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Fundamentals of direct multi-wavelength diode pumping of Ti:Sapphire lasers for enhanced optical-to-optical conversion efficiency across a broad spectral range

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Direct-diode-pumped titanium–sapphire lasers are gaining popularity as sources of coherent light due to their wide emission bandwidth, cost-effectiveness, ergonomics and compactness. Despite recent advances in this field, reported laser output powers remain relatively low. Here, we present a theoretically and experimentally described pumping technique that involves the spectral and collinear combination of blue and green laser diode radiation. We show that this approach yields an impressive average optical-to-optical efficiency of 16.6 % in continuous-wave laser mode and up to 43.6 % in femtosecond mode based on Kerr-lens mode-locking. Consequently, with a maximum pump power of 15 W, the generated output power at 770 nm reaches 2.5 W in continuous-wave mode. With a pump of 14.5 W we have 1.84 W in femtosecond mode. In the future, such titanium–sapphire lasers promise to become even more accessible and user-friendly.

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Femtosecond (FS) laser systems have transformed many areas of science and technology [1], spurring the development of more efficient, compact, and affordable designs. Semiconductor laser diodes (LDs), due to their high power, spectral diversity, and compact form factor, are increasingly considered as direct pump sources for Ti:Sapphire lasers, replacing traditional diode-pumped solid state (DPSS) lasers. Over the last 15 years, a number of diode-pumped Ti:Sapphire systems have been demonstrated, yet challenges remain in achieving high output power and slope efficiency. Early diode-pumped lasers offered modest efficiency ($\sim$1–6 %) and limited output (<1 W) [2–3], while recent works reached up to 3 W output using high-power 450 nm sources under 50 W pump power with cryogenic cooling [4]. Progress in combining multiple diodes at various wavelengths (455–525 nm) has improved absorption matching, but instabilities and mode-matching issues persist. Particularly in FS operation, slope efficiencies and output power have remained modest ($\sim$14 %, 1 W at 798 nm with 85-fs pulse duration) [5] and commercial diode availability in critical spectral ranges (470–510 nm) is limited. Thus, practical schemes utilizing available diodes for efficient, robust, and spectrally optimized multi-wavelength pumping are still needed.

In this study, we propose and experimentally realize a high-performance laser system based on the spectral and spatial combination of four diode sources emitting at 455, 465 nm, and two at 525 nm. The resulting pump beam profile is tailored to maximize overlap with the intracavity mode of a z-fold Ti:Sapphire oscillator. The laser architecture employs a z-shaped cavity design (Figs. 1a, c). The pump delivery system includes cylindrical telescope pairs for each diode, configured with convex ($F = 80$ mm) and concave ($F = -25$ mm) lenses to collimate and focus each beam individually before combination. Spectral and spatial beam combining is achieved using dichroic mirrors and a D-shaped mirror for co-linear alignment of the beams.

The demonstrated system achieves an optical output of 2.5 W in continuous-wave (CW) mode at 770 nm under 15 W of optical pump power, corresponding to an optical-to-optical efficiency of 16.6 %, Fig. 1b. The corresponding tuning bandwidth lies in the range from 705 to 1020 nm. Under Kerr-lens mode-locking (KLM) operation in FS mode experimental setup, stable FS pulses with a duration of 75 fs are generated at 798 nm with an output power of 1.84 W, driven by 14.5 W of pump power. These performance figures represent the state of

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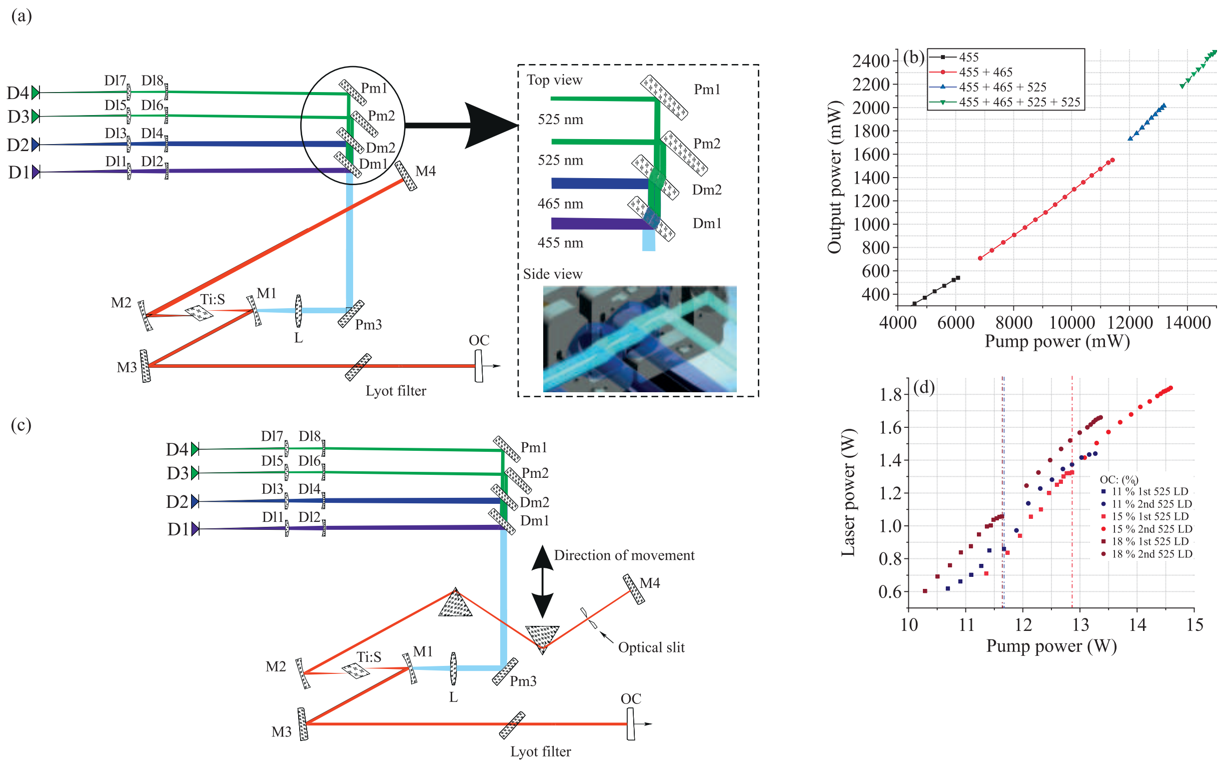

Fig. 1. (Color online) (a) – The optical scheme of the laser cavity for CW operation. The pump part consists of four LDs D1–D4, cylindrical lenses DL1–DL8 with focal lengths $F_{\text{convex}} = 80$ mm and $F_{\text{concave}} = -25$ mm, pump mirrors Pm1–Pm3, dichroic mirrors DM1–DM2, spherical lens ($F = 80$ mm). The laser cavity includes high-reflectance mirrors M# (two of them are spherical concave mirrors with a curvative radius $R = 100$ mm), Lyot filter and an output coupler. (b) – Output power of the laser in CW mode versus pump power. Laser wavelength is 770 nm. The slope efficiencies of the D1–D4 LDs are 13.8, 18.3, 24.9 and 26.6 % respectively. (c) – Laser cavity for FS operation (P1, P2 prisms made from the dense flint). The P2 prism is located on the a movable mechanical table with electromagnetic starter. An optical slit is attached to the table with P2 prism. (d) – The FS mode laser output power as a function of pump power is shown for various OCs. Blue LDs pump power was fixed at 10 W, while green LD pump power was increased. Vertical lines denote the points where the first 525 nm LD pump power was stopped and the second 525 nm LD was activated. Slope efficiencies for the first and second 525 nm LDs were 34.4 and 31.7 % (18 % OC), 27.4 and 31.4 % (11 % OC), and 43.6 and 26.9 % (15 % OC). The optimal OC is 15 %

the art for directly diode-pumped Ti:Sapphire lasers. Moreover, the emission wavelength of the laser can be tuned continuously from 730 to 860 nm in FS mode, encompassing a broad range suitable for multiphoton microscopy, ultrafast spectroscopy, and quantum photonics.

The corresponding slope efficiencies for each diode type are following: while the 455 nm diode exhibits a slope efficiency of 13.8 %, the 465 nm diode yields 18.3 %, and each 525 nm diode exceeds 24 % in CW mode. However the maximum observed slope efficiency of green LDs is 43.6 % in FS mode. These results underscore the synergy between spectral absorption characteristics of Ti:Sapphire and the spatial configuration of each pump source.

Key to the performance of the system is the spatial overlap between the pump beam profile and the fundamental transverse mode of the laser cavity. This overlap is optimized using both experimental alignment and numerical modeling. Experimental observations and theoretical calculations confirmed the importance of beam offset and profile shaping: offsetting the green pump beams from the geometric center of the focusing spherical lens improved performance by enhancing overlap with the cavity mode. Beam propagation was simulated using Fresnel diffraction integrals, and the overlap integral between the pump intensity distribution and the calculated intracavity mode was evaluated using a four-level laser gain model [6].

Unlike traditional Ti:Sapphire lasers pumped by DPSS or frequency-doubled Nd:YAG lasers, the described system reduces the overall size, weight, and cost. The design is scalable and modular, allowing for further enhancement of output power via higher-power diodes or double-side pumping schemes.

In summary, we present a comprehensive study of a directly diode-pumped Ti:Sapphire laser with optimized beam combining technique. The system demonstrates leading-edge performance in both CW and FS regimes, confirming the feasibility of all-diode-pumped Ti:Sapphire technology for demanding scientific and industrial environments. This work represents a key step toward the widespread adoption of compact, efficient, and wavelength-flexible ultrafast lasers.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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