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Diode-pumped Kerr-lens mode-locked Ti: sapphire laser with broad wavelength tunability*

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We report a direct blue-diode-pumped wavelength tunable Kerr-lens mode-locked Ti: sapphire laser. Central wavelength tunability as broad as 89 nm (736–825 nm) is achieved by adjusting the insertion of the prism. Pulses as short as 17 fs are generated at a central wavelength of 736 nm with an average output power of 31 mW. The maximum output power is 46.8 mW at a central wavelength of 797 nm with a pulse duration of 46 fs.

Keywords: blue-diode pump, Ti: sapphire, wavelength tunable, Kerr-lens mode-locked laser

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1. Introduction

Wavelength tunable femtosecond mode-locked lasers have many useful applications in case where specific wavelengths are desired, such as femto-chemistry,[1] multi-photon microscopy,[2] laser surgery,[3] superfine material processing,[4] etc. A broad range of laser wavelength tuning can be achieved directly by using a laser crystal that has a wide emission spectrum bandwidth. As is well known, the Ti: sapphire crystal is among the most popular near-infrared laser materials with the ultra-broad emission spectrum bandwidth (ranging from 650 nm to 1100 nm) for ultra-short pulse generation and broad wavelength tuning.[5,6] Back in 1991, Spence *et al.* firstly realized self-mode-locking operation in an argon ion laser pumped Ti: sapphire laser with proper dispersion compensation, which was later referred to as Kerr-lens mode-locking (KLM).[7] Based on the high beam quality pump source, the KLM technology and fine dispersion compensation make Ti: sapphire lasers a workhorse among the wavelength tunable femtosecond lasers.

Nevertheless, the Ti: sapphire laser needs to be pumped by sources in the blue–green spectral region, such as argon ion lasers,[8] frequency-doubled diode-pumped solid-state lasers (DPSSLs),[9] or green fiber lasers,[10] all of which tend to be complicated and expensive. In contrast, laser diodes (LDs) have the advantages of simple structures, stable performance, and relatively low prices. With the development of high-brightness, high-power blue and green LDs in recent years,[11] the direct diode-pumped Ti: sapphire femtosecond laser has become an attractive laser source.[12–21] In 2009, a direct diode-pumped Ti: sapphire laser achieved continuous wave (CW) output by using a 1-W blue LD at 452 nm, which was firstly reported by Roth *et al.* They also observed the pump-induced loss in the Ti: sapphire crystal when pumped by the 452 nm LD.[12] After that, they realized passive mode-locking with a saturable Bragg reflector by bilateral simultaneous pumping of two blue LDs. Pulses of 111 fs duration and an average power of 101 mW were demonstrated.[13] In 2012, Durfee *et al.* achieved 15 fs pulses with the average power of 30 mW using a pair of 1.2 W 445 nm LDs.[14] Next, Sawai *et al.* used a green LD emission at 518 nm that is closer to the absorption peak for the first time and implemented a semiconductor saturable absorber mirror (SESAM) based passive mode-locking operation.[15] Subsequently, Gürel *et al.* used two green LDs at 520 nm to pump bilaterally the Ti: sapphire crystal, scaling the average power of mode-locking to 450 mW.[16] Two years later, the optical frequency comb was achieved based on the LD-pumped mode-locked Ti: sapphire laser.[17] Rohrbacher *et al.* obtained 5 nJ 82 fs pulses based on blue-diode-pumped SESAM mode locking and succeeded in applying the laser system to multi-photon imaging.[18] Up to now, diode-pumped Ti: sapphire femtosecond lasers have shown the potential to replace DPSSLs-pumped Ti: sapphire oscillators in some of their traditional applications. A team from Moscow State University gained the same pulse width as that in Ref. [14], and increased the average power over fivefold to 170 mW.[19] In the same year, Coyle *et al.* achieved a broadly wavelength-tunable femtosecond diode-pumped Ti: sapphire laser with a SESAM and Kerr-lens mode-locking. The wavelength tunability ranged from 755 nm to 875 nm with the shortest pulse duration of 54 fs.[20] Then, a research team from Japan used a wavelength-multiplexed pump

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structure and obtained 48 fs pulses with the average power of 360 mW.[21] In terms of output parameters, there still is a gap between the diode-pumped Ti: sapphire lasers and the traditional DPSSLs-pumped Ti: sapphire lasers. Research on diode-pumped Ti: sapphire lasers is trying to close up the gap.

In this paper, we report a single 450 nm LD pumped wavelength tunable KLM femtosecond Ti: sapphire laser. The wavelength tuning range of the mode-locked laser is as broad as 89 nm (from 736 nm to 825 nm) by adjusting the prism insertion. The shortest pulse duration is 17 fs at the central wavelength of 736 nm with an average output power of 31 mW. When the central wavelength is tuned to 797 nm near the Ti: sapphire gain peak, the maximum output power is 46.8 mW with a pulse width of 46 fs.

2. Experimental setup and results

The schematic of the experimental setup is shown in Fig. 1, which consists of the pump source, the beam shaping system, the laser oscillator, and the extra-cavity compressor. In the experiment, we employed a 3.5 W, 450 nm multimode LD (Nichia Inc.) as the pump source. Due to the low quality of the pump beam, it is essential to shape it to a small focal spot on the crystal to realize KLM operation. An aspheric lens (L1), two cylindrical lenses (L2, L3), and a plano-convex lens (L4) as a beam shaping system were used to reshape the pump beam in the crystal. In order to make the divergence angles of the fast axis and the slow axis close to each other, an aspheric lens ($f_{L1} = 4$ mm) was used to collimate both the fast and slow axes of the LD, and two cylindrical lenses ($f_{L2} = -30$ mm and $f_{L3} = 300$ mm) were used to expand the slow axis of the LD. Then, a plano-convex lens ($f_{L4} = 75$ mm) was applied to focus the collimating beam into the Ti: sapphire crystal (Fig. 1). The pump spot waist radius is 41 μm×42 μm ($1/e^2$) in the gain medium, which was measured by the knife-edge method. The oscillator is a traditional X-fold cavity, which consists of two concave mirrors M1 and M2 with radii of curvature (ROC) of 50 mm, a Brewster-cut Ti: sapphire crystal, a high reflection (HR) broad-band mirror, a pair of Brewster-cutting fused silica (FS) prisms (P1 and P2), and a plane output coupler (OC) with 1% transmittance. A pair of chirped mirrors with totally -140 fs^2 group delay dispersion (GDD) per bounce (CM1 and CM2) were placed outside the cavity for extra-cavity pulse compression.

A 3-mm-long Brewster-cut Ti: sapphire crystal with 0.25% doping concentration was used and mounted on a copper heat sink maintained at a temperature of 17 °C by the water circulation. The single pass absorption of the pump power is about 71%, which is much less than that pumping with DPSSLs because the absorption coefficient at 450 nm is much smaller than that at the absorption peak of 490 nm. The laser mode radius on the intra-cavity crystal is approximately 20 μm. The pump spot is larger than the intra-cavity mode, which would affect the efficiency of the entire system and the mode-locking position. We realized the continuous wave (CW) output of 80 mW, which showed a good linear power growth, as depicted in Fig. 2(a). The phenomenon of pump-induced loss was also found in our experiment, as described in Refs. [12] and [22]. That is, the output power would decrease 10% in tens of seconds, and then remain a stable value. The LD beam presents an approximate circle at the best focusing position, but it is disadvantageous to KLM with soft aperture due to the larger spot size. By changing the focus position, the LD beam was further reduced in the longitudinal direction at the expense of the pump mode in the horizontal direction,[23] thereby realizing KLM. The total length of the cavity is 1250 mm corresponding to the repetition rate of 120 MHz. In order to balance the stability of the system and the stronger amplitude modulation, the lengths of the output arm and the dispersion compensating arm were designed to be 1 : 2. The tip-to-tip distance between the two prisms is 530 mm, which provides a second-order dispersion of approximately -426 fs^2 and is enough to support the establishment of mode-locking. The KLM operation needs to adjust the cavity to the stability edge of the cavity by moving M2 towards the crystal, accompanied by a decrease in the CW output power. Subsequently, starting the mode-locking could be done by quickly shaking the prism P2 back and forth. As shown in Fig. 2(a), the mode-locked threshold was at around the pump power of 3 W with an average output power of 20 mW. The output power of the mode-locked linearly increased to 31 mW as the pump power increased to the maximum. Running the LD at the maximum output power, an 1.2% root-mean-square (RMS) stability was demonstrated over 3 hours in open air, as depicted in Fig. 2(b). The mode-locked laser has been operated for a long time without any sign of power decay.

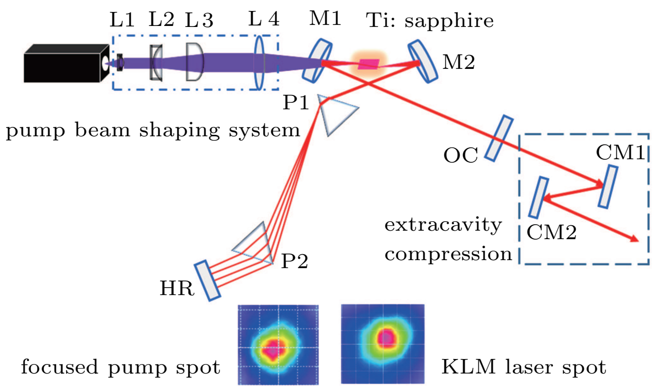

Fig. 1. Diagram of the diode-pumped Kerr-lens mode-locked Ti: sapphire femtosecond laser. LD: 450 nm blue laser diode; L1: aspheric lens; L2 and L3: two cylindrical lenses; L4: a plano-convex lens; M1 and M2: concave mirrors with ROC of 50 mm; HR: high reflection mirror; P1 and P2: fused silica prisms; OC: plane output coupler; CM1 and CM2: chirped mirrors with -70 fs^2 GDD per bounce.

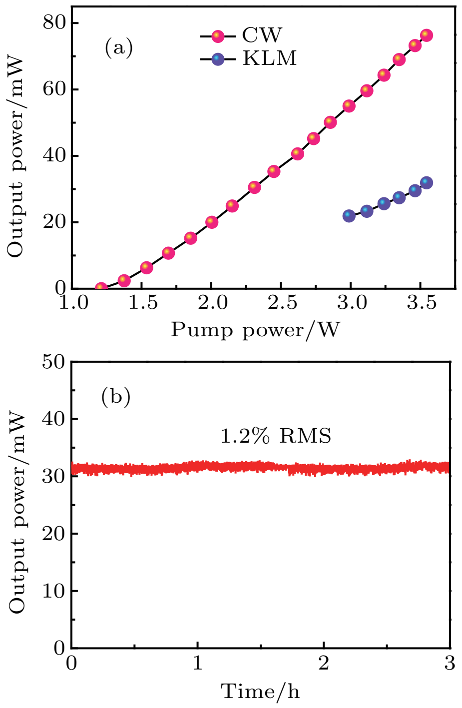

Fig. 2. (a) Output performances of the CW and the KLM operation of the Ti: sapphire laser. (b) Power stability of the diode-pumped Kerr-lens mode-locked Ti: sapphire laser over 3 hours.

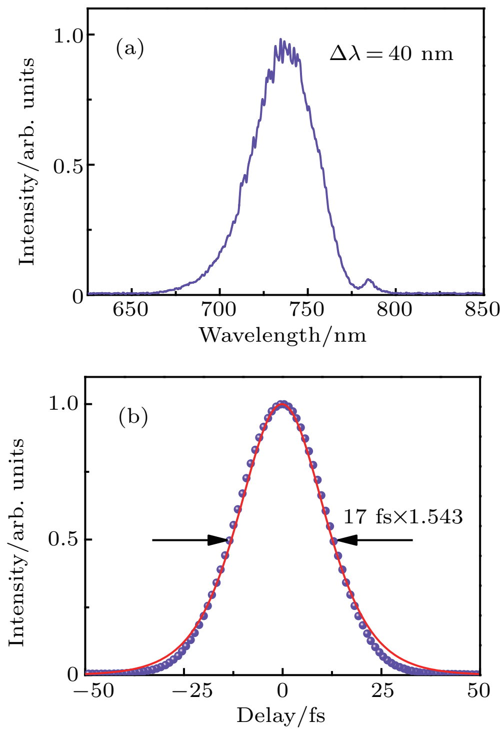

Fig. 3. Kerr-lens mode-locked operation with the shortest pulse duration of 17 fs at 736 nm. (a) The corresponding optical spectrum. (b) Auto-correlation trace of the shortest pulses (dotted curve) with a sech^2 fitting (solid curve) after extra-cavity compression with the chirped mirrors (CM1 and CM2).

Firstly, we achieved the KLM operation with an average output power of 31 mW when pumping at 3.5 W. The mode-locked laser spectrum was recorded by a commercial optical spectrum analyzer. The central wavelength is at 736 nm with 40 nm full width at half maximum (FWHM) bandwidth (Fig. 3(a)), which can support 14 fs Fourier transform-limited pulse duration assuming a sech^2 pulse shape. The pulse duration was measured by an intensity auto-correlator (APE Pulse Check USB). Assuming the sech^2 pulse profile, the pulse duration directly from the output of the oscillator is 26 fs, which is far beyond the transform-limited duration. Subsequently, a pair of chirped mirrors (CM1 and CM2: -70 fs^2 per bounce) were utilized to compress the pulse width to 17 fs, as shown in Fig. 3(b). The time-bandwidth product (TBP) of the pulses is 0.37, indicating that there are still some uncompensated chirp. The highest mode-locked output power of 46.8 mW was obtained when the central wavelength was at 797 nm, which is almost the gain peak of the Ti: sapphire crystal. The mode-locked spectral bandwidth is 15 nm FWHM and the pulse duration is measured to be 46 fs, as shown in Figs. 4(a) and 4(b), respectively. The TBP is 0.325, which is very close to the Fourier transform limitation.

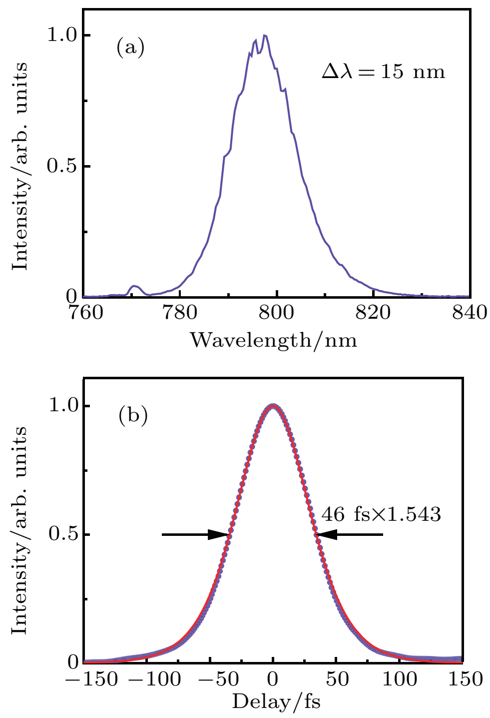

Fig. 4. Kerr-lens mode-locked operation with the highest output power of 46.8 mW at 797 nm. (a) The corresponding optical spectrum. (b) Auto-correlation trace of the KLM pulses (dotted curve) with a sech^2 fitting (solid curve) without extra-cavity compression.

Due to the broad emission bandwidth of the Ti: sapphire crystal, it was found that by slightly adjusting the insertion of the P2 prism, the central wavelength could be continuously tuned while keeping the KLM operation. The central wavelength tuning range covers a breadth of 89 nm (from 736 nm to 825 nm), as shown in Fig. 5(a). The tunable mode-locked spectral bandwidth at different central wavelengths is from 7 nm to 40 nm, while the pulse duration ranges from 104 fs to 17 fs, decided by the intra-cavity dispersion compensation. Such a broad wavelength tunability is due to the relatively small and flat dispersion compensation in a wide wavelength range provided by the fused silica prisms. The mode-locked spectral bandwidth decreases and the central wavelength red-shifts significantly with decreasing prism insertion. The central wavelength red-shifts as the high-frequency components are gradually cut off by adjusting the P2 prism insertion. Meanwhile, a decrease in the prism insertion increases the absolute value of the negative GDD introduced by the prism pair, which results in a weakening of the spectral broadening effect corresponding to a longer pulse duration. The pulse width and output power as a function of the central wavelength are shown in Fig. 5(b). The output power ranges from 20.8 mW at 825 nm to 46.8 mW at 797 nm. The central wavelength of the maximum mode-locked output is at the gain peak of the Ti: sapphire, where higher energy can be coupled out from the cavity. Since wider mode-locked spectra are concentrated at short waves, the shortest pulse is obtained in this region, which is down to 17 fs. As far as we know, this is the shortest pulse in the LD-pumped Ti: sapphire laser with broad wavelength tunability.

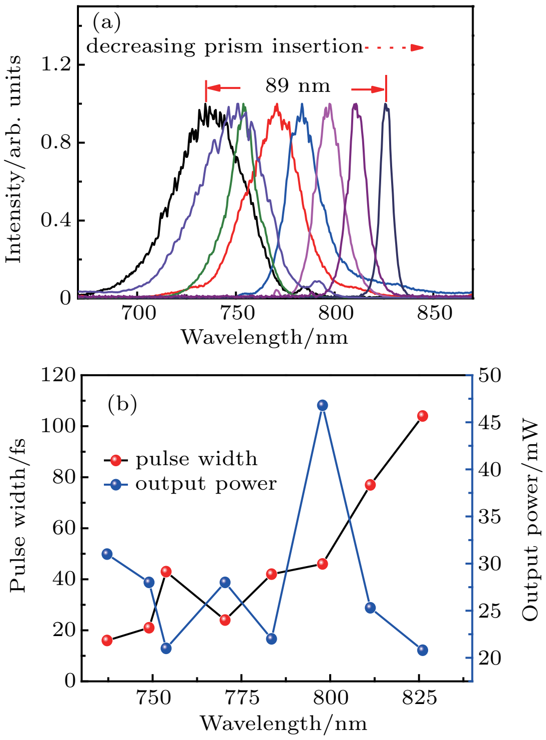

Fig. 5. (a) Wavelength tuning range of the Kerr-lens mode-locked Ti: sapphire femtosecond laser. (b) Pulse width and output power of the laser as a function of the central wavelength.

To check the status of the KLM operation, the radio frequency (RF) spectrum of the LD pumped Ti: sapphire laser at the central wavelength of 736 nm was measured by a photodetector with a 3-dB bandwidth of 1 GHz and a RF spectrum analyzer (Agilent E4407B). In the RF spectrum measured at a resolution bandwidth (RBW) of 1 kHz, as shown in Fig. 6(a), the distinct signal-to-noise ratio of the fundamental beat note at 120.5 MHz is as high as 65 dBc. Figure 6(a) shows a clean RF spectrum, where no side peaks of the harmonics of the fundamental frequency are observed. No harmonics modulation is observed in the 1 GHz range at a RBW of 100 kHz, as shown in Fig. 6(b). Moreover, the mode-locking states at different central wavelengths have a signal-to-noise ratio higher than 60 dBc at the fundamental frequency of the pulses.

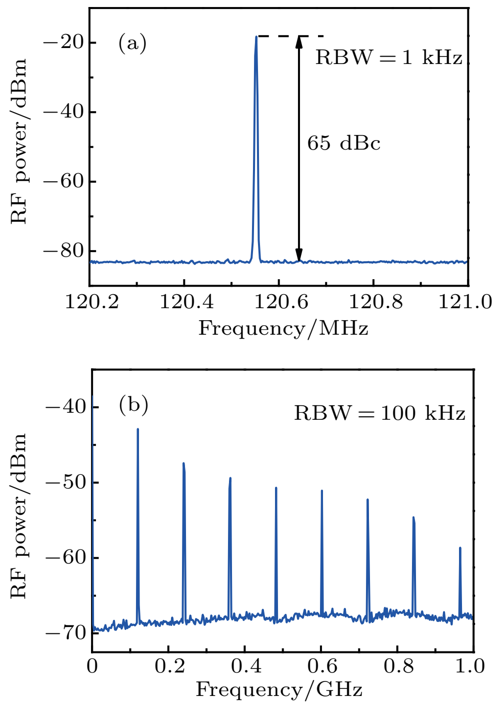

Fig. 6. Radio frequency (RF) spectra of the Kerr-lens mode-locked Ti: sapphire laser at the central wavelength of 736 nm. (a) RF spectrum at the fundament beat note with the resolution bandwidth of 1 kHz. (b) RF spectrum at 1 GHz wide-span range with the resolution bandwidth of 100 kHz.

3. Conclusion

We demonstrated a blue-diode pumped Kerr-lens mode-locked Ti: sapphire laser exhibiting a broad wavelength tunability. The tunable bandwidth of the mode-locked spectrum is 89 nm (736–825 nm). Pulses as short as 17 fs with the mode-locked output power of 31 mW was obtained at 736 nm with 40 nm FWHM. The maximum output power is 46.5 mW at 797 nm with a pulse duration of 46 fs. The results indicate that the LD-pumped KLM Ti: sapphire laser is able to generate ultrashort pulses with broad wavelength tunability. In future experiments, we will focus on higher laser output power and sub-10 fs pulse generation for multi-photon microscopy and optical frequency comb application.

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