Eye-safe Er:YAG Lasers for Coherent Remote Sensing

by

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G  CPFS Er:YAG slab design  

v
Multi-watt lasers with an output wavelength in the eye-safe band are required for many remote sensing applications, including Doppler or coherent laser radars (CLR’s). Er:YAG lasers at 1617 nm or 1645 nm operating on the $^4I_{13/2}$ to $^4I_{15/2}$ transition can potentially satisfy this need. Although this transition has been known for many years, the development of diode pumping makes these lasers practical.

Doppler wind-field mapping requires single frequency, diffraction limited pulses at a high pulse repetition frequency (PRF) to provide a spatially dense array of samples, allow signal averaging with minimal loss of temporal resolution and to minimize the time required to scan an extended volume. Pulses with energies $>$few mJ and pulse durations of $>$100 ns are essential for these measurements. Such requirements can be satisfied by continuous-wave (CW) pumping of a Q-switched free-space laser.

In this thesis I describe the design and development of a single frequency, continuous wave, Er:YAG laser at 1645 nm that uses resonant pumping at 1470 nm. With an intra-cavity polarizer and uncoated etalon, it produces up to 30 mW in a narrow line-width, single frequency, plane polarized, diffraction limited, TEM$_{00}$ output. The laser is suitable as a master oscillator of a CLR.

I also describe the development and characterization of an efficient high power Er:YAG laser that is resonantly pumped using CW laser diodes at 1470 nm. For CW lasing, it emits 6.1 W at 1645 nm with a slope efficiency of 40%, the highest efficiency reported for an Er:YAG laser that is pumped in this manner. In Q-switched operation, the laser produces diffraction-limited pulses with an average
power of 2.5 W at 2 kHz PRF, and thus is suitable as the slave oscillator of a CLR. To our knowledge this is the first Q-switched Er:YAG laser resonantly pumped by CW laser diodes.

This thesis also presents an experimental investigation of the observed reduction in the average output power of Q-switched Er:YAG lasers at low PRF. The experimental results are compared with the predictions of a theoretical model developed using rate equations so the primary causes can be determined, and thus could be minimized in a future design.
Statement of Originality

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SIGNED: .................................

DATE: ......................

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“Call to me and I will answer you and tell you great and unsearchable things you do not know.” – Jeremiah 33:3

Nick Chang, August 2012
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<th>Symbol</th>
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<td>$\eta_{abs}$</td>
<td>Pump absorption fraction</td>
</tr>
<tr>
<td>$\eta_{eff}$</td>
<td>Pump delivery efficiency</td>
</tr>
<tr>
<td>$\eta_{mode}$</td>
<td>Mode overlap efficiency</td>
</tr>
<tr>
<td>$\eta_{slope}$</td>
<td>Slope efficiency</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Gain coefficient</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\sigma_{al}$</td>
<td>Effective absorption cross section of the laser wavelength</td>
</tr>
<tr>
<td>$\sigma_{ap}$</td>
<td>Effective absorption cross section of the pump wavelength</td>
</tr>
<tr>
<td>$\sigma_{el}$</td>
<td>Effective emission cross section of the laser wavelength</td>
</tr>
<tr>
<td>$\sigma_{ep}$</td>
<td>Effective emission cross section of the pump wavelength</td>
</tr>
<tr>
<td>$\sigma_l$</td>
<td>Absorption cross section for the laser transition</td>
</tr>
<tr>
<td>$\sigma_p$</td>
<td>Absorption cross section for the pump transition</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Upper state storage lifetime</td>
</tr>
<tr>
<td>$\Delta l$</td>
<td>Laser inversion density</td>
</tr>
<tr>
<td>$\Delta \tilde{z}$</td>
<td>Laser inversion density per unit area (Rod-integrated)</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pump inversion density</td>
</tr>
<tr>
<td>$\Delta \tilde{z}$</td>
<td>Pump inversion density per unit area (Rod-integrated)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Pump cross section area</td>
</tr>
<tr>
<td>$C_{up}$</td>
<td>Upconversion rate</td>
</tr>
<tr>
<td>$f_{lens}$</td>
<td>Effective focal length of the thermal lens</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Cavity finesse</td>
</tr>
<tr>
<td>$f_l$</td>
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<td>$f_p$</td>
<td>Fractional Boltzmann population of the pump transition</td>
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$G$  
Round trip gain of the laser

$h_s$  
Gain medium height

$I_l$  
Laser intensity

$I_p$  
Pump intensity

$L_{cav}$  
One-way cavity loss

$l_s$  
Gain medium length

$M^2$  
Beam propagation factor

$N^2_2$  
Excited manifold density per unit area (Rod-integrated)

$N^2_{2\text{Total}}$  
Total excited upper-state (N2) population

$N_t$  
Doping concentration per unit volume

$P_{av(\text{CW})}$  
Average power in CW operation

$P_{cav}$  
Laser intra-cavity power

$P_{out}$  
Output power

$P_p$  
Pump power

$P_{th}$  
Threshold power

$r_0$  
Radius of the waist

$R'_{laser}$  
De-excitation rate via lasing

$R_{oc}$  
Reflectivity of the output coupler

$R_{pump}$  
Pump excitation rate

$R_p$  
Reflectivity of the coating for double pass pumping

$r_p$  
Radius of the pump

$r_s$  
Radius of the gain medium

$t_{\text{scatter}}$  
Backscatter time

$v_l$  
Frequency of the laser wavelength

$V_{\text{pump}}$  
Volume pumped by the pump light

$v_p$  
Frequency of the pump wavelength

$W_{ij}$  
Radiative decay rate from level i to level j
<table>
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<tr>
<td>$w_s$</td>
<td>Gain medium width</td>
</tr>
<tr>
<td>AOM</td>
<td>Acousto-optic modulator</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-reflection</td>
</tr>
<tr>
<td>BD</td>
<td>Beam diameter</td>
</tr>
<tr>
<td>CPFS</td>
<td>Coplanar folded slab</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous wave</td>
</tr>
<tr>
<td>DA</td>
<td>Full divergence angle</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized</td>
</tr>
<tr>
<td>EDFL</td>
<td>Erbium doped fibre laser</td>
</tr>
<tr>
<td>EO</td>
<td>Electro-optic</td>
</tr>
<tr>
<td>ESA</td>
<td>Excited state absorption</td>
</tr>
<tr>
<td>ETU</td>
<td>Energy-transfer-upconversion</td>
</tr>
<tr>
<td>FSR</td>
<td>Free spectral range</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half maximum</td>
</tr>
<tr>
<td>GSD</td>
<td>Ground-state depletion</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light detection and ranging</td>
</tr>
<tr>
<td>MP</td>
<td>Multi-phonon</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical aperture</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>PBSC</td>
<td>Polarization beam splitter cube</td>
</tr>
<tr>
<td>PRF</td>
<td>Pulse repetition rate</td>
</tr>
<tr>
<td>QWP</td>
<td>Quarter-wave plate</td>
</tr>
<tr>
<td>RTP</td>
<td>Rubidium Titanyle Phosphate</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermo-electric cooler</td>
</tr>
<tr>
<td>TFP</td>
<td>Thin film polarizer</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium aluminum garnet</td>
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