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Generation of Ultra-broad-bandwidth Femtosecond Laser Pulses in Infrared and Blue Region*

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Abstract Soft gain aperture effect from pump beam size inside the laser crystal is crucial for obtaining stable Kerr lens mode-locking and generating ultrabroad-bandwidth pulses in Ti : sapphire laser. Mode-locking dynamics is experimentally investigated for a diode-pumped all-solid-state laser. At the pump power of 4 W, the femtosecond laser pulses tunable from 794 nm to 835 nm are generated with high output power of 570mW and extremely large bandwidths at the maximum of 135 nm, which can support the transform-limited pulse width in sub-10 fs time duration. Moreover, this laser is extended to blue pulses tunable from 418 nm to 429 nm by using a 260 μm-thick BBO crystal. The measured ultrabroad bandwidths are unprecedent in this spectral region, and their transform-limited pulse durations are sub-15 fs.

Keywords Kerr lens mode locking; Femtosecond laser pulse; Soft gain aperture effect
CLCN TN24 **Document Code** A

0 Introduction

Over the past few years, considerable efforts have been made in ultrashort pulse generation from Ti : sapphire laser with the help of Kerr lens mode-locking (KLM) technique both for fundamental researches and applied interests[1,2]. The rapid progress in pulse-width reduction produced directly from the laser cavity is mainly contributed to the great improvements in intracavity dispersion compensation[3,4]. Generally, there are three different types of configurations for dispersion compensations inside the femtosecond laser oscillator. The first one is called as intracavity quarts-prism-controlled technique (QPC), in which the available pulse width will be limited by the remaining higher-order dispersions. The shortest time duration obtained by this method is only 8. 5 fs with a typical spectral bandwidth of 110 nm[5]. An advantage of the prism-pair technique is that the desired negative second-order dispersion can be adjusted continuously. The second one is using modern chirped-mirror-dispersion-controlled technique (MDC), in which the chirped mirrors can not only give the high reflectivity but also provide special dispersion compensations in a wide spectral range. And the generated pulse time duration by this means can be shortened to 7. 5 fs with a broad bandwidth of 120 nm[6]. The third configuration is the combination of above two techniques, in which both quart-prisms and chirped-mirrors are used intracavity to control group dispersions. Based on this method, the output laser pulses shorter than two optical cycles with bandwidth in excess of 150 nm have been achieved[7,8]. However, for most current Ti: sapphire laser oscillators, whatever they are commercial or home built, It is always very necessary and required to put some additional elements into the cavity, such as physical slits or modulators, to start or sustain Kerr-lens mode locking performance. The proper placement of these hard apertures would help enhance the discrimination between mode-locked and cw operations[9]. But for the reason of frequency-dependent mode size (FDMS) effects, they can act as a strong spectral filter as well, and eventually limit the generated pulse duration[10]. Recently, self-starting Kerr lens mode-locked Ti : sapphire laser without additional intracavity elements except the laser rod were reported[11]. However, the self-starting mechanism is still not well understood.

In this paper, it firstly demonstrates some practical design considerations for building a Ti : sapphire oscillator with KLM operation based on soft-aperture effect. Then KLM operation dynamics is investigated including the mode-locking range, the beam profile and power jumping situations. By reducing FDMS effects, the generated tunable femtosecond laser pulses with central wavelength from 794 nm to 835 nm are measured to have output power of 570mW and with very large spectral bandwidth at the pump power of 4 W. The transform-limited pulse

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durations supported by these ultrabroad spectral bandwidths would be less than 10 fs. Furthermore, blue laser pulses with central wavelength tunable between 418 nm to 429 nm are also obtained by focusing the infrared laser beam into a very thin BBO crystal. The measured unprecedent broad spectra could have potential pulse widths in shorter than 15 fs time duration.

1 Design considerations for a soft-gain-aperture KLM oscillator

The laser resonator is designed in an asymmetric "Z" fold four-mirror configuration as shown in Fig. 1. The highly doped 4.75 mm Ti : sapphire crystal is oriented at Brewster's angle $\theta = 60.4°$. A lens with 12.5 cm focal length is used for focusing the pump beam into the crystal from a very compact diode-pumped frequency-doubled Nd : Vanadate laser (Verdi, Coherent Inc.), which can provide single-frequency (532 nm) CW green output with lower noise at maximum power levels of 5 Watts in vertical polarization. In order to improve the pump absorption efficiency, a half-wave plate is inserted before the lens to change the laser polarization from vertical direction to horizontal direction. Total cavity mirrors are broad-band dielectric coated mirrors with low group velocity dispersions (CVI Inc.). The reflectivity of these mirrors are of >99.8% in the region of 650 ~ 950 nm except for the output coupler. Among these, M_1 and M_2 are two curved mirrors with the focal lengths of $f_1 = f_2 = 5$ cm, and they are separated in the proper distance to compose a small folding cavity. M_3 is a flat end mirror and M_4 is an output coupler with a transmission of 10% at 800nm. A pair of Brewster-cut fused silicon prisms, P_1 and P_2, with the separation of 46 cm are used for intracavity dispersion control. All these optical elements are mounted on the translation stages for precision adjustment. The short arm of this resonator is $\overline{M_2M_4} = 82$ cm, and the long one is $\overline{M_1M_3} = 96$ cm.

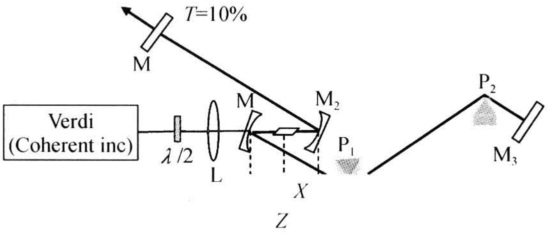


Fig. 1 Schematic diagram of all-solid-state KLM Ti : sapphire laser based on soft-aperture effect

For such a four-mirror cavity, the laser stable operation and KLM action will be strongly relied on two critical parameters. One is the folding curved-mirror distance Z, which essentially only determines the optical stability region. The other is the position of the Ti : sapphire crystal, which has a influence on the overlapping between the pump beam and the laser waist inside the crystal. According to the earlier studies, the effective folding mirror distance should be $Z = f_1 + f_2 + \delta$ for the stable laser operation[9]. Here δ is a stability parameter including two different parts with $0 < \delta < \delta_1$ and $\delta_2 < \delta < \delta_1 + \delta_2$, where

$$\delta_1 = \frac{f_2^2}{d_2 - f_2} \text{ and } \delta_2 = \frac{f_1^2}{d_1 - f_1}$$

Here d_1 and d_2 are the short-arm and long-arm distances of the resonator respectively. Therefore, two separated stability regions come out, and the laser action point is actually determined by the distance Z.

In order to start and maintain Kerr lens mode-locking operation, the cavity is usually aligned to work near the upper edge of the first stability region or the lower edge of the second stability region[12]. In the former case, the laser operation is verified to be more sensitive to the cavity misalignment due to the almost confocal configuration composed by two folding curved mirrors. But for the latter case, the long distance Z can make the resonator cavity have low misalignment sensitivity. Furthermore, the strong self-amplitude modulation (SAM) can always be achieved in the second case. That is why most researchers often adopt this kind of cavity design[13].

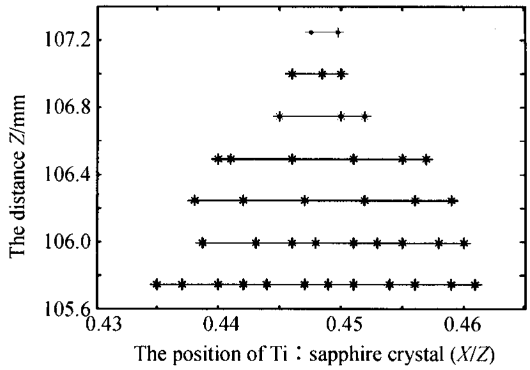
However, in some practical situations, the proper and rapid alignment of resonator cavity to work near the lower edge of the second stability region is always perplexed and time-consuming. Here an easy and practical way is found to tackle this problem by comparing laser beam sizes on the two flat end mirrors. If the beam size on the short-arm end mirror looks bigger than that at the end of the long arm, the laser operation will be located in the first stability region, and the distance between two curved mirrors should be extended otherwise the bigger beam size at the end of the long arm can tell that the laser action is working in the second region. After this processing laser operation at the proper point should be carried out. Actually, when the difference of two beam sizes on the flat end mirrors is small, it suggests that the laser point be placed near the upper edge of the second stability region. Whereas the big difference between two beam sizes may indicate that the laser action point is just close to the lower edge. With the help of this procedure the calibration of resonator cavity near the lower edge of the second stability region within short time has been achieved through proper translating of mirror M_2 and the crystal. During this process, the curved mirror M_1 was not touched.

To get a very short laser pulse in the time duration, the wide extending of pulse spectrum in the frequency domain should be required. Fortunately, self-phase-modulation (SPM) effect of the intense laser pulse in Kerr laser medium will broaden its spectra, leading to higher frequency in the rear part and lower frequency in the front part of the pulse. On the other hand, both starting and sustaining of KLM are induced by laser self-focusing in Kerr medium. And the intensity-dependent self-focusing effect can also make the high- and low-intensities have different mode sizes, which will be favorable or get suppressed respectively. Apparently, the combined effect of SPM and self-focusing will result in the generated high- and low-frequency components with relatively larger beam diameter than those in the center of the spectrum. That means that there are different mode sizes across the spectrum. This is the FDMS effect[10]. Due to this effect, when a hard aperture is put into the cavity near the output coupler to enhance the discrimination between mŏdes of operation, it can act as a strong spectral filter as well and prevent the increase of the laser bandwidth. However, J. Zhou et al have found that the pulse was always shortest within the crystal[5]. This measured result indicates that the spectral chirp from SPM inside the crystal is well compensated by the negative group dispersions from a prism pair. Therefore, the FDMS effect will be greatly reduced inside the crystal. If a soft gain aperture inside the rod is obtained by adjusting the focusing size of the pump beam slightly smaller than the laser cavity mode waist, the laser-intensity-dependent discrimination of mode operation will have little influence or limitation on the widely extended pulse spectrum. Moreover, higher gain due to the increased overlap of the laser with pump beam can increase the laser intensity and enhance SPM effect inside the crystal. Eventually, this will result in the generation of extremely broad bandwidth of pulses with high output power.

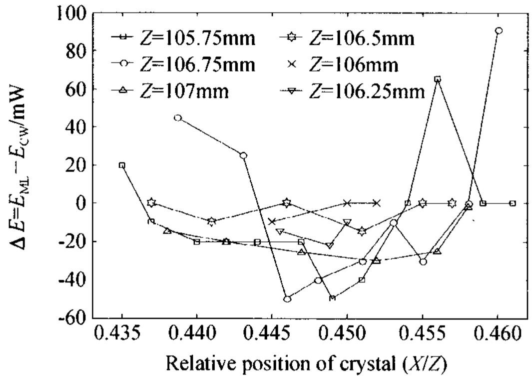
2 Experimental results and analyses

At the pump power of 4 W, Kerr-mode-locking was started only by pushing the prism P_2 gently, or by tapping one of cavity end-mirrors slightly. It was found that the output power got a big "jump up" from 430 mW in cw state to about 520 mW or higher in mode-locking state. Since there are no hard apertures or modulators inside the cavity, this can be referred as soft-aperture KLM. After optimization of the cavity parameters, the maximum output power can reach 570mW. The SAM introduced by soft-aperture effect from pump beam is sufficiently strong and the mode-locking operation has been found to be quite robust against various kinds of environmental perturbations. Here it should be mentioned that in our experiment a big "jump down" of output power from 540 mW in cw state to 490mW of the mode-locking state has been also observed, which can be explained by F. Sallin[14].

If the position of Ti : sapphre crystal is defined by the distance of X away from the curved mirror M_2, the dynamic range of KLM operation for different crystal positions and folding mirror distances is platted in Fig . 2 (a) . As it is seen



(a)Stable KLM region for different X and Z



(b)The output power jumping situations for the laser operation switching from CW state into KLM state

Fig. 2 Dynamic behaviors for KLM operation clearly, the profile of the dynamic regions for KLM action seem to have a pyramid shape. When the distance Z is smaller which means the laser action point is close to the lower edge, the available KLM operation range for the crystal position is relatively large, and it is also relatively easier to achieve mode locking. However, when the distance Z increases which means that the laser action point is moving from the lower edge toward the upper edge of the second stability region, the obtained region for the crystal position in KLM operation will be reduced, and the starting of mode-locking also becomes difficult. Fig. 2 (b) illustrates the output power "jump" situations when the laser operation is switching from cw state into KLM state. The power difference ΔE is equal to KLM output power E_{ML} minus cw output power E_{cw}. It seems that the "jumping-up" of the output power mostly occurs on the two sides of KLM dynamic range, especially for the small distance Z, or getting close to the lower edge. In other parts of KLM range, the output power usually has a "jumping down".

To study the beam profile and the quality of output laser during cw and KLM operations, we observed the laser beam spots on a white paper through CCD camera as shown in Fig. 3. Obviously the two situations are really quite different. The intensity distribution on the cross-section of CW laser beam looks uneven and there are many small disjunct spines sweeping around the beam brim, just like a bombed crater on the ground . But for KLM laser beam, the spinal intensities on the boarder of the beam spot disappear and the intensity distribution on the beam cross section becomes more even and bright. The beam profile looks like a polished plate with very smooth edges. Actually this kind of observation can be adopted as a simple method to estimate if the laser is mode-locked or not.

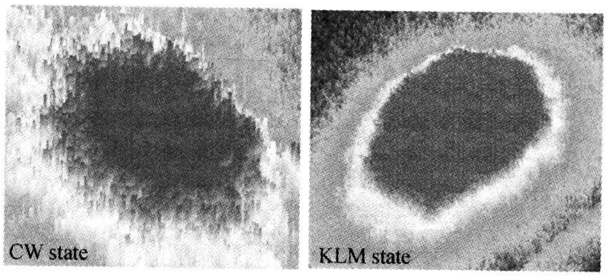


Fig. 3 The difference of the output laser beam profiles between CW state and KLM state operations, which is observed by CCD camera imaging of the beam spots on a white paper

Based on the soft-gain-aperture effect, KLM operation generates laser pulses with a significant broad spectrum extending from 670 nm to 920 nm, as shown in Fig. 4 (a). The central wavelength of this spectral distribution is 817 nm and it's full width half magnitude (FWHM) is about 107 nm. When the mode-locking operation of this laser system is achieved by inserting a hard aperture into the cavity, the frequency-dependent mode size effects will act as a strong spectral filter, which of course limits the generated pulse bandwidth[9, 10]. In addition, if the pulse is assumed to be temporal sech^2-shape and have an extracavity group velocity dispersion compensation, the transform-limited time duration supported by this extremely large bandwidth should be as short as 7 fs. Because the prism P_1 refracts different wavelength components to slightly different angles, and the prism P_2 then refracts all of them again to get a collimated beam with a spatial chirp. By reducing the amount of prism material that the light goes through in P_2, some short wavelengths can be removed out of the cavity. Thus, the wavelength tuning is realized. However, a mode-locked optical pulse with large bandwidth actually gives a limitation on this kind of wavelength tuning range. In Fig. 4 (b) the blue stars represent measured pulse bandwidths for different laser central wavelengths from 794 nm to 835 nm. Correspondingly each output pulse with very broad spectrum may support a transform-limited time duration less than 10 fs, as shown by the green stars in Fig. 4(b). In particular, the available spectral bandwidth at the central wavelength of 835 nm increases up to 135 nm, and its corresponding transform-limited pulse width has a time duration as short as about 5 fs, approximating several optical cycles. It is obvious that the generated pulse spectrum will be broadened with the increase of central wavelength, being similar to the previous exservations[11, 15]. One of the possibilities of extending pulse spectrum further can be attributed to Raman self-frequency shift in crystalline mode-locked lasers, which requires as much as 3 ~ 6 W intracavity power levels typical for Ti : sapphire lasers[15~17]. The theory of this phenomenon has been given by Haus[18]. Another possibility for this observation would be the contribution from higher-order dispersions in comparison with the low value of group-delay dispersion (GDD). However, it is known that higher-order dispersions lead to distortion of the pulse spectrum and increased sideband generation[5, 19, 20]. Actually, it did not observe any significant splitting in measured pulse spectra. Thus, it is belived that the self-frequency shift to be one of the major factors achieving larger bandwidth for longer wavelength.

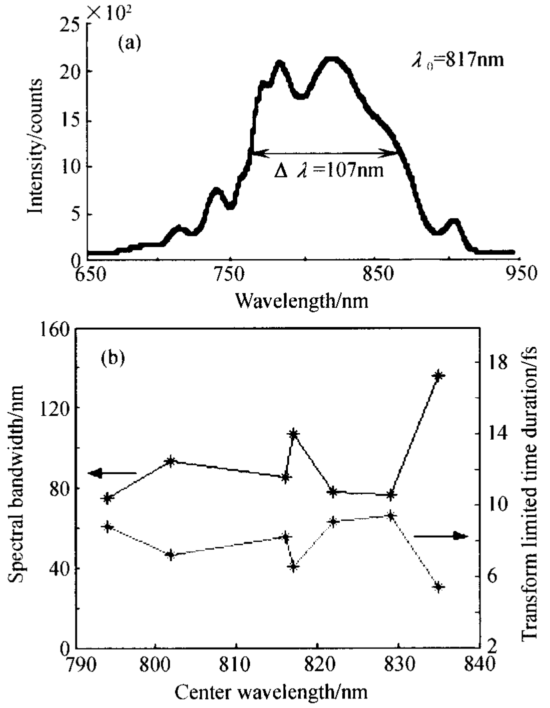


Fig. 4　The measured tunable infrared pulse spectra with ultrabroad bandwidths and their corresponding supported time durations

Owing to the extremely broad bandwidth of the generated laser pulses with potential very short time durations and much high peak powers, we performed the output infrared laser beam to get a tight focusing onto a 260 μm-thick BBO crystal through a lens, and produced blue laser pulses with very wide bandwidths. Fig. 5 (a) demonstrates a typical measured blue spectrum with FWHM of 28 nm at the central wavelength of 422 nm, which can support a transform-limited Gaussian shape pulses in the time duration of 8 fs. Through tuning of the incident fundamental laser wavelength, the tunable blue pulses is obtained as shown in Fig. 5(b), in which the measured different central wavelengths are varying from 418 nm to 429 nm. Blue stars is Fig. 5(b) are measured bandwidths of laser pulses with different central wavelengths. And they will become bigger when the central wavelength is getting longer. The maximum FWHM value will be up to 38 nm at the central wavelength of 429 nm. Within our knowledge, these generated ultrabroad bandwidths are unprecedented in this spectral range. Moreover, Green stars in Fig. 5(b) give the transform-limited pulse durations supported by their corresponding wide spectra, which are usually in fact less than 15 fs.

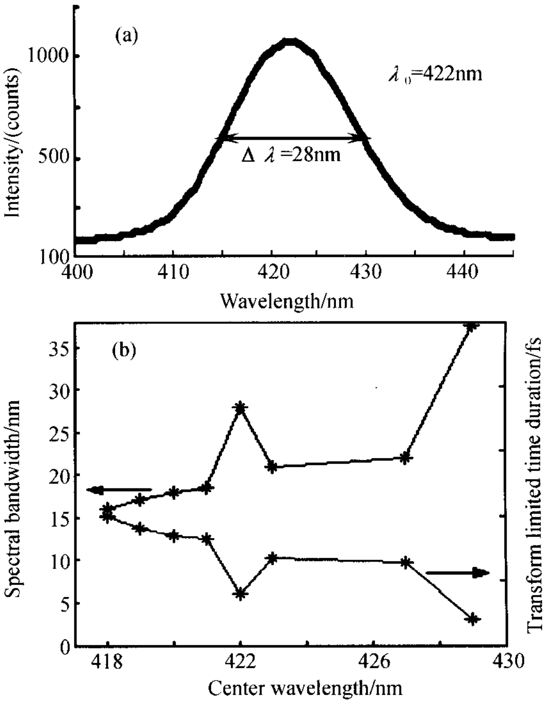


Fig. 5　The measured tunable blue pulse spectra with unprecedent broad bandwidths and their corresponding supported time durations

3 Conclusion

Dynamic characteristics has been demonstrated for a quarts-prism-dispersion-controlled self-starting KLM Ti: sapphire laser based on soft-gain aperture effect inside the crystal. Through optimizing the cavity design, the FDMS effects are greatly reduced, resulting in the generated output pulses having much high average power of 570 mW and extremely large spectral bandwidths at the maximum of 135 nm. The central wavelength of femtosecond laser pulses has been tuned from 794 nm to 835 nm. And their transform-limited time durations would be shorter than 10 fs. Moreover, such an infrared laser has been extended to blue pulses from 418 nm to 429 nm by using very thin BBO crystal. The generated unprecedent broad bandwidths in this spectral region would support the potential pulse widths less than 15 fs. It is hoped that such excellent performance of laser system would be attractive for future applications.

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超宽带近红外和蓝光飞秒激光脉冲产生的实验研究

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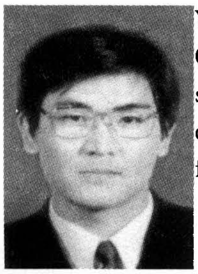
摘　要　增益介质中泵浦光束提供的软光阑效应对于实现克尔透镜稳定锁模及其超宽带光谱脉冲的产生具有非常重要的作用．实验上首先对半导体泵浦全固化钛宝石飞秒激光器的锁模动态特性进行了研究，在4 W绿光泵浦状态下获得了平均输出功率为570 mW、中心波长在794 nm～835 nm范围内调谐、光谱带宽最大可达135 nm的近红外光脉冲输出，其相应的时域变换极限脉冲宽度均小于10 fs．另外，将光束聚焦在超薄BBO晶体上，获得了中心波长在418 nm～429 nm之间调谐、光谱宽带时域变换极限小于15 fs的蓝光飞秒脉冲．

关键词　克尔透镜锁模；飞秒激光脉冲；软孔增益光阑效应



Yang Jianjun was born in 1970, and he received his Ph. D degree from Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, in 1999. Since then he spent his postdoctoral years in Braunschweig technical university of Germany, and continued his research work in Lund university of Sweden. Now his research interests are focusing on femtosecond laser micromachining and high field physics.