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Generalized characteristics of soliton in dispersion-managed fiber lasers

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ABSTRACT

The generic characteristics of dispersion-managed fiber laser are systematic investigated experimentally. When the net cavity group-velocity dispersion (GVD) is large negative or positive, it exhibits the features of fiber laser constructed by purely negative or positive components, respectively. Furthermore, we demonstrate that two types of soliton formation mechanisms simultaneously act on one mode-locked pulse as the fiber laser operates in the vicinity of zero net cavity GVD. The features of mode-locked pulse depending on the interaction and competition of cavity dispersion, fiber nonlinearity, laser gain saturation and spectral filtering. In addition, the characteristics of noise-like pulse under different net cavity GVD are also experimentally investigated.

1. Introduction

Passively mode-locking fiber lasers have attracted great attention as potential application in ultrafast optical communication, and as compact and economical sources for fundamental research [1–4]. Conventionally, the mode-locking pulses operation of a fiber laser is described by the Ginzburg–Landau equation (GLE), which takes into account the mutual interaction among the cavity dispersion, fiber nonlinearity and the laser gain medium [5]. The existence of periodical amplification and loss affects the detailed dynamics of the formed mode-locking pulse. Indeed it has been shown that the GLE could faithfully model the soliton dynamics of the lasers, bearing in mind that a soliton in a laser is in the sense of an average soliton [6].

Since the fiber laser was extensively investigated previously; various features such as the transform-limited soliton-pulse formation [7,8], multiple-soliton generation and pulse-energy quantization [8–10], bound states of solitons [11,12], period bifurcations [13], gain-guide soliton [14] and noise-like pulse output [15–17], have been observed. Smith et al. [18] have shown that, even in a fiber system with periodically varying positive and negative group-velocity dispersion (GVD), optical solitons can still be formed. Such a soliton was named a dispersion-managed soliton, and dispersion-managed soliton fiber lasers were extensively investigated [19–21]. Depending on the cavity design, a dispersion-managed fiber laser can operate either in the negative or positive net cavity dispersion regime. When a fiber laser is consist of purely negative dispersive components, the interaction between the fiber dispersion and nonlinearity naturally leads to the formation of the conventional solitons. A fiber laser can also be made of purely positive dispersive components. As shown by the GLE [22] and confirmed experimentally recently [14], soliton can still be formed in the laser due to the laser gain saturation and gain dispersion. And this kind of soliton is known as the gain-guided soliton. A gain-guided soliton has different properties to those of the conventional solitons. Different characteristics of the output pulse acquired with different dispersion regime. However, all the previous research on dispersion-managed fiber lasers is limited to a local regime.

In this paper, the dispersion management mode-locking fiber laser based on the nonlinear polarization rotation technology is systematically and comprehensively investigated by experiment. We experimentally demonstrated that even the cavity of a fiber laser is dispersion-managed, as far as the net cavity dispersion is large negative or large positive, the two types of solitons could still be formed, respectively. In particular, we also demonstrate that the two types of soliton formation mechanisms can simultaneously act on one pulse as the fiber laser operates in the vicinity of zero net cavity GVD. The features of mode-locked pulse depending on the interaction and competition of cavity dispersion, fiber nonlinearity, laser gain saturation and spectral filtering. In addition, the characteristics of noise-like pulse under different net cavity GVD are also experimentally investigated.

2. Experiment set-up

A schematic of the fiber laser used in our experiments is shown in Fig. 1. It has a cavity structure that consists of two segments of single mode fiber (SMF) with negative GVD of about $\beta_2 = -23\ \mathrm{ps^2/km}$ and a segment of 3 m EDF with positive GVD of about $\beta_2 = 43\ \mathrm{ps^2/km}$. The wavelength-division multiplexer (WDM)

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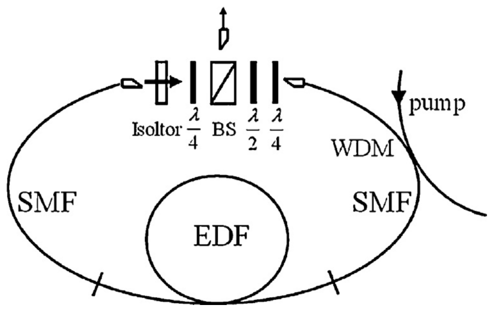

Fig. 1. Schematic of the dispersion management fiber laser setup. λ/4: quarter-wave plate; λ/2: half-wave plate; EDF: erbium-doped fiber; SMF: single mode fiber; BS: beam splitter; WDM: wavelength-division multiplexer.

used is made of the standard SMF. The initial loop length of the laser cavity is 31 m, and different net cavity GVD of the laser is achieved by varying the length of the SMF used.

The nonlinear polarization rotation technique is used to mode lock the laser [23]. For this purpose a polarization dependent isolator is inserted in the cavity to assure the unidirectional operation of the laser. Two polarization controllers, one consisting of one quarter-wave plates and the other one quarter-wave plates and one half-wave plate, are used to adjust the polarization of the light. The polarization controllers, polarization dependent isolator, and a polarizer are mounted on a 7-cm-long fiber bench, with which accurate polarization adjustments can be easily obtained. The laser is pumped by a pigtailed InGaAsP semiconductor diode of wavelength 1480 nm. The pump laser power can be continuously adjusted. The output of the laser is taken by a beam splitter and analyzed with an optical spectrum analyzer and a commercial optical autocorrelator.

The transmission coefficient of the setup or the laser cavity is [24]:

$$T = \sin^2\theta\sin^2\varphi + \cos^2\theta\cos^2\varphi + \frac{1}{2}\sin 2\theta\sin 2\varphi\cos[\Delta\Phi_l + \Delta\Phi_{nl}] \quad (1)$$

where θ and φ is the angle of the polarizer and analyzer orientation with respect to the fast axis of the fiber, respectively. $\Delta\Phi_l$ and $\Delta\Phi_{nl}$ is the phase delay between the two orthogonal polarization components caused by the linear and nonlinear fiber birefringence respectively. In a previous paper [25], Man et al. have shown that the linear cavity transmission of the laser is a sinusoidal function of the linear cavity phase delay $\Delta\Phi_l$ with a period of 2π. As will be shown below, the transmission coefficient plays an important role in decide the various features of the output pulse. It's worth noting that within one period of the linear cavity phase delay change, the laser cavity can provide positive feedback only in half of the period, in the other half of the period it actually has negative feedback.

3. Experimental results

Depending on the selection of the linear phase delay bias, the mode-locking pulses in the fiber lasers will exhibit different characteristics. We present here some of the typical experimental results for the purpose of a better understanding of the characteristic of generalized dispersion-managed fiber lasers.

First consider the case which the laser operation with large negative net cavity GVD. Initially, the cavity length is about 31 m, corresponded to a net cavity GVD about $-0.515\,ps^2$ at 1550 nm. Mode-locked pulse of the laser is readily obtained by simply increasing the pump power above the self-start threshold, provided that the orientations of the polarization controllers are

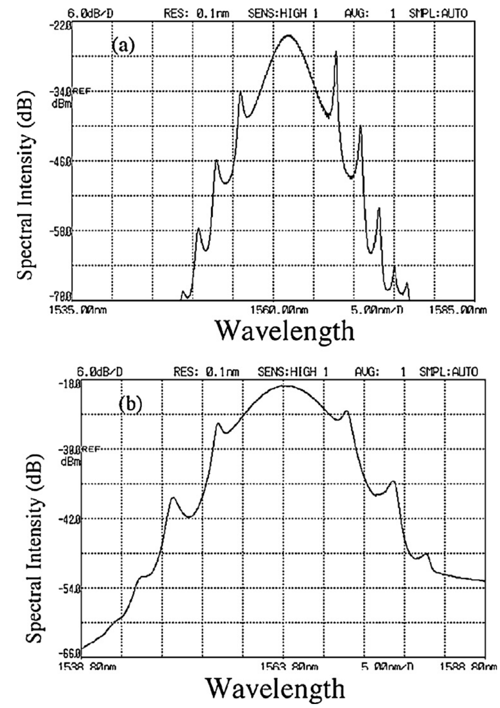

Fig. 2. typical mode-locked pulses spectra when the laser cavity length is 31 m (a) and 18 m (b).

appropriately set. Fig. 2a shows a typical soliton spectrum observed in the laser. The 3 dB spectral bandwidth is 3.4 nm and pulsed width (FWHM) is about 731 fs (The autocorrelation trace no shown here and a sech-form pulse profile is assumed) due to larger negative GVD. Indeed, despite the fact that the laser cavity is dispersion-managed, when the net cavity GVD is selected large negative, the mode-locked pulses display correspondingly features of the conventional solitons for the balance between the fiber nonlinearity and the cavity dispersion, characterized by the pronounced sidebands in the soliton spectrum. The interaction between the fiber dispersion and fiber nonlinearity lead to the formation of the conventional solitons [26] when the laser total cavity GVD is large negative. Generally speaking, due to that the spectral bandwidth of the formed solitons is much narrower than the laser gain bandwidth, which is a result caused by the pulse peak clamping effect [4] of the cavity and the soliton nature of the pulse [5], influence of the laser gain on the formed solitons is very weak. Therefore, conventional soliton fiber lasers predominately exhibit the conventional soliton features.

The number of sideband and pulse width decrease and the pulse energy increases as the cavity length decreases gradually. This can be seen clearly form Fig. 2b when the cavity length is 18 m corresponded to a net dispersion about $-0.219\,ps^2$. The pulse width decreases due to the decreases of dispersion [27]. The central wavelength shifting is a result of the existence of birefringence in the laser cavity and the same mechanism is one of the reasons responsible for the power asymmetry of sidebands appearing in the soliton spectrum [25]. Another is the higher-order dispersion [26,28].

When the linear cavity phase delay bias is selected to be small, on further increasing the pump power, the intensity of soliton reach a certain value then do not increase any more because the pulse peak power was clamped by the cavity peak clamping effect [4,29], as a result, new solitons could be generated one by one in the cavity. Due to the solitons share the same laser gain, gain competition between them combined with the cavity feedback feature results in that the solitons have exactly identical pulse parameters