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Volume Bragg grating external-cavity designs for coherent emission of an array of tapered diode lasers

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Outline

• Introduction
  – External cavity modelling
• Talbot external cavity
  – Principles
  – Numerical modelling
  – Experimental results
• Angular filtering external cavity
  – Numerical modelling
  – Experimental results
• Conclusion
### Introduction

<table>
<thead>
<tr>
<th></th>
<th>Near Field (µm)</th>
<th>Far Field (radians)</th>
<th>Brightness (W/cm²/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 laser diode</td>
<td><img src="image" alt="Near Field" /></td>
<td><img src="image" alt="Far Field" /></td>
<td>[ B_1 = \frac{P}{S_{em} \Omega} \propto \frac{P}{w \cdot \Delta \theta} ]</td>
</tr>
<tr>
<td>N incoherent laser diodes</td>
<td><img src="image" alt="Near Field" /></td>
<td><img src="image" alt="Far Field" /></td>
<td>[ B_N \propto \frac{w}{p} B_1 \leq B_1 ]</td>
</tr>
<tr>
<td>N coherent laser diodes</td>
<td><img src="image" alt="Near Field" /></td>
<td><img src="image" alt="Far Field" /></td>
<td>[ B_N^{coh} = N \times B_1 ]</td>
</tr>
</tbody>
</table>

Coherent emission of identical emitters in parallel

⇒ **scalability of the power & the brightness**
Purpose: passive coherent combining of diode lasers to induce an efficient coupling between emitters

External cavity designs

- Talbot self-imaging effect
  Near-field diffraction phenomenon

- Angular filtering
  Far-field filtering

HR coating

Diode laser array

Spectral/spatial filter

Output coupler

Coherent high power laser beam
External cavity designs

Purpose: passive coherent combining of diode lasers
⇒ to induce an efficient coupling between emitters
+ wavelength stabilization
⇒ volume Bragg gratings: Angular + spectral selectivity
Numerical modelling of external cavities

- N single-mode emitters
- Coupling matrix

\[
\kappa_{mn} = \frac{\int_{-\infty}^{+\infty} e_m^*(x) \times C[e_n](x) dx}{\int_{-\infty}^{+\infty} e_m^*(x) \times e_m(x) dx}
\]

\[
C[e_n] : \text{operator describing beam propagation + filtering}
\]

- \( r_0 r e^{2i\varphi} e^{2gL}\left\{\kappa_{mn}\right\} \times \vec{E} = \vec{E} \)

\( \Rightarrow \) N eigenmodes = N array supermodes

Near-field + far-field profiles
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**Talbot effect** = Near field diffraction self-imaging of periodical objects resulting from multiple beam interferences

- Self-images (amplitude & phase) at:
  - multiple of the Talbot distance $Z_T = 2p^2/\lambda$
  - fraction of $Z_T$: $p/2$ lateral shift of the in-phase mode at $Z_T/2$

- Edge losses due to finite size of the array

*Talbot external cavity set-up*  
*propagation of 10 in-phase Gaussian-shaped emitters*
Talbot cavity: modal selectivity

$2w \Rightarrow \alpha = \lambda/2p$

$\alpha_0 = \lambda/2p$

$L_{\text{ext}} = Z_T/4$

$\mathbf{C}[\mathbf{e}_n]$: free-space propagation on $2L_{\text{ext}}$ distance, with angled reflection

$\Rightarrow \alpha = \lambda/2p$: in-phase mode selection

Computation of the coupling efficiency of each array transverse supermode

$N = 10$, $p = 100 \mu m$, $w = 15 \mu m$, $\lambda = 976 nm$

- in-phase mode
  - (All emitters at the same phase)
  - $0 - 0 - 0 - 0 - 0 - 0 - 0 - 0 - 0 - 0$

- out-of-phase mode
  - (Adjacent emitters with $\pi$ dephasing)
  - $0 - \pi - 0 - \pi - 0 - \pi - 0 - \pi - 0$
Talbot cavity: in-phase mode

\[ \alpha_0 = \frac{\lambda}{2p} \]

\[ L_{\text{ext}} = \frac{Z_T}{4} \]

\[ C[e_n] : \text{free-space propagation on } 2L_{\text{ext}} \text{ distance, with angled reflection} \]

\[ \Rightarrow \alpha = \frac{\lambda}{2p} : \text{in-phase mode selection} \]

\[ N = 10, p = 100 \, \mu m, w = 15 \, \mu m, \lambda = 976 \, nm \]
External Talbot cavity Set-Up

10 emitters

\[ p = 100 \, \mu m \]

\[ \lambda_B = 975.4 \, \text{nm} \]
\[ R_B \approx 40 \% \]
\[ \Delta \theta = 2^\circ \text{ (FWHM)} \]
\[ \Delta \lambda = 0.3 \, \text{nm} \]

\[ \alpha = \lambda / 2p \]

\[ L_{\text{ext}} = Z_T / 4 = 5 \, \text{mm} \]

Index-guided tapered emitter

Single mode operation (\(M^2 < 2\))
High power (1 W)

- Far-field profile:
  - central peak width = 1.2 mrad (FWHM) \( \cong \frac{\lambda}{Np} \)
  - envelope width = 40 mrad (FWHM)
- High coherence evaluated from the fringe visibility: \( V=0.80 \)

\[
Visibility \quad V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]
- Spectral locking of each laser diodes
- Narrow linewidth ($\Delta \lambda < 0.1$ nm)

- Laser threshold $I_{\text{th}} = 0.9$ A
- $P_{\text{max}} = 1.7$ W @ 4 A (4 x $I_{\text{th}}$)
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Angular filtering extended-cavity

Angular selective feedback:
Selection of the array supermode of highest overlap with the angular filter in the far field

⇒ Numerical modelling:
\[ C[e_n] : \text{filtering of angular components in the far-field profile} \]

Angular filtering extended-cavity

⇒ Application to high filling-ratio array:

6 adjacent index-guided tapered lasers
Pitch $p = 30 \, \mu m \Rightarrow$ Filling ratio $\approx 100\%$
No coupling between adjacent emitters
⇒ Reduced number of peaks in the coherent far-field profiles

$L = 2.5 \, mm \quad L = 0.2 \, mm$

Out-of-phase mode

\[
\begin{align*}
\theta_0 &= \frac{\lambda}{2p} \\
\Delta \theta &= \frac{\lambda}{Np}
\end{align*}
\]

In-phase mode

\[
\begin{align*}
\theta_0 &= 0^\circ \\
\Delta \theta &= \frac{\lambda}{Np}
\end{align*}
\]
Angular filtering extended-cavity

⇒ Application to high filling-ratio array:

6 adjacent **index-guided tapered** lasers
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$L = 2.5 \, mm \quad L = 0.2 \, mm$

**Out-of-phase mode**

Feedback direction $\approx \lambda/2p$ ($= 16 \, mrad$)

*corresponds to one of the lobe in the out-of-phase array supermode*

Output beam on the symmetric lobe
Angular filtering with volume Bragg Grating

Reflection Bragg grating (RBG):
- $R \geq 99\%$ at $979$ nm
- $\delta \lambda = 0.3$ nm
- $\Delta \theta_{1/2} = 35$ mrad = $2^\circ$

Output power $\leq 0.7$ W
Wavelength locked to $979$ nm, $\Delta \lambda < 0.1$ nm

With external cavity:
- $50\%$ output power

Feedback angle
- $\Delta \theta_{1/2}$

Spectrum ($I = 3$ A)
- $\Delta \lambda < 0.1$ nm
Summary

- Numerical model to predict the modal properties of the extended-cavity diode laser bars

- Narrow spectrum $\rightarrow \Delta \lambda < 0.1$ nm thanks to Bragg gratings

Talbot cavity vs Intracavity angular filtering:

- In-phase mode selection with a high coherence
- $P_{\text{max}} = 1.7$ W @ 4 A (4x threshold)
- Scalable to high output powers

- Out-of-phase mode operation
- Quasi diffraction limited beam ($M^2 < 2$)
- Output power limited by AR coating

well-adapted to high filling factor arrays (reduced number of peaks in the far-field)
- Increase of the output power with high-power tapered laser bars
- Conversion of the in-phase supermode far-field profile in a Gaussian profile with phase diffraction gratings: ~80% conversion efficiency expected.

**Talbot cavity**