High Power Dense Spectral Combination Using Commercially Available Lasers and VHGs

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Content:

- Introduction: Coarse vs. Dense Wavelength Multiplexing (DWM)
- Volume Holographic Gratings for High Power Lasers DWM
- DWM Architecture – 1kW Fiber Coupled Unit
- Fabrication and Reliability of Volume Holographic Gratings
- Applications
- Conclusions
Coarse vs. Dense $\lambda$ Multiplexing

COARSE $\lambda$ multiplexing

Commercially Available High Power Laser Diode Wavelengths

DENSE $\lambda$ multiplexing

80X 91X 94X 97X

970 971 980

970 971 980
Challenges for Dense $\lambda$ Muxing

- **Broad Linewidth:** 2.5 – 4nm
- **High Temperature Dependence:** ~0.3nm/°C
## Requirement for Dense λ Muxing

### Laser Diodes

<table>
<thead>
<tr>
<th>Linewidth</th>
<th>Temperature Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 X improvement over state of the art laser diodes i.e. ( \sim 0.2 \text{nm} )</td>
<td>10 X improvement over state of the art laser diodes i.e. ( \sim &lt;0.03 \text{nm/°C} )</td>
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</tbody>
</table>

### Combiner

<table>
<thead>
<tr>
<th>Bandpass</th>
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<tbody>
<tr>
<td>20 X improvement over state of the art dichroics i.e. ( &lt;0.5 \text{nm} )</td>
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</tbody>
</table>
Volume Holographic Gratings (VHGs) in glass are critical for narrowing the spectral linewidth of High Power Laser Diodes.

VHG-FAC lenses improve off-the-shelf diode lasers:

10 X in linewidth: 4nm → 0.2nm
30 X in temperature dependence: 0.3nm/°C → 0.01nm/°C

P = 70.1 W ("free running")
P = 67.4 W (locked)
Commercially Available
VHG-FAC Combines
Collimation
And
Wavelength Narrowing
Into One
Linewidth Reduction Results

Lineshape without VHG-FAC

Lineshape with VHG-FAC

“Wavelength Stabilization of HPDL Array - Fast Axis Collimation Optic with Integrated VHG”:
C. Schnitzler, S. Hambuecker, O. Ruebenach, V. Sinhoff, G. Steckman, L. West, C. Wessling, D. Hoffman,
Ingeneric GmbH, Ondax, Inc., Fraunhofer ILT, Photonics West, Jan. 2007
Effects of Bar Smile and VHGP Alignment

Linewidth narrowing independent of bar smile and up to 3° FAC misalignment

Off-the-shelf High Power Laser Diodes are collimated and linewidth-narrowed to 0.2nm and collimated with a single VHGP-FAC. These sources meet the requirement for dense wavelength multiplexing.
Spectral combining of high power linewidth-reduced laser diodes

**Volume Holographic Gratings** (VHGs) in glass provide a solution for narrow wavelength combiners:

\[ \lambda_2 - \lambda_1 < 1 \text{nm} \]
Properties of VHG Combiners

- VHG combiners work in reflection
- VHG combiners have sub-nanometer reflection bandwidth
- Diffraction efficiency depends strongly on angle of incidence
  → for >90% combining efficiency, use FAC with less than 2 mrad rest divergence and 15 degree angle of incidence
Summary: Dense Wavelength Multiplexing

Off-the-shelf High Power Laser Diodes

+ VHG-FAC

Transform off-the-shelf High Power Laser Diodes into suitable sources for DWM

VHG Combiner

~90% Efficiency
Dense Wavelength Multiplexing (DWM) Modules

Repeat DWM with 80Xnm, 90Xnm, 94Xnm, 97Xnm and combine with coarse dichroic filters

Geometrical Stacking

Polarization Multiplexing

Beam Transformation

Coarse WM

Fiber Coupling
1kW Fiber Coupled with DWM

70W bars
975nm
978nm
975nm
978nm
975nm
978nm

80W bars
908nm
911nm
908nm
911nm
908nm
911nm

Geometrical Stacking

Polarization Multiplexing

Beam Transformation

Coarse wavelength Multiplexing

952 Watts Fiber Coupled D=600um NA=0.175

911nm
908nm
975nm
978nm

Fiber Coupled

975nm
978nm
Geometry of the Laser Diode Bars

<table>
<thead>
<tr>
<th>Diode laser bars (CW Power)</th>
<th>80 W</th>
<th>70 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter width [µm]</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Emitter pitch [µm]</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Filling factor [%]</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Number of emitters</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Length of resonator [mm]</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Wavelength [nm]</td>
<td>910</td>
<td>976</td>
</tr>
</tbody>
</table>

0.5% AR Coated Front Facet
→ Extended Locking Range (20nm)
1kW Fiber Coupled with DWM

2 Wavelength Combiner Block

High Power Laser with VHG

$\lambda_1 = 978 \text{ nm/911 nm}$

VHG Combiner

$\lambda_2 = 975 \text{ nm/908 nm}$

30°
1kW Fiber Coupled with DWM

Wavelength stabilization of 12 DWM units

Wavelength shift < 0.1 nm
The spectra of all DWM Modules demonstrate constant peak wavelength and narrow emission in the full operating range of the diode lasers.

Average combining efficiency for 6 units 908/911: 89.5%
Average combining efficiency for 6 units 975/978: 79.7%
1kW Fiber Coupled with DWM

Set up - 12 DWM units (separately exchangeable)

Collimating and Focusing Optic

Fiber coupling

Dimension of the diode laser (LxWxH): 700 x 550 x 220 mm³

2x3 DWM units
1kW Fiber Coupled with DWM

Fiber diameter 600 μm

\[ \text{NA}_{(95\%)} = 0.175 \text{rad} \]

- Optical power 952 W
- Power ratio
- Numerical Aperture [rad]

DWM Laser Diodes

Facility Unit (Water Cooling, Current Drivers):
- 1000 x 600 x 1200 mm³ (LxWxH)
By multiplexing more wavelengths, the power in the fiber can be increased without increasing the fiber core or its numerical aperture.

With the same performance VHGs used in the 1kW demo, up to 10 sources can be densely multiplexed with a cumulative efficiency of 70%.

Multi-kW fiber coupled power can thus be achieved from a 600 μm core and 0.175 N.A. fiber.
VHG Fabrication and Test

Wafer Fabrication – and Automated 100% Wafer Testing

Example of a wafer measurement from the database. All optical parameters of VHG measured at high spatial resolution.

150 μm spatial resolution
VHG Damage Threshold

High Damage Threshold: 3.85 J/cm² or 175 MW/cm²

- Pulsed 1064nm
- 20Hz Rep. Rate
- 20ns Pulse Width
- 0.5mm Spot Size

Test Results:
- Damage Threshold: 3.85 J/cm² or 174.8 MW/cm²
- Damage Type: Non-propagating pit(s)

Notes:
- Flash pit, in bulk.

Samples tested with AR coating meeting MIL-C-675
VHG Environmental Reliability

VHG's Kept at 150°C Show No Measurable Degradation Over Time

Index variation

Grating strength (Δn)
Applications of Kilowatt Laser Diode Systems

BPF: Beam Parameter Factor
Efficiency * Beam Quality

Power (W)
Volume holographic gratings (VHG) are enabling Dense Wavelength Multiplexing with High Power Lasers Diodes by:

narrowing the emission spectra of commercially available high power laser diodes and combining them

Commercially available VHGs are wafer produced and 100% tested.

FAC-VHGs incorporate collimation and line narrowing to reduce packaging costs.

952 W coupled in 600μm, NA:0.175 fiber with DWM by Fraunhofer Institute, Aachen:

Power loss due to wavelength narrowing: 5-10%

Combining efficiency at 908/911: 90%

Combining efficiency at 975/978: 80% cause by mismatch of the slow axis divergence (90% achievable)

Multi-kW fiber coupled power by adding Dense and Coarse wavelength combining