# Transverse Structure Optimization of Laterally-Coupled Ridge Waveguide DFB Lasers

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***Abstract*—A new figure of merit for single transverse mode operation and an accurate procedure for calculating the coupling coefficient in distributed feedback lasers with laterally-coupled ridge waveguide surface grating structures are introduced. Based on the difference in optical confinement between the pumped and un-pumped regions in the transverse plane, the single transverse mode figure of merit is effective and easy to calculate, while the improved coupling coefficient calculation procedure gives experimentally confirmed better results than the standard calculation approaches.**

## I. INTRODUCTION

Single transverse mode (STM) operation and accurate control of emission characteristics are important for applications ranging from optical communications to atomic clocks. Buried-grating distributed feedback (DFB) lasers have been the conventional solution. To avoid the problematic and costly overgrowth typical for those lasers, we have employed laterally-coupled ridge-waveguide (LC-RWG) surface gratings (Fig. 1), which are applicable to different materials and can be easily integrated in complex device structures.

The evaluation of STM operation and of the coupling coefficient in DFB lasers with LC-RWG surface gratings is complicated by the particularities of LC-RWG interaction with the optical field. The STM operation is determined by the transverse modal gain discrimination and by the coupling coefficient difference between transverse modes. Since the higher-order transverse modes generally have a higher coupling coefficient it is important to assess the range of LC-RWG dimensions that lead to the highest modal gain advantage for the fundamental mode. On the other hand, since high coupling coefficient values are difficult to achieve with surface gratings, the under-the-ridge confinement of the fundamental mode has to be reduced in favor of the confinement in the grating area in order to achieve a high enough coupling coefficient. The proposed simulation approaches enable the investigation of a large solution space in search of a good compromise.

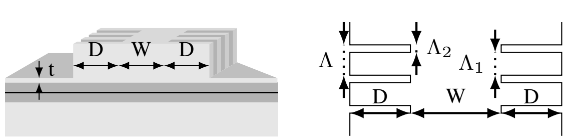


Fig. 1. Schematic 3D and top views of a LC-RWG grating.

## II. CALCULATION PROCEDURES

### A. Transverse mode discrimination

The transverse mode gain discrimination is given by the modal gain difference between the fundamental and higher-order modes. The magnitude of the modal gain $G_m$ for the m$^{\text{th}}$ transverse mode is determined by the correlation between the transverse distributions of the local material gain $g(x,y)$ in the active area $\Omega_{\text{act}}$ and the optical field intensity $\Psi_m^2(x,y)$ of the mode:

$$G_m = \frac{\iint \Psi_m^2(x,y)\cdot g(x,y)\,dx\,dy}{\iint \Psi_m^2(x,y)\,dx\,dy}. \quad (1)$$

The transverse optical field distributions in RWG and LC-RWG structures can be solved, for example by using a Mode Solver (MS) applied to the transverse refractive index distribution. For a LC-RWG grating with rectangular lateral corrugations (like in Fig. 1) the transverse refractive index distribution is obtained by longitudinally-averaging the distributions in the successive wide- and narrow-ridge grating slices:

$$n_{\text{avg}}(x,y) = \sqrt{\gamma \cdot n_{\text{wide}}^2(x,y) + (1-\gamma)\cdot n_{\text{narrow}}^2(x,y)} \quad (2)$$

where $\gamma$ is the grating filling factor ($\gamma = \Lambda_1/\Lambda$ from Fig. 1), $n_{\text{avg}}$, $n_{\text{wide}}$ and $n_{\text{narrow}}$ are the transverse distributions of the longitudinally-averaged refractive index and of the refractive index in the wide (W+2D) and narrow (W) ridge grating slices.

Since the local material gain distribution cannot be evaluated without significant computational effort, we employ an effective approximation which assumes that the local gain is constant and positive in the pumped active region under the ridge, constant and negative (i.e. absorption loss) in the un-pumped active region and zero elsewhere. This approximation assumes a step lateral distribution of the current in the active region and non-absorbing high-bandgap material outside the active region in all regions where the optical field intensity is non-negligible. Such an approximation is suited for deeply etched structures since deep etching, close to the active region, required to achieve a high coupling coefficient in LC-RWG structures, implies a limited lateral current diffusion. Also, since absorbing regions outside the active region affect the higher order modes more, the approximation is more likely to give a false negative than a false positive STM evaluation. Moreover, the lateral current diffusion can be taken into

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account by extending the pumped active region area laterally beyond the region placed strictly under the ridge and contact. With the approximation that the constant gain in the pumped area of the active region is equal with the constant absorption loss in the un-pumped area of the active region, the modal gain (1) can be simplified to $G_m = g\Gamma^{\pm}_m = g\Gamma^{+}_m - g\Gamma^{-}_m$, where $\Gamma^{+}_m$ and $\Gamma^{-}_m$ are the "under-the-ridge" and "not-under-the-ridge" optical confinement factors for the m$^{th}$ transverse mode in the pumped and un-pumped active region areas, respectively.

The modal gain discrimination condition for achieving single transverse fundamental mode operation is associated with maximizing for all m:

$$\Gamma^{\pm}_{1m} = \frac{g\Gamma^{+}_1 - g\Gamma^{+}_m}{g\Gamma^{+}_1} + \frac{g\Gamma^{-}_m - g\Gamma^{-}_1}{g\Gamma^{-}_m}. \quad (3)$$

Since $\Gamma_2$ is generally bigger than $\Gamma_4$, $\Gamma_6$, ... and $\Gamma_3$ is generally bigger than $\Gamma_5$, $\Gamma_7$, ..., the STM-operation can be evaluated by studying the normalized product of $\Gamma^{\pm}_{12}$ and $\Gamma^{\pm}_{13}$. The normalization enables the comparison between the modal gain selectivity of different structures:

$$\Gamma^{\pm}_{123} = \left(\Gamma^{\pm}_{12} \cdot \Gamma^{\pm}_{13}\right) \cdot \frac{1}{4}. \quad (4)$$

### B. LC-RWG grating coupling coefficient evaluation

An accurate evaluation of the coupling coefficient $\kappa$ is essential for designing DFB lasers. The standard formula generally used for calculating the coupling coefficient is:

$$\kappa \approx \frac{2 \cdot (n_2 - n_1)}{\lambda_0} \cdot \Gamma_g \cdot \frac{\sin(\pi m \gamma)}{m}, \quad (5)$$

where $m$ is the grating order, $n_1$ and $n_2$ are the refractive index values assumed constant in the successive low and high refractive index areas of the grating and $\Gamma_g$ is the optical confinement factor in the grating region. This standard formula is applicable only when the refractive index is transversely constant in the grating areas of the grating slices and is valid for conventional buried gratings, since the longitudinally alternating grating materials are semiconductors with refractive index values close to $n_{\text{eff}}$. However, for LC-RWG structures the formula (5) overestimates $\kappa$, because $n_1 + n_2 < 2 \cdot n_{\text{eff}}$, as one of the longitudinally alternating grating materials is a dielectric with much lower refractive index but a small influence on the grating effective refractive index. A more accurate formula for calculating $\kappa$ in LC-RWG gratings with rectangular lateral corrugations, applicable even for gratings where the refractive index varies transversely in the grating area of the slices, is [1]:

$$\kappa \approx \frac{2 \cdot (n_{\text{eff,wide}} - n_{\text{eff,narrow}})}{\lambda_0} \cdot \frac{\sin(\pi m \gamma)}{m}, \quad (6)$$

where $n_{\text{eff,wide}}$ and $n_{\text{eff,narrow}}$ are the effective refractive index values for the wide and narrow ridge grating slices. This formula includes the effective refractive index values of the grating slices, which are useful in transfer matrix calculations of the LC-RWG grating behavior.

The effective refractive index values for the wide and narrow ridge grating slices cannot be calculated directly with a MS because this would imply boundary condition violations in the longitudinal direction. A correct effective refractive index calculation procedure is to use the convolution of the transverse optical field distribution ($\Psi_{\text{avg}}(x, y)$) obtained for the longitudinally-averaged transverse refractive index distribution with the transverse refractive index distributions in the narrow and wide ridge grating slices (with 'slice' = narrow or wide):

$$n^2_{\text{eff,slice}} = \frac{\iint \Psi^2_{\text{avg}} \cdot n^2_{\text{slice}}\, dx\, dy}{\iint \Psi^2_{\text{avg}}\, dx\, dy} - \frac{\iint (\nabla \Psi_{\text{avg}})^2\, dx\, dy}{k_0^2 \cdot \iint \Psi^2_{\text{avg}}\, dx\, dy} \quad (7)$$

This corresponds also to the derivation of the coupling coefficient formula from coupled mode theory [1]–[3] since the second term on the right hand side of (7) is canceled in the effective refractive index contrast of (6).

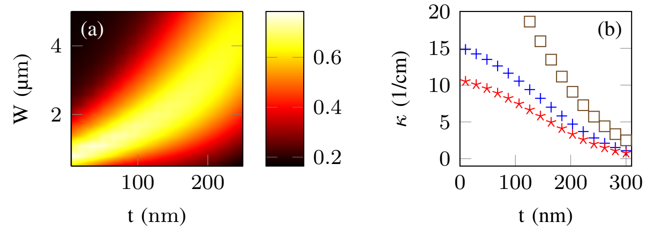


Fig. 2. Variation of (a) $\Gamma^{\pm}_{123}$ as a function of ridge width and etching depth and (b) $\kappa$ as a function of unetched cladding thickness evaluated using (5) (+), (6) and convolution (⋆), and (6) with $n_{\text{eff}}$ values for wide and narrow ridge slices obtained directly from a MS (□).

## III. Results and Conclusions

The left panel of Fig. 2 gives the variation of $\Gamma^{\pm}_{123}$ as a function of remaining un-etched cladding thickness ($t$) and central ridge width ($W$) for a 780 nm DFB laser with LC-RWG gratings having D=2.5 $\mu$m, while the right panel of Fig. 2 gives coupling coefficient calculation results obtained with different approaches for varying unetched cladding layer thickness (t). Stable STM operation has been experimentally obtained within the area with $\Gamma^{\pm}_{123} > 0.6$ for numerous RWG and LC-RWG structures, while experiments confirmed the accuracy of the grating coupling coefficient evaluation adapted for LC-RWG gratings.

The proposed STM figure of merit is easy to evaluate and gives a narrow parameter space for safe STM operation of RWG and LC-RWG structures, while the proposed coupling coefficient calculation is more accurate for LC-RWG gratings than the conventional approaches. Together they enable better and faster determination of the LC-RWG gratings structural parameters.

## References

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