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Control of Multiple Solitons in Mode Locked Figure-of-Eight Micro Structured Fiber Lasers to Improve Soliton Stability

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Abstract

In long distance optical communication systems a solution to the problem of dispersion phenomenon of pulses as they travel along the fiber is optical solitons since they maintain their shape over long distances. Multiple solitons or pulses are formed when the pumping is increased in fiber lasers. The soliton bunches and bound states of soliton patterns formed due to the multiple solitons are in non-stationary state because of the oscillations within the bunch. Hence these multiple solitons may become unstable. To improve the stability of multiple solitons intensity modulation technique is used. In this paper a review on the multiple solitons, their stability and recently developed techniques to increase stability are discussed.

Keywords: Multiple solitons, soliton bunches, soliton bound states, SESAM

I. INTRODUCTION

Fiber is one among many other channels for communication. In high bit rate and long distance optical communication systems, the main problem observed is the dispersion of optical pulses .An alternative to this dispersing optical pulses are the optical solitons. Solitons are optical pulses that maintain their shape at constant speed. Solitons are formed when the negative group velocity dispersion and Kerr non-linearity of fiber comes in to a balance. Hence the stability of solitons are mainly based on these two effects.

Multiple solitons in optical fiber lasers are formed by the increase in pumping. Peak power limiting effect of the fiber laser cavity leads to the formation of multiple solitons in laser. Soliton collapse gets suppressed by the peak power limiting effect. In a passively mode-locked fiber lasers the operation of solitons exhibit a common feature – under the influence of strong pumping multiple solitons are always formed and soliton energy quantization [1], independent of the mode locking .The interaction of solitons leads to the formation of soliton bound states or oscillating bunches of solitons. The presence of dispersive wave in the fiber laser cavity leads to irregular soliton motion. And the soliton bunches become unstable as the solitons within the bunch interact together. Control of relative phases between the solitons is hence necessary for stability of the soliton groups formed. These can be done by considering the fiber cavity loss and mode locking.

II. MULTIPLE SOLITONS

Solitons in the fiber lasers formed by the balance between the negative cavity dispersion and Fiber Kerr non-linearity needs to be stabilized. The solitons which are adjacent to each other may interact and may leads to soliton instability. By band limited amplification (BLA) the interaction between adjacent solitons can be reduced to some extent. By using sliding filters the BLA induced soliton instability as well as soliton interactions are reduced [2]. The optical pulse shaping can be implemented in fiber lasers to generate ultra-short pulses. This involves mode locking techniques. Mode locking can be done by incorporating either an active element or a passive element with the fiber laser cavity. These elements play an important role in the formation of ultra-short pulses.

A. B. Grudinin and S. Gray [3] conducted an experimental and theoretical study on passive harmonic mode locking in soliton fiber lasers. Fiber non-linearity based mode locking in combination with the negative fiber cavity dispersion results in the formation of solitons. When pulses propagate in the fiber they experiences periodic loss and gain which leads to the formation of non-soliton components. The output of laser hence consists of both solitons and non-soliton components. These non-soliton components influence parameters of nearby solitons. Based on the phase difference between these soliton and non-soliton components, the adjacent solitons may attract or repel each other. The pump power fluctuations lead to a change in number of pulses circulating in the cavity. Also the parameters of individual solitons are not affected by the pump power-fluctuations .Suppression of non soliton component is best done in a fiber laser with a hybrid saturable absorber.

The excellent stability of duration and energy of each soliton pulses can be achieved by the effects of energy quantization of fiber soliton lasers. But this has a negative impact that it leads to pulse repetition rate instabilities. This problem can be avoided by operating the laser with just a single soliton pulse inside the fiber cavity, but this leads to another problem that this slows down the repetition rate and hence low output power. But this has become a problem since as the time advanced, high speed communication systems with multi gigahertz repetition rates became necessary. Studies have been focused mainly on harmonically mode locked configurations using active modulation techniques [3] – [4] since it was too difficult to construct a laser cavity with multigigahertz repetition rates.

The fundamental soliton energy is quantized by the cavity energy which tends to produce multiple solitons .Also if total cavity energy is raised the number of pulses in the cavity can be increased. The temporal spacing between the multiple solitons formed in the laser cavity is generally unstable. To keep a certain phase relationship between the solitons active modulation is employed. Self-pulse ordering is observed in many experiments for fibers operating in soliton regime. J. Nathan Kutz et al. [5] conducted an analytical study which mainly focused on the interpulse dynamics in passively mode locked soliton fiber lasers. The experimental studies which supported the said area found that a group velocity drift is imparted to the interpulse spacing by the gain depletion in conjunction with its recovery.

Vector solitons are formed when two components with different polarization or frequencies become self-trapped. Multi component vector solitons are formed when more than two components are employed. From the experimental studies on vector solitons it has been observed that between the vector solitons collision and coupling takes place. Zhigang Chen et al. [6] studied the simplest vector soliton interaction. The balance of force between the interacting soliton components leads to the formation of bound states of vector solitons. These can also result from the induced coherence between the interacting solitons.

The soliton pulses within the laser cavity may group themselves in a stable and tight packet. This behavior of solitons called soliton bunching has been observed over the decades .The duration of these pulse bunches are actually smaller than the round trip time of the cavity. Ph. Grelu1 and J M Soto-Crespo [7] conducted experiments to observe the multiple solitons in the laser cavity. A multisoliton state undergoes a sudden transition to a state with long bunches of pulses when the pumping power is increased in anomalous dispersion regime. In case of normal dispersion regime, increasing pump power results in stretching of pulse only.

The laser operation can be tuned in to mode locked state by shifting the linear cavity phase delay where these mode locked pulse contain noise like pulses in a bunch [8]. The spectrum of the mode locked pulse even though showed broad bandwidth. It has been observed that the effect of positive cavity feedback and soliton collapse together contributes to the output laser emission from this mode locked lasers. That is, the bunches of noise like emissions are caused by the combined effect of positive cavity feedback and soliton collapse.

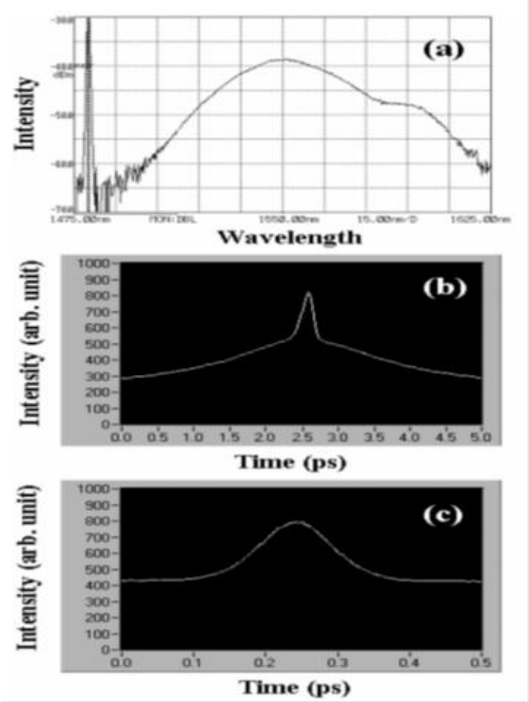

Fig. 1: bunched noise-like pulse emission. (a) Optical spectrum of the state; (b) Autocorrelation trace with a scan span of 5 ps; (c) Autocorrelation trace with a scan span of 0.5 ps. [8]

In the past years it was found that the soliton operation of mode locked fiber lasers is possible only in a fiber laser with negative cavity Group Velocity Dispersion (GVD). But studies have shown that the lasers with net positive cavity GVD can be mode locked and suitable for soliton operation [9]. Here the mode locking is done by the nonlinear polarization rotation technique. The soliton spectrum obtained by this mode locking technique has steep edges. And also the edge to edge bandwidth is gain limited. Here also the variation in parameters of solitons like peak power, pulse width and frequency chirp varies. It has been observed that the effect of gain saturation and gain bandwidth on the mode locked pulse in these lasers cannot be neglected.

The final shape of the mode locked pulses is determined by the properties of gain medium. Here, even though there is no net negative cavity dispersion the pulse adapts the shape and frequency chirp to form a stable non-linear pulse. The pulses circulating in the cavity have low peak power and also low nonlinearity since there is no negative cavity dispersion. Due to this feature these laser cavity results in higher mode-locking threshold than that of the lasers with negative dispersion in the fibers.

Besides the gain guided soliton formation discussed previously, noise like emissions are also observed in the laser cavity. This noise like emissions can be traced back in to the cavity. But no multiple gain guided solitons (GGS) are observed similar to the normal multiple soliton formation due to the interaction between the noise like emissions and solitons.

The bound states of solitons have been studied experimentally in an ytterbium fiber laser. This fiber laser has a dispersion managed cavity. The observations made from this experiment put forwarded that multiple gain guided solitons are possible under appropriate conditions. L. M. Zhao et al [10] conducted an experiment and observed that multiple GGS are generated in a fiber with purely normal dispersion. It was found that the reason for this multiple GGS is the pulse peak clamping effect under the condition of narrow gain bandwidth. If the gain bandwidth is smaller than the spectral width of solitons are also narrower. The spatial separation of solitons from the dispersive waves becomes easier under this condition. Fig.2 shows the multiple GGS formed .It was also found that the characteristics of GGS are similar to the general solitons.

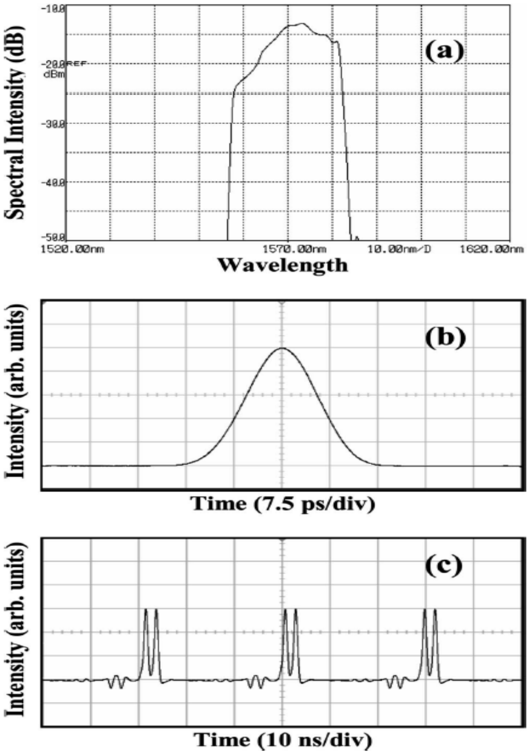

Fig. 2: Multiple gain guided state of fiber laser. (a) Optical spectrum, (b) autocorrelation trace, (c) oscilloscope trace. [10]

The pulses generated in the passively mode locked lasers are in self-organized way in the form of dissipative solitons. Besides passive mode locking techniques, active mode locking can also be employed to create pulses in the laser cavity. This involves external phase or gain loss modulation. Wonk Eun Chang et al. [11] conducted studies to understand the influence of active mode locking by external phase and gain loss modulation on bound solitons in laser systems. The effects of modulation has been conducted for both shorter and longer periods of modulation. The modulation with longer period of modulation influenced the soliton separation while in the case of modulation with shorter modulation period solitons splits and they find positions in different equilibrium states. It was clearly understandable from previous studies that the favorable condition for generation of pulses in the cavity is provided by the passive mode locking and the time location and shape of pulses are determined by the active mode locking. The vector soliton formation discussed earlier was again studied where the interaction of vector soliton in a fiber laser mode locked with SESAM has been experimentally observed [12]. The vector solitons move like contraction and expansion. It has been observed that the features of vector solitons are not affected by the formation of solitons.

Dissipative solitons (DS) formed in soliton fiber lasers needs to be stabilized. The loss and gain in the laser cavity depends these DSs formation. Different types of DSs were reported based on the cavity phase delay and pump power. Partially polarized DSs were observed [13]. Studies show that along a laser cavity the polarization state of broadband DSs changes to partially polarized. It has been found that the pulse peak power affects the polarization state of DSs and also the non-linear polarization technique and other non-linear effects in the cavity results in the partially polarized state. The observation of bound states of solitons has been reported in different mode locked fiber lasers like non-linear polarization rotation mode locked fiber lasers, figure of eight fiber lasers and also in actively mode locked lasers. It has been further reported that bound states of solitons are also observed in an erbium doped laser mode locked by using carbon nanotube saturable absorber [14].Single wall carbon nanotubes (SWCNT) is a saturable absorber which have the advantages like easy fabrication, controllable modulation depth and potentially broadband saturable absorption. Both tightly and loosely bound solitons are observed in these lasers as shown in Fig.3 and Fig.4 respectively.

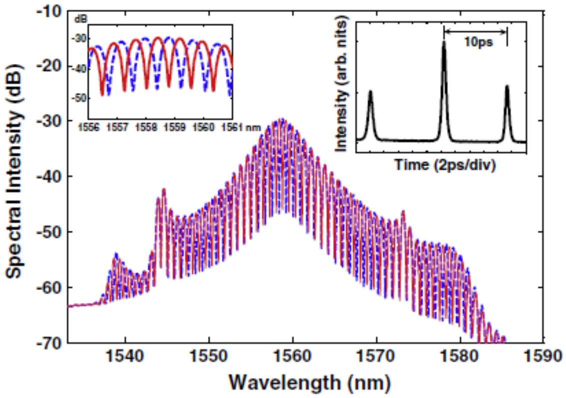

Fig. 3: Optical spectrum of loosely bound solitons [14]

The tightly bound solitons observed in these fiber lasers have a fixed discrete phase difference. They are ultra-stable and also they have fixed pulse separations. But the loosely bound solitons observed here does not exhibit these features. The experimental conditions largely effect the soliton separation as well as soliton phase difference. Also the soliton states are highly sensitive to the environmental conditions. From all the studies conducted it has been concluded that bound soliton emission is an intrinsic feature of mode locked lasers.

A bound state of solitons is observed as a normal mechanism or phenomenon in mode locked fiber laser cavities. These bound states of soliton formation are independent of the mode locking as well as dispersion regime. Studies have shown that many patterns and states of multiple solitons are visible in the figure-of-eight laser cavity [15]. Many soliton states such as soliton gas, soliton liquid, soliton crystal, and polycrystal are observed.

Usually the wide gain bandwidth and long length of the cavity generates a large number of modes. This results in the abrupt polarization dynamics due to the spontaneous mode locking. But when active or passive mode locking is introduced this abrupt polarization is suppressed and leads to the regular dynamics in the form of dissipative soliton formation.

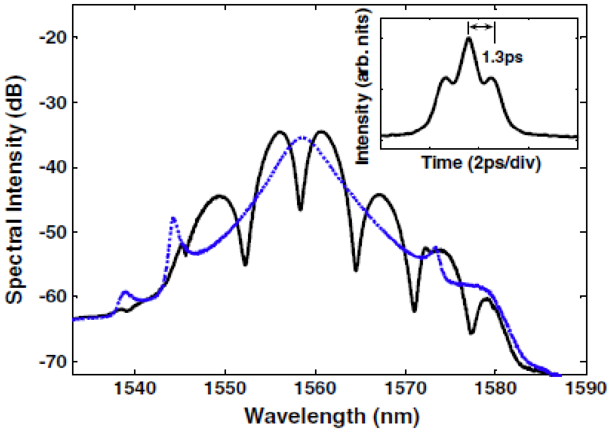

Fig. 4: Optical Spectrum of tightly bound solitons [14]

The number of round trips in the laser cavity determines the stability of solitons and also dynamics of solitons. In a study by Sergey V et al. [17], new families of vector solitons in a carbon nanotube mode-locked fiber has been found. This mode locked fiber operates in the anomalous dispersion regime. The observation was done with an in-line polari meter. New types of vector solitons were observed with slowly evolving and locked states for fundamental and multisoliton operations.

Regina Gumenyuk and Oleg G. Okhotnikov [17] presented the role of dispersion in the gain medium on the bound states of solitons. In both the normal dispersion gain medium as well as in the anomalous dispersion gain medium the effects are studied .The experimental set up is shown in Fig.5. In the presence of slow recovering saturable absorber less loss was experienced by the tightly spaced solitons and thus leads to soliton group formation. This is because of the fact that the slow recovery time gives much more time for the group. However, if the fast recovery component is responsible for the short pulse regime start-up. In the case when the average dispersion and dispersion map strength are kept constant, the impact of gain medium is also studied. And found that these factors do not affect largely the sign of the active medium. The normal dispersion gain medium supports stable bound solitons But in the anomalous dispersion gain medium soliton bunches are observed.

The phase difference between the soliton pulses is considered one important fact that has to be considered in multiple soliton transmission. Inorder to reduce the interactions between solitons in the absence of polarization mode dispersion the phase difference between adjacent solitons are usually set to π/4 .The phase difference between the pulses affects the interaction of solitons using Ginsburg-Landau equations. The effect of difference in initial phase values on Q-values was experimentally studied [18] .Two optical pulse generators were used in this experimental study an finally they found out that a phase difference of 3 rad between the laser phases of the two optical pulse generators must be maintained.

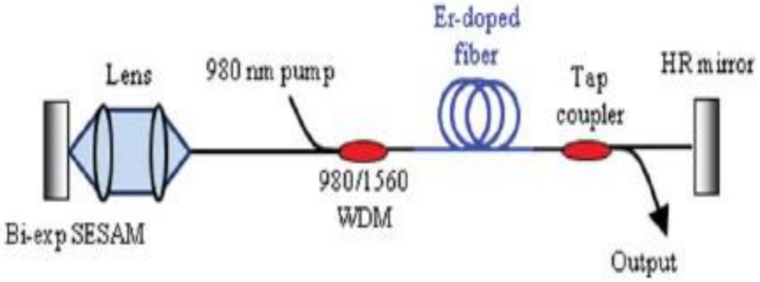

Fig. 5: Experimental set up of mode locked fiber laser [17].

The presence of dispersive wave in the soliton laser cavity results in random soliton motion and eventually leads to soliton instability. The soliton stability can be improved by suppressing the background noise.Eventhough on suppression of background noise, dispersive wave exists in the cavity which indicates the perturbation of solitons in every round trip. Temporal soliton stability achieved by mode locking using amplitude or phase modulation. The suppression of noise and stabilization of relative pulse positions in the cavity has been reported due to the regular loss variation. When phase modulation is applied, the noise along with the solitons experiences a frequency shift and eventually filtered out. By applying loss modulation in to the cavity stable bound solitons are formed [19].Efficient control of relative phases of solitons is achieved by the loss modulation at high harmonic of cavity frequency. This prevents the irregular soliton bunching and stationary group of solitons are formed.

Multiple solitons solitons have observed in many of the previous studies. Modes of multiple soliton operations are also observed. These modes include soliton collisions, soliton bunches, bound states of solitons etc. If polarization sensitive components are removed from the laser cavities multiple vector solitons are formed. The vector nature of propagation of light in the cavity of leads to the formation of these multiple vector solitons. When SESAM with different recovery times was introduced, vector soliton bunching was examined.

Recently, since the atomic layer graphene based saturable absorbers have polarization independent saturable absorption, fiber lasers with these absorbers are used [20]. Because of the characteristics of these saturable absorbers like broad bandwidth and ultrafast recovery time, multiple vector solitons formed have many dynamic features. Yu Feng Song et al. conducted experimental studies on the multiple vector soliton operation in these type of saturable absorbers. The different characteristic modes of operation of the multiple vector solitons are observed depending on the laser cavity. A state of giant pulse emission was observed when the pumping was very strong. The other characteristic operation modes observed include restless vector soliton bunches, the vector soliton bunches, vector soliton rains and random static vector soliton distribution. The direct soliton interaction, unstable CW related global type of soliton interaction, the saturable absorber induced soliton-soliton attraction and the dispersive wave mediated long range soliton interaction determines the multiple vector soliton operation.

Dispersion management in the fiber lasers have been considered by using dispersion compensation fiber (DCF) or discrete component. Regina Gumenyuk and Oleg G. Okhotnikov [21] used DCF and grating pair to tune the cavity dispersion. The use of DCF introduced non-linearity in to the cavity and the grating pair provides non-linearly free compensation .The separate impact of both dispersion and nonlinearity on soliton group formation has been studied by using these two compensation techniques. It was found that the stable bound solitons are destroyed by the excessive non linearity and dispersion in the fiber laser cavity. As a result soliton bunches are formed with random motion of solitons within the bunch. The combined effects of non-linearity and modulational instability leads to the collapse of the bound solitons.

Although we have observed a number of parameters that affect soliton group formation, a study conducted by D.A. Korobko et al. [22] Distinguished the particular impact of saturable absorber, non-linearity and dispersion management has be taken in to consideration. The stability and transformation of stationary bound states and bunch propagation have been also addressed. They found that the intensity profile of dispersive wave is dependent on the slow recovery component of saturable absorber, this determines the drift velocity. The relative pulse velocities responsible for the formation of bound states of solitons are defined by the saturation fluence. Also the degree of absorber saturation defines the stability of bound soliton states. When the number of pulses in the cavity becomes high the absorber slow component gets saturated. This reduces the difference in dispersive wave intensity at the front and trailing edges of the pulse. Here the dispersive wave induces a subsequent decrease of effective force which eventually leads to elimination of stabilization mechanism and leads to soliton instability.

In a fiber ring laser we can induce the nonlinear polarization rotation mode locking (NPRML) by introducing a component with polarization dependent loss (PDL) characteristic. Sheng-Fong Lin et al. [23] elucidated that even with the bent intracavity and without a strong PDL component, saturable absorption effect can be created in the cavity. This leads to the NPRML mechanism. But CW lasing component and severe timing jitter has been observed concurrently. If the cavity contains a strong

PDL component then the erbium doped fiber laser (EDFL) produce short and stable pulses and eventually evolves to a soliton laser. The soliton splits in to two or more fundamental solitons if the soliton period in the EDFL cavity is greater than the gain or loss perturbation period when the cavity energy increases. Thus emitting dispersive waves. These dispersive waves induce long range soliton interaction and produce a strong attraction force. Due to this strong attraction force, the multiple solitons eventually evolves to tightly bunched solitons.

Besides all the observations based on multiple pulses in the fiber laser cavity, it has been found that these multiple pulsing occurs along with multistability and hysteresis. These was studied in a figure-of-eight microstructured fiber laser and found that they are independent of the mode locking mechanism [24].The non-linear coefficient of the fiber and small signal gain are taken into consideration. In steady state, the number of pulses in the laser cavity and hysteresis dependency on these two factors is studied. Based on the study conducted it was observed that between two adjacent stable pulse emissions there exists narrow regions of instability. In anomalous dispersion regime, the pulse splitting takes place due to energy quantization also. Since the non-linear coefficient of microstructured fiber have a control over the dispersion and non-linearity of the cavity, it affects the dissipative pulse evolution strongly. When nonlinear coefficient is increased the number of pulses in the cavity also increases.

In a graphene mode locked fiber laser, polarization locked vector solitons (PLVS) was observed. This laser emits vector solitons having variations in pulse energy and polarization rotation. The multiple soliton dynamic patterns of vector solitons was observed in these lasers [25]. The orientation of intra-cavity polarization controller can be adjusted. And by adjusting this polarization rotation, state of vector soliton character is changed to polarization locked state. We thus get the dynamic patterns of vector-soliton polarization. By adjusting the pump power and intra-cavity orientation, the dynamics of vector characters obtained for both the polarization locked state and polarization rotation state of fundamental soliton, bunched soliton, bound solitons etc.

III. CONCLUSION

Control of multiple solitons is very much important for secure communication over large distances and for high bit rate communications. Multiple soliton operation is determined by the direct soliton interaction, dispersive wave mediated long range soliton interaction, and saturable absorber induced soliton interaction. Soliton stability can be improved by suppressing the background noise. But it was observed that even though background noise is suppressed soliton instability occurs. It has been observed from the reviewed papers that the bound states of solitons formed due to the multiple solitons in the laser cavity are not stable in all cases of the fiber laser systems. When non-linearity and dispersion in the fiber cavity is exceeded the bound states of solitons are collapsed and soliton bunching takes place. Relative phases between solitons are controlled by loss modulation. It has been recently observed that the multiple soliton operation occurs along with multistability and hysteresis.

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