Lasers and Laser Systems for Astronomy

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Outline

• Basic laser stuff
  — Lasers
  — Fiber optics
  — Laser Safety

• Lasers beacons
  — Rayleigh beacons
  — Sodium beacons
  — 589nm lasers
In its simplest form a laser is an optical gain media contained in a resonator that provides feedback.

- Laser energetics are determined by the gain media and modeled using rate equations.
- The pump must be matched to an absorption line of the gain media.
- The spatial and spectral properties of the output beam are determined via interaction between the optical modes of the passive cavity and the gain media properties.
Optical gain is possible in atomic systems that can achieve population inversion.

<table>
<thead>
<tr>
<th>3-level energy diagram</th>
<th>4-level energy diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="3-level diagram" /></td>
<td><img src="image2" alt="4-level diagram" /></td>
</tr>
</tbody>
</table>

3 and 4 level atomic systems are analyzed using rate equations which allow one to optimize and predict the laser output power and efficiency and the minimum required pump power.

See A.E. Siegman, Lasers for extensive information on rate equations and laser energetics.
A key feature of lasers is their temporal coherence, which arises from their narrow spectral emission.

Laser wavelength is determined by the gain media.

Lasers can produce very narrow spectral linewidths.

The most common high power lasers are Nd based at 1.06µm and CO₂ based at 10.6µm.

The laser spectra is determined via an interaction with the passive laser resonator longitudinal modes and the gain dynamics.
The spectral and temporal properties of the laser can be quite useful.

- Study of atomic spectra
  - Selective excitation of narrow spectral lines such as the sodium D\(_2\) line

- Very high resolution interferometers
  - Precise measurement of distances
  - Measurement of gravitational waves (LIGO)
  - Inertial rotation measurements

- Holography

A downside of temporal and spectral coherence is the possibility of unintended multi-path interference. This typically leads to unexpected power fluctuations.
A laser cavity must satisfy the “stability criterion” which can be calculated from ray optics.

### Example laser cavities

<table>
<thead>
<tr>
<th>Type</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemispherical</td>
<td>(0, 1)</td>
</tr>
<tr>
<td>(-1, 0)</td>
<td></td>
</tr>
<tr>
<td>Plane-parallel</td>
<td>(1, 1)</td>
</tr>
<tr>
<td>Concentric</td>
<td>(-1, -1)</td>
</tr>
<tr>
<td>Confocal</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Concave-convex</td>
<td>(2, 1/3)</td>
</tr>
</tbody>
</table>

### Stability Criterion

\[
0 < \left(1 - \frac{L}{R_1}\right) \left(1 - \frac{L}{R_2}\right) < 1
\]

\[
g_1 = 1 - \frac{L}{R_1}, \quad g_2 = 1 - \frac{L}{R_2}
\]

A benefit of a stable laser cavity is spatial coherence of the output beam.
A laser beam is typically a Gaussian mode

An ideal laser has a 00 mode, a non-ideal laser likely has some random combination of modes leading to imperfect beam quality
An ideal laser beam obeys the propagation equations for Gaussian beams

- $2z_0$ is known as the Rayleigh range — It is the distance over which the beam can travel without changing appreciably in size

- $\omega(z)$ is the beam radius as a function of position

- $\omega_0$ is the radius of the beam waist

- $R$ is the radius of curvature of the beam wavefront at position $z$

- $\lambda$ is the laser wavelength

- $n$ is the refractive index of the medium

These equations are for the free space propagation of a beam assuming the beam waist is at $z=0$. For a more general treatment of Gaussian beam propagation see A.E. Siegman, Lasers or A. Yariv, Optical Electronics in Modern Communications
However, not all lasers produce ideal beams

- Non-ideal laser beams contain significant power content in the higher order modes and diffract more rapidly than ideal laser beams.

- Siegman* showed that this effect could be accounted for with a parameter known as M2.

- M2 is typically measured by focusing the beam, measuring its diameter at a variety of locations including the waist and then fitting the first equation to the resulting data.

- Other beam quality measurements may be useful in illuminating what is happening with an imperfect beam; these other methods include power in the bucket, Strehl ratio and beam parameter product (beam diameter times divergence).

\[ \omega^2(z) = \omega_0^2 \left[ 1 + \left( \frac{\lambda \cdot M^2 \cdot z}{\pi \omega_0^2 n} \right)^2 \right] = \omega_0^2 \left( 1 + \frac{z^2}{z_0^2} \right) \]

\[ R = \left[ 1 + \left( \frac{\pi \omega_0^2 n}{\lambda \cdot M^2} \right)^2 \right] = \left( 1 + \frac{z_0^2}{z^2} \right) \]

\[ z_0 = \frac{\pi \omega_0^2 n}{\lambda \cdot M^2} \]

Lasers are often classified according to their temporal power characteristics

- Continuous wave (CW) laser have effectively constant output power as a function of time.

- Long pulse or quasi-CW lasers are turned on and off on a micro-second time scale.
  - These lasers produce higher peak powers, but for short periods of time.

- Short pulse lasers typically have pulse durations on the order of nanoseconds and can easily reach MW or GW peak powers.

- Ultrashort pulse lasers have pulse durations of femto-seconds to picoseconds and can reach peak powers of Peta-watts.
  - These lasers typically have broad spectral bandwidths and require careful control of the system dispersion in order to maintain their ultrashort pulsewidths.
  - We will not be considering ultrashort pulse lasers further in this talk.
Lasers can employ non-linear optics efficiently

• An EM wave propagating through a material typically interacts with the electrons in the material via a linear process
  — However, at very high intensities this process becomes non-linear and the polarization of the material begins to radiate harmonics of the fundamental excitation frequency

• The process is very fast, conserves energy of the photons involved and typically requires the phase velocities of all the involved waves to be the same in order to be efficient

• Non-linear frequency conversion schemes include, but are not limited to second harmonic generation (SHG), sum frequency mixing (SFM), third harmonic generation (THM) and four wave mixing (FWM)

\[ \frac{1}{\lambda_3} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \]

\[ P_{2\omega} = \frac{2}{\pi c} \left( \frac{\mu}{\epsilon_0} \right)^{\frac{3}{2}} \frac{\omega d^2 L^2}{n^3} \left( \frac{P_\omega^2}{\pi \omega_0^2} \right) \sin^2 \left( \frac{\Delta k L}{2} \right) \left( \frac{\Delta k L}{2} \right)^2 \]
There are many types of lasers

- I will highlight
  - Semiconductor lasers
  - Dye lasers
  - Solid state lasers
  - Fiber laser

- Other lasers
  - Excimer lasers
  - Gas discharge lasers (Argon ion, Helium neon)
  - Diode pumped alkali vapor lasers (DPALs)
  - Chemical Oxygen Iodine Lasers (COIL)
  - Optically pumped semiconductor lasers
Semiconductor lasers

• Directly convert electrical current into light

• Can achieve very high power levels, but with very power beam quality

• Often used as pumps for other lasers particularly solid state and fiber lasers

• Can be made at almost any wavelength between 650nm to 1600nm
Dye Lasers

• Use an organic dye as the laser gain media — Rhodamine 6G is a common dye

• Typically pumped with a green laser such as frequency double Nd:YAG

• Usually have a broad spectral tuning range

• Have been deployed as lasers for guide star applications, particularly at Lick and Keck Observatory

• Not preferred due to poor efficiency and chemical hazards
Solid state lasers

- Typically use a rare earth ion in a crystal or glass as the laser medium
  — Other atoms are used, particularly Ti in sapphire

- Often pumped with semiconductor lasers or flashlamps

- Can reach kW power levels and kJ pulse energies

- Many vendors, robust designs, easy to use

- Most common at 1.06µm and harmonics or 800nm
Fiber lasers

- Uses rare earth ions in glass: Nd, Yb, Er, Tm, Sm

- Waveguide defines beam quality and provides enhanced reliability, safety, efficiency and thermal management

- 6kW CW powers have been demonstrated at 1088nm with ideal beam quality

- Small aperture limits pulse energy and enhances non-linearities
Optical fibers are flexible waveguides that can carry light with low loss over long distances.

For a fiber to guide a beam without degrading the beam quality it must be single mode.
Efficient coupling of light into an optical fiber

- For optimum coupling the beam should be both normal to the lens and centered upon it
  - Two mirrors prior to the lens is one way to accomplish this
  - If the lens can be adjusted to be normal to the beam, it may be easier to have the lens on an x-y stage and move it rather than the beam

- The fiber needs to be able to translate in x, y, and z directions. If the fiber is angle cleaved on an angle polished connector, tip-tilt adjustment will also be needed
  - Most fiber ends and connectors are not AR coated (it is possible to purchase AR coated connectors), so angle cleaving or polishing is desirable to avoid 4% back-reflections and creating Fabry Perot cavities in the fiber

- The fiber is silica glass, for nano-second pulses damage thresholds are typically much less than 40J/cm² and for CW beams 2-5W/μm² is OK
  - FC/APC connectors will have much lower damage thresholds
  - High power connectors will be needed for power levels in the Watt range or high energy pulses

- For PM fibers, a waveplate may be useful prior to the lens to optimize the polarization state
By creating stress induced birefringence, optical fiber can also be made polarization maintaining

• Photo-elastic effect creates a refractive index difference for light polarized parallel to the stress axes compared to light polarized perpendicular to the stress axes

• The propagation constant \( k \) of the light traveling down the optical fiber is then different for the two cases

• This leads to a momentum difference between the orthogonally polarized modes
  — This momentum difference serves to prevent power sharing between the polarization states unless the fiber is perturbed strongly enough to overcome the difference
  — \( \Delta n > 10^{-4} \) is sufficient to provide strong polarization holding over long fiber lengths

• Connectorized fibers can be purchased where the key is aligned to the slow axis of the fiber

It is important to align the input polarization state with the slow axis of the fiber.
Light manipulated by refraction

Conventional fiber based on material variations

PCF fiber based on geometrical variations

$\phi = 125 \, \mu m$

$\phi = 7 \, \mu m$
Photonic Crystal Fibers are made by stacking rods and tubes into specific shapes.

Process: Stack, over-clad and draw

- Furnace and preform feed
- Draw tower
- Take-up reel
- Power supply and process control
Stimulated Brillouin Scattering (SBS) is of concern when propagating guide star laser light.

\[ \Omega_{\text{stokes}} = \Omega_{\text{laser}} \cdot \left(1 - \frac{n \cdot \nu_{\text{sound}}}{c}\right) \]

Numerous schemes have been proposed to raise the SBS induced narrowband power limit, but all can be accounted for via \( g_B(\Delta \nu) \).
Hollow core photonic crystal fibers may offer promise for transporting energetic beams from lasers to launch optics.

- The periodic array of holes creates the photonic equivalent of band gap, a region where light of certain wavelengths cannot propagate.
- These fibers can trap light predominantly in air greatly increasing the threshold for the onset of non-linear effects.
- Presently, loss limits their usefulness at short wavelengths such as 589nm.
Laser Safety

Eyes are particular vulnerable to lasers

Max exposure vs. wavelength

- Retina
- Cornea
- Iris
- Lens
- Macula

Graph showing max exposure vs. wavelength with different time durations (0.25s, 100 µs, 1 µs, 1 ns, and 100 fs) and wavelength ranges.
Lasers are classified according to their hazard levels

- **Class 1**: Safe under all conditions
- **Class 1M**: Safe except when viewed with magnifying optics
- **Class 2**: Visible lasers with sufficiently low power (<1mW) that blink reflex suffices to keep you safe
- **Class 2M**: Visible lasers that are safe due to blink reflex except when viewed through magnifying optics
- **Class 3R**: Considered safe with careful handing, exceeds MPE but with low risk of injury. Visible lasers <5mW
- **Class 3B**: Hazardous if viewed directly, CW lasers from 315nm-IR with <0.5W CW power or 400-700nm with <30mJ long pulse. Diffuse reflections not hazardous. Require key switch, safety interlock and appropriate laser eyewear.
- **Class 4**: All lasers with >500mW power or >30mJ pulses, all invisible lasers. Require key switch, safety interlock and appropriate laser eyewear
  - Diffuse as well as specular reflections considered hazardous
  - May ignite combustible materials
  - May burn skin
Laser hazard controls

• Engineering
  — Class 3B and higher laser should be in an enclosed room and interlocked
  — Systems should be in an enclosure with beam paths enclosed when possible
  — Use beam block to stop stray beams, this is especially important for vertical beams
  — Beams should be contained as much as possible

• Administrative
  — Lasers should be clearly labeled with their class, power and wavelength
  — Warning lights should be active inside and outside the laser room when laser is running
  — Be sure to communicate with others in the room when turning a laser on or beginning a new alignment procedure
  — There should be written procedures for laser alignment that include safety precautions
  — Access to the laser and laser room should be restricted to personnel with proper training

• Personal protective equipment
  — Appropriate laser eyewear should be worn at ALL times
  — Keep skin covered as much as possible for lasers with a burn danger or UV lasers
    – Sunscreen will not protect your skin from all UV lasers
Laser eye-wear

- Needs to have the correct OD at the correct wavelengths in order to work
  - This should be determined by a qualified laser safety professional so as to ensure any exposure will be attenuated to less than the MPE

- Should fit comfortably
  - Prescription eye-wear is available
  - Alternatively, goggles that fit over existing eye-wear is a good choice

- Try to pick glasses with maximum visibility outside of the range where OD is required
  - This greatly reduces the tendency of inexperienced personnel to take the glasses off or look over them

- Should not be used if scratched or in poor physical condition

I have seen many laser post-accident analyses, they all begin with the injured person was either not wearing safety glasses, not wearing the right safety glass or took their glasses off or looked over them for “a second”.

Lasers associated hazards

• Electrical
• Fire
• Startle
• Tripping
• Chemical
Rayleigh Beacons

\[ \eta_R = \frac{N_p}{E} \propto \frac{\exp(-z/z_0) \cdot \Delta \alpha}{\lambda^3 \cdot D_p} \]

- \( N_p \), number of received photons
- \( E \), pulse energy
- \( D_p \), diameter of laser projection mirror
- \( z \), propagation distance
- \( \Delta \alpha \), angular size of the beacon
- \( z_0 \), characteristic decay length for scatterers
- From J.W. Hardy, “Adaptive Optics for Astronomical Telescopes” equation 7.67

Uses short wavelength, 100W class lasers correction range is limited to around 15km. Appropriate green lasers can be readily obtained from commercial vendors.
Sodium atoms are abundant in a layer of the atmosphere about 90km above ground.

Laser guide stars are created by resonant back scattering of laser light by sodium atoms in the mesosphere.

A wavefront sensor measuring the scattered laser light is used to correct wavefront aberrations of the target object.

Laser guide stars enable diffraction limited images over > 60% of the sky.
Atomic sodium transitions

\[
\begin{align*}
2p_{3/2} & \rightarrow 3p \\
2p_{1/2} & \rightarrow 3s
\end{align*}
\]

D\textsubscript{1} \quad \lambda = 589.15833 \text{ nm}

D\textsubscript{2a} \quad \lambda = 589.15908 \text{ nm}

D\textsubscript{2b} \quad \lambda = 589.15799 \text{ nm}

“Bohr” Model
Na D Fine Structure

Na D\textsubscript{2} Hyperfine Structure

\[F' = 3, \quad \Delta \nu = 42.4 \text{ MHz}\]
\[F = 2, \quad \Delta \nu = 664.4 \text{ MHz}\]
\[F = 1, \quad \Delta \nu = 1107.3 \text{ MHz}\]

Spot elongation occurs for large telescope apertures

The laser beam forms a column in the sodium layer close enough to large aperture telescopes that portions of the aperture see the side of the column not just the end
Rayleigh scatter also impacts the performance of sodium guide stars

Rayleigh scatter negatively impacts the performance of laser guide star adaptive optics systems, but it can be gated out with the correct pulse format.
The laser design allows for a programmable pulse format

Rayleigh blanking: ~70μs pulses at 2.7kHz repetition rate scaled by the secant of the azimuthal angle of the telescope ~20% duty cycle
Key challenge: Low repetition rate impacts laser efficiency and square pulse distortion.

Pulse tracking: ~3μs pulses at 14kHz, ~4% duty cycle
Key challenge: low duty cycle, SBS may limit power

D. Gavel 6/26/07
Common requirements for 589nm sodium laser guide stars

- Output power: > 10W diffraction limited

- Wavelength: 589.2nm locked to the D2 line of the sodium atom

- Bandwidth: <3GHz, preferably around 500MHz
  - 3GHz is the doppler broadened linewidth of the Na atom in the sodium layer of the atmosphere
  - Some evidence suggests that broadening should be accomplished by creating narrow spectral lines via phase modulation with a minimum spacing of 180MHz

- Polarization: Circular
  - The earth’s magnetic field effect the laser interaction with the sodium atoms and can enhance the measured return significantly for the right polarization state, but this requires alignment of the telescope point with the earth’s magnetic field

- Formats
  - CW
  - Pulsed
    - Rayleigh Scatter
    - Spot Elongation
A wide array of laser technologies have been or are being developed for this application.
## Lasers in use

<table>
<thead>
<tr>
<th>Facility</th>
<th>Principal Investigators</th>
<th>Laser Maker and Type</th>
<th>Return / Watt (nominal)</th>
<th>Average Power</th>
<th>Apparent on-sky Spot Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lick Mt. Hamilton</td>
<td>Claire Max, Don Gavel</td>
<td>LLNL Tunable Dye</td>
<td>10 ph/s/cm²/W</td>
<td>12 W</td>
<td>2 arcsec</td>
</tr>
<tr>
<td>Starfire Optical Range</td>
<td>Bob Fugate, Craig Denman</td>
<td>SOR Solid state, resonant sum-frequency generator[1]</td>
<td>100 ph/s/cm²/W seasonal average[2]</td>
<td>50 W</td>
<td>seeing limited 1.4-3 arcsec (site has r0=7.8cm avg)</td>
</tr>
<tr>
<td>W. M. Keck Observatory</td>
<td>Peter Wizinowich</td>
<td>LLNL Tunable Dye</td>
<td>10 ph/s/cm²/W</td>
<td>12-15 W</td>
<td>1.8” x 2.3” (average stacked)</td>
</tr>
<tr>
<td>Palomar</td>
<td>Richard Dekany, Ed Kibblewhite</td>
<td>University of Chicago Solid state sum-frequency mode-locked [3][4]</td>
<td>30-130 ph/s/cm²/W [5]</td>
<td>6-8 W</td>
<td>as good as 2.3 FWHM arcsec in 1.0 arcsec V-band seeing @ 5.5 W power</td>
</tr>
<tr>
<td>Subaru</td>
<td>Masanori Iye, Yutaka Hayano</td>
<td>solid state sum-frequency</td>
<td>unreported</td>
<td>4.7 W</td>
<td>Currently fixing launch telescope problems</td>
</tr>
<tr>
<td>Gemini North</td>
<td>Francois Rigaut, Celine D'Orgeville</td>
<td>Lockheed Martin Coherent Technologies diode-pumped solid state 1.06+1.32 micron sum-frequency laser [6]</td>
<td>27 photons/cm²/s/W (laser power projected to the sky, i.e. out of the LLT) with linear polarization (~30% increase with circular polarization)</td>
<td>~12 W at the output of the laser, ~9W projected to the sky; measurement made in May 2005, during season of lowest sodium abundance</td>
<td>1.3 arcsec</td>
</tr>
<tr>
<td>Very Large Telescope</td>
<td>Domenico Bonaccini, Calia</td>
<td>Max Planck Institutes Tunable Dye [7]</td>
<td>54 ph/s/cm²/W</td>
<td>10 W</td>
<td>1.25 arcsec</td>
</tr>
</tbody>
</table>

AFRL 589 nm Laser

Subaru telescope mode locked YAG lasers

LM CTI and Caltech/ Kibblewhite lasers also use mode-locked SFM Nd:YAG schemes

Lasers under development

<table>
<thead>
<tr>
<th>Institution</th>
<th>PI</th>
<th>Sponsor</th>
<th>Laser Type</th>
<th>Progress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockheed-Martin Coherent Technologies (LMCT)</td>
<td>Allen Tracy, Allen Hankla</td>
<td>AODP</td>
<td>Sum frequency solid state, 1319nm+1064nm into PPSLT, modular pulse format</td>
<td>1.5 W / 10 W goal</td>
</tr>
<tr>
<td>Lawrence Livermore National Laboratory (LLNL)</td>
<td>Dee Pennington, Jay Dawson</td>
<td>AODP and CfAO</td>
<td>Sum frequency fiber, 1583nm+938nm into PPSLT, modular pulse format, 500 MHz linewidth</td>
<td>3.5 W / 5-10 W goal</td>
</tr>
<tr>
<td>Lockheed-Martin Coherent Technologies (LMCT)</td>
<td>Allen Hankla</td>
<td>Keck I and Gemini South Telescopes</td>
<td>Sum frequency solid state, 1319nm+1064nm into LBO, 0.7 nm pulse every 12 ns quasi CW</td>
<td>&gt;40W of 589nm demonstrated in the lab for GS laser (October 2007)</td>
</tr>
<tr>
<td>European Southern Observatory</td>
<td>Domenico Bonaccini Calia</td>
<td>ESO</td>
<td>Doubled 1178 nm fiber-Raman, modulated CW (to 1GHz) or Q switched micropulse</td>
<td>Demonstrated modulated CW, 4.2 W @ 589 nm</td>
</tr>
</tbody>
</table>

We are developing a fiber laser approach for the sodium guide star

Key challenges: 938nm laser operation, scaling to high average power, frequency conversion, pulsed operation with narrow line width (especially for the 938nm laser)


“High power 938nm fiber laser and amplifier,” Dawson et.al., ROI #IL-11224
938nm laser operation is achieved in Nd$^{3+}$ doped fiber with no aluminum or phosphorous co-doping. This leads to severe restrictions on the doping concentration (<10dB/m @ 808nm), which in turn forces a long laser amplifier.

Al or P pulls the emission wavelength shorter to 915nm which pushes the SFM wavelength to 1653nm out of the Er$^{3+}$ amplification window.
A 938nm Nd\textsuperscript{3+} laser is challenging because of gain competition from the 1088nm 4-level line.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original Fiber (7.5 \textmu m)</th>
<th>Large Core Fiber (30 \textmu m)</th>
<th>Small Core Fiber (20 \textmu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha @ 810nm (dB/m)</td>
<td>19.10</td>
<td>4.00</td>
<td>6.00</td>
</tr>
<tr>
<td>Amplifier Length (m)</td>
<td>200.00</td>
<td>25.00</td>
<td>27.00</td>
</tr>
<tr>
<td>Inversion at 293K (Room Temperature)</td>
<td>0.21</td>
<td>0.55</td>
<td>0.39</td>
</tr>
<tr>
<td>Gain at 938nm @ 293K (dB)</td>
<td>10.03</td>
<td>10.05</td>
<td>10.00</td>
</tr>
<tr>
<td>Gain at 1088nm @ 293K (dB)</td>
<td>283.04</td>
<td>23.76</td>
<td>27.29</td>
</tr>
<tr>
<td>Gain at 905nm @ 293K (dB)</td>
<td>-944.02</td>
<td>2.62</td>
<td>-17.84</td>
</tr>
</tbody>
</table>

Increasing the core/clad ratio increases the overlap between the pump and the core leading to a shorter amplifier and a higher operating inversion.

The difference in gain at 1088nm and 938nm is a minimum at full inversion.
The 938nm laser operates at room temperature, but some thermal management is required.

Calculated absorption cross section of Nd$^{3+}$ in silica at 938nm
We have obtained up to 15W of 938nm light in a CW format with narrow line width.

- **200mW 938nm LD**
  - Isolator and filters
  - 35W 808nm pump lasers
  - 25m, 20μm core Nd³⁺ doped fiber
  - Isolator and filters
  - 3.5W@938nm

- **90W 808nm pump laser**
  - 40m, 30μm core Nd³⁺ doped fiber
  - Isolator and filters
  - Output 15W@938nm

**938 nm output power at various spots in the system**

- Blue: Total Output Power
- Pink: Short Pass Filter
- Green: Isolator
- Red: Incident on Crystal

**Graph Details**
- **Diode Current (A) [50A is max]**
- **Measured Power (W)**
  - Y-axis starts at 0 and goes up to 18 in increments of 2
  - X-axis starts at 0 and goes up to 50 in increments of 10
Our first pulsed experimental set-up yielded >10W of average power with >50W peak power

- Pulsed at 100kHz with 20% duty cycle
- Laser architecture was the same as for the 15W CW result
- >95% of optical power was in 938nm signal line as determined from spectral measurement
- Signal line width was 500MHz and there was no sign of SBS
- Currently working on packaged system with repetition rates appropriate for Rayliegh blanking and spot tracking
The 1583nm fiber laser is mostly constructed from commercially available components.

- Koheras SM 100mW/1583nm
- PM Lithium Niobate amplitude modulator, 20dB extinction ratio
- Lithium niobate phase modulator
- IPG 1583nm amplifier
- Isolator
- New amplifier under development
- Temperature Controlled Oscillator
- WDM Coupler
- Amplifier Output
In CW mode the system produces 14W of 1583nm light with >98% of the power in the signal.

Power vs. Pump Current

Output spectrum at full power
Commercial Er/Yb fiber amplifiers have been problematic in pulsed operation but we have made some progress.

Square pulse distortion correction

1928Hz at 20% duty cycle: 2.9mW average input power, 1.4W average output power

Power vs frequency and duty cycle

Performance of pulsed laser system at 1583nm, CW output was 6.0W

These are results prior to the new final amplifier stage, which is presently under development.
2.7W of CW 589nm light was generated with a 3cm PPKTP crystal using Boyd-Kleinmann focusing

- Co-linearity of the 1583nm and 938nm beams was determined with irises spaced 1.5m apart
- The optimum spot diameter ratio of the beams was established to be 0.77
- At the focusing lens (f=75mm) the 938nm beam was 1.5mm diameter and the 1583nm laser was 2.0mm as determined with a Coherent Mode Master
- Beam waists of the collimated beams were located in the plane of the focusing lens

The PPKTP showed evidence of damage at these power levels, although it was not as severe as for 532nm or 469nm frequency conversion.
3.5W of 589nm light was generated in a 3cm PPSLT crystal at 100kHz and 20% duty cycle.

Again, the 1583nm laser had some significant CW leakage to a large percentage of its power is not contributing to frequency conversion.

The PPSLT showed no signs of damage at these power levels. The PPKTP was more efficient using this pulse format, but achieve no greater power than in the CW case. It simply rolled off a lower combined IR power.
Useful books and web sites

• A. E. Siegman, Lasers

• Amnon Yariv, Optical Electronics in Modern Communications

• Walter Koechner, Solid State Laser Engineering

• John Buck, Fundamentals of Optical Fibers

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