Diode-Laser-Pumped Solid-State Lasers

(DPSSL’s)
Energy Levels of Nd:YAG.

Fig. 2.5. Energy level diagram of Nd:YAG

From Koechner “Solid-State Laser Engineering.” Springer Verlag 1988
<table>
<thead>
<tr>
<th>Physical and optical properties of Nd:YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
</tr>
<tr>
<td>Weight % Nd</td>
</tr>
<tr>
<td>Atomic % Nd</td>
</tr>
<tr>
<td>Nd atoms/cm³</td>
</tr>
<tr>
<td>Melting point</td>
</tr>
<tr>
<td>Knoop hardness</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Rupture stress</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
</tr>
<tr>
<td>[100] orientation</td>
</tr>
<tr>
<td>[110] orientation</td>
</tr>
<tr>
<td>[111] orientation</td>
</tr>
<tr>
<td>Linewidth</td>
</tr>
<tr>
<td>Stimulated emission cross section</td>
</tr>
<tr>
<td>Relaxation time (⁴I₁₁/₂ → ⁴I₉/₂)</td>
</tr>
<tr>
<td>Radiative lifetime (⁴F₃/₂ → ⁴I₁₁/₂)</td>
</tr>
<tr>
<td>Spontaneous fluorescence lifetime</td>
</tr>
<tr>
<td>Photon energy at 1.06 μm</td>
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<tr>
<td>Index of refraction</td>
</tr>
<tr>
<td>Scatter losses</td>
</tr>
</tbody>
</table>
Absorption Spectrum of Nd:YAG

Fig. 2.7. Absorption spectrum of Nd: YAG at 300 K

From Koechner “Solid-State Laser Engineering.” Springer Verlag 1988
Continuouswave Laser Diodes - CW power from 50 mW to 4 W with options including MPD, TEC, fiber output and packaging. High power, small aperture laser diodes provide capability for pumping, printing, ranging, illumination, communications and medical systems.

Single Mode CW Laser Diodes - Index guided lasers provide 50 to 200 mW cw single longitudinal, single transverse mode. High power, diffraction limited output, frequency stability and over 60,000 hour reliability are key features.

CW Linear Arrays - Up to 20 W cw monolithic linear arrays are ideal to side pump Nd:YAG rod or slab lasers. Total efficiency is >30%.

Fiber Coupled Laser Diodes - CW power up to 10 W from 400 µm core fiber for medical and micro-materials processing.

Visible Laser Diodes - CW power up to 500 mW from small aperture and 3 W from a fiber coupled laser. 660 to 690 nm wavelength.
Diode-laser pumped solid-state lasers

GaAlAs Diode laser
At 810nm

Lens to focus
Light into rod

Nd:YAG
Gain medium
1064nm output

cavity

EFFICIENT
Electricity to Light (40%)

HIGH POWER, HIGH COHERENCE &
HIGH EFFICIENCY LIGHT
Diode-Laser-Pumped Nd:Vanadate Laser I
Diode-Laser-Pumped Nd:Vanadate Laser II
Diode-Laser-Pumped Nd:Vanadate Laser III

3W GaAlAs laser diode as pump at 800nm.

1.5W CW output at 1064nm
Pumping geometry

- Image source (diode-laser) into the gain medium
- Situation of 3-D imaging
- Smaller the image, the higher the gain/unit length
- Smaller the image the higher the beam divergence in the medium
- Hence the shorter the length over which the high gain condition is maintained
- Aim to optimise the total gain (i.e. the gain integrated over the length).
Helmholtz-Lagrange Invariant: \( n_1 w_1 \theta_1 = n_2 w_2 \theta_2 \)

\[ w_1 n_1 \theta_1 = \frac{\lambda}{\pi} \quad \text{For diffraction-limited source (Gaussian Beam)} \]

\[ = N_D \left( \frac{\lambda}{\pi} \right) \quad \text{For non-diffraction-limited source (ND: number of times above diffraction limit)} \]
Focusing into the gain medium I

\[ w_p = w_{po} + (l / 2) . \theta_p \]

and

\[ \theta_p = \left\{ \frac{\lambda_p}{\pi w_{po} n} \right\} N_D \]

Change \( w_{po} \) in order to minimise \( w_p \)

Hence look for the condition:

\[ \frac{dw_p}{dw_{po}} = 0 \]
Focusing into the gain medium II

\[ w_{po} = \left\{ l \lambda_p N_D / (2\pi n) \right\}^{1/2} \]

Pick \( l \) for high absorption of pump, e.g. say 85%.

Then \( l = 2/\alpha_p \), where \( \alpha_p \) is the absorption coefficient for the pump light.

\( \alpha_p(Nd:YAG) = 4 \text{ cm}^{-1} \)

\[ I_{\text{pump (out)}} = I_{\text{pump (in)}} \cdot \exp \{ -\alpha_p l \} \]
Optical Gain in DPSSLs

Integrated Gain = \( G \)

\[ = \sigma_{21} l N_2 \]

\[ = \sigma_{21} l \tau_2 \Lambda \]

Fraction of Pump absorbed

\[ = \sigma_{21} l \tau_2 \left[ \frac{\eta_{abs} P_p}{h \nu_p Vol} \right] \]

\[ = \left[ \frac{2 \tau_2 \sigma_{21} n \eta_{abs} P_p}{h \nu_p \lambda_p l N_D} \right] \]

\[ G = \left[ \frac{2 \tau_2 \sigma_{21} \eta_{abs} n P_p}{h c l N_D} \right] \]

\[ l \text{ is fixed by absorption length} \]

\[ Area = \pi w^2_{po} = \pi \left[ \frac{l \lambda_p N_D}{2 \pi n} \right] \]

\[ Volume = \frac{l^2 \lambda_p N_D}{2n} \]
Configuration

II-Recap

\[ \frac{dN}{dt} = \Lambda - \left( \frac{N}{\tau} \right) - \left( N(2I)\sigma / h\nu \right) \]

Saturation of the gain medium due to both travelling waves, hence the factor of 2

\[ P_{out} = \beta_o A I_{\text{steady-state}} = \beta_o A \frac{h\nu}{2\sigma\tau} \left( \frac{\Lambda}{\Lambda_{\text{threshold}}} - 1 \right) \]

\[ \Lambda_{\text{threshold}} = \frac{L}{(lc\sigma\tau\tau_{\text{cav}})} \]

(Same as before)

\[ \tau_{\text{cav}} = 2L / \beta c \]
Power output from DPSSLs
Substitute for the excitation rate per unit volume and the threshold pump rate in the previous expression.
The excitation rate/volume is: \[ \Lambda = \frac{2\eta_{\text{abs}} P_P n}{h c l^2 N_D} \]

\[ P_{\text{out}} = \beta_o A I_{\text{steady-state}} = \beta_o A \frac{h \nu}{2\sigma\tau} \left( \frac{4n \eta_{\text{abs}} P_P \sigma\tau}{h c \beta l N_D} - 1 \right) \]

Well above threshold this expression tends to:

\[ P_{\text{out}} = \frac{\beta_o}{\beta} \frac{\nu}{\nu_p} A_{\text{mod e}} \frac{A_{\text{pump}}}{\eta_{\text{abs}} P_p} \]

Determines Slope Efficiency.
Explore Psst

• Go to Psst programmes for steady-state laser performance
• Explore DPPSLs
• Explore output power as function of parameters
• For example, how is the output coupling optimised?
• Obtain an analytical expression for this.
Following photographs/diagrams are from Andy’s Project Report:
“Diode Pumping of a Miniature Nd:YAG Laser”
September 1985
Figure I.1 Schematic of optical configuration employed in diode pumping of Na:YAG cavity.
Figure 4.11 Mode spectra at different diode pump powers (C) in YAG laser.