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Cavity-length optimization for high energy pulse generation in a long cavity passively mode-locked all-fiber ring laser

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In order to achieve higher pulse energy in a passively mode-locked fiber ring laser, a long cavity length is commonly implemented. However, a long cavity operating in the anomalous dispersion regime also leads to pulse broadening, which reduces the average pulse power. In this paper, the trade-off between cavity length and average pulse power is investigated with the aim of optimizing the cavity length to achieve maximum pulse energy. Numerical simulation results, presented here, indicate that there exists an optimum cavity length for which the pulse energy is maximum and the optimum length shifts as the pump power changes. The simulation results for a pump power of 500 mW are verified by measurements carried out on a long cavity nonlinear polarization rotation mode-locked all-fiber ring laser operating in the anomalous dispersion regime. With a repetition rate of 266 kHz for the dissipative solitons, we achieve a pulse energy of 139.1 nJ for a cavity length of 700 m. Higher pulse energy can be expected by using a pump laser diode with higher pump power. © 2012 Optical Society of America

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1. Introduction

Fiber lasers, which utilize an optical fiber doped with rare-earth elements such as erbium or ytterbium as the active gain medium, have been widely investigated in the recent years. Pulsed fiber lasers have key advantages including high peak power and short pulse duration, which avoids the heat diffusion effect and hence, increases the quality of laser processing. Currently, mode-locked fiber lasers, which are a specific form of pulsed lasers, have found applications in the following four main areas: communication, material processing, biological metrology, and spectroscopic analysis.

In order to meet the increasing demands of various applications, the mode-locked fiber lasers need to

produce a pulse train with high pulse energy. A common way to achieve higher pulse energy is to increase the cavity length as primarily proposed in [1]. The idea of using a long cavity length to achieve high pulse energy is based on the following equation:

$$E = P_{\text{av}} T_R = P_{\text{av}} \frac{nL}{c}, \quad (1)$$

where E is the pulse energy, P_{av} is the average power, T_R is the round trip time, L is the cavity length, and c/n is the speed of light in the fiber, assuming that there is only one pulse propagating in the resonance cavity for each round trip. Clearly, for a given fiber and average power, as the cavity length increases, higher pulse energy can be achieved.

In recent years, much work has been done with the aim of generating high energy pulses by using ultra-long cavities with lengths of hundreds of meters [2,3],

or even several kilometers [1,4,5], based on normal dispersion fiber. It has also been shown theoretically that high energy passively mode-locked pulses can be generated within anomalous dispersion regime [6]. Subsequently, high energy pulses have been experimentally demonstrated using a 720 m long anomalous dispersion fiber [7], generating dissipative solitons with an energy as high as 715 nJ by implementing a forward and backward pump structure with an overall pump power of 1000 mW. However, [7] mainly investigates the relationship between pulse duration and pump power, while an explanation of how the cavity length of 720 m is chosen has not been provided.

When the length of the cavity is increased, the pulse width broadening effect needs to be taken into consideration. The pulse broadening effect leads to the increase of pulse duration. As a result, the saturation absorber component in the laser cavity will absorb a greater fraction of the pulse power. Hence, as the cavity length is increased, P_{av} in Eq. (1) will decrease. Therefore, there is a trade-off in Eq. (1) between the average power and the cavity length.

In this paper, going further with respect to the work reported in [7], we aim to examine the above-mentioned trade-off and find the optimized fiber cavity length so that the passively mode-locked fiber ring laser can generate pulses with maximum energy. First, we carry out simulations to study the variation of pulse energy with cavity length and the variation of optimized cavity length with pump power. Next, the simulation results for a pump power of 500 mW are verified through an experiment. The fiber laser constructed operates in the anomalous dispersion regime and is adjusted to generate dissipative solitons. By increasing the fiber length in the cavity from 100 to 1000 m in steps of 100 m, variation of pulse energy is observed. The highest dissipative soliton energy obtained is 139.1 nJ for a fiber length of 700 m. The corresponding repetition rate is 266 kHz. To the best of our knowledge, this is the first time the trade-off between cavity length and average pulse power is investigated in the case of a long cavity passively mode-locked fiber ring laser for high energy pulse generation in the anomalous dispersion regime.

2. Numerical Simulation

A C++ program is written to simulate the performance of a passively mode-locked fiber ring laser. The schematic of the ring laser is shown in Fig. 1. The simulation program is based on the split step Fourier method [8] which considers the dispersion and nonlinearity as independent effects. The method treats the fiber as summation of a large number of segments and for each segment only one of the effects is taken into consideration. The complex Ginzburg–Landau equation (CGLE), which includes the effect of passive fiber and gain [9], is solved numerically. The polarizer in combination with the polarization controller (PC) is separately modeled to simulate the effect of saturable absorber (NPR mode-locking).

Fig. 1. Passive mode-locked fiber ring laser model.

The output coupler is also separately modeled by simply introducing a fixed loss of 10%. The propagation of optical pulse is described in matrix mathematically. The pulse is calculated according to the amplification effect from erbium doped fiber (EDF), the energy absorption effect from saturable absorber (SA), the dispersion effect, and the nonlinearity effect in passive single-mode fiber (SMF), independently. The initial condition of the simulation is white noise. The simulation result is independent of the noise seed as long as all the cavity parameters are set. Hence, the simulation is run only once for each case.

It is an instantaneous model. The amplifier is modeled as a gain element. The gain value will decrease until the gain saturation state has been reached. The gain profile is assumed to be parabolic near the spectral bandwidth of the optical pulse. The size of temporal grid and number of grid points are properly set to cover wide enough in time and spectrum domain. The pulse energy is calculated by the integral over the time domain for the full width of the pulse.

Since the SMF used in the experiment has a loss of 0.24 dB/km, corresponding to an attenuation constant of $5.53 \times 10^{-5} \text{ m}^{-1}$, this is the value of α in simulation program. For anomalous dispersion fiber, the second-order dispersion parameter β_2 is set to be $-0.02 \text{ ps}^2/\text{m}$, while the higher order dispersion terms have been ignored. The nonlinear parameter is γ set to be $1.8 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$. The simulation is considered to be reaching a steady-state, i.e., the pulse parameters have converged, only when the pulse parameters do not change any more with the increase of the round trips in the simulation. For our laser parameters setting, 300 round trips is enough for the system to reach steady-state. Table 1 presents the various parameters values in the simulation program.

In the simulations, the cavity length is varied from 100 to 1000 m in steps of 100 m. The corresponding variation in pulse energy is shown in Fig. 2. We observe that as the cavity length increases from 100 to 700 m, the pulse energy keeps increasing

Table 1. Parameter Settings in Simulations

Parameter	Value
EDF saturation power	3.0 W
EDF attenuation constant α	$5.53 \times 10^{-5} \text{ m}^{-1}$
EDF second-order dispersion parameter β_2	$-0.02 \text{ ps}^2/\text{m}$
EDF nonlinear parameter γ	$1.8 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$
SA saturation power P_{sa}	0.3 W
SA absorption coefficient of saturation α_0	0.169
SA absorption coefficient of nonsaturation α_{na}	0.825
SMF attenuation constant α	$5.53 \times 10^{-5} \text{ m}^{-1}$
SMF second-order dispersion parameter β_2	$-0.02 \text{ ps}^2/\text{m}$
SMF nonlinear parameter γ	$1.8 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$
Output coupler ratio	90/10
Number of round trips	300

and reaches a peak value at 700 m. This indicates that below the cavity length of 700 m, the effect of increasing cavity length on pulse energy exceeds the effect of decreasing average pulse power in Eq. (1). However, above the cavity length of 700 m, the situation reverses and the overall pulse energy starts to decrease; the pulse broadening effect leads to absorption of a greater fraction of pulse energy by the SA in the laser cavity. Hence, the highest pulse energy, which is proportional to the product of average pulse power and cavity length, occurs for a cavity length close to 700 m. These results clearly show that the relationship between the pulse energy and the cavity length is not linear or monotonic.

Furthermore, the relationship between pump power and optimized cavity length has been investigated in simulations. As the pump power is increased from 500 mW to 550 mW, the optimum cavity length shifts to a smaller value; on the other hand, as the pump power is decreased from 500 mW to 450 mW, the optimum cavity length shifts to a larger value. These results can be explained as follows: when the pump power increases, the nonlinear effects in the

Fig. 2. Simulated pulse energy versus cavity length.

laser cavity increase. Increased nonlinearity leads to broadening in the frequency domain. Since the cavity is operating in the anomalous dispersion regime and the pulse is highly chirped, the broadening in the frequency domain would correspond to broadening in the time domain as well. Hence, the dispersion effects in the laser cavity need to decrease to maintain the same pulse width. As a result, the optimum cavity length tends to decrease. The increase in the optimum cavity length when the pump power is decreased can be explained by a similar reasoning. In addition, simulation results also show that a larger pump power gives rise to higher pulse energy and vice-versa.

3. Experiment

Figure 3 shows the experimental setup of a long cavity passively mode-locked fiber ring laser which is used to verify the simulation results. A 980 nm continuous wave (cw) laser diode with maximum output power of 500 mW is used as the pump source. This cw signal is pumped into a wavelength-division-multiplexer (WDM) in the clockwise direction. A length of 1.0 m long erbium-doped fiber (EDF, ER-80) is used as the gain medium. The isolator is inserted in the ring cavity to ensure unidirectional propagation. Two PCs and a polarizer are included in the setup to change the polarization of light in the laser cavity as well as to achieve mode-locking through nonlinear polarization rotation (NPR). The NPR method is frequently used to achieve mode-locking state with high energy pulses as the output [10,11]. A different length of fiber with anomalous dispersion is inserted in the cavity each time. The fiber length is increased from 100 to 1000 m in steps of 100 m. A 90:10 coupler is used to couple the light out of the cavity for measurements. The output pulses are coupled into a 2 GHz photo detector and then monitored using a 350 MHz sampling oscilloscope.

Fig. 3. Schematic diagram of long cavity fiber ring laser.

Fig. 4. Temporal profile of the generated dissipative soliton.

The entire laser cavity is constructed by fusion splicing, with splicing loss less than 0.02 dB at each joint. The fiber in the pig-tails of various components and the fiber rolled in the two PCs are anomalous dispersion fiber. The EDF is also made of anomalous dispersion fiber. The total length of these fiber segments is 20 m. Hence, the total length of the laser cavity is 20 m in addition with the length of the SMF inserted. This 20 m fiber length does not affect the dispersion status in the laser cavity.

4. Results and Discussion

Due to the variation of net cavity birefringence, different lasing operation states are observed. Adjusting the PCs and reducing the pump power, the single pulse regime is obtained and dissipative solitons are observed on the oscilloscope. The temporal profile of the solitons presented in Fig. 4 shows the shape of the dissipative solitons when 700 m of SMF fiber length is inserted. The steep edge at the front of the pulse clearly verifies the dissipative nature of

Fig. 5. Soliton pulse energy versus cavity length based on experiment and simulation.

Fig. 6. Temporal profile of the pulse train generated for 700 m inserted SMF fiber length.

the solitons. The pulse width is measured as 25 ns. Figure 5 depicts the measured pulse energy as a function of the cavity length, with the pump power adjusted to the maximum value for the laser to operate in the single pulse regime, which is around 500 mW, and with the PCs adjusted to obtain maximum value of the pulse power. Simulation results are also included in Fig. 5 and a good match with the measured results is seen. Except for a slight dip in the measured values around a fiber length of 300 m, an overall increasing trend is observed as the fiber length increases from 0 to 700 m.

At 700 m, the pulse energy output from the 90:10 coupler is 13.91 nJ, which is the peak value. Hence, the pulse energy in the laser cavity is 139.1 nJ, with 500 mW pump power, which is the upper limit for the pump laser diode in our setup. Around this fiber length, the product of the average pulse power and the fiber length reaches a maximum.

Fig. 7. Spectrum of the dissipative soliton for 700 m SMF fiber length.

Fig. 8. Soliton pulse width versus cavity length based on experiment.

As the fiber length inserted increases beyond 700 m, the pulse energy starts to decrease. For 700 m SMF inserted in the laser cavity, the temporal profile of the soliton pulse train is shown in Fig. 6. The pulse interval is 3.76 μ s, which corresponds to a sub-megahertz low repetition rate of 266 kHz. The optical spectrum of the solitons for the same fiber length is illustrated in Fig. 7. The pulse is centred at 1570 nm with a 20 nm bandwidth. In addition, the pulse width obtained experimentally for different fiber lengths is illustrated in Fig. 8. The pulse width increases linearly with the fiber length. We find this is due to the fiber dispersion. For standard single mode fiber, the pulse broadening induced by 1000 m fiber is $17 \text{ ps/km/nm} \times 1 \text{ km} \times 20 \text{ nm} = 0.34 \text{ ns}$, which is very similar to the experimental observation of $\sim 0.5 \text{ ns}$ pulse width change when the fiber length increased from 100 to 1000 m.

Last but not least, the peak soliton energy in our experiment is limited by the upper limit of our laser pump. It has been shown theoretically and numerically that, as long as the pump power is high enough, under proper setting of parameters for the CGLE, the dissipative solitons can attain very high energy in the anomalous dispersion regime [12,13]. Our simulation results also show that as the pump power is increased, a higher soliton energy can be obtained. Dissipative soliton resonances have attracted great interest in fiber laser research with the aim of improving the pulse energy [7,14–16]. Therefore, our experimental setup can be expected to achieve higher energy dissipative solitons if the power of the pump diode can be raised.

5. Conclusion

In this paper, we have shown through simulations that there exists a trade-off between the average power and cavity length in the context of high energy pulses in passively mode-locked fiber ring lasers using long cavity lengths and operating in the anomalous dispersion regime and that the optimum cavity length shifts as the pump power changes. Measured

results, obtained for a pump power of 500 mW, verify the optimum cavity length obtained in simulations. We have demonstrated that the highest dissipative soliton energy obtained is 139.1 nJ for a fiber length of 700 m in an NPR mode-locked all-fiber ring laser, working in the anomalous dispersion regime, at a repetition rate of 266 kHz. The energy of the pulse in our experiments is limited by the maximum output of the pump diode. It should be possible to achieve higher pulse energy by using a pump diode with a higher power.

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