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Effect of periodic optical pumping on dynamics of passive mode-locked fiber laser

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ABSTRACT

We report on the effect of periodic optical pumping on a passively mode-locked fiber laser (MLFL) based on an erbium-doped fiber (EDF). We investigate the influence of various parameters (including average pump power into the fiber laser, the modulation frequency and duty cycle of the pump, and the polarization state of the light inside the cavity) on the transient response characteristic of the MLFL such as: relaxation oscillation (RO) build-up time (defined as the time delay from the onset of pumping to the generation of passively mode-locked pulses) and the power of the detected RF signal at the fundamental cavity-mode frequency (determined by the ring cavity length), which reflects the stability of mode-locking pulse train.

We have found that the RO build-up time is inversely proportional to the average pump power while the RF power of the detected fundamental cavity mode (produced by the ring cavity) is proportional to the average pump power. A change in the duty cycle effectively leads the average pump power to vary, which in turn leads to changes in the transient response. The modulation frequency of the pump is rather related to the stability of the MLFL than its response time. Generally, the lower the modulation frequency, the more stable the mode-locked pulses generated in the fiber laser. Finally, the RO build-up time and, consequently, the pulse-generation time are highly sensitive to the state of polarization in the MLFL cavity.

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1. Introduction

Mode-locked fiber lasers (MLFL) have proved to be extremely useful systems for generating short pulses [1], and despite their technology having matured over the years, they still attract considerable research interest. Therefore, several research studies on MLFLs have been published in recent years, especially on short pulse generation [2], scaling of the pulse repetition rate [3], multi-wavelength operation [4], wavelength tunability [5], pulse repetition rate control [6,7], mode-locking using different types of gain medium [8,9], stability of mode-locking operation to temperature variation [10], and their noise characteristics [11]. Active mode-locking is generally used for the generation of high-repetition rate pulses, due to the flexibility that it offers in its configuration, whereas passive mode locking is suitable for generating trains of pulses of a very short width, typically of the order of femtoseconds. The dynamic response of passively MLFLs has been studied in [12–15]. It was also demonstrated recently, that passive mode-locking can be maintained in a ring cavity based on erbium doped fiber (EDF) pumped using a periodically modulated beam, and subsequently the typical transient response model for such a system was proposed [16].

In this paper, we study the effect that the various parameters of the optical pump modulation (i.e. average power, frequency, duty cycle, and polarization) have on the transient response of the passive MLFL. To achieve this, we characterize the passive MLFL in both the time and the frequency domain, measuring its RO build-up time [17], delay in the pulse generation, and the RF power of the fundamental cavity mode (detected by photodiode) of the MLFL. We find that as the average pump power increases the RO build-up time decreases. Additionally, the change in the duty cycle effectively varies the average pump power, consequently changing the transient response. The modulation frequency of the pump affects the stability of the MLFL.

The paper is organized as follows: Section 2 describes the effect of average pump power. Section 3 contains the effect of pump modulation duty-cycle and frequency. Section 4 describes the transient behavior depending on the polarization states of the ring cavity. We finally summarize the paper in Section 5.

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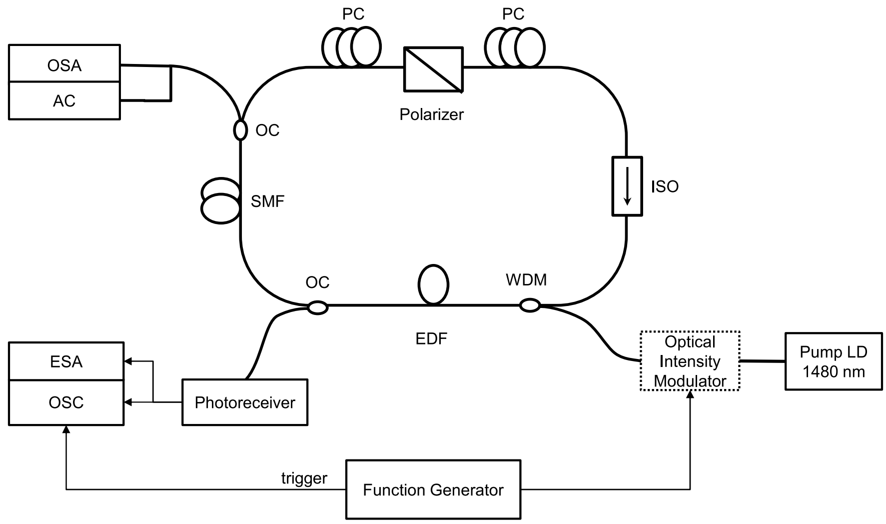

Fig. 1. Experimental setup (OSA: Optical Spectrum Analyser, AC: Autocorrelator, OSC: Oscilloscope, ESA: Electrical Spectrum Analyser, AWG: Arbitrary Waveform Generator, SMF: Single Mode Fiber, OC: Optical Coupler, PC: Polarization Controller, WDM: Wavelength Division Multiplexer, ISO: Isolator, EDF: Erbium Doped Fiber).

2. Effect of average pump power

The experimental setup of the passive MLFL is shown in Fig. 1, which is same as the one in Ref. [16], and is based on nonlinear polarization rotation (NPR) [1]. Fig. 2 shows a measured temporal waveform of the passive MLFL with periodic optical pumping when the average pump power is 18.7 mW at the output of the optical intensity modulator, and the frequency and duty cycle of the pump light are 100 Hz and 50%, respectively. The upper trace (trace 1) in Fig. 2 is the generated pulse train and the lower trace (trace 2) is the optical pump fed into the cavity. With periodic pumping into the cavity, the mode-locked laser shows the typical behavior reported in [16], where its pulse-train is stably generated while the pump is on. Also, there is a time delay (0.67 ms) between the onset of the pump and the first presence of the MLFL output, which is called the relaxation oscillation (RO) build-up time and it signifies the time when the population inversion occurs in the EDF [17].

If a curve fitting is performed using the measured data points in Fig. 3 to fit the RO build-up time to an equation of the form [14]:

$$\tau \approx \tau_0 \ln\left(\frac{P_p/P_{th}}{P_p/P_{th}-1}\right), \tag{1}$$

where τ_0 is the upper state lifetime in EDF, P_p is the average pump power, and P_{th} is the threshold pump power for starting lasing, it is estimated that τ_0 is 1.4 ms and P_{th} is 8.53 mW for our MLFL. We show that the set of measurement results (black squares in Fig. 3) is well fitted to the curve of the form (1) (red line in Fig. 3). To be specific, the RO build-up time was inversely proportional to the pump power, decreasing from 5.2 ms to 0.5 ms as the power was increasing from 8.7 to 21.4 mW. This experimental result is well agreed with the previous one [14] for different erbium doped fiber lasers.

To see the consistency of the pump-power dependence of the RO build-up time at higher modulation frequencies, we increase the modulation frequency from 100 Hz to 1 kHz. The average optical pump powers into the cavity were 24.15 mW and 33.11 mW in Figs. 4 and 5, respectively. The RO build-up times were measured to be 35 μs for 24.15 mW pump power, and 25 μs for 33.11 mW, showing the consistent pump-power dependence as shown in Fig. 3, which is for 100 Hz pump modulation. Additionally, as can be expected, the RF power at the fundamental cavity frequency (i.e. 13.7 MHz) is increased as the pump-power increases (e.g. −44.5 dBm and −39 dBm RF-power when the pump power is 24.15 mW and 33.11 mW, respectively).

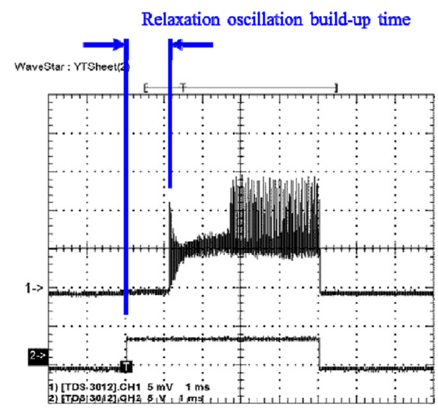

Fig. 2. Measured waveform of the passively mode-locked pulses. (Pump modulation frequency = 100 Hz, duty cycle = 50%, average pump power= 18.7 mW.)

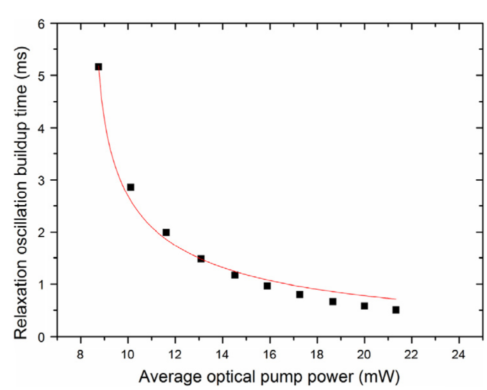

Fig. 3. Effect of average optical pump power on RO build-up time (Black squares: measurement, red line: calculation based on Eq. (1)). The pump modulation frequency is 100 Hz with 50% duty cycle.

3. Effect of periodic-pumping duty cycle and frequency

In this section, we investigate the effect of the duty cycle of the periodic pumping on the transient response of the passive MLFL. Figs. 6 and 7 show the measured results for two different duty cycles: 70% (Fig. 6) and 50% (Fig. 7), respectively, when pump modulation frequency is

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