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# Experimental study on relaxation oscillation in a detuned FM harmonic mode-locked Er-doped fiber laser

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**Abstract**

We experimentally studied the relaxation oscillation characteristics in a FM harmonic mode-locked fiber laser when the modulation frequency has a small detuning. The relaxation oscillation can lower the laser output power and make the amplitudes of output pulses uneven both in normal and abnormal dispersion cavities. While combined with self-phase modulation and the optical filter, the abnormal intra-cavity dispersion can suppress the relaxation oscillation phenomenon.


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Harmonic mode-locked Er-doped fiber laser can produce high repetition rate short pulses around 1550 nm wavelength and it is suitable for high-speed optical communication systems. In traditional method, the fiber laser is mode-locked when the modulation frequency ($f_m$) is exactly equal to the fundamental cavity frequency or its harmonics [1]. The small detuning effects have also been studied theoretically and experimentally [2,3]. Recently, some works show that asynchronous mode locking can be achieved in a FM mode-locked fiber laser when $f_m$ has a small detuning from a harmonic frequency, so it overcomes the unstable problem when the modulation frequency and the cavity length mismatch each other due to the environment fluctuation [4,5]. And it has also been used to realize an optical fiber ring buffer [6]. While another well-known detrimental phenomenon, relaxation oscillation [7–10], is enhanced when $f_m$ is asynchronous. It

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leads the laser output to a similar Q-switching mode-locking status [11]. So, how to suppress relaxation oscillation and keep all output pulses with the same amplitude is important. In this paper, we study it experimentally and show that the relaxation oscillation can lower the output pulse quality either the intra-cavity dispersion is positive or negative. So it is necessary to keep the modulation frequency into a limitation that may lead to relaxation oscillation when using asynchronous mode-locking method. But with self-phase modulation (SPM) effect and an optical filter we can suppress the relaxation oscillation in an abnormal dispersion cavity.

The basic physical mechanism of relaxation oscillation is the interplay between the oscillation field in the resonator and atomic inversion [12]. An increase in the field intensity leads to a reduction in the inversion due to the increased rate of stimulated transitions. This leads to a reduction in the gain that tends to decrease the field intensity. The change in the field intensity is mainly caused by the change of pumping rate of the amplifier medium or the cavity loss of the resonator. In FM mode-locked fiber laser, the main cause for the change of field intensity is the change of the cavity loss when $f_m$ is asynchronous as shown in Fig. 1. In synchronized modulation condition, the pulse always passes through the modulator at the maximum or minimum point of the modulation waveform then get almost no frequency shift. So it has the smallest loss after it passes through the optical filter. When the laser works stably, the saturated gain in the cavity is clamped in a certain level which can just compensate the pulse roundtrip loss. Another important factor in the cavity is the ASE noise. It also experiences the same gain in the cavity. But the loss of ASE noise is greater than pulse due to its wide spectrum. So, in synchronized modulation case, the noise decays relative to the pulse so that the laser can work stable. While when there is a small frequency detuning, the pulse passes through the modulator with a small time shift, $\Delta t$, from the maximum or minimum point of the modulation waveform. So it always experiences some frequency shift after modulation. Therefore, it has a larger loss after it passes through the filter than the synchronized case. The saturated gain required maintaining this pulse in the cavity increases accordingly. Now, the problem is that the ASE noise can get more gain in this case and whether it can compensate the loss to create a new pulse. If the detuning is small enough, the increased saturated gain is not enough to compensate the noise's loss. So the noise is still decay relative to the pulse then the pulse is also stable in this case. But when the frequency detuning becomes large, the pulse will shift from the maximum or minimum point a large amount, to $t_0$. In this process, the modulation loss for this pulse becomes larger and larger and the pulse decays. So the saturated gain in the cavity increases. A new pulse can be built up from ASE noise when the gain can compensate the loss at the maximum and minimum point of the modulation waveform, which is the smallest loss point in the cavity. The new pulse grows soon and the old one decays at the same time because the new one experiences smaller loss than the old pulse. Finally, the old pulse disappears and the new one creates a strong spike. This process repeats again and again because this new pulse is also shifted to $t_0$ some time later. When this period is coincident in the range of relaxation oscillation frequency ($f_r$) in the cavity, this process is enhanced by the cavity effect and the output becomes periodically strong spike in the relaxation oscillation frequency range. So, the laser behavior is similar to a Q-switching mode-locking case.

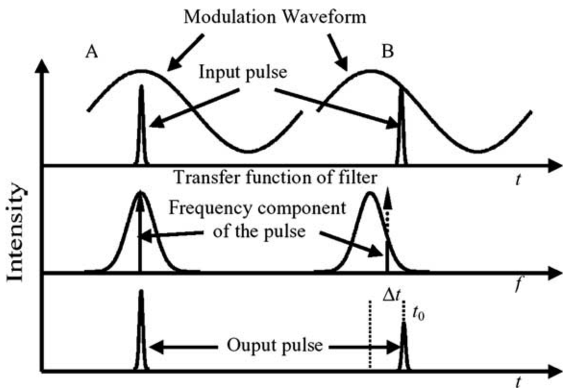


Fig. 1. The principle of producing modulation loss variation in an asynchronous mode locking: A is the synchronized modulation case and B is the asynchronous modulation case.