High power diode pumped solid-state femtosecond laser systems

S P Nikitin¹, A N Chabushkin¹, S A Babaev¹ and A A Kolosvetov²

¹ OOO “FemtoVision”, Russian Quantum Center group, Skolkovo, Moscow Region 143025, Russia
² Moscow Institute for Physics and Technology, Dolgoprudny, Moscow Region 141701, Russia

e-mail: s.nikitin@rqc.ru

Abstract. We demonstrate high power direct diode-pumped femtosecond laser based on a commercially available configuration and pumped by multi-diode laser modules delivering high brightness and average power. The multi-diode modules employ beam-combining scheme preserving linear polarization and focusing properties of individual laser diodes. Stable passive Kerr lens modelocked (KLM) laser operation was demonstrated, producing 30 fs pulses at ~300 mW average output power. A simple approach to numerical modelling of KLM laser operation in cases when longitudinal pump beam exhibits strong astigmatism is also discussed.

1. Introduction

Ultrafast laser systems generating optical pulses shorter than 100 femtoseconds in duration are important tools in both science and technology. Their applications include chemically selective microspectroscopy, metrology, time-resolved diagnostics of various physical processes, generation of coherent pulses from THz to X-rays, industrial and medical applications based on high precision processing of materials and biological tissues. In the family of ultrafast lasers, Ti:sapphire systems remain indispensable due to their extremely broad gain spectrum which provides tunability over more than 300 nm in near IR as well as capability to generate pulses as short as 5 fs directly from the laser.

Spectral properties of Ti: sapphire require a linearly polarized laser with wavelength near 500 nm as its pump source [1]. Furthermore, femtosecond operation of Ti:sapphire lasers is based on passive KLM mechanism making focusing properties of the pump beam an important parameter both for laser efficiency and for robustness of KLM femtosecond operation [2]. External lasers commonly used to pump Ti: sapphire systems earlier resulted in high costs and complexity of such systems. The situation changed with the advent of compact and inexpensive blue-green laser diodes [3]. Output intensity of such diodes is currently approaching 3W at >25 % energetic efficiency opening a possibility to build a compact and efficient diode pumped solid-state femtosecond laser.

While Kerr lens mode locked (KLM) operation of Ti: sapphire laser has been demonstrated by using single diode pumping schemes [4, 5] further development of high power direct diode pumped Ti: sapphire laser systems requires solutions to increase average power while preserving pump beam linear polarization and its focusability.
2. Experimental results

A possible solution to this problem is beam combining of multiple laser diodes based on spectrally selective polarization transformation. In this case beam combining is accomplished by using common polarization beam combiners followed by a set of specially designed birefringent plates [6]. Such approach allows beam combining with overall losses less than 10%, preserves linear output polarization and, most important, results in high brightness of the combined beam, which is important for reliable KLM operation.

Due to high efficiency of the laser diodes used in these modules (typically in the range of 20-30%), their compact size and overall affordability such multi-diode modules offer an attractive alternative to frequency doubled Nd:YAG lasers which are commonly used to pump Ti:sapphire lasers nowadays. Same approach to beam multiplexing can be used to develop high brightness multi-diode laser sources to pump other media characterized by sufficiently broad pump absorption spectra.

Such multi-diode laser pump modules were successfully used to achieve stable KLM femtosecond operation by using femtosecond laser «TiF-Kit-20», commercially available from “Avesta Project”, LLC. The standard optical layout of the femtosecond laser kit has been originally designed for operation with frequency doubled diode pumped solid state (DPSS) Nd:YAG laser. The femtosecond laser kit was modified to implement dual side pump configuration and to compensate pump astigmatism by using cylindrical telescopes.

Figure 1 shows a 5 mm Brewster cut Ti:sapphire crystal pumped from both sides by two laser diode modules operating in 465 – 475 nm range. Overall pump efficiency and beam focusability was found to be adequate to provide stable KLM operation of this femtosecond laser system. Mode locked pulses spectral properties, durations and overall system behavior were generally very similar to the case when frequency doubled DPSS Nd:YAG laser is used as a pump source.

![Figure 1. Ti:sapphire crystal pumped by multi-diode laser modules based on spectrally selective polarization transformation.](image)

A typical spectrum (FWHM = 31 nm) and corresponding autocorrelation function (FWHM = 48 fs) obtained at the output of the diode-pumped femtosecond laser are shown in Figure 2. By using total pump power ~ 7 W average output power of the laser was in the range 100-300 mW depending on accuracy of pump alignment.
In order to optimize pumping geometry Kerr lens mode locked laser operation was modelled by using standard ray transfer matrices. In this model Ti:sapphire crystal is sliced on multiple layers and femtosecond pulse intensity is approximated by a Gaussian function:

\[ I(x, y, t) = A \frac{E}{\tau \omega_x \omega_y} \exp(-\frac{2t^2}{\tau^2} - \frac{2x^2}{\omega_x^2} - \frac{2y^2}{\omega_y^2}) \]  

(1)

Focal distances of an astigmatic Kerr lens induced in a thin layer of thickness \( \Delta z \) can be approximated on optical axis as follows:

\[ F_{x,y}(\Delta z) = \frac{4 A \tau \omega_x \omega_y \omega_{x,y}^2}{n_2 E \Delta z} \]  

(2)

Here \( A = \sqrt{8/\pi^3} \) is the normalizing constant, \( E \) is the laser pulse energy \( n_2 \sim 3 \times 10^{-16} \text{ W/cm}^2 \) is Ti:sapphire nonlinear refractive index [7], \( \tau \) is femtosecond pulse duration, \( \omega_x \) and \( \omega_y \) are beam radial dimensions, which are different due to astigmatism. Subsequent application of ABCD ray matrices [8] in two orthogonal planes was used to evaluate KLM laser mode evolution in the laser crystal.

Astigmatic beam pump intensity inside the crystal can be approximated using longitudinal pump model [9] and using generalized Gaussian beam [10] with beam quality parameters \( M_{xy}^2 \), waist sizes and waist locations specified differently in two orthogonal planes. The model also naturally includes femtosecond pulse broadening due to optical dispersion, gain saturation and gain guiding effects [11, 12].

Pump efficiency for the laser diodes operating at 470 nm wavelength with beam quality parameter \( M_x^2 = 3 \) in one plane and \( M_y^2 = 9 \) in the other, which is typical for high energy blue-green laser diodes, was evaluated by using the specified approach. Numerical modeling results were found to be in reasonable agreement with the experimentally obtained 300 mW average power at 7 W pump level. Additionally, model confirmed somewhat higher pumping efficiency of KLM laser mode compared to the CW mode.

Our future plans include numerical modeling of diode pumped KLM femtosecond laser aimed to improve its efficiency and overall performance of Ti:sapphire lasers pumped by astigmatic beams typical for laser diodes.
3. Conclusion

Powerful high-brightness multi-diode laser pump modules were developed and successfully integrated into a typical femtosecond laser optical layout to ensure its stable Kerr lens modelocked operation. Such laser diode modules are characterized by high brightness and nearly linear optical polarization.

Modelocked operation of the Ti:sapphire laser has been experimentally achieved by using ~7 W pump level resulting in 300 mW average output power and ~30 fs pulse duration at the output of Ti:sapphire laser. The demonstrated beam combining technique allows power scaling in excess of 10 W basing on currently available blue-green laser diodes. Multi-diode pump of other laser media by using the same beam combining technique is also possible.

Self-consistent ABCD numerical model accounting for multimode astigmatic pump beam, Kerr lensing in laser crystal, pump guiding and optical dispersion effects is suggested.

These results demonstrate that the multi-diode laser modules are well suitable for longitudinal pump of Kerr lens modelocked femtosecond lasers and open possibility to replace existing pump lasers with new powerful, compact and energy efficient multi-diode laser sources, enabling development of compact and highly efficient DPSS femtosecond lasers for multiple applications in science, industry and medicine.

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References

[1] Moulton P F 1986 J. Opt. Soc. Am. B 3 125
[2] Shai Y and Pe’er A 2013 Applied Sciences 3 694
[3] Nakamura S, Senoh M, Nagahama S I, Iwasa N, Matsushita N and Mukai T 2000 Appl. Phys. Lett. 76 22
[4] Backus S, Kirchner M, Durfee C, Murnane M and Kapteyn H 2017 Opt. Express 25 12469
[5] Kopylov D, Esaulkov M, Kuritsyn I, Mavritskiy A, Perminov B, Konyashchenko A and Maydykovskiy A 2018 Laser Phys. Lett. 15 045001
[6] Pochechuev M, Suvorina A, Shcheglov P, Nikitin S and Zheltikov A 2018 J. Opt. Soc. Am. B 35 2842
[7] Major A, Yoshino F, Nikolakakos I, Aitchison J S and Smith P W 2004 Opt. Lett. 29 602
[8] Bélanger P A 1991 Opt. Lett. 16 196
[9] Alfrey A (1989) IEEE J. Quantum. Elect. 25 760
[10] Siegman A E 1993 Proc. SPIE vol 1868 p 2
[11] Salin F, Squier J and Piche M 1991 Opt. Lett. 16 1674
[12] Salin F and Squier J 1992 Opt. Lett. 17 1352