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Modern High-Efficiency Solid State Lasers

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Abstract. This work reviews recent advancements in modern neodymium-doped solid-state lasers, with a particular emphasis on Nd:YLF. Key innovations include highly efficient passively Q-switched configurations and the demonstration of novel emission wavelengths. Nd:YLF lasers achieved record-breaking efficiencies in both traditional and in-band pumping schemes, with a notable demonstration of 41 mJ pulse energy and 46 MW peak power in a sub-nanosecond Q-switched system employing a Cr⁴⁺:YAG saturable absorber and a side-pumping scheme. Nd:YAG systems achieved 40 mJ pulse energy with an 18 ns duration, underscoring their suitability for laser designation applications. Additionally, new wavelengths at 863 nm and 1370 nm were demonstrated in Nd:YLF crystals, enabling applications such as blue light generation and astrophysical studies. Multichromatic emissions were also investigated, highlighting the potential of Nd-doped lasers to produce simultaneous outputs at multiple wavelengths. These findings emphasize the versatility, efficiency, and scientific importance of Nd-doped lasers, paving the way for further innovations in laser technology.

1. Introduction

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 [1,2].

Solid-state lasers are employed across various fields. In medicine, they are utilized in procedures like laser surgery and dermatological treatments due to their precision and control [3]. In manufacturing, they are applied in high-precision cutting and welding, benefiting from their high beam quality and efficiency [4]. In scientific research, they serve as sources of fast and highly energetic laser pulses [4,5]. Additionally, they are employed in communication and defense sectors, including free-space and quantum communications, LIDAR for autonomous vehicles, and military defense systems [5].

Since the 1980s, solid-state lasers were primarily pumped by flash and arc lamps, which had broad emission spectra and consequently very low conversion efficiencies (<3%). Before diode lasers could be used to pump solid-state lasers, two major milestones needed to be achieved. The first was the invention of semiconductor lasers based on gallium arsenide (GaAs) in 1962 [6-9]. However, these early diode lasers required cryogenic cooling and high current densities, limiting their practicality. The second milestone came in the 1970s with the introduction of heterostructure lasers [10]. By using layered semiconductors to confine charge carriers and photons, these designs enabled continuous-wave (CW) operation at room temperature. This breakthrough paved the way for the transition from lamp-pumped to diode-pumped solid-state lasers, which marked a significant advancement in laser



technology. Laser diodes provided narrowband, wavelength-specific pumping, greatly improving efficiency and compactness.

Until today, 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 [11].

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% (for the 976 nm pump wavelength) and 50% wall-plug efficiency have been achieved [12], 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 [13].

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 ⁴F_{3/2} energy level at wavelengths between 863 nm and 885 nm [14,15], 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.

Traditionally, longitudinal pumping has been perceived as more efficient, but experimental evidence suggests otherwise [14-21]. 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 wave-length, 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. 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.

This paper begins with a brief discussion on the pumping schemes and characteristics of various Nd-doped crystals. Next, we examine the efficiencies of modern solid-state lasers, followed by their applications in Q-switched operation and multichromatic and new wavelengths emissions.

2. Pumping

Pumping schemes significantly impacts the efficiency, scalability, and beam quality of solid-state lasers. Two primary configurations, longitudinal and transverse pumping, offer distinct advantages and

limitations, tailored to different applications and operational needs. This section explores these schemes, their technical details, and their relevance to Nd-doped laser crystals like Nd:YAG, Nd:YVO, and Nd:GdVO.

2.1. Longitudinal Pumping

Longitudinal pumping offers a high degree of overlap between the pump and laser beams, which is essential for maximizing efficiency. This overlap ensures that nearly all pump power is absorbed and converted into laser action, making it an ideal choice for applications requiring high beam quality. The pump beam can be shaped into a circular profile with a near-TEM₀₀ mode using specialized optics, such as fiber-coupled diode lasers. This enhances the optical quality, achieving diffraction-limited performance, which is crucial for precision applications like ophthalmic surgery and metrology. Fig. 1 presents a scheme of a longitudinally pumped laser.

However, longitudinal pumping is limited by thermal effects, particularly at higher power levels. The localized heat deposition creates radial thermal gradients, leading to a thermal lens effect. These gradients can distort the beam profile and reduce output power stability. Moreover, excessive thermal stresses may lead to crystal fracture, necessitating careful thermal management [23,24].

Longitudinally pumped Nd:YVO lasers, for instance, have demonstrated slope efficiencies around 53%, with optimized configurations achieving even higher efficiencies [25,26]. Techniques such as annular-shaped beam profiles have been proposed to mitigate thermal lensing by distributing heat more uniformly across the crystal.

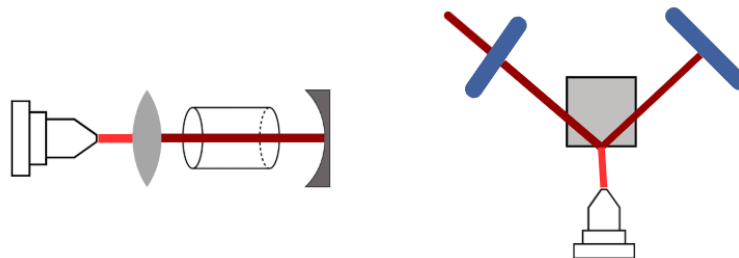


Figure 1. Longitudinal and transverse pumping scheme.

2.2. Transverse Pumping

Transverse pumping, in contrast, distributes the pump power along the length of the active medium. This reduces localized thermal gradients and alleviates issues associated with heat buildup, allowing for greater power scalability. Multiple diode stacks can be positioned around the crystal, or across a larger area of the crystal, providing uniform pumping and enabling higher power outputs. This configuration is widely used in industrial applications, such as high-power cutting and welding, where beam quality is less critical than power output [3].

However, transverse pumping have historically faced challenges in achieving a diffraction-limited beam. Since the pump beam is not collinear with the laser mode, the energy absorbed outside the TEM₀₀ mode may excite higher-order modes, reducing beam quality. Additionally, the thermal gradients in transverse pumping are more complex and anisotropic, complicating thermal management and potentially impacting the long-term stability of the laser [24,27].

In industrial applications, transversely pumped Nd:YAG lasers have set records for high output powers while maintaining reasonable efficiency. For instance, transversely pumped Nd:YAG systems are commonly used in laser cutting and marking due to their ability to handle high thermal loads.

3. Beam quality

The M^2 parameter is used to quantify the quality of a laser mode. The best beam quality, corresponding to the diffraction-limited beam, has M^2 equal to unity. Beams with worse quality have a

higher M^2 . From now on, we will consider a beam of good quality as a beam in the TEM_{00} mode, that is, with M^2 from 1 to 1.5 [27].

There are several configurations to improve the quality of the laser beam mode in transverse pumping. We can again separate these configurations into two classes: one class that forces the occurrence of the high-quality mode by introducing greater losses for the higher-order modes (with M^2 above 1.5). The other class of devices causes a favoring of the TEM_{00} mode by a greater gain for this mode in relation to the higher modes [27].

Another way consists of creating a TEM_{00} mode so large that it encompasses practically the entire pumped volume or at least so large that the remaining inverted volume is not sufficient to allow the oscillation of a larger mode. These devices generally require cylindrical or telescopic optics to create the strongly asymmetric beams necessary to cover the entire gain volume.

Another way to favor the TEM_{00} mode through a higher gain for this mode relative to the higher modes uses the fact that there is competition for gain when two or more beams propagate side by side and with a certain degree of overlap between their cross sections within the gain region. If the degree of overlap and the beam width are chosen correctly, the higher order mode is not able to obtain a higher net gain than the fundamental mode. One very common way of measuring the M^2 value is through the so called Knife-edged method [28,29].

When the beam waist is measured by varying the distance from the focus of a spherical lens, the waist values are typically determined at the points corresponding to 10% and 90% of the laser power. These measurements can be converted to the $1/e^2$ value using a correction factor of 1.561 [29]. The beam waist data points are then plotted, and a nonlinear curve fit is applied to the experimental data. The equation for a Gaussian beam fit is presented in Equation 1.

$$w = w_0 \cdot \sqrt{1 + \left(\frac{M^2 \cdot \lambda (z - z_0)}{\pi \cdot w_0^2} \right)^2} \quad (1)$$

4. Neodymium doped crystals

The use of neodymium as a material for doping solid-state active media was first reported in 1961, in a $CaWO_4$ matrix [30]. And currently it continues to be a material with many applications, the most common crystals doped with neodymium are Nd:YAG, due to its excellent mechanical qualities, Nd:YVO and Nd:GaVO, due to linearly polarized emission, and Nd:YLF, due to its small birefringence, low variability of the refractive index as a function of temperature, and long lifetime of electrons in the excitable state [27]. Traditionally, Nd:YLF, as well as other neodymium-doped crystals, are pumped in the 800 nm band, due to the peak of the crystal absorption coefficient in this region, as illustrated in the Figure 2. However, studies have reported advantages of taking advantage of other peaks in the Nd:YLF spectrum, which presents advantages in the lower contribution of heat in the crystal and lower quantum defect, when compared to traditional pumping [13].

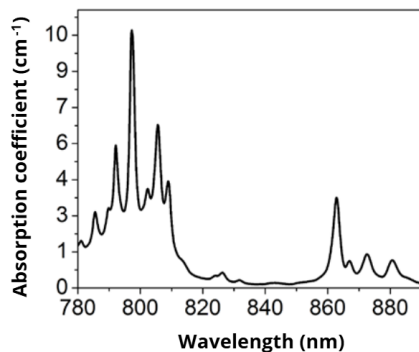


Figure 2. Absorption coefficient of an Nd:YLF crystal with 1% mol doping.

Table 1 presents the key properties of the Nd:YAG, Nd:YVO, and Nd:YLF crystals, along with their principal laser emission wavelengths.

Table 1. Nd-doped crystal properties [27,19,20].

Property	Nd:YAG	Nd:YLF	Nd:YVO ₄
Crystal Structure	Cubic	Tetragonal	Tetragonal
Lattice Constants	$a = 12.01 \text{ \AA}$	$a = 5.16 \text{ \AA}, c = 10.73 \text{ \AA}$	$a = 7.12 \text{ \AA}, c = 6.29 \text{ \AA}$
Density	4.5 g/cm^3	3.99 g/cm^3	4.22 g/cm^3
Thermal Conductivity	$14 \text{ W/m}\cdot\text{K}$	$6.3 \text{ W/m}\cdot\text{K}$	$5.23 \text{ W/m}\cdot\text{K}$
Thermal Expansion Coefficient	$7.8 \times 10^{-6} / \text{K}$	$13.3 \times 10^{-6} / \text{K}$ (a-axis), $3.8 \times 10^{-6} / \text{K}$ (c-axis)	$4.43 \times 10^{-6} / \text{K}$ (a-axis), $11.37 \times 10^{-6} / \text{K}$ (c-axis)
Refractive Index	1.82 (1064 nm)	1.448 (1053 nm); 1.45 (1047 nm)	1.95 (1064 nm)
Emission Cross-Section	$2.8 \times 10^{-19} \text{ cm}^2$ (1064 nm)	$1.2 \times 10^{-19} \text{ cm}^2$ at (1053 nm)	$2.5 \times 10^{-18} \text{ cm}^2$ at 1064 nm
Fluorescence Lifetime	230 μs	480 μs	90 μs
Absorption Cross-Section	$6.0 \times 10^{-20} \text{ cm}^2$ (808 nm)	$1.8 \times 10^{-20} \text{ cm}^2$ (797 nm)	$6.0 \times 10^{-19} \text{ cm}^2$ at 808 nm
Emission Wavelengths	1064 nm ($4F_{3/2} \rightarrow 4I_{11/2}$)	1053 nm [π] ($4F_{3/2} \rightarrow 4I_{11/2}$)	1064 nm ($4F_{3/2} \rightarrow 4I_{11/2}$)
	946 nm ($4F_{3/2} \rightarrow 4I_{9/2}$)	1047 nm [σ] ($4F_{3/2} \rightarrow 4I_{11/2}$)	1342 nm ($4F_{3/2} \rightarrow 4I_{13/2}$)
	1123 nm ($4F_{3/2} \rightarrow 4I_{11/2}$)	1321 nm [π] ($4F_{3/2} \rightarrow 4I_{13/2}$)	914 nm ($4F_{3/2} \rightarrow 4I_{9/2}$)
	1319 nm ($4F_{3/2} \rightarrow 4I_{13/2}$)	1314 nm [σ] ($4F_{3/2} \rightarrow 4I_{13/2}$)	1085 nm ($4F_{3/2} \rightarrow 4I_{11/2}$)
	1444 nm ($4F_{3/2} \rightarrow 4I_{13/2}$)	1370 nm [σ] ($4F_{3/2} \rightarrow 4I_{13/2}$)	1386 nm ($4F_{3/2} \rightarrow 4I_{9/2}$)

5. Single and Double bounce configurations

5.1. Single-bounce configuration

The bounce configurations relies on a single total internal reflection (TIR) at the pump facet of the crystal, where the oscillating laser mode interacts with the region of maximum population inversion, typically located near the pumped surface. The precise spatial overlap between the center of the oscillating mode and the gain region facilitates that the TEM₀₀ mode, which has the highest power density at its center, receives the greatest gain.

The geometry of the single-bounce configuration can be optimized to enhance efficiency by controlling the angle of incidence at the pump face, the crystal absorption coefficient, and the pump beam size. The angle of incidence must satisfy the conditions for total internal reflection, which depend on the refractive index of the crystal. Additionally, proper beam shaping, such as the use of cylindrical lenses or volume Bragg gratings, ensures maximal overlap between the pump beam and the oscillating laser mode, enabling efficient energy extraction. The simplicity of this setup reduces optical losses compared to more complex designs, as fewer reflections and a shorter optical path minimize scattering and absorption losses. Single-bounce resonators are particularly advantageous due to their compact design, ease of alignment, and stability.

One of the earliest single-bounce configurations to achieve remarkable efficiency was demonstrated in a Nd:YVO₄ laser operating at grazing incidence, characterized by a very low incidence angle. This approach was particularly effective due to the short absorption length of the vanadate crystal. The authors reported impressive results, achieving a slope efficiency of 72% and an optical-to-optical efficiency of 64%. [31].

5.2. Double-bounce configuration

The double-beam mode-controlling cavity is a double-bounce configuration that ensures high laser efficiency, stable TEM₀₀ operation, and power scalability by utilizing total internal reflection (TIR) on the pumping face of the active medium and two carefully controlled beam passes through the same surface. The oscillating laser beam undergoes TIR on the pumping face, where its center aligns with the region of maximum population inversion, typically concentrated near the surface. Since the TEM₀₀ mode has the highest power density at its center, it benefits the most from this gain distribution, ensuring that it is the first mode to oscillate at low pump powers, as shown in Fig. 3.

To maintain TEM₀₀ dominance even as the pumping power increases, the beam is reflected a second time on the pumping face, creating two passes that are laterally separated by a controlled distance D . This separation, combined with optimized parameters such as the beam diameter (w), absorption coefficient (σ) of the gain medium, and incidence angle (ϕ), ensures significant overlap between the two beams. The overlap prevents higher-order modes from achieving a higher net gain than the TEM₀₀ mode, while simultaneously covering nearly the entire inverted gain volume. As a result, there is insufficient residual gain volume to allow higher-order modes to oscillate, even at elevated pump powers. This precise control of geometry, beam positioning, and gain optimization makes the double-bounce configuration highly efficient, capable of delivering high beam quality with TEM₀₀ operation and excellent power scalability [32].

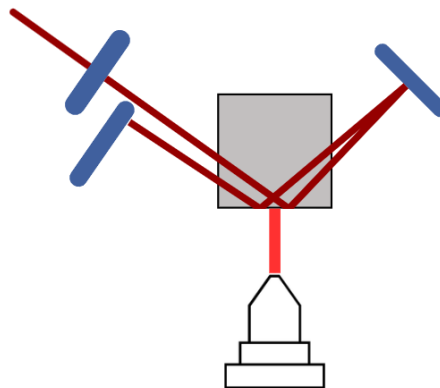


Figure 3. Double-pass configuration - DBMC.

6. Efficiency of Modern Solid State Lasers

6.1. Nd:YAG lasers

Nd:YAG lasers have seen remarkable advancements in efficiency and performance. One of the most notable works is a highly efficient Nd:YAG laser operating at 946 nm, was reported in 2020. This laser achieved a slope efficiency as high as 80% with respect to absorbed pump power (with a low quantum defect of 91.7%). The experimental setup utilized a 15-mm-long, 3×3 mm², 0.3 at.% Nd:YAG crystal, cryogenically cooled to approximately 80 K using a closed-cycle acoustic Stirling cryostat. Pumping was achieved using a volume-Bragg-grating-stabilized diode laser bar operating at 868 nm, directly exciting the upper laser level to minimize quantum defect heating. The laser delivered over 110 W of output power with a maximum pump power of 150 W. The optical-to-optical conversion efficiency reached 74% [33].

Another significant work is a high optical efficiency Nd:YAG ceramic laser, that utilized a direct end-pumping scheme at 885 nm with a high-optical-quality Nd:YAG, 3 mm, ceramic rod (0.6% mol). The experimental setup achieved a slope efficiency of 62.5% and an optical-to-optical conversion efficiency of the same value, this is to date the highest optical conversion efficiency acquired in an Nd:YAG ceramic. The maximum output power was 144.8 W, obtained under an absorbed pump power of 231.5 W [34].

In 2018, a high-power single-slab QCW Nd:YAG (0.6% mol) laser demonstrated a slope efficiency of 67.8%. This system operated at a pulse repetition rate of 160 Hz with an adjustable pulse duration (200 - 470 μ s), delivering an average output power of 7.3 kW. The optical-to-optical for this high power system reached 57%. The pumping source were laser diodes emitting at 808 nm, with an average pump power of 18 kW [35].

6.2. Nd:YVO lasers

Nd:YVO₄ lasers have demonstrated remarkable efficiency in various experimental configurations, with several studies even achieving slope efficiencies near the quantum defect limit.

While longitudinally pumped directly into the emitting level at 914 nm, a Nd:YVO laser emitting at 1064 nm reached a slope efficiency of 80.7%, with respect to the absorbed power. This set up also reached an optical-to-optical efficiency of 78.7%, delivering 11.5 W at 1064 nm for an absorbed pump power of 14.6 W. The M^2 value was measured to be 1.2×1.1 in the y- and x-direction [36].

In 2016, a passively mode-locked Nd:YVO, pumped at 914 nm, reached a slope efficiency of 77.1% and an optical-to-optical efficiency of 60.7%. This configuration produced 6.7 W of output power in 17 ps pulses, demonstrating the potential of in-band pumping to maximize efficiency [37].

Nd:YVO lasers also reached slope efficiencies of near 80% when pumped at 880 nm. This efficiency was reached under Ti:sapphire laser pumping. An optical-to-optical conversion efficiency of 79% was also recorded, and even with diode laser pumping, a slope efficiency of 75% was achieved [38]. The highest demonstrated slope efficiency of 74% under 808 nm pumping was, to our knowledge, reported by our group in 2009 [39].

6.3. Nd:YLF lasers

Nd:YLF lasers have recently demonstrated record efficiencies in various configurations, making them highly effective for applications requiring excellent beam quality and efficiency.

Using the traditional pumping around 800 nm, a side-pumped Nd:YLF (1% mol) laser emitting at 1053 nm achieved a slope efficiency of 68% and an optical-to-optical efficiency of 66%, utilizing volume Bragg grating-equipped diodes as the pumping source at 797 nm. The optimized setup delivered a peak output power of 67 W. The very compact cavity (~10 cm) produced the highest efficiency to date for this pumping wavelength [16,17].

While direct pumped, a Nd:YLF laser that demonstrated a near quantum-defect slope efficiency of 78.2%, the highest reported for this crystal. The laser employed a side-pumping scheme, with Brewster angle of incidence, with a cavity design optimized to minimize thermal effects and maximize overlap between the pump and laser modes. To reduce loss, two intracavity cylindrical lenses were added and achieved a near diffraction limited laser beam (M^2 of ~1.04) [14].

In double bounce configuration, a diode-side-pumped Nd:YLF laser reported a slope efficiency of 65% and an optical-to-optical efficiency of 63.3%. Although this sqcheme presented a lower efficiency, the double pass configuration was able to produce a better beam quality with higher pumping powers [23,32].

7. Passively Q-switched lasers

Q-switching generates short, high-energy pulses by temporarily blocking laser action while the active medium is pumped, creating a near-complete population inversion. When unblocked, the accumulated gain exceeds cavity losses, producing nanosecond-scale pulses. Switching can be active, using electro-optic or acousto-optic elements for precise control, or passive, relying on saturable absorbers like Cr:YAG, which transition from absorption to transparency at a certain fluence. Active switching offers better control but is costlier and more complex, while passive switching is simpler and more economical, requiring minimal configuration adjustments. This work explores recent advancements in passively Q-switched lasers.

Passively Q-switched lasers have made significant advancements in generating high-energy, short-duration pulses for various scientific, industrial, and medical applications. These lasers leverage

saturable absorbers, such as Cr⁴⁺:YAG, to achieve efficient Q-switching, producing high peak powers and excellent beam quality. In 2023, a Nd:YLF/Cr:YAG laser delivered 41 mJ per pulse. With a pulse width of 894 ps and a peak power of 46 MW, this system employs a side-pumping configuration using a 12-bar diode stack operating at 797 nm (~1.5 kW pumping). The Nd:YLF gain medium, coupled with a Cr⁴⁺:YAG saturable absorber, benefits from the long upper-state lifetime of the YLF crystal, enabling efficient energy storage and rapid energy release. The compact cavity design, featuring a single-bounce resonator, minimizes intracavity losses, allowing for the generation of intense, high-energy pulses [40].

In the Nd:YAG laser system generating 40 mJ pulses, an end-pumped configuration was utilized to achieve a pulse duration of 18 ns and a peak power of approximately 2.2 MW. This laser was designed for laser designation applications, where high pulse energy and precise targeting are critical [41].

The high-peak-power Nd:YAG/Cr⁴⁺:YAG microchip laser achieved a pulse energy of 24.1 mJ with an impressive peak power of 59.2 MW and a pulse duration of 407 ps. This system employed an innovative unstable resonator design, enabling energy scaling while maintaining high beam quality. A quasi-continuous-wave (QCW) fiber-coupled diode laser operating at 808 nm provided efficient pumping, while a hexagonal pump beam profile optimized mode matching. The resulting beam exhibited a near-field donut pattern, transitioning to a Bessel-like far-field distribution, achieving exceptional brightness [42].

8. Multichromatic emission of Nd:doped lasers

In Nd:YLF lasers, simultaneous emissions at 1047 nm and 1053 nm have been observed. Recent advancements have demonstrated efficient trichromatic emission at 1047 nm, 1053 nm, and 1314 nm, achieved through precise cavity alignment and optimization [39,43]. This trichromatic operation reached efficiencies exceeding 31% for all wavelength combinations, with record slope and optical-to-optical efficiencies at 1314 nm when pumped at 797 nm. Similarly, Nd:YAG lasers exhibit multichromatic emission capabilities. Dual-wavelength outputs at 1064 nm and 1342 nm or 1064 nm and 946 nm have been reported, facilitated by the crystal's capacity to support multiple emission lines [44]. These multichromatic emissions are particularly advantageous in applications like Laser-Induced Breakdown Spectroscopy (LIBS), where accessing multiple absorption lines enhances material analysis [45].

Recent advancements in Nd:YLF lasers have introduced new wavelengths. A notable achievement is the realization of laser emission at 863 nm transition. This marks the lowest wavelength ever reported for Nd:YLF lasers, achieved through a diode-pumped setup with a maximum output power of 1.46 W at an absorbed pump power of 19.7 W. The slope efficiency reached 10.2%, and frequency doubling yielded blue light at 432 nm with 410 mW output power have also been shown [46]. Another new emission was at 1370 nm using a diode-end-pumped Nd:YLF crystal. This wavelength is especially valuable for astrophysical and atmospheric studies. The laser achieved a maximum output power of 4 W with a slope efficiency of 35.5% at a pump power of 14.6 W [47,21].

Acknowledgments

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