A Compact, Totally Passive, Multi-Pass Slab Laser Amplifier Based on Stable, Degenerate Optical Resonators

John J. Degnan
Sigma Space Corporation
14th International Workshop on Laser Ranging
San Fernando, Spain
7-11 June 2004
Why do we need compact multipass amplifiers?

• Availability of small, high repetition rate, picosecond pulse sources (e.g. microchip and SESAM oscillators) and photon-counting techniques is opening up a wide range of new applications, e.g.
  – compact photon-counting SLR stations (SLR2000)
  – Airborne/spaceborne 3D imaging lidars
  – Lunar and interplanetary transponders

• Most of these applications require pulse energies between 40 and 4000 μJ whereas the oscillators produce sub-μJ (10 ps SESAM) up to 250 μJ (custom 400 psec microchip).

• At several KHz repetition rates with CW diode pumping of the amplifiers, the gain per pass can be relatively low so highly multi-passed amplifiers are desirable and more efficient.
Unsaturated Multipass Gain

\[ G_0 = \text{single pass unsaturated gain} \]
\[ G_{mp} = G_0^{2N} = \text{multipass unsaturated gain} \]
Multipass Amplifier Approaches

Passive Amplifier/Multiple Mirrors
(e.g. Q-Peak laser in SLR2000)

Regenerative Amplifiers
(e.g. NASA STALAS Laser or High-Q laser at Graz)

Degenerate Optical Resonators
Stable Degenerate Resonators*

• A stable optical resonator is defined by two spherical mirrors with radii of curvature, \( b_1 \) and \( b_2 \), and separated by a distance \( d \) such that 
  \[ 0 \leq (1-d/b_1)(1-d/b_2) \leq 1 \]

• At certain mirror separations, \( d \), the resonator becomes “degenerate” and can be characterized by an integer \( N \).

• At a mirror separation with “degeneracy” \( N \):
  – The Hermite-Gaussian resonator modes divide into \( N \) discrete frequencies separated by \( c/2NL \) where \( L \) is the resonator length; thus, \( N=1 \) represents the highest degeneracy where all spatial modes oscillate at the same frequency.
  – Hole-coupled lasers exhibit large power losses because the frequency-degenerate modes can couple together to create a low loss composite mode with a null at the coupling hole.
  – Ray paths can be defined which repeat themselves after \( N \) round trips (useful for multipass amplifiers).

General Resonator

If $b_1$ and $b_2$ are the mirror radii of curvature, the degenerate mirror separations are given by

$$d_{\pm}(N,K) = \frac{b_1 + b_2}{2} \pm \frac{1}{2} \sqrt{b_1^2 + b_2^2 + 2b_1b_2 \cos \frac{2\pi N K}{N}}$$

where $N$ is the degeneracy factor, $K = 0$ for $N = 1$, and

$$1 \leq K \leq \frac{N}{2}$$

for $N > 1$ provided $K > 1$ is not divisible into $N$.

<table>
<thead>
<tr>
<th>$N$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Symmetric Resonator ($b_1 = b_2 = b$)

$$d_{\pm} (N, K) = b \pm \cos \frac{NK}{N}$$
Symmetric Resonator \((b_1 = b_2)\)

\(N=4, \, K=1\)

**Ecliptic**

**Non-Ecliptic**
Symmetric Resonator \((b_1 = b_2)\)

\(N=5, \ K=2\)
Flat-Concave Resonator ($b_2 =$ )

$$d (N, K) = \frac{b_1}{2} \cos \left( \frac{2 \sqrt{K}}{N} \right)$$

Resonator Length (normalized to $b_1$)
Flat-Concave Resonator \((b_2 = )\)

**Ecliptic**

- **N = 4**
- **K = 1**

**Non-Ecliptic**

- **N = 5**
- **K = 2**
**Ecliptic vs Non-Ecliptic Amplifiers**

<table>
<thead>
<tr>
<th>Ecliptic</th>
<th>Non-Ecliptic</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Amplifier entrance and exit rays overlap</td>
<td>• Amplifier entrance and exit rays do not overlap</td>
</tr>
<tr>
<td>• Requires optical isolation from the oscillator</td>
<td>• Probably does not require optical isolation from the oscillator</td>
</tr>
<tr>
<td>• Requires a means to insert and extract the beam (e.g. polarization rotation)</td>
<td>• Does not require a means to insert and extract the beam (e.g. polarization rotation)</td>
</tr>
<tr>
<td>• Samples less of the laser slab (less efficient extraction?)</td>
<td>• Samples more of the laser slab (more efficient extraction?)</td>
</tr>
</tbody>
</table>

• Generally easier to align since the insertion axis always lies along mirror normal

• With one flat mirror, a variable pass amplifier can be constructed using one translatable mirror.

• Generally more difficult to align since the insertion angle varies with degeneracy N.
Ecliptic Variable Pass Amplifier

Excellent Beam Control: Collimated beam in, same size collimated beam out!
Summary

• Microchip and SESAM oscillators can generate picosecond pulses at multi-KHz rates but at low single pulse energies (microjoules or less)
• Many airborne and spaceborne applications require amplifications of 10 to $10^3$ in a compact, efficient, diode-pumped package.
• Since CW-diode pumped amps typically have low single pass gains, many passes through the amplifier may be required to reach the required pulse energies and to extract the stored energy efficiently.
• Degenerate resonator multipass amplifiers can provide:
  – high multipass gain in a compact, easily aligned package
  – A fair amount of isolation from the oscillator and reduced internal feedback for suppressing self-oscillations
  – Variable number of passes with one translating mirror which can be set for optimum performance or compensate for a degradation in oscillator power
  – Excellent beam control since it preserves the gaussian parameters of the input beam at the output due to periodic refocusing