# Diode-pumped Kerr-lens mode-locked $Yb:CaGdAlO_4$ laser with tunable wavelength



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# Diode-pumped Kerr-lens mode-locked $Yb:CaGdAlO_4$ laser with tunable wavelength

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**Abstract**
We experimentally demonstrated a wavelength tunable Kerr-lens mode-locked femtosecond laser based on an $Yb:CaGdAlO_4$ (Yb:CGA) crystal. The Kerr-lens mode-locked wavelength tuning range was from 1043.5 to 1076 nm, as broad as 32.5 nm, by slightly tilting the end mirror. Pulses as short as 60 fs were generated at the central wavelength of 1043.8 nm with an average output power of 66 mW. By using an output coupler with 1.5% transmittance, the Kerr-lens mode-locked average output power reached 127 mW with a pulse duration of 81 fs at a central wavelength of 1049.5 nm.

Keywords: $Yb:CaGdAlO_4$ crystal, Kerr-lens mode-locking, tunable wavelength, laser diode

(Some figures may appear in colour only in the online journal)

## 1. Introduction

In recent years, compact, efficient and robust diode-pumped all-solid-state femtosecond lasers in the infrared spectral region are desired for many scientific researches and industrial applications, such as ultrafast spectroscopy, medical treatment, and superfine material processing. Laser systems based on Yb-doped laser materials have proved their potential for efficient femtosecond lasers, benefiting from the numerous excellent spectral and thermal characteristics of the Yb-doped materials. To date, a number of diode-pumped femtosecond mode-locked lasers have been generated based on various Yb-doped laser materials [1–13], by using a semiconductor saturable absorber mirror (SESAM) for passive mode-locking. Kerr-lens mode-locking (KLM) is a well developed technique for mode-locking which has been widely used in femtosecond Ti:sapphire laser. For diode-pumped all solid state lasers, KLM operation is much more difficult mainly due to the low brightness and bad beam quality of the pump diode laser. However, there is big potential for producing much shorter pulse duration by use of the KLM technique. Up to now, many research progresses on diode pumped KLM Yb lasers have been reported with sub-100 fs duration [14–24].

Among the Yb-doped laser materials, $Yb:CaGdAlO_4$ (Yb:CGA) crystal combines remarkable spectral and thermal properties for femtosecond operation. First of all, because of two surroundings for one crystallographic site for both $Ca^{2+}$ and $Gd^{3+}$ cations, Yb:CGA crystal shows a broad and flat emission bandwidth. Benefiting from the superior spectral properties, as short as 47, 40 and 32 fs laser pulses, respectively, were reported from the mode-locked Yb:CGA lasers [25–27]. Secondly, the thermal conductivity of the 2 at.% Yb:CGA crystal was measured to be as high as 6.3 and 6.9 W $m^{-1}$ $K^{-1}$ along the *c*-axis and *a*-axis [28], respectively, which enables high power operation by this crystal. To date, sub-100 fs pusles with 12.5 W average power from a bulked Yb:CGA oscillator was reported [29]. Femtosecond thin-disk oscillator based on the Yb:CGA crystal was demonstrated with an average output power of 28 W and a duration of 300 fs [30]. While the shortest pulse duration achieved from the Yb:CGA thin-disk laser was 62 fs with 5.1 W of average output power [31].

Wavelength tunable femtosecond mode-locked lasers have useful applications in case specific wavelengths are desired. Besides nonlinear optical parametric processes, for example synchronously pumped femtosecond OPO, one can accomplish it by tuning the wavelength within the gain bandwidth of the laser medium. Agnesi *et al* reported wavelength tunable range across 20 nm with 15 mW output power in a SESAM mode-locked Yb:CGA laser [26]. Ge *et al* realized wavelength switchable passively mode-locked Yb:LuAG laser between 1031 and 1046 nm with watt-level output power [13]. Recently, sub-50 fs 40 nm wavelength tunable Yb:CYA laser was reported pumped by a 400 mW single mode laser diode [32].

In this work, we report on a Kerr-lens mode-locked Yb:CGA laser with broad wavelength tunability by simply adjusting the cavity end mirror. With an output coupler (OC) of 0.8% transmittance, the wavelength tuning range of the Kerr-lens mode-locked laser was as broad as 32.5 nm from 1043.5 to 1076 nm, the shortest pulse duration was 60 fs at the central wavelength of 1043.8 nm with an average output power of 66 mW. When using an OC with larger transmittance (1.5%), 127 mW average power and 81 fs pulse duration were obtained.

## 2. Experimental setup

In our experiment, we used a 8 at.% $Yb^{3+}$-doped Yb:CGA crystal as the laser medium, which was 2 mm in thickness and $3 \times 3\,mm^2$ in aperture. The sample was cut along with the *c*-axis. To eliminate thermal load, the Yb:CGA crystal was wrapped with an indium film and placed on a water-cooled copper heat sink maintained at 12 °C. The uncoated crystal was arranged at Brewster's angle in order to reduce the reflection loss. A 7 W high-brightness fiber-coupled diode laser (Jenoptik, JOLD-7.5-BAFC-105) was used as the pump source and its emission wavelength was temperature-controlled at 979 nm. The fiber has a core diameter of 50 $\mu$m and a numerical aperture of 0.22. The pump-laser output from the fiber was coupled into the laser medium by a coupling system with a magnification of 0.8. The beam waist was about 21.8 $\mu$m measured by the knife-edge method. The laser cavity consisted of two concave mirrors M1 and M2 with radii of curvature (ROC) of 75 mm, a high reflection end mirror (HR), a pair of Brewster-cutting SF6 prisms (P1 and P2) and a plane output couple (OC). The overall experimental setup was shown as figure 1.

## 3. Experimental results and discussion

Firstly we characterized the Yb:CGA laser medium in continuous-wave (CW) operation, as seen in figure 1. In this case, prism P1 was moved out of the cavity and the laser was coupled out from OC1. The OCs with different transmittances of

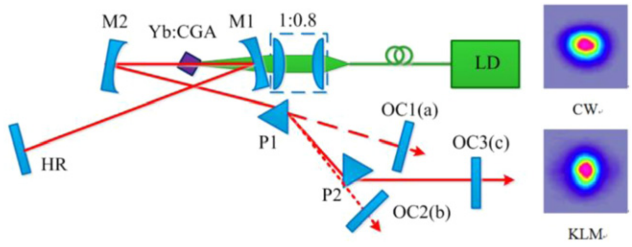


**Figure 1.** Experimental setup of the Kerr-lens mode-locked Yb:CGA femtosecond laser. LD: fiber-coupled diode laser; M1 and M2: concave mirrors with ROC of 75 mm; HR: high reflection mirror; P1 and P2: SF6 prisms; OC1, OC2 and OC3: plane output coupler for (a) continuous-wave, (b) wavelength tuning and (c) Kerr-lens mode-locking operation.

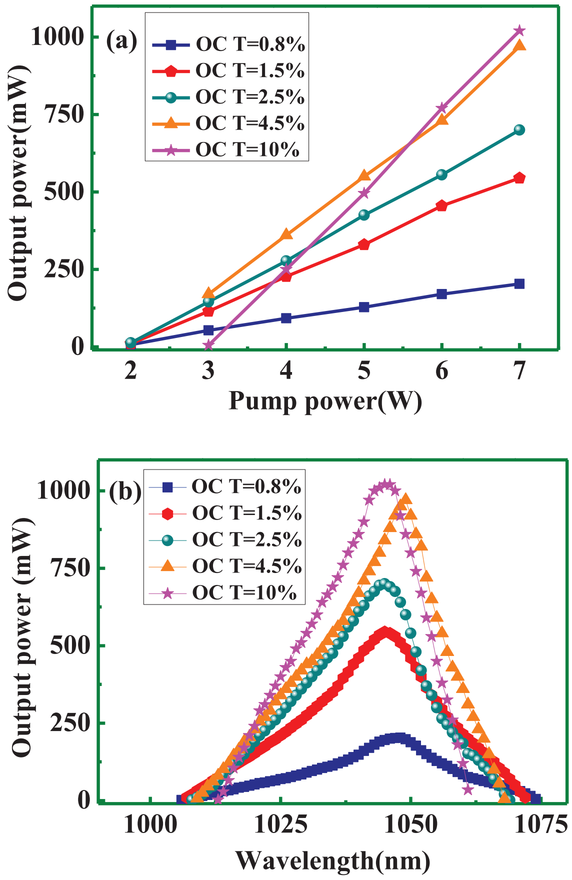


**Figure 2.** (a) CW output power *versus* the pump power. (b) Wavelength tuning curves for OCs with different transmittances under the pump power of 7 W.

0.8%, 1.5%, 2.5%, 4.5%, and 10% were used to get CW output. The CW performance of the laser is shown in figure 2(a). Under the pump power of 7 W, a maximum output power of 1.02 W was obtained with the 10% OC, corresponding to a slope efficiency of 25.5%. With a SF6 Brewster prism (P1) inserted into the output arm of the laser cavity, wavelength tuning properties were studied by slightly adjusting the end mirror (HR). The result was shown in figure 2(b). A broadest wavelength tuning range of 68.5 nm (1006–1074.5 nm) was obtained with a 0.8% OC. The broad and smooth wavelength tuning curve verifies that the Yb:CGA crystal is an excellent candidate to generate ultrashort femtosecond laser pulses.

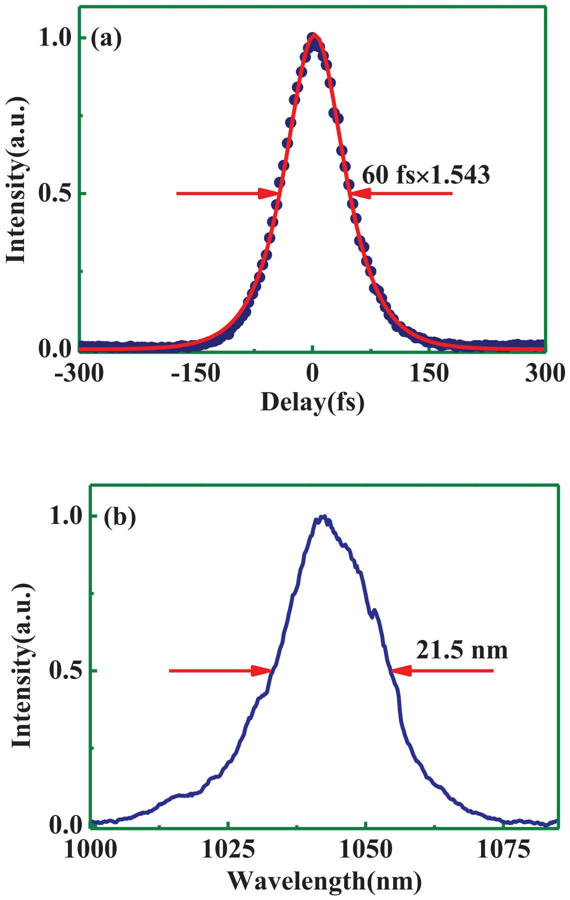


**Figure 3.** (a) Autocorrelation trace of the shortest pulses (dotted curve) with a $sech^2$ fitting (solid curve). (b) The corresponding spectrum.

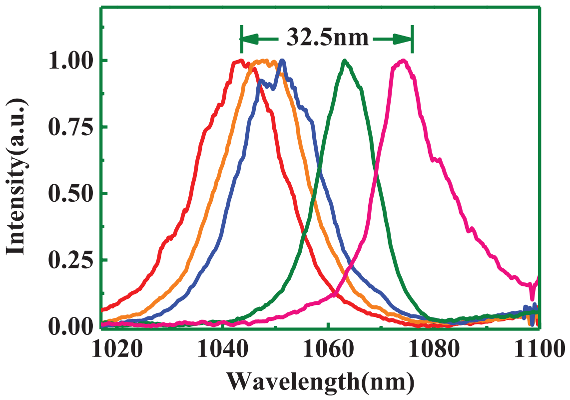


**Figure 4.** Wavelength tuning range of the Kerr-lens mode-locked Yb:CGA laser.

Next we investigated the Kerr-lens mode-locking performance of the Yb:CGA laser. To compensate for the normal dispersion resulted from the Yb:CGA crystal and other dispersion inside the cavity, a pair of SF6 prisms was inserted into the output arm of the laser cavity. The tip-to-tip distance between the two prisms was 247 mm, introducing a negative group-delay dispersion of $-1400$ fs$^2$. The entire cavity length was about 1.3 m, corresponding to a pulse repetition rate of 115 MHz. Based on the ABCD matrix formalism, the beam diameter of the laser mode in the Yb:CGA crystal were

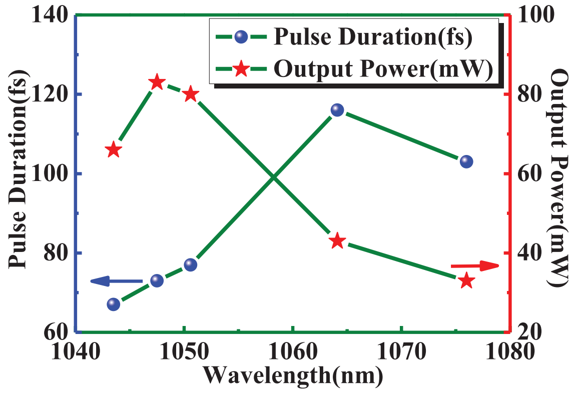


**Figure 5.** Pulse duration and output power of the Kerr-lens mode-locked Yb:CGA laser as a function of the central wavelength.

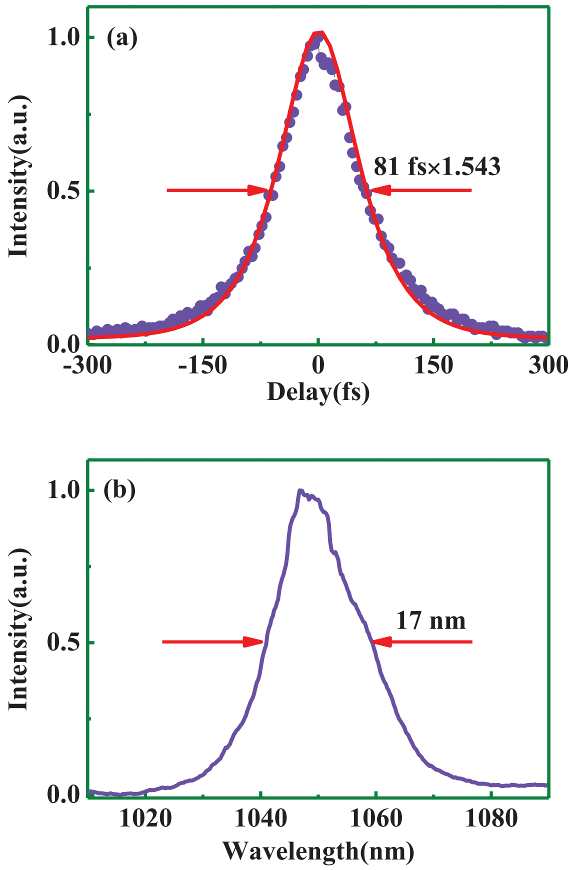


**Figure 6.** (a) Autocorrelation trace of the KLM pulses (dotted curve) with a $sech^2$ fitting (solid curve) for the case of highest output power. (b) The corresponding spectrum.

estimated to be 39.2 $\mu$m $\times$ 39.6 $\mu$m, well matching that of the pump laser beam. To obtain KLM operation, an OC with 0.8% transmittance was used to enhance the intracavity laser intensity in the crystal. KLM was initiated by carefully adjusting the position of M2 mirror as well as fastly moving the end mirror HR. At the proper position, the CW average output power was decreased to 53 mW and the KLM output power was 66 mW. We measured the pulse duration by a commercial intensity autocorrelator (APE: pulseCheck USB). The shortest pulse width (full width at half maximum, FWHM) of the autocorrelation trace was about 92 fs. Assuming a $sech^2$-pulse shape, the shortest pulse duration was 60 fs, as shown in figure 3(a). Figure 3(b) shows the corresponding spectrum measured by an optical spectrum analyzer. The FWHM spectral bandwidth was about 21.5 nm at the center wavelength of 1043.8 nm. The corresponding time-bandwidth product of 0.352 was close to the Fourier transform limitation (0.315). The near-field beam profiles in the CW and Kerr-lens mode-locked operations were shown in figure 1.

Due to the broad emission bandwidth of the Yb:CGA crystal, we found by slightly varying the position of the M2 mirror or adjusting the angle of the end mirror HR, the central wavelength could be continuously tuned while keeping KLM running. The central wavelength tuning range covers from 1043.5 to 1076 nm, as broad as 32.5 nm, as shown in figure 4. Beyond this wavelength range, KLM could not be stably sustained. The mode-locked spectral bandwidth at different central wavelength is typically 12–20 nm. While the pulse duration ranges from 67 to 116 fs, which is decided by the intracavity dispersion compensation. The pulse duration and the average output power as a function of the central wavelength was shown as figure 5. The average output power ranges from 83 mW at 1047.5 nm to 33 mW at 1076 nm. To the best of our knowledge, this is the broadest tuning range of a Kerr-lens mode-locked Yb:CGA laser.

By replacing the OC with a 1.5% one, stable KLM operation would also be realized. In this case, the pulse duration became longer while the average output power increased accordingly. A typical pulse duration of 81 fs was depicted in figure 6(a). The FWHM spectral bandwidth was 17 nm centered at 1049.5 nm. The corresponding time-bandwidth product was 0.375. For the pump power of 5.3 W, the maximum average output power of 127 mW was obtained.

## 4. Conclusion

In summary, we have reported a broadly wavelength tunable Kerr-lens mode-locked femtosecond laser based on the Yb:CGA crystal. The wavelength tuning range of the Kerr-lens mode-locked laser was as broad as 32.5 nm from 1043.5 nm to 1076 nm when an OC with 0.8% transmittance was employed. To the best of our knowledge, this is the widest wavelength tuning range of a Kerr-lens mode-locked Yb:CGA laser. Mode-locked pulses as short as 60 fs at the center wavelength of 1043.8 nm were obtained. The average output power was 66 mW under the pump power of 5 W. When an OC with 1.5% transmittance was used, stable KLM operation was also obtained with a maximum average output power of 127 mW and a pulse duration of 81 fs at 1049.5 nm. The experiment results indicate that the KLM Yb:CGA laser is a promising candidate for sub-100 fs pulse generation as well as an excellent seed source for a diode-pumped femtosecond amplification system.

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