Kerr-Lens Effect and Mode Locking in Ring Cavity Ti:Sapphire Laser*

ZHANG Gui-zhong, MIAO Lin-shi, XIANG Wang-hua
Department of Precision Instruments, Tianjin University, Tianjin 300072

(Received 1 August 1995)

This paper presents the results of our numerical simulation, made by employing Split-step Fourier Method, of pulsewidth dependence on the physical quantities in ring cavity Ti:sapphire laser. It is revealed through the computed results that Kerr-lens effect which is now quantitatively considered plays a dominant role in forming ultrashort pulses and its interaction with dispersion finally determines the duration of the pulse, which sheds light on further theoretical investigation of the mode locking mechanism. Meanwhile, the self-consistent results also provide a guideline for the experimental alignment of the laser.

PACS: 42. 65. Re, 42. 60. Fc

It can be safely said that mode locked Ti:sapphire laser has approached maturity since its self starting was implemented by Lai[1] and Cerullo[2] *et al.* in 1994. In so far as the mode locking mechanism is concerned, however, the so-called Kerr-lens effect and its role in the mode locking process still need to be thoroughly studied. Kerr-lens effect is a third order nonlinear optical effect, and its presence in the Ti:sapphire rod makes the self-phase modulation effect (SPM) more obvious than usual.

In order to investigate the function of the Kerr-lens effect that is contained in SPM term, we employ the nonlinear Schrödinger equation (NLSE) to treat the pulse propagation in the Ti:sapphire rod and consider the four prism sequence to compensate the second order dispersion or group velocity dispersion (GVD) in the ring cavity configuration.[3] By satisfying the self-consistent conditions of root mean square pulsewidth,[4] we numerically simulated the pulse propagation within the ring cavity, whereby we have obtained the variations of pulsewidth with such physical quantities as the extent of SPM (Kerr-lens effect), GVD, average power and chirp, etc. It has been demonstrated through the calculated results that the Kerr-lens effect intrinsically contained in SPM predominates the formation of pulse and the interaction between SPM and GVD eventually determines the pulse duration. These results confirmed the postulation that Kerr-lens mode locking was the possible mechanism in Ti:sapphire laser and provided a clue to further theoretical investigation. At the same time, our results could guide the alignment of this laser in the self mode locking regime.

The numerical simulation was carried out for our X-shaped cavity Ti:sapphire laser.[3] In this kind of pulsed laser, the SPM effect is very strong due to the high peak power, and the gain medium itself also exhibits large positive dispersion, henceforth, the Kerr-lens effect appearing in SPM term in NLSE is significant and the four prism sequence is needed to compensate the

* Supported by the Young Teachers' Foundation of the State Commission of Education.

©by the Chinese Physical Society

GVD effect. The model for simulation is as follows: starting from one end of the laser rod with secant hyperbolic envelope, the pulse propagates through the Ti:sapphire crystal which is dealt with by means of Split-step Fourier Transform,[4] then it passes the four prism sequence and finally returns to the initial position with the self consistent conditions gratified.

The NLSE for pulsewidth of around 100 fs is

$$\mathrm{i}\frac{\partial A}{\partial z} = -\frac{\mathrm{i}}{2}\alpha A + \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} - \gamma|A|^2 A \,. \tag{1}$$

The first term is the loss term. In our case, it should be replaced with the following saturable gain term as we neglect the loss in the calculation:

$$G = \frac{1}{2}\left[\frac{g_0}{1 + I/I_s} - l\right] \,, \tag{2}$$

and the second term is the GVD effect. By using the Sellmeier equation[4] for the Ti:sapphire rod, we obtained the GVD coefficient. Its summation with the negative dispersion provided by the four prism sequence is the net dispersion in the cavity. The third term refers to the SPM effect, where the cross sectional area of the laser beam within the active medium is measured by taking account of the Kerr-lens effect. We use the Distributed Lens Approach to evaluate this effect.[3] In order to calculate the pulsewidth in a more precise way than usual, as the pulse envelopes are always deviating from a perfect secant hyperbolic or oscillating in the temporal domain after circulating in the ring cavity, we employ the root mean square pulsewidth, σ, to characterize the width of the ultrashort pulses:[4]

$$\sigma^2 = \langle T^2\rangle - \langle T\rangle^2 \,. \tag{3}$$

The input pulse is secant hyperbolic which best depicts the pulse shape in the femtosecond region:

$$A = A_0 \mathrm{sech}\left[\frac{(2\ln 2)t}{T_0}\right] \,. \tag{4}$$

Based on the mathematical model described above, we have performed extensive calculation of the variations of pulsewidth with the important variables such as beam size within the laser crystal, pulse energy, second order dispersion, chirp and so on.

The physical picture of Kerr-lens mode locking is: The stronger the intensity of the laser beam, the more intense the Kerr-lens effect is and the smaller the beam size will be due to focusing. Henceforth, the loss that this sort of beam experiences is smaller when passing through an iris in the ring cavity than that for a weaker intensity component experiences. To our knowledge, we consider quantitatively the Kerr-lens effect in the study on pulse evolution in the cavity for the first time. By doing so, the spot size of the beam will be varying along the laser rod, wherefore the SPM effect is anticipated to be different from the situation of a constant beam size assumption. Throughout the calculation, a constant saturation pulse energy, I_s, of 1.2×10^{-7} J is used. Figure 1 gives the calculated variation of pulsewidth with initial spot size ω_0. It can be seen from Fig. 1 that in the wide range of relatively large initial spot size, the pulsewidth does not vary much when other conditions are not changed, which manifests that

because of the large beam size, the Kerr-lens effect or the SPM effect is not obvious. But, when the spot size is reduced from about 200 μm, the pulsewidth is narrowed profoundly due to the onset of strong Kerr-lens focusing effect. Correspondingly in experiments, it has been measured that the pulse duration decreased from 80 to 35 fs when the length of the Ti:sapphire rod shortened from 20 to 5 mm.[5,6] This fact can be explained that the shorter medium will have a smaller average spot size as the Gaussian beam always has a waist within the crystal, therefore, the Kerr-lens effect will be stronger and the pulsewidth is narrower. In real setups, the two folding concave mirrors are always of small radius of curvature and the pump laser is always TEM_{00} mode[5] to make the spot size as small as possible. The results drawn from Fig. 1 agree well with the experimental data. These analyses show that the Kerr-lens effect indeed plays a dominant role in the formation of the ultrashort pulses. Within the precision of 0.5% for relative pulsewidth change, $\omega_0 = 300\,\mu$m, $T_0 = 100$ fs, $L = 20$ mm, $\beta_2 = 60\,\text{fs}^2/\text{mm}$ and $E = 40$ nJ are suitable parameter choice for self consistent operation of the ring cavity laser.

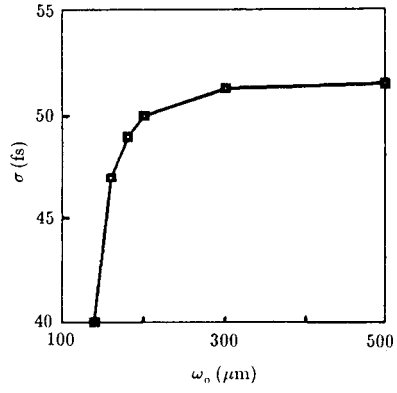

Fig. 1. Variation of pulsewidth vs initial spot size.

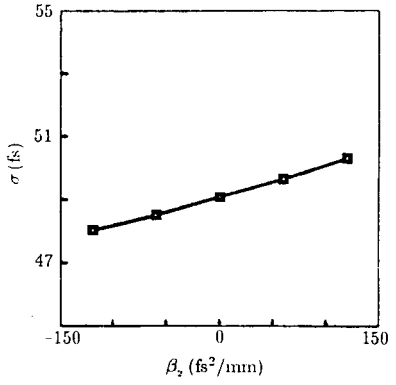

Fig. 2. Variation of pulsewidth vs dispersion.

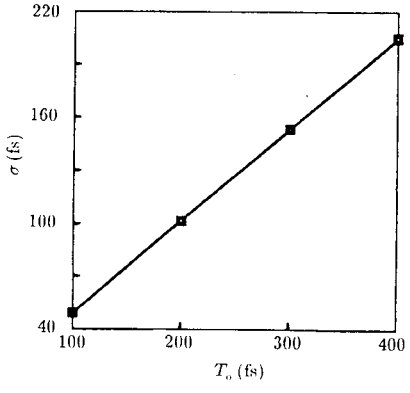

Fig. 3. Variation of pulsewidth vs input pulse duration.

The existence of positive dispersion of the laser rod and the chirp induced by the SPM effect requires the four prism sequence to compensate them in order to achieve stable Kerr-lens mode locked pulse train. For the purpose of emphasizing the function of dispersion, we select a relatively large ω_0 value of 180 μm and a linearly chirped pulse[4] to simulate the dependence of pulsewidth upon the net dispersion. The result is illustrated in Fig. 2. Although the pulsewidths have not changed much significantly over the dispersion range of about -120 to $+120\,\text{fs}^2/\text{mm}$ due to the weak Kerr-lens effect, the trend that the minus net dispersion gives the shortest pulsewidth for up chirped pulse can still be seen. Again, the fact that the wide dispersion value range supports appro-ximately the same pulsewidth shows that the Kerr-lens effect

predominates the pulse formation. Our detailed analyses on the structures in both the temporal and frequency domains also show that some side-band features appear in the spectra and the corresponding oscillations are present in the pulse envelopes for $\beta_2 < -100\,\mathrm{fs}^2/\mathrm{mm}$ and $\beta_2 > +100\,\mathrm{fs}^2/\mathrm{mm}$ values, which is reflected by the sharp increase of pulsewidth. Experimently, prism pair was inserted in laser cavity to compensate both the laser rod dispersion and the chirp to get pulses of 180 fs duration.[5] When two quartz prism pairs were used to produce larger negative dispersion (the net dispersion was closer to null now) than that of the prism pair, the pulsewidth was reduced to about 60 fs.[6] Our calculations confirmed this conclusion but the room here prevents us from presenting any more curves. Once more, the variation of pulsewidth with net dispersion shows that the Kerr-lens effect has indeed played a dominant role in the formation of pulse and its interaction with the net dispersion has determined the pulse duration.

Figure 3 gives the changes of pulsewidth with increasing pulse duration. The NLSE describes ultrashort pulses in ps and fs regimes, the functions of the nonlinear effect and dispersion effect terms will become less effective for longer pulses. In our calculation, we found that pulses with duration of greater than about 200 fs always satisfy the self-consistent condition, which supports this argument. The curve of a monotonic decrease of pulsewidth with increasing pulse energy can also be reasonably explained by the Kerr-lens function. The stronger the pulse intensity, the greater the peak power density (for a constant pulsewidth), the more effective the Kerr-lens function, therefore, the shorter the pulses become. This result not only verifies the role of Kerr-lens effect, as discussed earlier, but also it guides the practical adjustment of the laser. As a matter of fact, the mode locked pulses were shortened in duration from 180 fs for pulse energy of 9 nJ to 60 fs for pulse energy of 54 nJ.[5,6] Considering other factors, these data agree fairly well with the experiments.

In conclusion, by using the Split-step Fourier method, we have performed extensive calculation of the relations between pulse duration and many important physical quantities for our ring cavity Ti:sapphire laser. The Kerr-lens effect has been taken into account quantitatively in the SPM effect. It has been found that the Kerr-lens effect plays a dominant role in the formation of ultrashort pulse and the interplay between the SPM effect and the GVD effect eventually determines the pulse duration.

REFERENCES

[1] Ming Lai, Opt. Lett. 19 (1994) 722.
[2] G. Cerullo *et al.*, Opt. Lett. 19 (1994) 1040.
[3] Guizhong Zhang *et al.*, Chinese Journal of Lasers, B 3 (1994) 481.
[4] G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, New York, 1989).
[5] Wanghua Xiang *et al.*, Acta Optica Sinica, 14 (1994) 36 (in Chinese).
[6] Jianming Dai, Doctoral Dissertation, Tianjin University, 1994 (in Chinese).