Kerr-lens mode-locked Ti:sapphire laser with an additional intracavity nonlinear medium

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Abstract: We demonstrate a Kerr-lens mode-locked Ti:sapphire laser with an additional Yb^{3+} doped Potassium Yttrium Tungstate crystal (Yb:KYW) in the laser cavity, where not only the pump threshold to start mode-locking but also the stable regions to maintain mode-locking can be well-controlled by varying the position of Yb:KYW nearby the confocal focus to change the intracavity Kerr-effects. The pump threshold is reduced down to 800 mW to start the mode-locking operation, which is about 27% less than that for a Ti:sapphire laser without an additional Yb:KYW.

OCIS codes: (140.0140) Lasers and laser optics; (140.4050) Mode-locked lasers (190.7110) Ultrafast nonlinear optics.

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1. Introduction

Due to the broad gain profile and excellent physical properties of titanium-doped sapphire crystal, Ti:sapphire laser is still one of the most attractive lasers for both commercial applications and scientific researches [1-5]. The typical mode-locking mechanism for most Ti:sapphire lasers is soft-aperture Kerr-lens mode-locking (KLM). Since the pump beam is usually smaller than the laser beam in the gain crystal, the Kerr effect of the gain crystal results in intensity-dependent gain distribution and beam overlapping of the laser and pump beams. Thus, the short pulse experiences a higher gain than the multimode continuous-wave (cw) signals, resulting in stable mode-locking [6]. In this kind of lasers, the Ti:sapphire crystal works as not only a gain crystal to supply energy but also a Kerr medium to start mode-locking, whereby there is a limited controllability of the cavity features, such as the pump threshold to start mode-locking which depends on the nonlinearities inside the cavity, the stable regions to maintain mode-locking whose gap depends on the asymmetry of the cavity [7], and so on. The controllability of the KLM Ti:sapphire laser can be extended if there is an additional medium with a large nonlinear coefficient in the cavity. The contribution of additional nonlinearity for KLM was previously suggested in Ref. [8]. Additional glass plates were employed to obtain octave-spanning spectra directly from Ti:sapphire lasers [9,10]. Self-started KLM Nd:YAG laser was obtained with a piece of additional glass [11]. The additional nonlinearities in the cavity may decrease the mode-locking pump threshold, and the intracavity nonlinearities can be well-controlled by changing the position of the additional medium, leading to a controllable pump threshold to start mode locking. The additional intracavity nonlinearities may also alter the nonlinear propagation of the laser beam and thus the laser beam waist. Accordingly, the cavity asymmetry changes with the position of the additional medium in the cavity. As a consequence, the stable mode-locking regions could be well-controlled. Furthermore, multiple-pulse operation and harmonic mode-locking can be controlled by moving the additional nonlinear medium in the cavity [12]. Such a controllability-extended laser with an additional medium is quite useful for passive synchronization of separate lasers based on cross-phase-modulation [1,2], where pulses from separate lasers are coupled in a sharing Kerr medium to affect their mode-locking behaviors. The synchronization can be achieved more easily if the separate lasers can be well-controlled.

To validate the extended controllability, in this paper, we demonstrate a soft-aperture KLM Ti:sapphire laser with an Yb:KYW crystal in the cavity. The Yb:KYW crystal provides a much larger nonlinear refraction-index (8.7×10^{-16}cm^2/W) [13] than Ti:sapphire. Varying the position of Yb:KYW nearby the confocal focus to change the intracavity Kerr-effects, we can control the pump threshold to start mode-locking and stable regions to maintain mode-locking. The nonlinear ABCD matrices including the effects of the intra-cavity crystals support the experimental results.

2. Experiment and results

Figure 1 shows the schematic of our experimental setup. A 2.5-mm-thick Brewster-cut Ti:sapphire crystal (Ti:S) is used as the gain medium for the laser while a 4-mm-thick 5% doped Yb:KYW crystal (K) is used as an additional nonlinear medium. A lens with a radius of 50 mm is used to couple the pump laser into the crystal. Four pairs of broadband high-reflection chirped mirrors (M1-M8), each with the average group-velocity dispersion (GVD) of -70 fs^2, are used to compensate for the positive intracavity GVD. M1 and M2 are concave mirrors with the same radius of 100 mm while M7 and M8 are concave mirrors with the same radius of 150 mm. OC is a 3% output coupler. For additional tunability of the intracavity GVD, fused silica prism pair (P1 and P2) with a separation of 750 mm is inserted in the cavity. The total cavity length is about 602.5 cm, corresponding to the repetition rate of 24.9 MHz. During the experiments, both M2 and Yb:KYW are fixed on translation stages and can be moved along the direction of the intra-cavity laser beam, for the purpose of obtaining stable mode-locking regions and changing intra-cavity nonlinearities, respectively.

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When M2 is adjusted to a suitable position, KLM can be self-started with a suitable pump power in the presence or absence of a Yb:KYW crystal in the laser cavity. As the Yb:KYW crystal is set at the confocal focus between curved mirrors M7 and M8, the mode-locking pump threshold is about 800 mW and the spectrum is shown in Fig. 2(a). In comparison, a Ti:sapphire laser with the same cavity geometry but without Yb:KYW between curved mirrors M7 and M8 starts mode-locking at a pump threshold of 1.1 W. In a soft-aperture KLM laser, the power-dependent gain distribution caused by the self-focusing effect of the gain medium is responsible for the mode-locking operation. For a Gaussian beam, since the effective focusing length of the center part is much shorter than that of the leading and trailing parts, the temporal distribution of beam intensity is transformed to spatial one when it goes through a Kerr medium. Combined with the intensity-dependent gain distribution of the gain medium, the intracavity nonlinearity, which is dependent upon the nonlinear refraction and intracavity intensity, results in stable mode-locking. With the help of the additive Yb:KYW, the pump threshold to start mode-locking is reduced, as shown in Fig. 2(b). As we precisely vary the position of Yb:KYW, the mode-locking pump threshold of the laser changes accordingly. When the Yb:KYW is moved towards the focus, the corresponding nonlinear refraction effect increases because of the decreasing beam size in it and as a consequence, the pump threshold is decreased. Since the pump threshold depends on both the total nonlinearity of the cavity and the gain distribution of the gain medium, the function in Fig. 2(b) is not monotonic with the relative position of Yb:KYW and the confocal focus. This will be explained later with the help of the nonlinear ABCD matrix. The corresponding variation of the output power is shown in Fig. 2(c). Note that no obvious changes of the laser spectrum or pulse duration are observed as the Yb:KYW varies between the curved mirrors M7 and M8, because neither the self-phase modulation (SPM) nor the net intracavity GVD changes obviously at the pump threshold to start mode-locking.

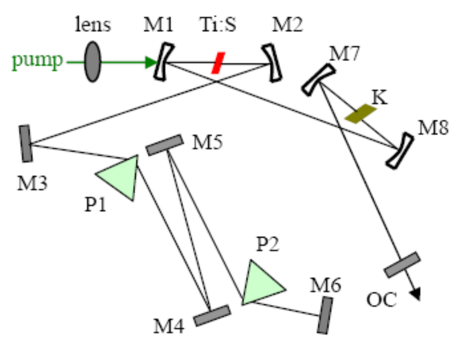

Fig. 1. Schematic of our Ti:Sapphire laser. Ti:S is a 2.5-mm-thick Ti:sapphire crystal and K is a 4-mm-thick 5% doped Yb:KYW. M1-M8 are broadband high-reflection coated chirped mirrors and OC is the output coupler. M1 and M2 are concave mirrors with a curvature radius of 100 mm; and M7 and M8, 150mm. The fused silica prisms P1 and P2 supply tunable dispersion.

The addition of an Yb:KYW crystal in the laser cavity affects the stable mode-locking regions. In order to display the effect of the Yb:KYW crystal, we at first measures the stable mode-locking regions of the laser without Yb:KYW. With a pump power of 2.1 W, mode-locking maintains stable with two separate regions separated by a gap of 0.025 mm as M2 moves along the intracavity laser beam. The range is 0.01 mm for the region far away from Ti:S and 0.15 mm for the region close to Ti:S. With the same pump power, when Yb:KYW is at the focus of the confocal cavity, the corresponding gap becomes zero and the total region to maintain mode-locking is 0.105 mm. Additionally, the stable regions change with the position of Yb:KYW. The variations are given in Fig. 2(d). It is clear that if there are two stable regions, the closer the Yb:KYW to the focus, the narrower is the gap between the two mode-locking regions. The discontinuity of the gap and the region far away from Ti:S at $Z\text{-}Z_0$~-5 mm indicate that only the stable region close to Ti:S can be found, while the discontinuity of

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both regions at Z-Z_0~0 mm implies that the two stable regions combines into one region. The changes of the beam waists and cavity asymmetry caused by the addition of Yb:KYW are responsible for the variations.

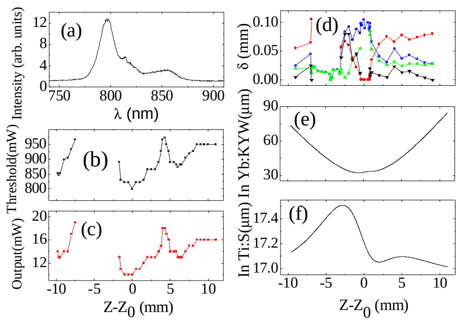

Fig. 2. (a) The output laser spectrum. (b)-(f) The variations versus the position of Yb:KYW relative to the focus of the confocal cavity, where Z is the position of Yb:KYW and Z_0 is the position of the confocal focus. (b) The experimental pump threshold to start mode-locking. (c) The output power of the laser. (d) The experimental variations of the ranges of the region far away from Ti:S (black line and symbol) and region close to Ti:S (green line and symbol) for mode-locking. The symbolized red line is the gap of the two stable regions and the symbolized blue line is the total range of them. (e) The calculated beam waist inside Yb:KYW. (f) The calculated beam waist inside Ti:sapphire.

3. Analysis

To understand the dependences of the pump threshold and stable regions on the Yb:KYW crystal and the discontinuity of the stable KLM regions, we firstly get insight into the mode-locking mechanism of our Ti:sapphire laser. In our experiment, since no apertures are installed in the cavity, the intensity-dependent laser beam spot size is responsible for the mode-locking operation. Actually, two mechanisms of operation act, which contains the nonlinearity-dependent average gain and transverse radiation redistribution. The former is caused by power-dependent beam overlapping, and the latter, by radially varying gain [8]. Better beam overlapping can be obtained with stronger self-focusing effect inside the cavity, while better radiation redistribution for mode-locking can be obtained with a higher pump power, which is equivalent to a soft aperture. Thereby, for a cavity with a given intracavity laser power, the pump power to start mode-locking depends on the beam waists of the intracavity crystals.

The gap between the two stable regions can be defined by a cavity asymmetry factor given as [7]

$$s = \frac{f_1^2\left(n_{l2}d_2 - f_2\right)}{f_2^2\left(n_{l1}d_1 - f_1\right)} \quad (1),$$

where d_1 and d_2 correspond to the linear distances from M1 to OC and M2 to M6, respectively, n_{l1} and n_{l2} are the average refraction indexes of the two arms, while f_1 and f_2 are the focuses of M1 and M2 in our setup. A smaller cavity asymmetry factor *s* means a narrower gap. As no nonlinear effects are considered, n_{l1} and n_{l2} are fixed to 1 [7]. In our experiments, n_{l2} is a constant of 1, while n_{l1} is dependent on the refraction index of Yb:KYW which changes with the intensity of the laser in the additional crystal. With the given average power, the dependence on the intensity can be converted to the dependence on the beam waist.

To obtain the information of the variation of the beam waists and display the effect of the additional medium, we calculate the nonlinear ABCD matrices through our laser cavity including the optical nonlinearities of both crystals. The nonlinear ABCD matrix of the crystal can be given by [14]

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$$T = \begin{pmatrix} \cos(\gamma l) & \sin(\gamma l)/(n_I \gamma) \\ -n_I \gamma \sin(\gamma l) & \cos(\gamma l) \end{pmatrix} \quad (2),$$

with $\gamma = \frac{1}{\omega^2}\sqrt{\frac{8n_2 P}{nc\varepsilon n_I \pi}}$, $n_I = n + \frac{2n_2 P}{nc\varepsilon\pi\omega^2}$, where c and ε are the speed of light and the electric permittivity in vacuum, respectively, n_2 is the electric field coefficient of the nonlinear refractive index, ω is the beam waist, and P is the average power. The evolutions of the beam waists relative to $Z\text{-}Z_0$ obtained utilizing the nonlinear ABCD matrices are given in Fig. 2.

According to Figs. 2(e) and 2(f), the beam waist inside the Yb:KYW decreases with the distance between the additional crystal and the focus, while the beam waist inside the Ti:sapphire is not a monotonic function of the distance. So the state of the laser, which would be mode-locking or cw operation, depends on the competition of the two mechanisms. At first, the increase of the Kerr effect of the Yb:KYW can not compensate for decreases of the Kerr effect of the Ti:sapphire and the average gain which depends on the beam overlapping, so the pump threshold increases. When the beam waist inside the Ti:sapphire keeps on increasing sharply, no mode locking can be achieved until the Kerr effect of the Yb:KYW is large enough to dominate the mode-locking operation, and then the evolution of the pump threshold follows that of the beam waist inside the Yb:KYW. After the focus, the effect of the Yb:KYW becomes weaker with the increasing beam waist inside, so when the beam waist inside the Ti:sapphire decreases, the pumping threshold decreases. The following increase of the threshold is caused by the Yb:KYW dominating mechanism since the change of the beam waist inside the Yb:KYW is much sharper than that inside the Ti:sapphire.

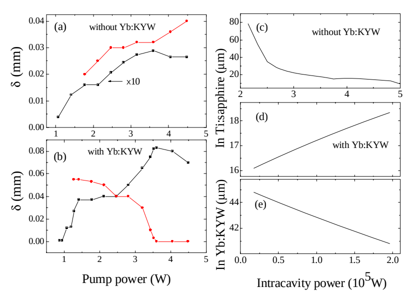

Fig. 3. (a) and (b) are the experimental variations of the gap (red line and symbol) between the two stable regions and the total range of the stable regions for mode-locking (black line and symbol) versus the pump power for cavities without the Yb:KYW crystal and with Yb:KYW 8 mm in front of the confocal focus, respectively. The words "×10" in (a) mean that the data in the figure is 10 times less than the experimental data. (c), (d) and (e) are the variations of the calculated beam waists of the cavity versus the intracavity power. (c) The beam waist in the Ti:sapphire crystal while there is no Yb:KYW in the cavity. (d) The beam waist in the Ti:sapphire crystal when Yb:KYW is 8 mm in front of the focus of the confocal cavity. (e) The beam waist in the Yb:KYW crystal with the same conditions as (d).

The calculated results are also used to display the mechanism of the variation of the stable regions for a KLM laser with nonlinear effects considered. For the sake of simplicity, we study the situation of a Ti:sapphire laser without Yb:KYW firstly, where we get different intracavity Kerr lensing by changing the pump power. The experimental results are given in Fig. 3(a). The gap, shown as red line and symbol, is a monotonic function of the pump power, while the total stable range, shown as symbolized black line, is not. Figure 3(c) shows the calculated beam waist inside Ti:sapphire which decreases with the intracavity power. It is clear that the larger the beam waist, the closer are the two stable regions, and the smaller is the total stable range. Since the mode-locking is hardly achieved when the displacement of the

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Ti:sapphire crystal to the beam waist is around zero [14], it can be understood that the division of the two stable regions is caused by the varying position of the beam waist. In practice, the physical limitation of the beam spot size inside the Ti:sapphire crystal sets the upper and lower limits. The smaller the beam waist, the broader the gap is observed. The larger stable range is due to the better beam overlapping and the higher pump power. But a smaller beam waist corresponds to a larger divergence angle, so when the beam waist is too small, the stable range decreases. For the laser with a Yb:KYW crystal, the situation is a little complicated. The variations of the stable range and the gap under different pump powers are also measured when the Yb:KYW is placed 8.0 mm in front of the focus of the confocal cavity and the results are given in Fig. 3(b). When the Yb:KYW is at the confocal focus, the tendency of the variation is the same, but the gap disappears at a much lower pump power. Here, the function of the total range is similar to that in Fig. 3(a), while the function of the gap is reversed. Figures 3(d) and 3(e) show the calculated variations of the beam waists inside the Ti:sapphire and Yb:KYW. We find that with the Yb:KYW crystal in the cavity, the function of the beam waist inside the Ti:sapphire crystal is also reversed with that in Fig. 3(c). Thereby, the reversal results in Figs. 3(a) and 3(b) can be well understood. Additionally, because of the Kerr nonlinearity, the decreasing beam waist inside the Yb:KYW results in an increasing n_{l1} in the asymmetry factor *s*, which also results in a narrower gap. Meanwhile, the decreasing beam waist inside the Yb:KYW and increasing intracavity power supply enhanced Kerr effects of the cavity. As a consequence, mode-locking can still be achieved even when the beam waist inside the Ti:sapphire increases, and the stable mode-locking range is increased. However, when the pump power keeps on increasing, a decrease of the stable mode-locking range is observed for the biggest beam waist inside the Ti:sapphire as the mode-locking operation is limited. The variations of the gap and the total stable range for mode-locking with the position of the Yb:KYW shown in Fig. 2(d) can also be well explained with the help of the calculated beam waists. The increase of the gap at the beginning and the existence of the discontinuous part where only one stable region can be found are caused by the competition mechanism for mode-locking discussed in the above paragraph. After that, the increased beam waist inside the Ti:sapphire and decreased beam waist inside the Yb:KYW result in a gap decreasing at first. Then, after the maximum beam waist, the sign of the effect of the Ti:sapphire changes and the dominating role that the Yb:KYW plays is confirmed. That is why the gap keeps on increasing after the focus although the beam waist inside the Ti:sapphire increases. The dependence of the stable range on the intracavity Kerr effects is also confirmed. The additional nonlinearity results in a re-imaging of the side of the cavity and therefore the cavity asymmetry. Thus the gap of the stable regions for mode-locking which depends on the cavity asymmetry can be controlled by modifying the nonlinearity, while the physical length of the cavity keeps constant.

4. Conclusion

In summary, a soft-aperture KLM Ti:sapphire laser with an additional Yb:KYW crystal has been demonstrated. Owing to the Kerr-effect of the additional medium, both the mode-locking pump threshold and the stable mode-locking regions can be well controlled by changing the relative position of Yb:KYW to the confocal focus. The closer the Yb:KYW to the focus, the lower is the pump threshold and the closer are the two stable regions of the mode-locking laser. A 27% decrease of the pump threshold to start mode-locking has been obtained in comparison with a Ti:sapphire laser without additional medium. Analysis shows that the gap between the two stable regions is dependent on the beam waists inside both nonlinear media in different ways. The bigger the beam waist in the gain medium, the narrower is the gap, while the dependence on the beam waist in the additional crystal is conversed.

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