Numerical Simulation of Optoelectronic Devices
Nottingham, UK
1-4 September, 2008

Properties of Laterally-Coupled Distributed Feedback Lasers with Higher Order Gratings

Ron Millett, K. Hinzer, T. Hall, and H. Schriemer

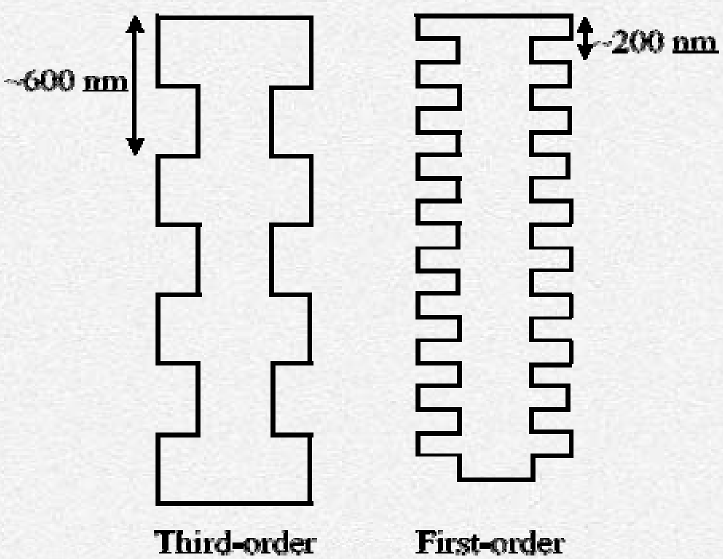
Centre for Research in Photonics
University of Ottawa
Ottawa, ON, Canada
K1R 7T1

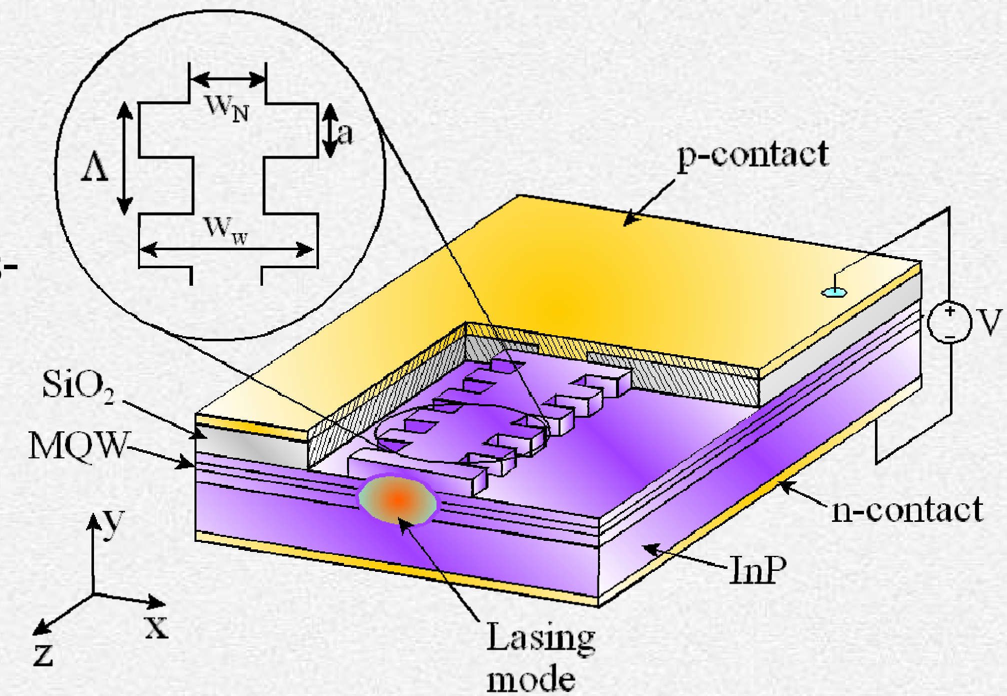
Outline

- Laterally-coupled distributed feedback (LC-DFB) laser introduction
- Higher order gratings
- Effect of grating geometry on performance
  - Grating order
  - Duty cycle
  - Grating height and width
- Cavity length
- Grating tooth rounding
- $\lambda/4$ phase-shifts

LC-DFB Laser Introduction

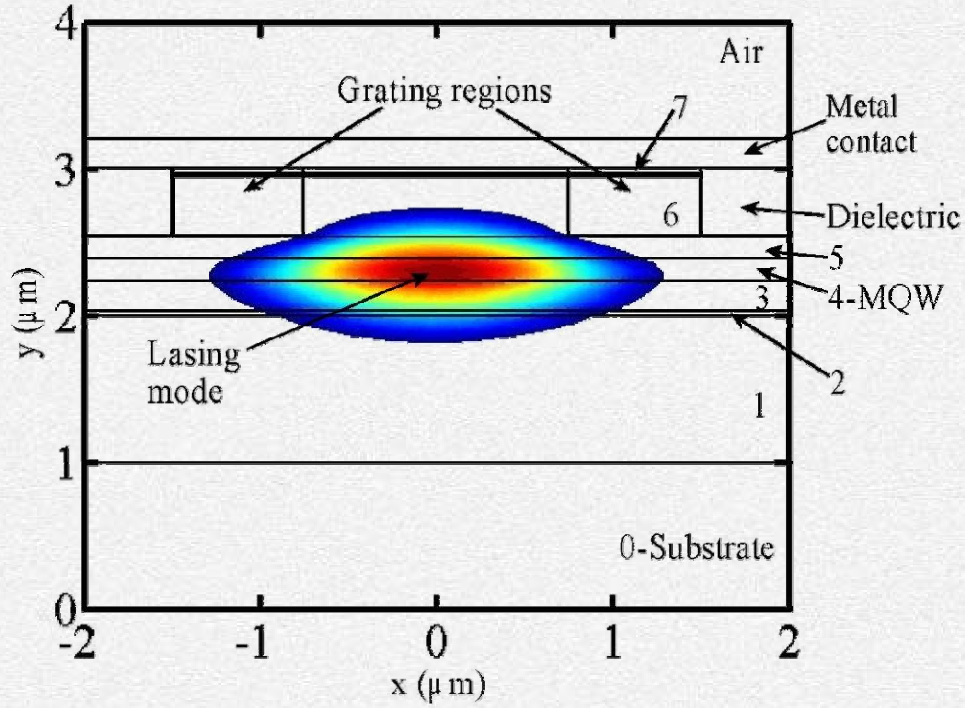
- Grating patterned out of upper ridge waveguide
- Higher order grating
- Can be fabricated using stepper lithography or nano-imprinting – amenable to mass-manufacturing





LC-DFB Laser Introduction

- Fundamental mode is evanescently coupled to laterally-positioned grating regions
- MQW active region
- Au/Pt/Ti contact with SiO_2 dielectric



Modified coupled-mode theory

In higher order gratings, additional terms are included to account for light radiating in transverse direction:

$$\frac{dA}{dz} + \left(-\alpha - i\delta - i\zeta_1\right) A = i\left(\kappa_p^* + \zeta_2\right) B$$

$$-\frac{dB}{dz} + \left(-\alpha - i\delta - i\zeta_3\right) B = i\left(\kappa_p + \zeta_4\right) A$$

A,B = longitudinal mode fields

κ_p = Coupling coefficient

α = modal gain

δ = Bragg frequency detuning

$\zeta_{1,\ldots,4}$ = Streifer correction terms

Modified coupled-mode theory

Correction terms are determined through the solution of the wave equation:

$$\frac{\partial^2 \varepsilon_m^{(i)}(x,y)}{\partial x^2}+\frac{\partial^2 \varepsilon_m^{(i)}(x,y)}{\partial y^2}+\left[k_0^2 n_0^2(x,y)-\beta_m^2\right]\varepsilon_m^{(i)}(x,y)$$
$$=-k_0^2 A_{m-i}(x,y)\varepsilon_0(x,y), \qquad m\neq i, i=0,p.$$

ε_m = partial wave field of order m

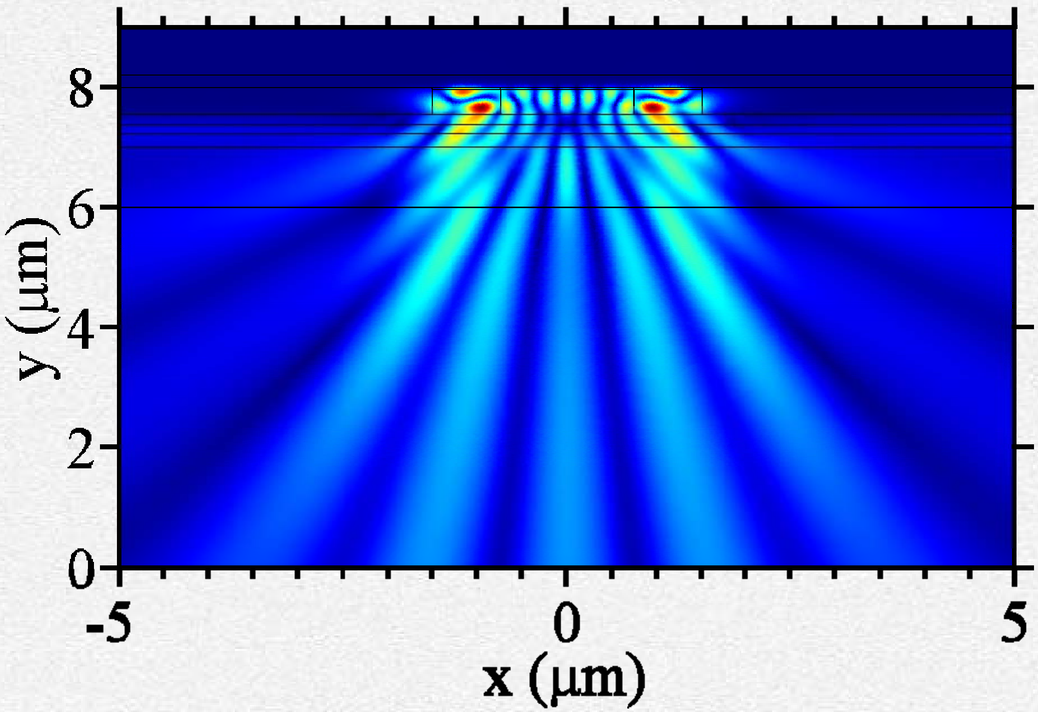
ε_0= fundamental TE mode field

k_0 = Vacuum wavenumber

β_m= partial wave propagation constant

A_q = q^{th} order Fourier coefficient

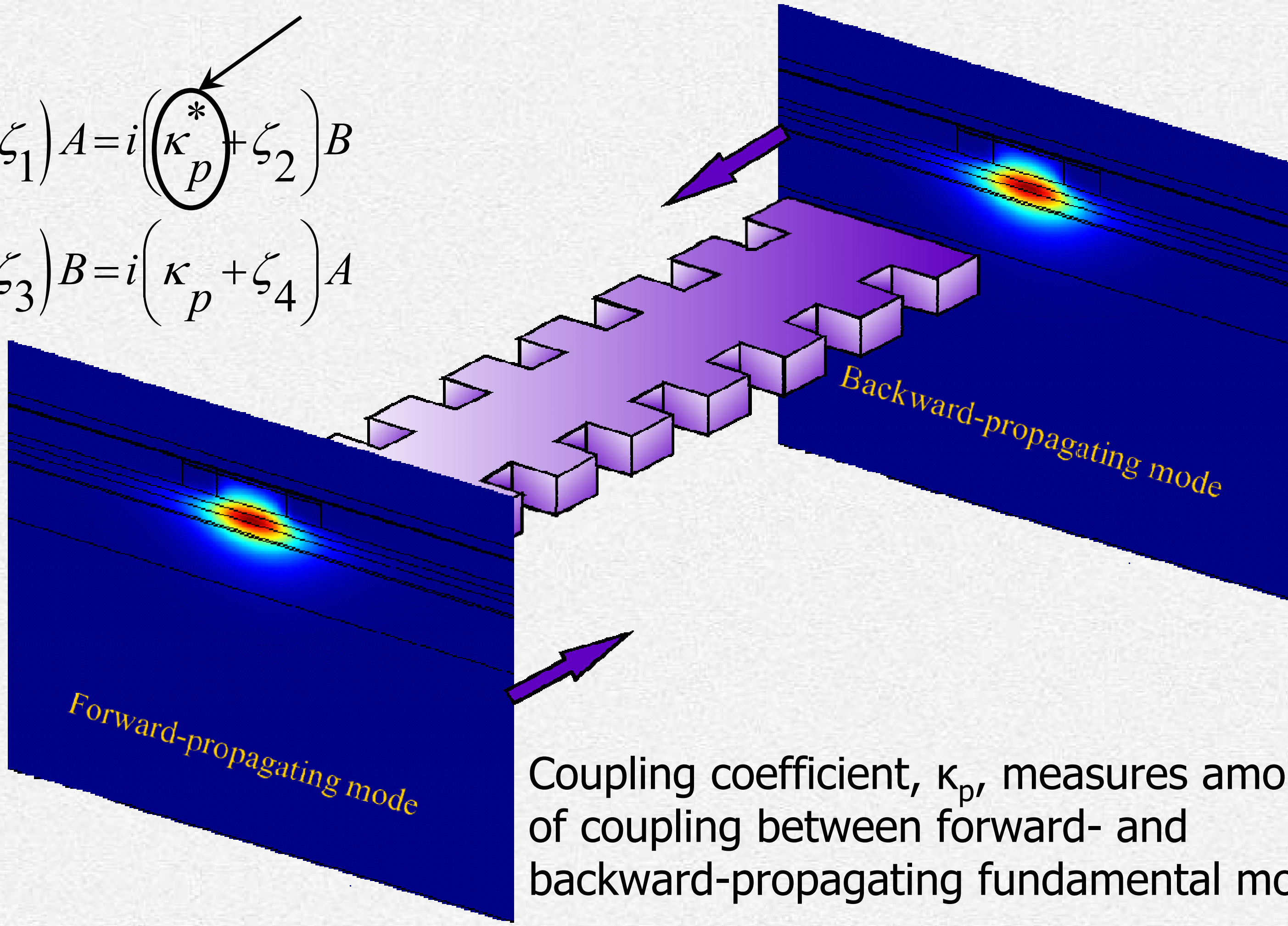
Radiating partial wave fields are calculated using the finite-element method with absorbing boundary conditions



Coupling coefficient

$$\frac{dA}{dz}+\left(-\alpha-i\delta-i\zeta_1\right)A=i\left(\kappa_p^{*}+\zeta_2\right)B$$

$$-\frac{dB}{dz}+\left(-\alpha-i\delta-i\zeta_3\right)B=i\left(\kappa_p+\zeta_4\right)A$$

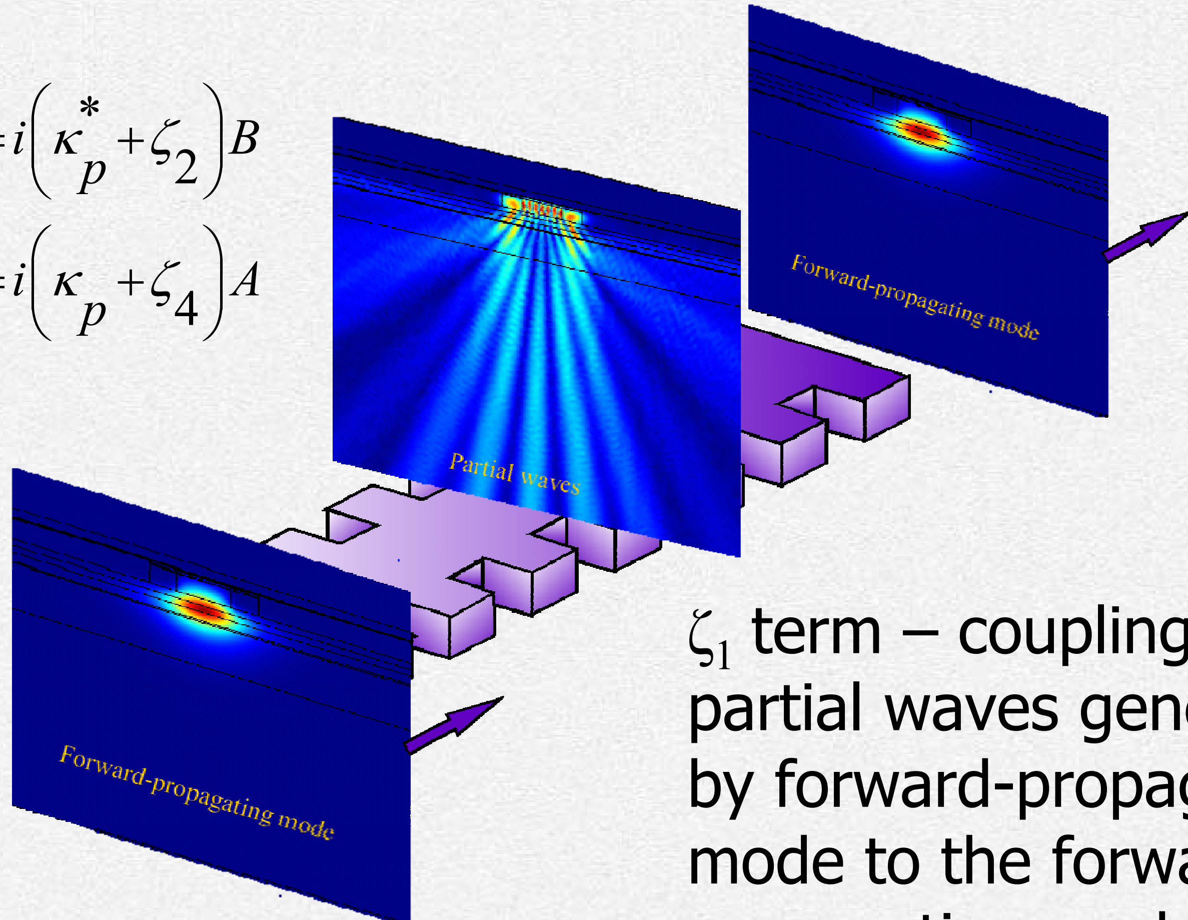


Coupling coefficient, κ_p, measures amount of coupling between forward- and backward-propagating fundamental modes

Streifer correction terms

$$\frac{dA}{dz}+\left(-\alpha-i\delta-i\zeta_1\right)A=i\left(\kappa_p^{*}+\zeta_2\right)B$$

$$-\frac{dB}{dz}+\left(-\alpha-i\delta-i\zeta_3\right)B=i\left(\kappa_p+\zeta_4\right)A$$

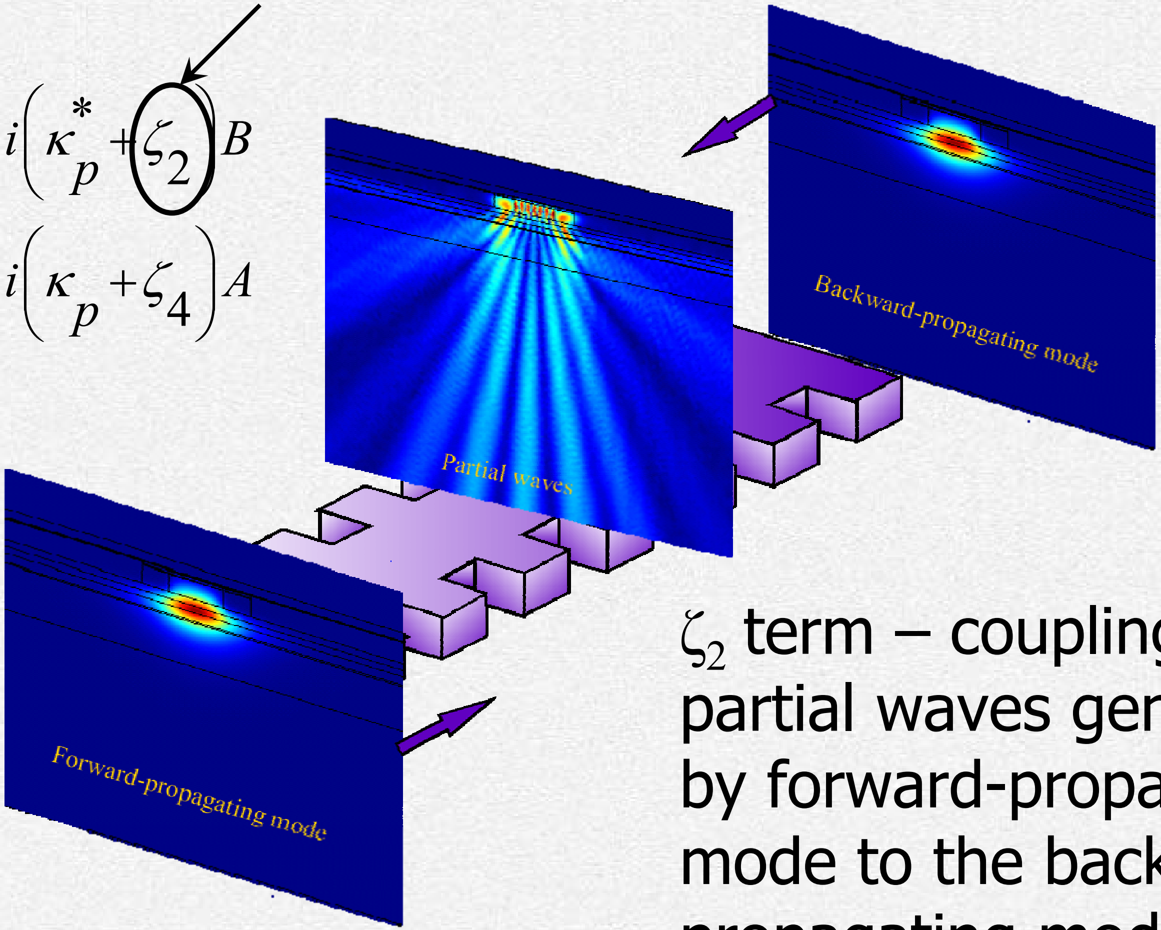


ζ_1 term – coupling of partial waves generated by forward-propagating mode to the forward-propagating mode

Streifer correction terms

$$\frac{dA}{dz}+\left(-\alpha-i\delta-i\zeta_1\right)A=i\left(\kappa_p^*+\zeta_2\right)B$$

$$-\frac{dB}{dz}+\left(-\alpha-i\delta-i\zeta_3\right)B=i\left(\kappa_p+\zeta_4\right)A$$



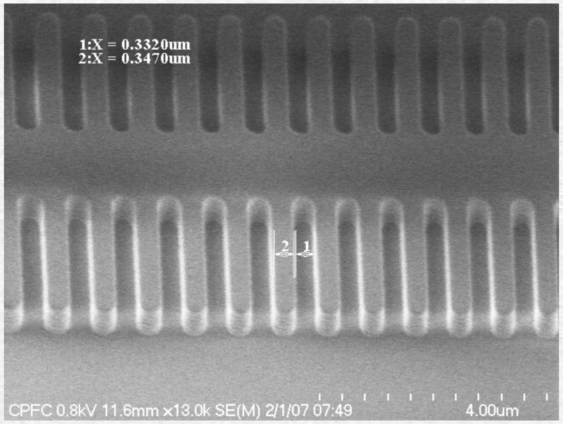
ζ_2 term – coupling of partial waves generated by forward-propagating mode to the backward-propagating mode

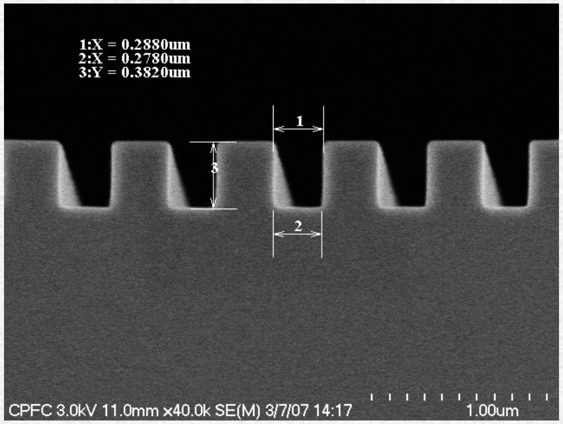
Grating strength

- A measure of grating strength in higher order gratings is the effective coupling coefficient:

$$\kappa_{eff} = \sqrt{\left(\kappa_p^* + \zeta_2\right)\left(\kappa_p + \zeta_4\right)} = \left|\kappa_{eff}\right| e^{j\phi\left(\kappa_{eff}\right)}$$

- Combination of all coupling terms between forward- to backward- propagating (and vice versa) waves
- Values of $\kappa L \approx 1.25$ (L=cavity length) are desirable for DFB lasers

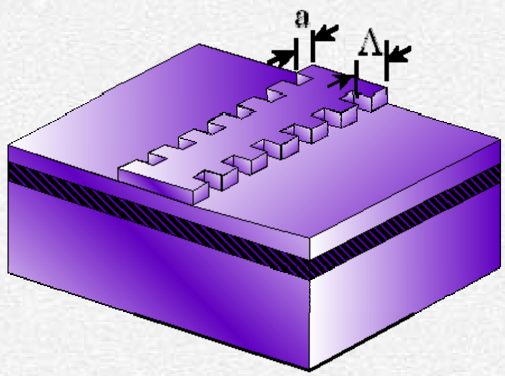




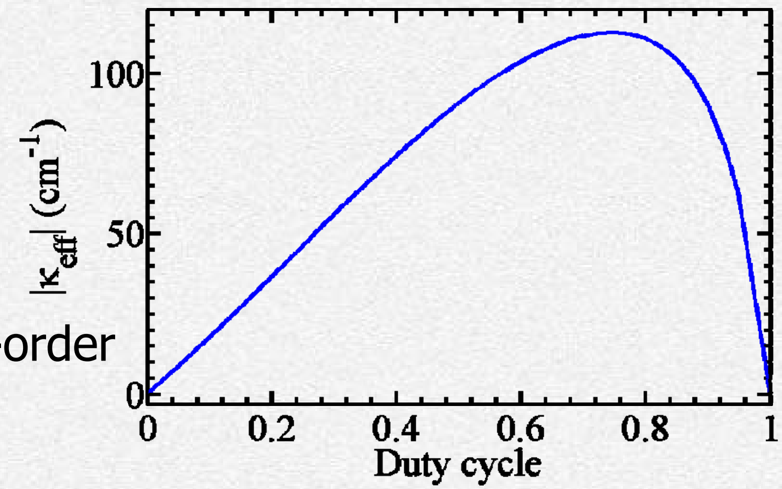
Courtesy of Canadian Photonics Fabrication Centre

Duty cycle/Grating order

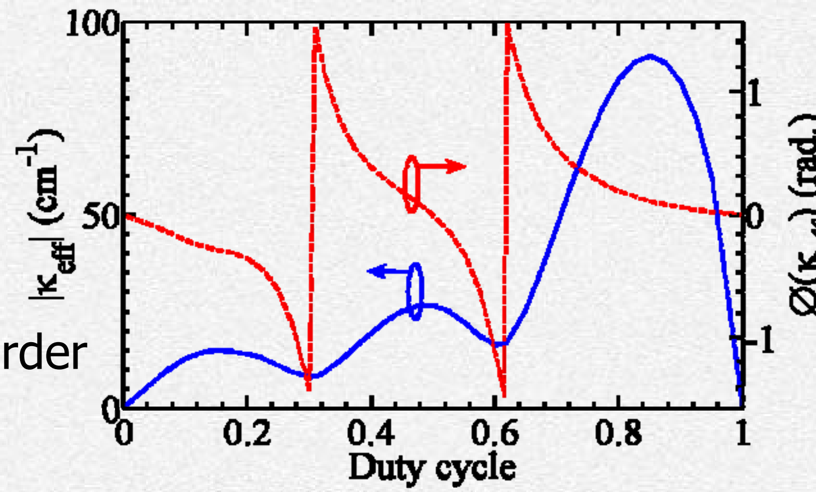
- Duty cycle = a/Λ
- LC-DFB performance is sensitive to duty cycle – larger values (> 0.5) are generally better



First-order



Third-order



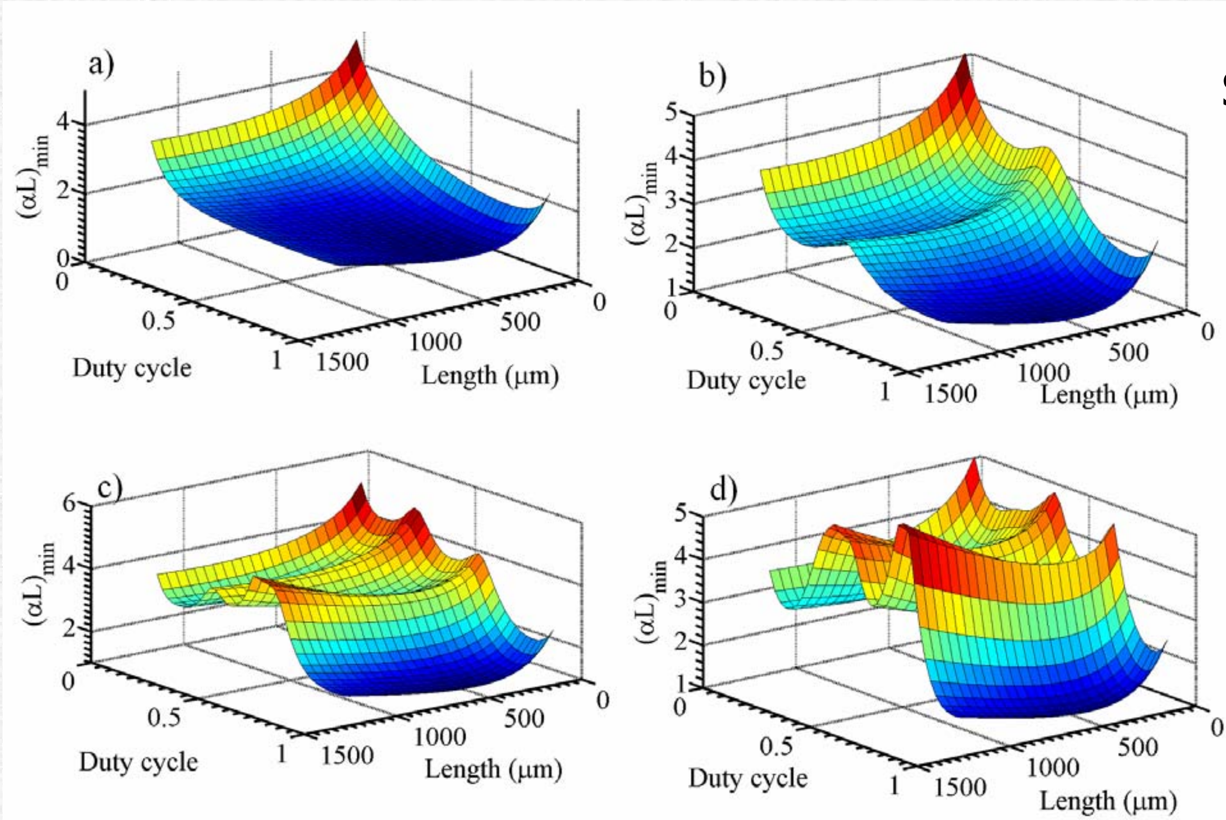
R. Millett et al., J. Quantum Electron., in press, 2008

NUSOD 2008

Threshold gain vs. cavity length/duty cycle

First-order

Second-order

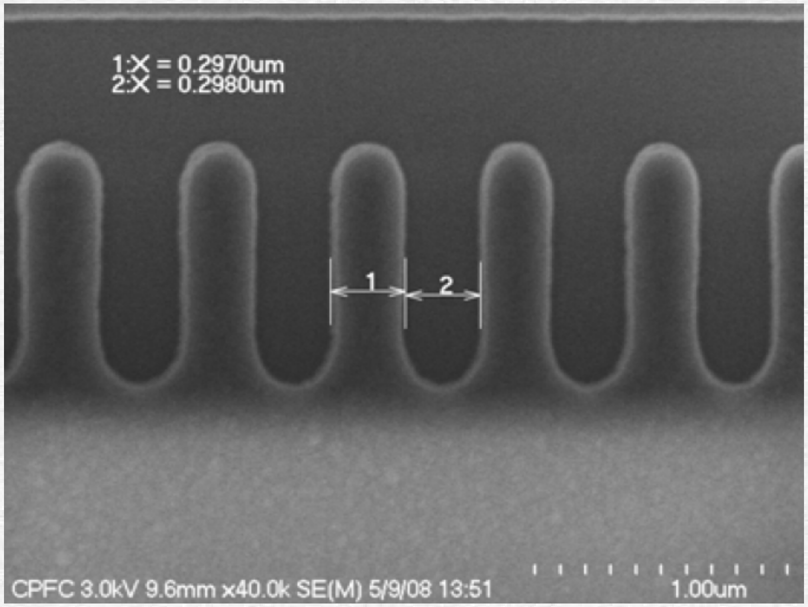


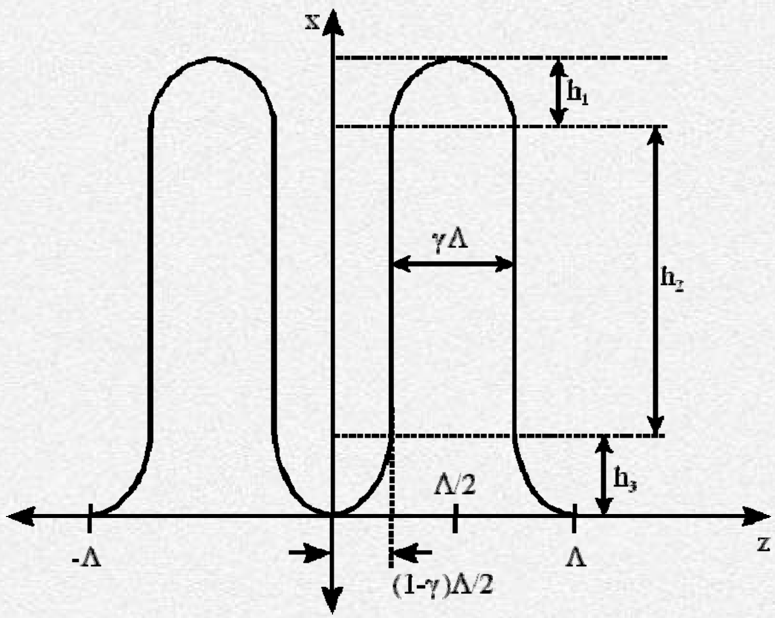
Third-order

Fourth-order

- Minimum threshold gain cavity lengths can be found (e.g. ~500 microns for 3rd order gratins) for all grating orders
- Form of threshold gain vs. duty cycle dependence is related to magnitude of effective coupling coefficient, and remains similar for all cavity lengths.

Grating tooth rounding





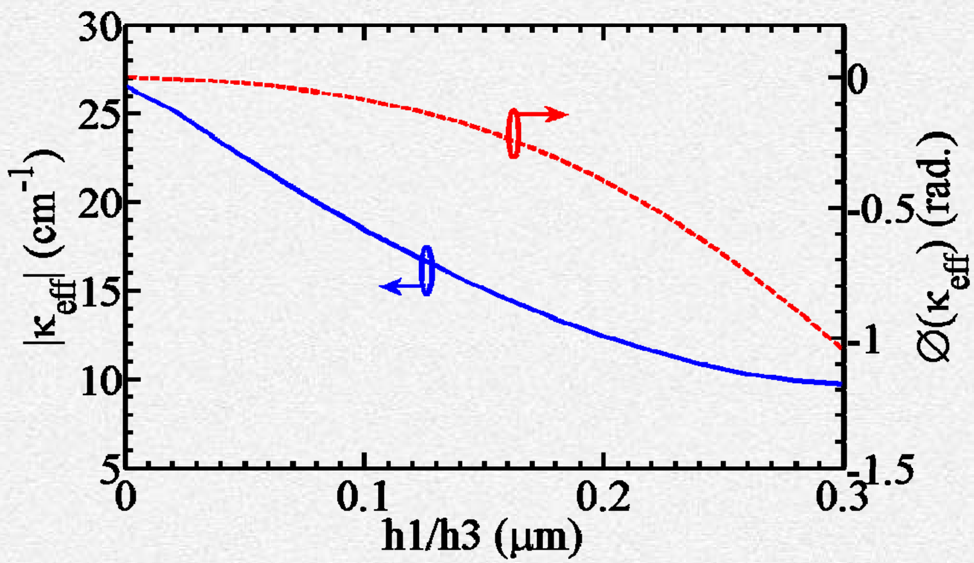
- Gratings showed significant rounding of the grating teeth during fabrication
- This can be modeled with a change of the Fourier coefficient of the grating

Grating tooth rounding

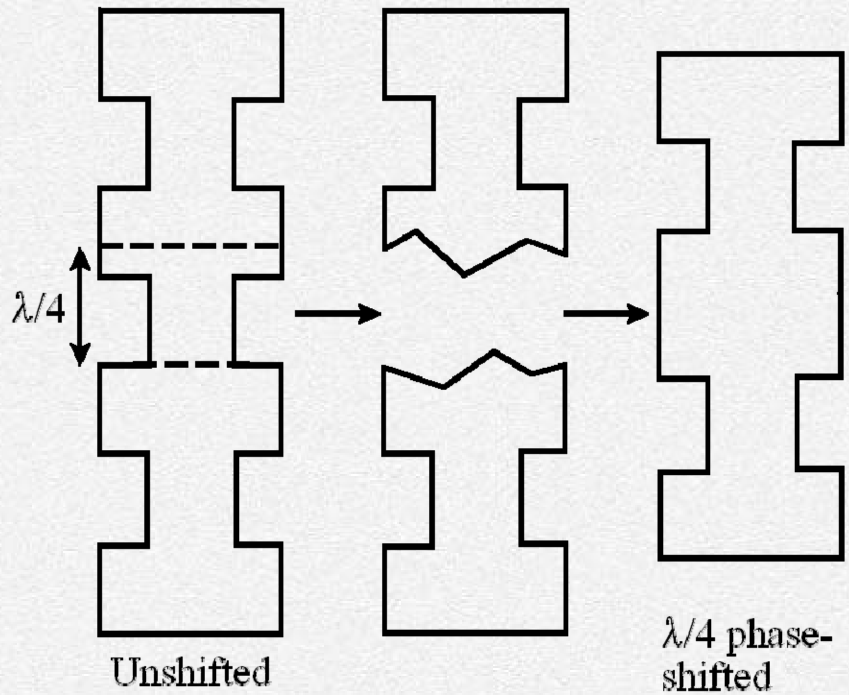
- Using Fourier coefficients of the form:

$$A_q(x) = \begin{cases} -\left(\frac{n_2^2 - n_1^2}{\pi q}\right)\sin\left[\gamma\pi q\sqrt{1-\frac{(x-h_3)^2}{h_3^2}}\right] & 0 < x < h_3 \\ -\left(\frac{n_2^2 - n_1^2}{\pi q}\right)\sin\left[\gamma\pi q\right] & h_3 \le x \le h_2 + h_3 \\ -\left(\frac{n_2^2 - n_1^2}{\pi q}\right)\sin\left[\gamma\pi q\sqrt{1-\frac{(x-h_1-h_3)^2}{h_1^2}}\right] & h_2 + h_3 < x \le h_1 + h_2 + h_3 \end{cases}$$

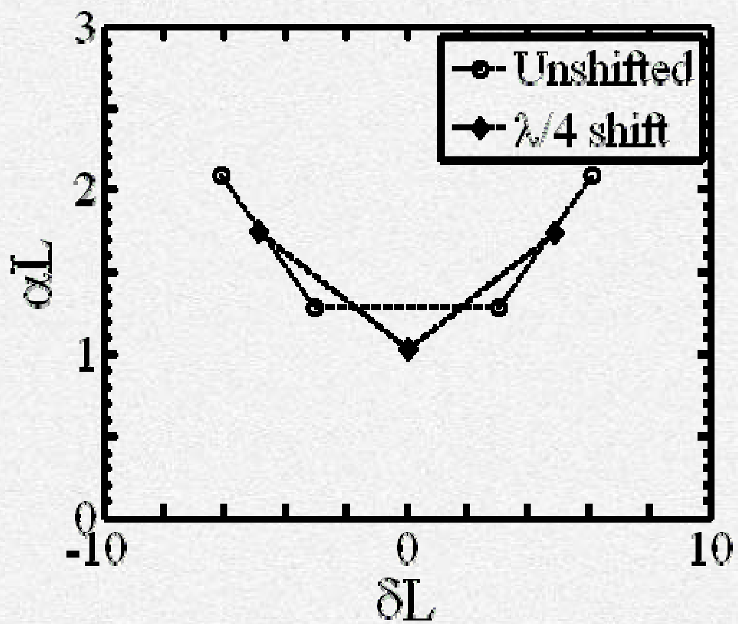
- Significant degradation of the grating strength (nearly half) is observed as the grating becomes more rounded



Effect of phase-shift



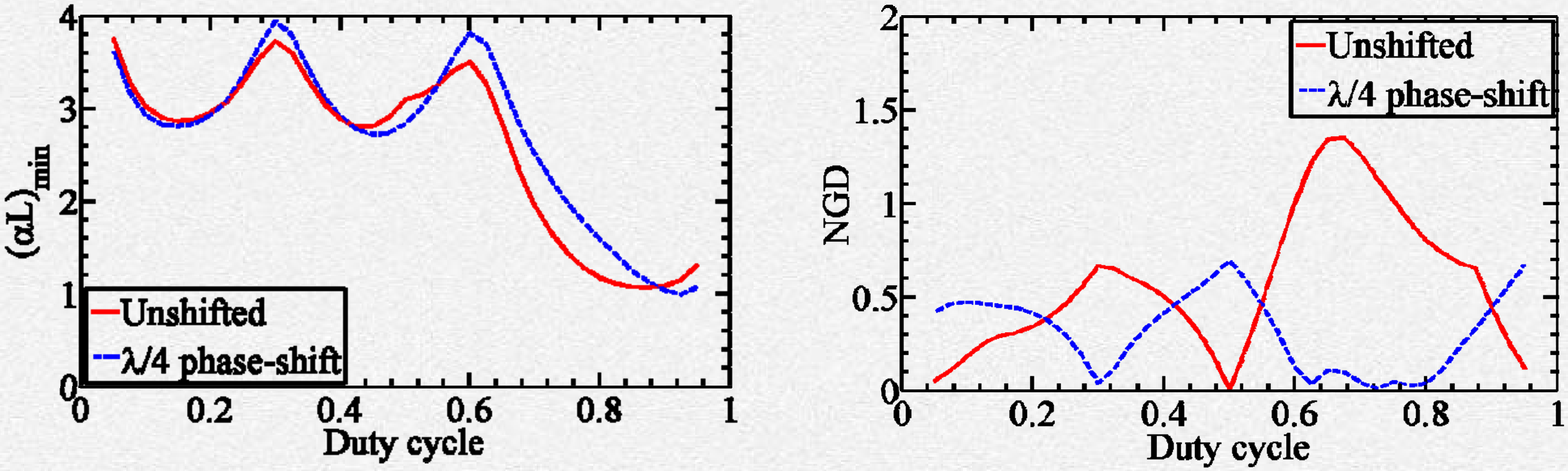
First-order grating



In first-order gratings, adding a λ/4 phase-shift will improve longitudinal mode discrimination and lower threshold gain

Effect of phase-shift

Third-order grating

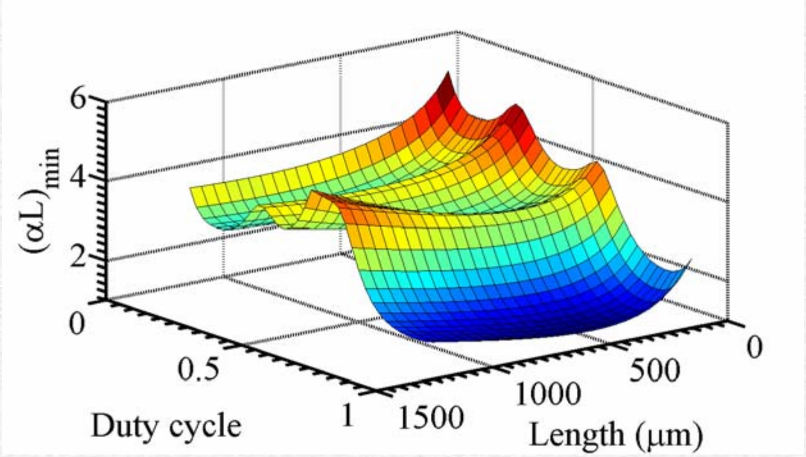


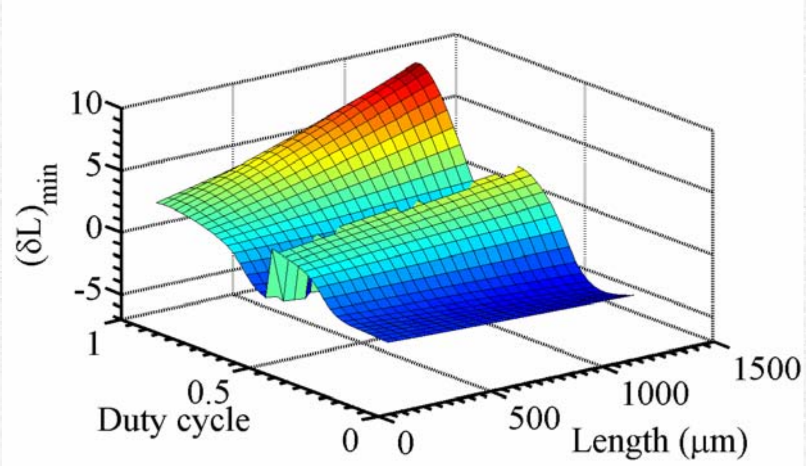
- Generally worse performance (higher threshold, lower gain discrimination) in higher order gratings when using a central λ/4 phase-shift

R. Millett, et al., Proc. SPIE, vol. 7099

Design Example

- Assuming a manufacturing process capable of third-order gratings and a duty cycle of 0.7
- Minimum threshold gain cavity length occurs at L=500 μm
- At this L, the required threshold gain is 38.6 cm^{-1}, Bragg frequency deviation is δ=3800 m^{-1} (~0.3 nm wavelength deviation)
- Using LAS2D simulation tool, this corresponds to a threshold current of ~10.9 mA





Conclusions

- LC-DFB lasers with higher order gratings can be manufactured using stepper lithography
- Laser performance and tolerances are determined by grating geometry, especially duty cycle
- Addition of a phase-shift, or rounding of the grating teeth, is generally detrimental for higher order grating performance
- Radiating partial wave effects should be included in the calculation of LC-DFB lasers with higher order gratings

Acknowledgments

Support has been provided by:

- Ontario Centres of Excellence (OCE)
- Canadian Foundation for Innovation (CFI)
- Natural Sciences and Engineering Research Council (NSERC)
- OneChip Photonics
- Canada Research Chairs Program
- CMC Microsystems
- Canadian Photonics Fabrication Centre
- Ontario Graduate Scholarship Program
- Communications Research Centre Canada