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Diode-pumped broadly tunable (809–910 nm) femtosecond Cr:LiSAF laser

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Abstract

We describe the performance of a soft aperture Kerr-lens mode-locked femtosecond Cr:LiSAF laser continuously tunable from 809–910 nm. Pumped by two 500 mW near-diffraction limited red diode lasers, the mode-locked laser generated near-bandwidth limited pulses with durations as short as 70 fs with a repetition rate of 88 MHz. The amplitude modulation required to sustain stable mode-locking was produced by a soft aperture generated within the Cr:LiSAF crystal as a result of the excellent quality of the focused pump beam. The soft aperture nature of the mode-locking ensured stable day-to-day operation of the laser. © 1998 Elsevier Science B.V.

There has been much recent research activity in the area of compact, directly diode-pumped, mode-locked femtosecond laser sources. Advances in this field have been precipitated by the development of new materials, new mode-locking techniques, and new pump sources. To date, the materials of choice for compact systems have been Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) [1] and Cr^{3+}:$LiSrGaF_6$ (Cr:LiSGaF) [2] due to both their wide potential tuning range, from 800–1000 nm, and the advantage of having a strong absorption band in the 640 to 680 nm spectral region, thus allowing the use of AlGaInP diode lasers as a pump source. All-solid-state systems producing femtosecond pulses have been successfully demonstrated. These have been based on the passive techniques of Kerr-lens mode-locking (KLM) [3,4] and saturable absorber mirror (SAM) mode-locking using either a saturable Bragg reflector (SBR) [5] or an antiresonant Fabry–Perot saturable absorber (A-FPSA) [6].

However, improving the overall performance of directly diode-pumped systems remains a challenge. Although direct diode-pumping offers the benefits of compactness, reduced complexity and lower price, the power output and mode-locked tunability characteristics reported thus far have often been somewhat poor. This is largely because of two factors, one being the thermal quenching of the upper-state lifetime which causes a reduction in quantum efficiency and the other being the low gain of the material due to the small emission cross-section. Thermal quenching can be particularly severe in diode pumped fluoride [7–9] lasers where pump light needs to be absorbed at a small cavity mode waist. Where broad area diode lasers with poor beam quality are used, the highly divergent pump light has to be absorbed over a very short absorption length in a highly doped crystal. This results in a very small pump volume where heat is deposited. This heat is difficult to dissipate because of the low thermal conductivity inherent in fluoride materials. With a less divergent, diffraction limited pump beam, one may use a lower doped material with a longer absorption length. This results in a more manageable distribution of heat, within a larger pump volume, over the length of the crystal. Therefore, using a high quality, diffraction limited beam greatly reduces the problem of thermal quenching as well as enabling a small pump waist, which reduces the laser threshold and maximises the gain. The use of a low doped crystal is also advantageous as scattering losses are kept to a minimum.

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Recently, Tsuda et al. [10] used a high brightness master-oscillator power-amplifier (MOPA) laser (SDL-7350-A6) pumping a 0.8% doped Cr:LiSAF crystal in combination with a low loss SBR to produce 70 fs pulses with 100 mW of average power at 868 nm, tunable over 10 nm. With a similarly doped Cr:LiSAF crystal, but using a different MOPA pump source, constructed from discrete elements, we have demonstrated [11] a KLM mode-locked laser which produced 94 fs pulses with 50 mW of average power at 857 nm tunable over 40 nm. Recently, Kopf et al. [12] used an A-FPSA in a cavity optimised for low losses to produce pulses with durations as short as 60 fs and average powers of up to 125 mW tunable over 50 nm. In this case, two broad area diodes were used to pump a 3% doped Cr:LiSAF crystal.

With regard to tunability, KLM has a significant advantage over SAM mode-locking in that the KLM saturable absorber action is inherently broadband, being based on the nonlinear Kerr effect, which is normally nonresonant over the whole emission bandwidth of the laser gain material. When using a SAM, tunability is limited to a fraction of the emission by the relatively short bandwidth of the AlAs/AlGaAs Bragg mirror which is part of the semiconductor structure [12]. However, the pump requirements when using a SAM based system are less stringent. A high efficiency KLM laser requires that there is a good overlap between the pump and the cavity mode volume as well as a high pump brightness. Since the cavity mode waist in the laser crystal is typically only ~ 20 μm, these requirements are impossible to meet with currently available high brightness diode arrays. Furthermore, a poor overlap necessitates the operation of the mode-locked laser near to the edge of cavity stability, in combination with an external hard aperture. This aperture produces the amplitude modulation required to descriminate between KLM and cw behaviour. The resulting laser is very sensitive to alignment. However, with a near diffraction limited pump beam, as exhibited by our diode lasers, an excellent overlap can be achieved resulting in higher efficiencies and soft aperture KLM [13]. With soft aperture KLM, the laser may operate away from the stability edges and will thus be less sensitive to alignment [14].

In order to improve the performance of compact, all-solid-state devices and fully utilise their potential advantages, new pumping techniques have been investigated. The approach that we have taken has been through the use of novel diode lasers, based on tapered amplifiers [15]. For convenience, we name this device a tapered diode laser (TDL). Each TDL has a tapered broad area geometry with an input of ~ 5 μm and a 250 μm broad emitter. The tapered geometry of the active area allows an input signal to grow in power while the overall power density remains at a manageable level. A diagram of our TDL configuration is shown in Fig. 1. Both the input and output facets of each TDL chip were antireflection (AR) coated at 675 nm and mounted in a sealed housing, with windows AR coated at 675 nm. The temperature of each TDL could be controlled by a Peltier element, and two aspheric lens collimators were used for efficient coupling of the input and output radiation. The output beam collimator was an $f =$ 6.5 mm triplet and further beam shaping was achieved with a cylindrical telescope in both axes.

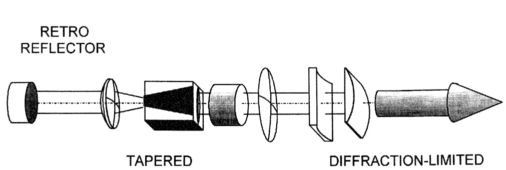

Fig. 1. Schematic diagram of the TDL.

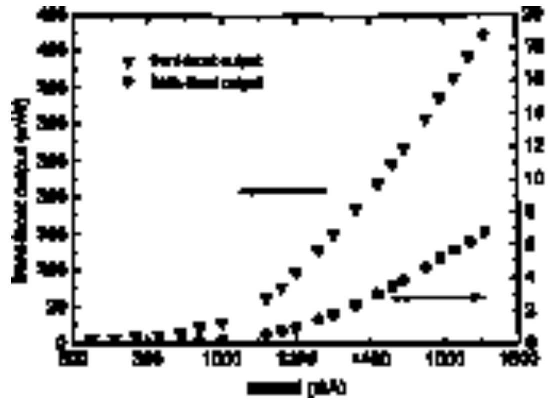

Fig. 2. Output from front and back facet of amplifier as a function of amplifier current for TDL1.

When drive current was applied, a small fraction of residual radiation was emitted from the input facet of the free-running TDL. This radiation was collimated and then retro-reflected back through the input facet of the TDL. The signal was then amplified. It should be noted that, unlike broad area diode arrays, with the TDL there is only amplification without oscillation. As such, no high-order transverse cavity modes are generated, and the output of each TDL was measured to be near diffraction limited, with an M^2 parameter of less than 2. In comparison, the currently available generation of high brightness laser diode arrays have an M^2 parameter of ~ 20 in the slow axis due to the emission of high order cavity modes. Fig. 2 shows, for one of the amplifiers, TDL1, the radiation emitted from both the input and output facets as a function of drive current. This configuration proved to be stable and was much simpler than that used during our earlier work [11], where a frequency stabilised, single-longitudinal-mode diode laser was used as a master-oscillator for the tapered diode. The maximum output of TDL1 was 422 mW for a drive current of 1710 mA. The output characteristics of TDL2 were similar to those shown in Fig. 2, but with a maximum output of 500 mW for a drive current of 1600 mA.

When the power output of each TDL was optimised, their respective temperatures differed. This temperature difference resulted in a shift between their spectral outputs. Fig. 3 shows the spectral characteristics of each diode output. The maximum output of TDL1 was centred at 676 nm, with a bandwidth of 4.2 nm. The maximum output of TDL2 was centred at 668.5 nm and had a width of only 0.4 nm. This narrowing of the spectrum was probably caused by a weak resonance between the chip facets due to the operation of this diode at a wavelength differing from the centre wavelength of the AR coatings. For the purposes of pumping Cr:LiSAF, the spectral outputs of both TDLs are ideal, being close to the wide absorption peak at ~ 650 nm. Furthermore, the TDLs are well suited to being used to pump the crystal from opposite sides because residual radiation from one TDL, which is not absorbed by the crystal and passes through the beamshaping optics and into the output facet of the other, is not amplified by that TDL. Any amplification of radiation injected into the front facet of the TDL would result in catastrophic damage to the device. Thus it is extremely important that the amplification bandwidths of each diode do not overlap when pumping the crystal from opposite sides. This pumping technique is beneficial since there will be a more even distribution of heat throughout the crystal as compared to pumping from only one side.

Fig. 4 shows a schematic diagram of the mode-locked laser. We used a four-mirror, astigmatically compensated, X-cavity design. The cavity was symmetric, each arm being 810 mm long. The dopant level of the Cr:LiSAF crystal was 1.5% and each face was Brewster-cut. The crystal was 6 mm long and housed in an aluminium mount. The temperature was stabilised at 15°C by a thermoelectric Peltier element. The crystal was positioned between two mirrors of 100 mm radius of curvature (ROC), M_1 and M_2, which were AR coated at 670 nm and highly reflection (HR) coated ($\geq 99.6\%$) from 800 to 900 nm. The plane mirror, M_3, was also HR coated ($\geq 99.9\%$) from 820 to 920 nm. The cavity was completed with an output

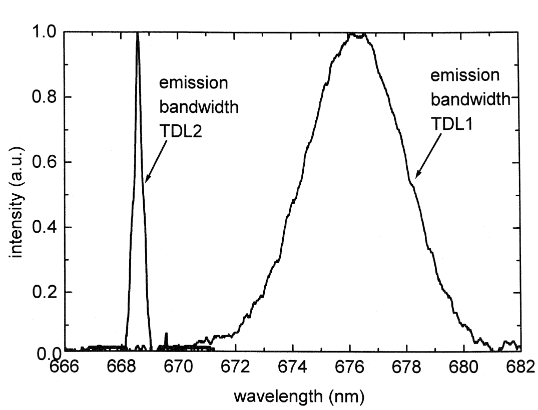

Fig. 3. Spectral characteristics of each amplifier output.

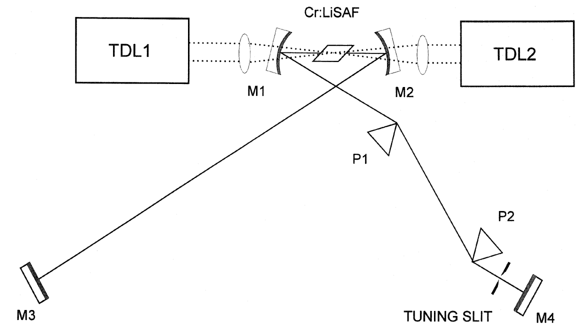

Fig. 4. Schematic diagram of the mode-locked Cr:LiSAF laser.

coupler, M_4. The folding angle required to compensate the astigmatism due to the crystal was 16°. Both pump beams were focused down to waists of ~ 20 μm using an $f = 80$ mm lens. Kerr-lens mode-locking was achieved following the introduction of two quartz prisms into the cavity (P1, P2) with which to control the cavity dispersion. The prism separation was 560 mm. Initially, we chose the precise configuration of the crystal and mirrors following the cavity mode analysis approach as described by Magni et al. [16]. With this method, insertion of a hard aperture close to M_3 favours the mode-locked regime as the Kerr-lens effect due to high intensity pulses reduces the laser mode size at the aperture. However, mode-locking could be achieved without this hard aperture. In fact, optimum mode-locking occurred when the cavity was very close to the centre of the stability region (for a symmetric configuration), with $z = 104 \pm 1$ mm and $x = 49 \pm 1$ mm. We have previously observed mode-locking due to gain aperturing within the Cr:LiSAF crystal when pumping with a single MOPA source [11] and believe that this was again the main mechanism which produced the amplitude modulation necessary to sustain KLM. In this case, mode-locking occurs in a region where the cavity is more stable and less sensitive to cavity alignment because the spatial gain profile created by the pump beam discriminates against cw operation [17]. In fact, the crystal could be translated by 2.56 mm around the centre of stability while still mode-locking. Initially we used a 0.3% output coupler. By translating the vertical slit, it was easy to continuously tune the laser while maintaining femtosecond, KLM operation. To ensure mode-locked operation, it was necessary to control both the bandwidth and the central emission wavelength of the laser. To maintain the shortest pulses at all times, the prism (P2) insertion was varied as the wavelength was tuned. A simultaneous measurement of the pulse duration and bandwidth of the output was made as the laser was tuned over 100 nm between 809 and 910 nm. Fig. 5 shows the pulse duration and the time–bandwidth product of the output as a function of centre wavelength. The output pulse duration varied from 70 fs at the centre of the tuning range to 170 fs at the low wavelength edge of

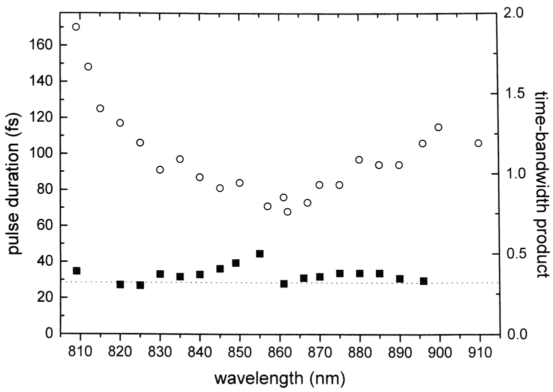

Fig. 5. Pulse duration (○) and time-bandwidth product (■) as the laser is tuned from 809–910 nm. The output coupling is 0.3%. The dotted line shows the Fourier transform limit for $sech^2$ pulses.

the range. It can be seen that there was a marked increase in pulse duration for wavelengths shorter than 825 nm, this was due to the fact that there was a sharp cut-off in the reflectivity of end mirror M_3 below this wavelength. The time–bandwidth product varied from 0.30 to 0.50, and it can be seen from Fig. 5 that nearly transform limited pulses were produced over the whole tuning range. The deviation of some time–bandwidth data points in Fig. 5 from the transform limited value is most likely due to improper adjustment of prism path insertion, resulting in nonoptimised dispersion compensation at the time of measurement. The pulse repetition rate was 88 MHz. Fig. 6(a) shows a typical collinear intensity autocorrelation of the pulses obtained at a wavelength of 862 nm. Assuming a $sech^2$ pulse envelope, the duration was measured to be 70 fs. A simultaneous measurement of the spectrum, shown in Fig. 6(b), indicates a FWHM of 11.4 nm ($\Delta\nu = 4603$ GHz) producing a time–bandwidth product, $\Delta\tau\Delta\nu$ of 0.32. Stable mode-locking was achieved over the entire tuning range. The threshold pump power for mode-locking (measured at an output wavelength of 860 nm) was 215 mW. The average mode-locked output power available in this configuration was a maximum of 40 mW at 910 nm, decreasing to 14 mW at 809 nm. It was noted that the laser could be tuned to longer wavelengths up to 940 nm, however, no mode-locking was observed in this region because the transmission of the cavity mirrors was too large.

In order to provide a greater output power, the 0.3% OC, M_4, was replaced by a 1% output coupler (800–900 nm). It was then possible to continuously tune the laser between 830–905 nm whilst mode-locking. Over this range, the pulse duration characteristics were similar to those described previously, although the shortest pulse observed, at 80 fs, was a little longer ($\sim$ 10 fs) than that observed with the lower output coupling and the threshold pump power (measured at an output wavelength of 868 nm) required for mode-locking was 275 mW. Fig. 7 displays the pulse duration and mode-locked output power as a function of wavelength. The power output varied from 110 mW at 870 nm to 43 mW at 905 nm. The mode-locked tuning range on the short wavelength side was limited by the sharp decrease in reflectivity of the mirror, M_3, which resulted in a decrease in intracavity power below that required for mode-locked operation. The mode-locking was stable over the full tuning range.

We observed that the transverse mode of the output beam remained TEM_{00} whether the laser output was cw or mode-locked, however there was a slight displacement of the beam in the horizontal direction. We measured the amplitude fluctuations to be of the order of $\pm 1\%$. A significant point to note is that there were no indications of thermal loading problems when pumping with the TDLs. Self starting behaviour was often observed, but it was occasionally not instantaneous and we placed one mirror on a low voltage piezoelectric transducer, moving it only ± 0.2 μm at a frequency of 100 Hz. This perturbation was sufficient to initiate and maintain long term mode-locked

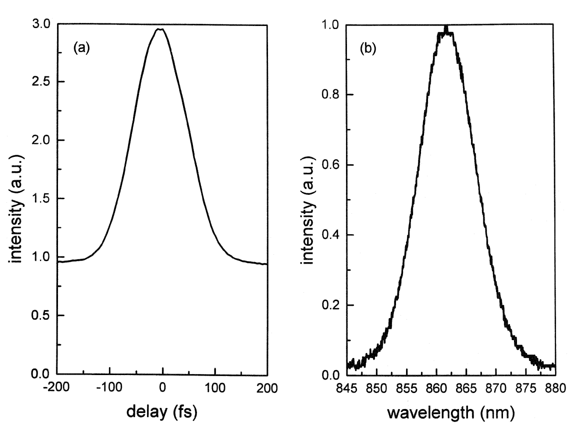

Fig. 6. (a) Typical collinear autocorrelation; (b) spectral bandwidth of the Cr:LiSAF.

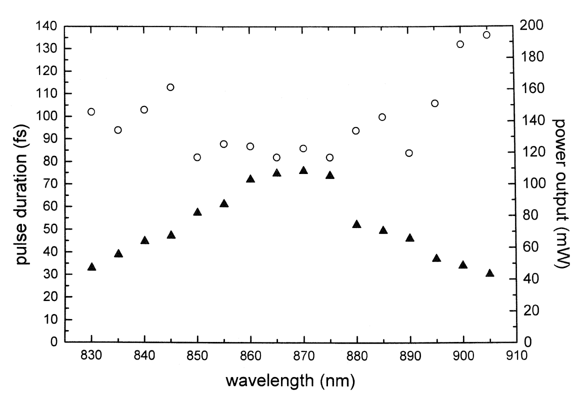

Fig. 7. Pulse duration (○) and average output power (▲) as the laser is tuned from 830–905 nm. The output coupling is 1%.

operation without any adjustments of the cavity. This improvement in initiation of mode-locking by periodic variation of the cavity length is due not only to increased mode-beating fluctuations but also to the displacement of the standing-wave pattern of the field energy density in the gain medium [18]. In this manner, the laser would remain mode-locked for periods of many hours. Furthermore, the position of the laser cavity elements could be adjusted and optimized without interrupting the mode-locking, indicating the increased stability expected with soft aperture mode-locking.

It should be mentioned that we have also used a combination of one TDL and one broad area diode to pump the Cr:LiSAF. Initial results have been almost identical to those described above, in terms of tunability, pulse duration and mode-locking stability. The difference in performance between the systems has been in the average output power, with a decrease of 25% measured. What is clear from these results and those presented in our earlier work [11] is that the use of even a single diffraction limited diode laser pump significantly improves the performance of KLM in Cr:LiSAF, enabling high efficiency, soft aperture mode-locking and wide tunability. These advantageous properties have not been observed in systems pumped solely by broad area diodes.

We intend to further improve the laser by using a second mirror set to access the 900–1000 nm spectral region. Addition of further broad area diode or TDL units will also be used to increase the power output. Further reduction of higher order dispersion would reduce the pulse duration. We also plan to compare the performance of Cr:LiSGaF with Cr:LiSAF.

To summarize, we have reported a soft aperture Kerr-lens mode-locked Cr:LiSAF laser which produced femtosecond pulses tunable over a range of 100 nm between 809 and 910 nm, pumped by the near diffraction-limited output of two tapered diode lasers. To our knowledge, this is the widest tuning range of any diode-pumped femtosecond laser reported to date. Furthermore, we measured average output powers of up to 110 mW and pulse durations down to 70 fs. The high brightness and excellent beam quality of the output of the tapered TDLs enabled the operation of soft aperture KLM by gain aperturing within the Cr:LiSAF crystal itself. The TDL proved to be a stable and efficient pump source. Long term mode-locked operation could be maintained by moving one of the cavity mirrors. This relatively simple diode-pumped source could be used as an alternative to Ti:sapphire systems for applications requiring tunable femtosecond pulses with average powers in the hundred milliwatt range.

References

[1] S.A. Payne, L.K. Smith, R.J. Beach, B.H.T. Chai, J.H. Tassano, L.D. DeLoach, W.L. Kway, R.W. Solarz, W.F. Krupke, Appl. Optics 33 (1994) 5526.
[2] L.K. Smith, S.A. Payne, W.L. Kway, L.L. Chase, B.H.T. Chai, IEEE J. Quantum Electron. 28 (1992) 2612.
[3] M.J.P. Dymott, A.I. Ferguson, Optics Lett. 20 (1995) 1157.
[4] V.P. Yanovsky, F.W. Wise, A. Cassanho, H.P. Jenssen, Optics Lett. 20 (1995) 1304.
[5] S. Tsuda, W.H. Knox, E.A. de Souza, W.Y. Jan, J.E. Cunningham, Optics Lett. 20 (1995) 1406.
[6] D. Kopf, K.J. Weingarten, L.R. Brovelli, M. Kamp, U. Keller, Optics Lett. 19 (1994) 2143.
[7] M. Stadler, M. Bass, B.H.T. Chai, J. Opt. Soc. Am. B 9 (1992) 2271.
[8] D. Kopf, J. Aus der Au, U. Keller, G.L. Bona, P. Roentgen, Optics Lett. 20 (1995) 1782.
[9] R. Knappe, G. Bitz, K.-J. Boller, R. Wallenstein, Optics Comm. 143 (1997) 42.
[10] S. Tsuda, W.H. Knox, S.T. Cundiff, Appl. Phys. Lett. 69 (1996) 1538.
[11] A. Robertson, R. Knappe, R. Wallenstein, J. Opt. Soc. Am. B 14 (1997) 672.
[12] D. Kopf, A. Prasad, G. Zhang, M. Moser, U. Keller, Optics Lett. 22 (1997) 621.
[13] I.T. Sorokina, E. Sorokin, E. Wintner, A. Cassanho, H.P. Jenssen, in: Conf. on Lasers and Electro-Optics Europe ’94, paper CThN3, Optical Society of America, Washington, DC, 1994.
[14] T. Brabec, Ch. Spielmann, P.F. Curley, F. Krausz, Optics Lett. 17 (1992) 1292.
[15] L. Goldberg, D. Mehuys, M.R. Surette, D.C. Hall, IEEE J. Quantum Electron. 29 (1993) 2028.
[16] V. Magni, G. Cerullo, S.D. Silvestri, Optics Comm. 101 (1993) 365.
[17] M. Piché, F. Salin, Optics Lett. 18 (1993) 1041.
[18] F. Krausz, T. Brabec, Optics Lett. 18 (1993) 888.