Properties of mode-locked ultrafast fiber lasers

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Abstract. Lasers, including solid-state lasers, fiber lasers and ultrafast fiber laser, are critical to our daily lives. Different kinds of laser have their own advantages and disadvantages. For solid-state lasers, they can generate short duration, high energy pulses but are difficult to maintain and expensive. Fiber lasers, which are compact, low-price, high-efficiency, can provide a novel solution to these issues. Here, we illustrate the theory and main features of the most important ultrafast fiber laser designs: soliton laser, dispersion-management soliton, dissipative soliton and Mamyshev oscillator. At last, we focus primarily on the promising future of the ultra-fast fiber lasers.

1. Introduction
High-power ultrafast lasers are widely used in additive 3D printing, welding, micromachining, medical imaging etc [1-3]. In the past, the main workhorses were solid-state lasers as they have been carefully engineered for over 30 years. For instance, solid-state Ti:sapphire lasers offers a remarkable combination of short duration and high pulse energy, which completely changed the ultrafast science and industry since they were invented. However, these lasers suffer from large footprint, difficulty to manufacture and maintain, and high price.

With the increasing demand of ultrafast pulses, more-compact, user-friendly and economical laser sources are needed. Fiber lasers are invented to resolve the problems of solid-state lasers, which were listed above. The clear advantages of fiber laser solutions (compared to their solid-state counterparts) are: compact design, easy thermal management, minimal alignment, high spatial beam quality, and low cost. Consequently, fiber systems have already become a competent option for applications requiring continuous wave or long-pulse operation.

Nevertheless, the pulsed fiber lasers have their own challenges. In the pulsed operations, the benefits of fiber lasers come at the cost of tighter confinement of the light, which cause larger nonlinear phase accumulation that can rapidly degrade the pulse quality [4]. In order to cope with the problem, different types of mode-locked fiber lasers have been invented [5]. Furthermore, recent works had shown that much higher pulse energies and peak powers can be achieved in fiber lasers that operate at large normal dispersion. For instance, self-similar laser and dissipative soliton fiber lasers can provide over 10-nJ and less than 100 femtosecond pulse width, which are competitive to most of commercial solid-state lasers [6-8].

The aim of this paper is to present the properties of different ultrafast fiber lasers, as well as the physics governing the formation of stable pulses. The paper is organized as follows: stating the main features of each laser, as well as its theoretical knowledge one by one, with the comparison of the specifications of the four lasers in the end.
2. Fiber lasers

2.1 Soliton Lasers:
In optics, soliton generally refers to an optical field that remains unchanged temporally or spatially during propagation. The soliton is classified as temporal solitons and spatial solitons. Its difference mainly comes from the formation mechanism: nonlinearity and dispersion for the temporal soliton, and nonlinearity and spatial diffraction for spatial soliton. In ultrafast laser field, soliton laser typically means temporal soliton. Soliton lasers are created by incorporating passive single-mode fiber and active gain fiber and keeping a large net cavity dispersion negative. This is accomplished by either exploiting anomalous dispersion fiber or dispersive components. The optical Kerr effect is one of the most common nonlinear effects in such fibers [4]. The generated pulse in a cavity is also determined by the dissipative effects of gain, loss, saturable absorption, and spectral filtering. Despite this, dissipative effects and gain remain only of secondary importance in soliton lasers when compared to as dispersion and Kerr nonlinearity.

Therefore, soliton laser in single mode fibers is described by the nonlinear Schrodinger equation as follows:

\[
\frac{\partial A}{\partial z} = -i\beta_2 \frac{\partial^2 A}{\partial t^2} + i\gamma |A|^2 A
\]  

where \( A \) is the slow varying envelope of the optical pulse, \( \gamma \) is the nonlinear parameter, \( \beta_2 \) is the second order dispersion coefficient which corresponds to the group velocity dispersion effect.

The fundamental bright soliton solution is given by:

\[
A(z,t) = \sqrt{2\gamma \eta} \exp \left\{-4i(\frac{\zeta^2 - \eta^2}{\eta})z - 2i\zeta t + i\varphi \right\} \text{sech} \left(\frac{2\eta(t - t_0)}{8\eta \zeta} \right)
\]  

where \( \eta, \zeta, \varphi \) and \( t_0 \) are all constants and \( \beta_2 = -2 \).

Conventionally, soliton oscillators output approximately transform-limited pulses. With the laser action builds up from noise, the cavity’s gain and loss elements periodically perturbed the pulse. Following each perturbation, the pulse adjusts itself to satisfy the soliton area theorem, at the same time shedding some energy as a dispersive wave. This resonant phenomenon generates narrow spectral sidebands, and restricts the pulse durations and energy [9,10].

In general, with its simplicity and lower requirement for saturable absorber, the soliton laser is still the most widely used laser in industry and laboratories.

2.2 Dispersion-Managed Soliton Lasers:
The dispersion-managed soliton laser, which is also called stretched pulses laser, is a soliton in a cavity-averaged sense. Fibers with different signs of dispersion are placed in different sections of the cavity. Pulse stretches and compresses temporally twice per roundtrip as it passes through each dispersion elements (positive and negative), reducing the averaged nonlinearity per roundtrip and permitting higher energy. Net cavity dispersions ranging from slightly anomalous to slightly normal are possible for stable output [11]. The shortest pulses are achieved near zero net dispersion [12].

Large temporal breathing reduces the accumulated nonlinearity compared to a static solitary pulse of the same energy, allowing more energetic pulses than a comparable soliton laser. The output coupler can be place at different places in the cavity, and the output pulses may be up-chirped or down-chirped.

The dispersion management soliton can be modeled by Master Equation:

\[
\frac{1}{\tau_R} \frac{\partial}{\partial T} a = (g - l) a + \left( \frac{1}{\tau_s^2} + j\Omega_{\text{net}} \right) \frac{\partial^2}{\partial \tau^2} a + (\gamma_0 - j\delta_0) |A_0|^2 \left( 1 - \mu \frac{\tau^2}{\tau_s^2} \right) a
\]  

In the equation stated above, \((g-l)\) means the net gain of the bandwidth and the modulation frequency, \(\tau_R\) means the round-trip time, \(A_0\) means the amplifier when \(n=0\), \(\tau\) satisfies the equation

\[
\tau^4 = \frac{2g}{(MA_0^2)^2 \Omega_m^2} \quad (\Omega_m \text{ is the modulation frequency}), \quad a \text{ and } A \text{ is a Fourier-transform with the Fourier-transform pairs when } A \text{ is the amplifier, } T \text{ is the long term time variable, while the } \gamma \text{ satisfies}
\]
the equation $\gamma = \frac{s_0}{I_{sat}A_{eff}}$ (Isat means the saturation intensity of the absorber, $s_0$ is the unsaturated loss, $A_{eff}$ is the intensity multiplied by the effective area of the mode), $D$ is the group velocity dispersion parameter, $\delta$ is the Kerr-coefficient whose value is $((2\pi/\lambda)m2L/A_{eff})$, $\Omega_f$ is the filter of bandwidth, $\mu$ is a coefficient which values variationally.

This equation has a group of Gaussian-pulse solutions. In the experiments, the measured pulses are also closer to a Gaussian shape compare to the soliton lasers. The output bandwidth can be greater than the gain medium bandwidth. The first dispersion management soliton laser was achieved at 1550 nm by inserting a new Erbium doped fiber with normal dispersion into the laser cavity. The net dispersion is close to zero and the pulse was stretched and compressed strongly (20-fold) in the cavity. At other wavelengths, such as 1030 nm, the anomalous components can also come from dispersion delay systems, which are similar to soliton lasers.

The typical performance for the stretched pulse cavity design is <100 fs de-chirped pulse duration with energies of ~2 nJ [11,12].

2.3 Dissipative Soliton Lasers:
In contrast to soliton lasers, dissipative soliton lasers are formed as a combination between the mutual nonlinear interactions among the normal self-phase modulation, cavity dispersion, effective gain bandwidth filtering and gain saturation, properties of which are determined by the Ginzburg-Landau equation [13].

Optical pulse evolution in the presence of Kerr nonlinearity, dispersion, dissipative and gain process can be modeled by the cubic-quintic Ginzburg-Landau equation:

$$U_z = g U + \left(1 - \frac{D}{2} \right) U_{tt} + (\alpha + i\gamma)|U|^2U + \delta|U|^4U \tag{4}$$

where $U$ is the electric field envelope, $z$ represents the propagation coordinate, $t$ is the retarded time, $D$ is GVD, $g$ is the net gain, $\Omega_f$ is relevant with the filter bandwidth, $\alpha$ is a cubic saturable absorber term, $\gamma$ is the cubic refractive nonlinearity of the medium, and $\delta$ is the quantic saturable absorber term [14].

From the solution of this equation, one can find the spectral filter plays a significant role in the pulse shaping process. It contributes to both the dissipation and spectral filtering and the filter bandwidth strongly determines the output pulse shape, duration and energy [14]. The output pulse owns a sharp spectral boundary, which differs dissipative soliton from any other laser cavities. In spite of their sharp spectral features, dissipative solitons can usually be compressed to within 20% of the transform limit and still maintain a low secondary structure. Compared to conventional soliton lasers, dissipative soliton lasers are able to generate up to 20 nJ and 200 fs or ~10 nJ and 80 fs pulses. This is significantly greater than soliton and stretched pulse designs. Using photonics crystal fiber, the pulse energy can be scaled up to hundreds of nanojoules.

2.4 Mamyshev Oscillator:
The development of the above fiber lasers improved the output pulse energy. However, in order to be widely used outside the laboratory, the environmental stability is another big concern. Many research have been explored to obtain the environmental-stable design [15-17]. However, their performance is not as good as the traditional designs. This prevents the lasers from having even more importance in wider industrial applications.

One promising solution for this is the Mamyshev Oscillator. This oscillator includes two major parts: One is a laser cavity with two gain segments and two filters and the other is a starting arm that creates a fluctuating field that seeds the mode-locked state. This cavity design originates from the idea of signal regeneration in telecommunication field [18]. Laser based on reamplification and reshaping can be used to generate short pulses [19–23]. Self-similar pulses propagate in both cavity arms. And near linear phase is accumulated during the propagation. Self-phase-modulation (SPM) and two spectral filters shaped the pulse. The two spectral filters limit the continuous wave growing, which lead to larger nonlinear phase for the pulses. Therefore, the pulse energy is higher than all other laser
designs. All the cavity is made by polarization maintaining fiber and it can tolerate strong environmental perturbation. Using single mode fiber, this is the first fiber laser that reach megawatt peak power. Energy scaling was demonstrated by Sidorenko et. al [23].

3. Conclusion

Table 1. Performance summary of fiber oscillators for different pulse evolutions

| Pulse evolution       | Nonlinear Phase | Typical Performance | Best Performance       |
|-----------------------|-----------------|---------------------|------------------------|
| Soliton               | near 0          | 100 pJ, 300fs       | less than 1nJ, 100fs   |
| DM Soliton            | 0–π             | 1nJ, 100fs          | up to 3nJ, down to 50fs|
| Dissipative Soliton   | 2π–10π          | 6nJ, 150fs          | up to 20nJ, down to 70fs|
| Mamyshiev oscillator  | >60π(experiment)| /                   | 50nJ, 40fs(experiment) |
|                       | >140π(simulation)| /                   | >190nJ, <20fs(simulation)|

With the development of the lasers, from soliton, DM soliton to dissipative soliton and Mamyshiev oscillator, the nonlinear phase gradually increases, which cause both the typical performance and the best performance to improve.

In this article, we discussed the four types of soliton lasers---soliton lasers, dispersion management soliton lasers, dissipative soliton lasers and Mamyshiev oscillator, all of them have their own advantages and disadvantages. We also emphasize the theory as well as demonstrate the performances of these four lasers. All these four lasers have already been applied and employed in the new materials, new further relevant researches. It can be anticipated that the fiber lasers and its techniques will be a powerful tool for the studies in the future [24].

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