High-brightness Yb:YAG planar waveguide laser with an unstable resonator formed with a novel laser-machined, toroidal mode-selective mirror

Ian J Thomson, Krystian L Wlodarczyk, Denis R Hall and Howard J Baker
School of Engineering and Physical Science and the James Watt Institute, Heriot-Watt University, Edinburgh, UK

Introduction
Previously (1), we have shown that a large core height Yb:YAG planar waveguide section can be efficiently core-pumped by diode bar stacks. The gain section was tested in a variety of external cavities. In multimode operation, it produced 400W cw output and 75% internal slope efficiency. The work showed that issues such as matching many diode bars into the 150 micron core height and suppression of internal parasitic oscillation have been successfully dealt with, and a gain coefficient of 1 m⁻¹ achieved for MOPA applications (2). However, there remains the requirement for improvement of the beam quality of the hybrid unstable/waveguide resonator which is the preferred method for extracting oscillator power from the large aspect ratio gain cross-section.

Ideally, such a resonator should use just two mirrors, and provide mode selection in the narrow, waveguide direction. In this poster, we describe the development of a novel fabrication method for micro-stripe toroidal mirrors using CO₂ laser machining of silica. We show that the use of this highly mode selective end mirror solves previous problems of interference between core and cladding light found with simple spherical mirror unstable resonators. An output of 326 W is obtained in a single spot elliptical mode, with M²<1.5

Amplifier module
Composite YAG /Sapphire slab
Core 150 micron, 2 at.% Yb doping
(Onyx Optics)

480 W, 6 bar Stack.
941nm

480 W, 6 bar Stack.
941nm

38 mm EFL cylinder lens

Slow axis reflectors

Copper microchannel water cooling

Negative branch confocal hybrid resonator using spherical mirrors

Confocal condition (parallel output beam)
(R₁+R₂)/2 = d₁ + d₂ + d₃₁̂ₐ₀
Output coupling = 1- R₁/R₂

Output edge-coupling mirror
R₁ = 155mm concave spherical
R₂ = 138mm concave spherical
11% out-coupling
(magnification R₁/R₂ ≈ 1.123)

Low loss configurations for coupling between guided and free-space sections

Case I
z small, R large
(z = πa²/8λ, R = 2z)
(Based on Degnan and Hall, IEEE J. Quantum Electron, 1973)

Case III
z >> πa²/8λ
(R = z)

Case II
z ≈ πa²/8λ
(R₁ = R₂)

Coupling into sapphire claddings by non-optimum rear mirror RoC
Significant loss to claddings
Interference fringes with high contrast superimposed on y direction far-field
Rear mirror needs to be toroidal to satisfy both the confocal UR requirement in X and correct mode matching to the active core only in Y
**Laser Machining Of Toroidal Mirrors**

**Method**
- Smooth evaporation of silica by linear scanning of CW beam, 5 mm/sec
- 10.6μm wavelength CO₂ laser, with power of 8 to 9 W
- Active laser power stabiliser, ~1%
- 1 mm diameter on silica surface
- Evaporation on the 100 nm depth scale in a 200 μm melt track width
- Trench generated to match mirror requirements by multi-pass treatment

**Machining on cylindrical substrates**
- Conventionally ground and polished UV grade silica cylindrical lenses used as mirror substrates
- Negative branch confocal UR needs typically Rx=200 mm with sag of 0.3 mm at centre.
- Rayleigh range of CO₂ laser beam >> sag, so uniform width is obtained without focus adjustment.

**RoC in the region for Case III mode matching**

<table>
<thead>
<tr>
<th>RoC (mm)</th>
<th>Rx (mm)</th>
<th>Ry (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210 μm</td>
<td>9.3</td>
<td>240 μm</td>
</tr>
<tr>
<td>240 μm</td>
<td>13.4</td>
<td>280 μm</td>
</tr>
<tr>
<td>23.4 mm</td>
<td></td>
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</tr>
</tbody>
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**Summary**
- Process produces custom microstripe toroidal mirrors
- Mirrors can be matched in both stripe width and RoC to optimise mode matching and reject higher order modes
- 2/5 wavefront errors
- Mirror quality is sufficient for use with UR which tolerates long period waviness

**Negative branch UR resonator with toroidal rear mirror**
- Selection of toroidal micro-stripe mirrors tested in a 20% output coupling UR with 230mm nominal RoC cylindrical substrate
- 23.4 mm RoC gave best output properties at 10 mm spacing from waveguide facet
- Easily aligned, as there is sharp improvement in beam quality and output power as the stripe is scanned vertically through the correct height and rotated about laser axis

**Outcomes**
- Resonator quality micro-stripe toroidal mirrors made by laser machining
- Excellent mode quality for further development of lasers using planar waveguide gain sections
- Mirrors applicable to folded configurations in planar waveguide MOPA

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