaks (1:2:1), one can infer that the two subpulses are identical. Appropriately adjusting the PC, the tightly soliton molecule can also be observed. Due to operating in the slight-normal dispersion regime, the spectrum exhibits sharp edges and has a broad spectral bandwidth of 70 nm as shown in Fig. 4(c). The spectral modulation has a spatial period of 0.97 nm. The AC in Fig. 4(d) shows the pulse time separation is 8.5 ps, which matches the spectral modulation period. The pulse duration is ~2.4 ps. Thus, the inter-pulse separation is ~3.5 times the pulse width, demonstrating that the subpulses inside soliton molecule are tightly bound with each other. It should also be noted that the modulation depth of the spectrum increases with the decrease in soliton separation. Thus, tightly soliton molecule exhibit larger modulation depth on the spectrum as smaller pulse separation causes stronger mutual interaction between solitons.

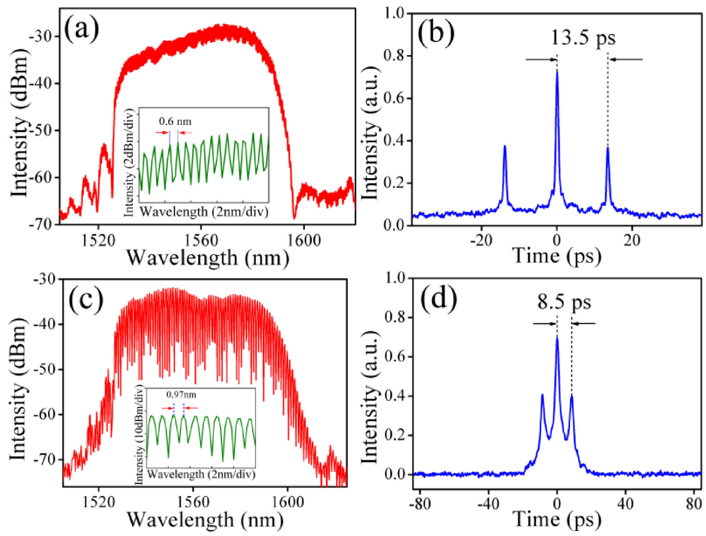

Fig. 4. Loosely and tightly two-soliton molecules. (a) Spectrum and (b) AC for loosely soliton molecule. (c) Spectrum and (d) AC for tightly soliton molecule.

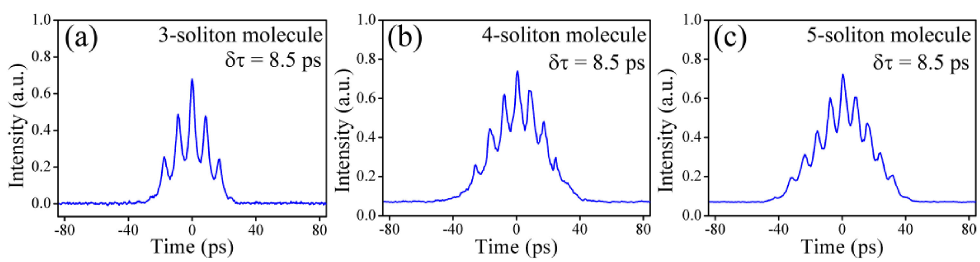

Fig. 5. Multi-soliton molecule with fixed soliton separation. ACs of (a) 3-soliton, (b) 4-soliton, and (c) 5-soliton molecule.

Increasing pump power and fixing the state of PCs, the soliton number inside soliton molecules is increased one by one due to soliton energy quantization effect, heralding the generation of multi-soliton molecules. Fig. 5 shows the ACs of 3-soliton, 4-solition and 5-soliton molecules, respectively. The AC in each state exhibits symmetrical triangular envelope. The peak-to-peak spacing is equidistant and the intensity ratios are 1:2:3:2:1 for Fig. 5(a), 1:2:3:4:3:2:1 for Fig. 5(b), and 1:2:3:4:5:4:3:2:1 for Fig. 5(c). These results indicate that all the solitons in the molecules are identical and the soliton separations are fixed at 8.5 ps.

3.3. Structural Soliton Molecules

Because soliton molecule is vulnerable to cavity parameters, different soliton molecules can be easily obtained by appropriate adjustment of the PCs. The aforementioned soliton molecules with regular triangle autocorrelation profile are assembled with identical sub-solitons, here, novel soliton molecules with more fine structures in AC are also observed in the fiber laser. Fig. 6 presents two structural soliton molecules with alternate soliton intensities. The ACs shown in Fig. 6(a) and 6(c) exhibit jagged peaks in the profile, distinct from the conventional AC with triangle intensity distribution. The peaks of high and low intensities are interleaved and the peak-to-peak spacing is equidistant. The spacing between high intensity peaks is 15.4 ps for Fig. 6(a) and 5.5 ps for Fig. 6(c), respectively. The corresponding spectra of these soliton molecules depicted in Fig. 6(b)

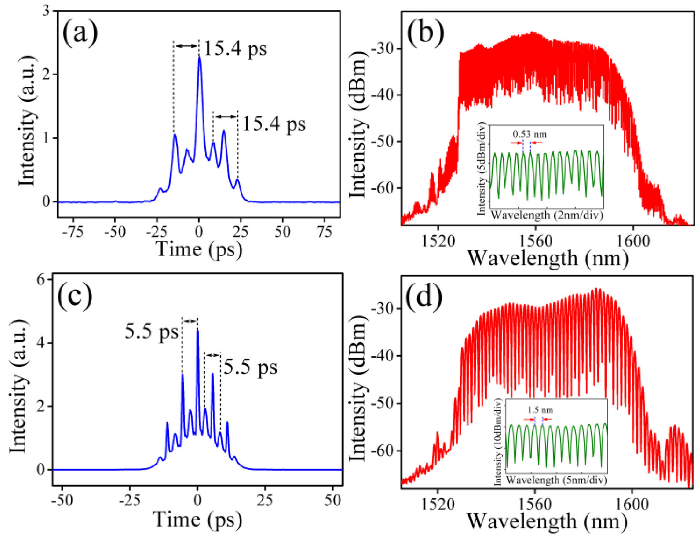

Fig. 6. Structural soliton molecules with alternate soliton intensities. (a) AC and (b) spectrum for 4-solion molecule. (c) AC and (d) spectrum for 6-soliton molecule.

and Fig. 6(d) are strongly modulated. From the magnified sections of the spectra shown in inset of Fig. 6(b) and Fig. 6(d), we can see that the spectral periods are 0.53 nm and 1.5 nm, corresponding to the pulse separation of 15.4 ps and 5.5 ps, respectively.

Due to significant difference in ACs between regular and structural soliton molecules, we believed that there exist fine structures inside the soliton molecules. In order to clarify the pulse distribution inside these molecules, we have conducted the numerical simulation similar to the method described in [35]. For a four-soliton molecule, it can be described in the time domain by

$$u(t) = a \bullet f(t) + b \bullet f(t - t_1)\, exp\,(j\theta_1) + c \bullet f(t - t_2) \exp(j\theta_2) + d \bullet f(t - t_3) \exp(j\theta_3) \qquad (1)$$

Here, $u(t)$ and $f(t)$ represent temporal envelope of a four-soliton molecule and a single soliton, respectively. a, b, c and d are relative intensities of four solitons. t_1, t_2 and t_3 are soliton separations. θ_1, θ_2 and θ_3 are phase differences.

The simulation results are shown in Fig. 7. As shown in Fig. 7(a), high and low intensity pulses arrange alternately inside the soliton molecule. In other word, two sets of pulses with different intensities constitute a soliton molecule. The spacing between pulses is equal and the intensity ratio is 3.5:1. The profile of AC in Fig. 7(b) is good agreement with the direct measured one in Fig. 6(a). Fig. 7(c) shows the soliton molecule essentially consists of six subpulses. High and low intensity pulses are alternately distributed. According to pulse intensity, six subpulses can be regarded as two groups. The intensity ratio of the two groups is 4.1:1. The corresponding AC is shown in Fig. 7(d), which exhibits the similar fine structure as the measured one in Fig. 6(c). Therefore, the simulation results confirm the pulse distribution inside soliton molecules. We can regard as this type of molecule assembled by two sets of pulses with alternate soliton intensities.

Due to soliton splitting and strong soliton interaction in the dispersion-managed fiber laser, more complicated structural soltion molecules can be generated in the fiber laser as well. Fig. 8 shows two types of novel soliton molecules with unusual AC. As shown in Fig. 8(a), there are nine peaks appeared on the AC. Every three peaks behave as a unit. There exit two different temporal intervals between peaks, corresponding to 1.6 ps and 6.4 ps respectively, which imply that twofold modulation would be generated on the spectrum. As expected, the spectrum depicted in Fig. 8(b) is double modulated and the spectral periods are 5.18 nm and 1.27 nm as shown in Fig. 8(c), which is consistent with the two temporal intervals of 1.6 ps and 6.4 ps. Another kind of complicated soliton molecule, which has not been reported in the previous literature, is observed as shown in Fig. 8(d).

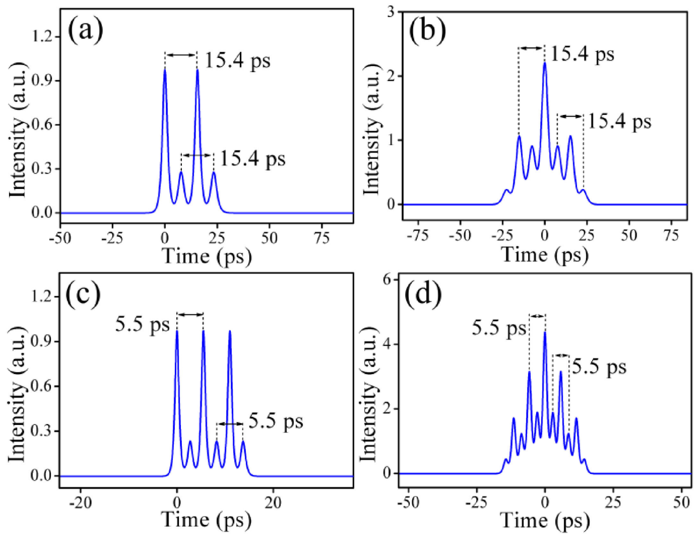

Fig. 7. Simulation results of structural soliton molecules with alternate soliton intensities. (a) Soliton distribution and (b) AC for 4-solion molecule. (c) Soliton distribution and (d) AC for 6-soliton molecule.

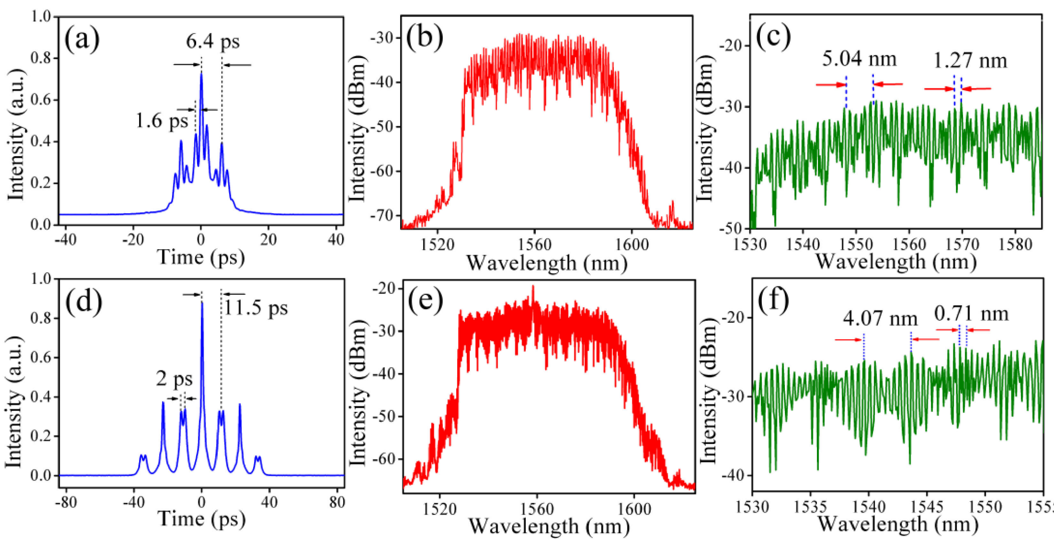

Fig. 8. (2+2)-type and (1+2+1+2)-type structural soliton molecules. (a) AC, (b) spectrum and (c) zoom-in of the spectrum for (2+2)-type molecule. (d) AC, (e) spectrum and (f) zoom-in of the spectrum for (1+2+1+2)-type molecule.

The soliton molecule seems to be composed of several single solitons and soliton pairs. The peak separation within soliton pair is 2 ps and the separation between a single soliton and soliton pair is 11.5 ps. As presented in Fig. 8(e) and Fig. 8(f), we can see that the spectrum is also twofold modulated and the modulation periods are 4.07 nm and 0.71 nm, respectively.

In order to verify the “soliton atoms” inside the soliton molecules, the similar numerical simulation method is used again to reconstruct the soliton distribution. According to experimental ACs presented in Fig. 8(a) and Fig. 8(d), the corresponding soliton distribution inside the soliton molecules is recovered in Fig. 9(a) and Fig. 9(c). From the Fig. 9(a), we can see that two solitons behave as a group. Then, two groups with amplitude ratio of 1.7 are further bind together to

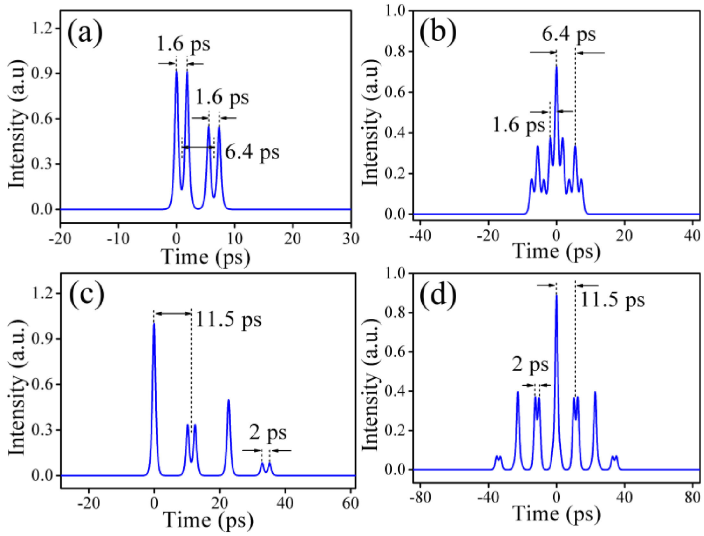

Fig. 9. Simulation results of (2+2)-type and (1+2+1+2)-type structural soliton molecules. (a) Soliton distribution and (b) AC for (2+2)-type molecule. (c) Soliton distribution and (d) AC for (1+2+1+2)-type molecule.

form a soliton molecule. The soliton separation inside every group is 1.6 ps and the separation between groups is 6.4 ps. Therefore, this type of soliton molecule is termed as (2+2)-type molecule, which is assembled by two solion-pairs. In the Fig. 9(c), the soliton molecule is constituted by two single-solitons and two soliton-pairs with different intensities. The pulse separation between the single-soliton and the soliton-pair is 11.5 ps, agreeing with the small modulation period of 0.71 nm. The separation inside soliton-pair is 2 ps, which is in accordance with the large modulation of 4.07 nm. Therefore, we can term this type of soliton molecule as (1+2+1+2)-type molecule. The simulated ACs are shown in Fig. 9(b) and Fig. 9 (d), which is almost perfectly consistent with the measured ones shown in Fig. 8(a) and Fig. 8(d). Therefore, the simulated results further corroborate the assumption about the soliton distribution inside soliton molecules.

As far as we know, the formation of multiple solitons is related to the accumulated cavity nonlinear effects. When overdriven nolinear effects exist in the laser cavity, the multipulse operation is unavoidable due to the so-called pulse splitting. Generally, the generated multiple solitons are randomly arranged in the cavity and can exhibit various soliton behaviors, such as soliton cluster, harmonic soliton and soliton molecule because of complex interactions from gain, loss, nonlinearity, dispersion. However, through adjusting PCs, the interactions between solitons can be changed and multiple solitons rearrange themselves in the cavity. Once fixed phase difference and constant separation between solitons are formed, multiple solitons will be bound together to form various soliton molecules. Therefore, the soliton number inside soliton molecules mainly depends on the pump power due to the soliton splitting, and the phase relationships of the multiple solitons are sensitive to the setting of PCs which eventually affect the soliton temporal distribution. In our experiment, we observed soliton molecules with diverse structural ACs. It is found that the fine structure of ACs is closely related to soliton number, soliton intensity and soliton separation. When soliton molecule is composed of solitons with equal intensity and equal separation, the conventional AC trace with a regular triangular envelope will be formed. Whereas, the AC trace with complicated structural envelope is formed due to unequal soliton intensities or/and unequal soliton separations [36]. Moreover, unequal separations between solitons are also responsible for the double modulation periods of optical spectrum. In addition, considering real-time diagnostic method based on the dispersive Fourier transformation (DFT) [37], [38], the routine detection of soliton behaviors is insufficient to some extent. Therefore, we would like to make more efforts on the real-time observation of bound states in the future, which would be beneficial for further investigating the versatile features of soliton molecules.

4. Conclusion

In conculsion, we report on the generation of dispersion-managed soliton and various structural soliton molecules from a slight-normal dispersion fiber laser. The fiber laser emits the dissipative sotion with the broadband spectrum of 56.5 nm and the NLP with the bandwidth of 71.4 nm. More importantly, due to soliton splitting and strong soliton interaction in the dispersion-managed fiber laser, various soliton molecules are observed, including conventional soliton molecules and special structural soliton molecules. Theoretical simulations are carried out to further confirm the experimental phenomena. The soliton molecules exhibit different features in ACs, which are found to be caused by the different peak intensities and pulse separations between pulses within the soliton molecules. The results contribute to explore the soliton dynamic characteristics in the slight-normal dispersion regime.

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