Modern High-Efficiency Solid State Lasers

N U Wetter[1] and F M Prado[1]

[1] *Centro de Lasers e Aplicações, Instituto de Pesquisas Energéticas e Nucleares, 05508-000, São Paulo, Brazil.*
Contact Phone: +11 992285506
Contact Email: nuwetter@ipen.br

Modern lasers are characterized by various advancements, including novel operation wavelengths, increased output energy and power, shorter pulse durations, lower manufacturing and maintenance costs, reduced footprints, and greater ease of operation. Among these, high energy conversion efficiency stands out as a critical feature. High efficiency translates to lower energy consumption, reduced heat removal requirements, smaller footprint, and generally lower costs at equivalent output power levels. For example, a lamp-pumped laser from the 1990s with a wall-plug efficiency of 1% is thirty times less efficient and significantly larger than a modern diode-pumped solid-state laser (DPSSL) with a wall-plug efficiency of 30%. Low energy consumption is particularly crucial for high-power lasers where energy costs are significant. In optically pumped lasers, the maximum achievable efficiency is limited by the quantum defect, defined as the ratio of the pump to laser wavelength. Highest slope efficiency is generally observed in ytterbium amplifiers due to their very low quantum defect of 94% (976 nm pump wavelength) and 50% wall-plug efficiency have been achieved, partly because of advancements in InGaAs laser diodes emitting at 940 or 976 nm. The commercial success of kW-class Yb fiber lasers, capable of up to 10 kW in singlemode and 100 kW in multimode, drove the development of these diodes. The success of Yb fiber lasers was mainly due to overcoming common high-power laser issues like heat removal and thermal lensing.

However, for single ytterbium oscillators, maximum slope efficiency with respect to incident pump power drops to approximately 78% due to reabsorption. Among four-level lasers operating at room temperature, similar efficiencies to those of ytterbium lasers have been achieved since the early 2000s with neodymium-doped vanadate hosts such as YVO4 and GdVO4, due to their high absorption and emission cross-sections. Other hosts like YAG and YLF required nearly two additional decades to achieve comparable efficiencies. Currently, efficiencies for neodymium-doped hosts are close to 80% when directly pumped into the 4F3/2 energy level at wavelengths between 863 nm and 885 nm, with the respective pump diodes becoming more efficient, facilitating wall-plug efficiencies similar to the best ytterbium lasers.

Neodymium lasers are preferred for applications requiring lightness, robustness, and compactness, along with output powers and pulse energies up to approximately 100 Watts and 100 mJ, respectively. This work focuses on Nd:YLF lasers, which are advantageous due to their birefringence, minimal thermal lensing, high beam quality, extensive dynamic operating range, and suitability for passively Q-switched lasers due to their longer upper-state lifetime.

Traditionally, longitudinal pumping has been perceived as more efficient, but experimental evidence suggests otherwise. Today, there are nearly as many side-pumped configurations that hold records for slope efficiency among neodymium lasers as there are longitudinally pumped lasers. By using a total internal reflection (TIR) at the pump facet of the laser crystal, bounce resonators place the optical path of the laser beam within the crystal in the area of highest population inversion, forming a line of contact with the pump facet. This contact line at the crystal surface can be perfectly overlapped spatially with the line focus of a diode stack formed by a spherical lens. Additionally, a very short absorption length might be accomplished by using Volume-Bragg-Grating (VBG) equipped diode stacks. These spatio-spectrally overlapped lasers have achieved the highest efficiencies known to us by combining the regions of highest absorption with highest intracavity oscillator intensity.

This work presents a review of our advancements in side-pumped Nd:YLF lasers, including new wavelength, single- and double-bounce resonators, and compares them to the best crystalline lasers such as Yb:YAG, Nd:YVO and Nd:YAG. In particular, we demonstrate the details of a fundamental mode laser with 78% slope efficiency and Q-switching with close to 50 MW, sub-nanosecond pulses.