Analysis of High-Order Surface Etched Gratings for Longitudinal Mode Selection in DFB Lasers

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Abstract— **A model to analyze longitudinal mode selection in high-order laterally coupled DFB lasers is developed and used to verify an ability to control the complex coupling resulting in a single-frequency lasing by manipulating the grating shape.**

Keywords – DFB laser; laterally-coupled grating; integration

I. INTRODUCTION

Photonic integration in indium phosphide (InP) is a key technology for optical components for emerging optical networks because of its potential for low cost and high reliability [1]. One integration technique that is particularly suited for this purpose is the multi-guide vertical integration (MGVI) platform, which is implemented in a single epitaxial growth process, and allows photonic integrated circuits (PICs) with multiple device functions by vertically stacking the associated optical waveguides in order of ascending their core layer's bandgap wavelength and using a lateral tapers defined at each guiding level to transition between the waveguides [2].

Although MGVI is flexible in terms of the PIC functionality, it is a challenging integration technique as it concerns to design and optimization of devices delivering these functions. Specifically, it is not at all trivial to design an on-chip laser source that would be compatible with MGVI platform and yet demonstrate a high performance. One approach that meets these criteria is based on effective ridge, laterally coupled (LC) surface etched grating distributed feedback (DFB) laser design [3], which has been successfully demonstrated both as a MGVI compatible transmitter building block [4,5] and also as a part of bidirectional transceiver PIC for access [6]. While the basic design trade-offs of this MGVI compatible on-chip laser source have been discussed previously [4-6], the fine features of its performance optimization need further analysis. Given the complexity of the LC-DFB structure, it is not possible without adequate physical models and accurate numerical simulations.

Here, a longitudinal mode selection in a LC-DFB laser – an important process that defines suitability of a laser to operate as a single-frequency source – is analyzed. First, a physical model of the LC-DFB laser featuring high-order grating with arbitrary shaped teeth is described. Then, results of numerical simulations of the single frequency lasing spectra are provided for a device featuring 3rd order LC grating. Finally, a comparison with actual spectra measured in LC-DFB lasers with surface-etched grating is discussed.

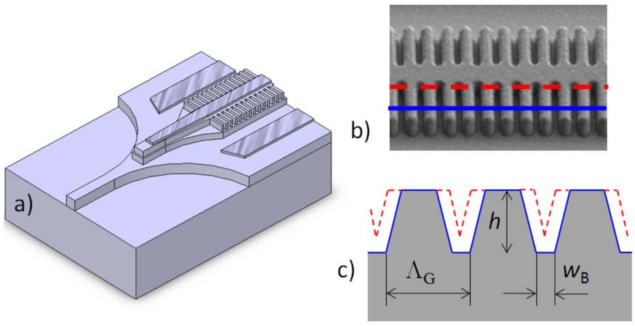

Figure 1. Schematics of a LC-DFB laser. a) a sketch of the device; b) a fragment of the surface-etched LC grating; c) LC grating profile

II. MODEL

Fig. 1 shows schematics of the LC-DFB laser and surface-etched grating, which serves both to define the lateral waveguide and provide the optical feedback to the guided mode [3]. The cross section of the LC grating has a trapezoidal profile with a duty cycle $\gamma = 1 - W_B/\Lambda_G$, where W_B and Λ_G are the grating opening at the bottom of the etch and period, respectively.

In the modeling of optical properties of a high-order grating, we follow the coupled-mode approach originally formulated by Streifer *et al* for a one dimensional grating formed in a slab waveguide [7] and then generalized to two dimensional effective-ridge waveguide by Zhong *et al* [8]. Essentially, this is a coupled mode perturbation theory, in which the mode field is decomposed into a sum of partial waves (both propagating and evanescent) which are coupled by the spatial harmonics of the grating. Accordingly, in a DFB laser with m order grating, there are $m + 1$ propagating modes, in which the 0 and m order modes are the forward and backward guided waves that propagate along the DFB cavity axis, while the modes with the orders from -1 to $1 - m$ correspond to non-guided partial waves that are radiated away from the waveguide. In a Bragg resonance case, typical for DFB lasers, radiating waves interact with the contradirectional guided waves and, in this way, partially coupled back into the laser waveguide. Since the interaction with the co-directional / contradirectional radiating waves results in an exponential decrease / increase, of the guided wave intensity, in effect, it is equivalent to additional loss / gain experienced by the guided wave. Consequently, the high-order grating acts as a complex coupled grating (even though there is no spatial modulation of either optical loss or gain), and can be described by

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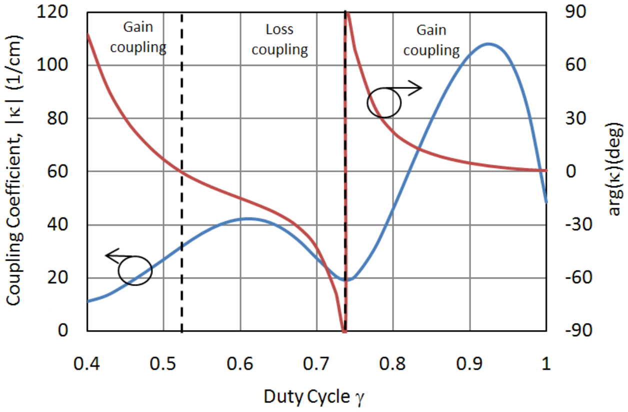

Figure 2. Complex effective coupling coefficient as a function of duty cycle for the 3rd order LC grating with $\Lambda_G \approx 0.6\mu m$ (1.3μm laser).

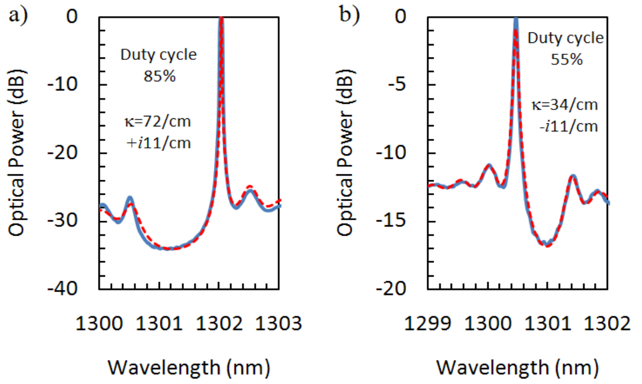

Figure 3. Sub-threshold spectra of the LC-DFB lasers featuring 3rd order gratings with different duty cycles: a) γ=0.85, b) γ =0.55. Solid line is the experiment. Dashed line is a fit by using κ numbers as shown in insets.

introducing 4 additional (to a direct index coupling coefficient κ_m) coupling coefficients, which in the case of symmetrically shaped grating are reduced to just two complex quantities, ζ_1 and ζ_2 [7]. Then, the radiation loss / gain of the guided waves is given by $2Im(\zeta_1)$, while their resonant coupling is described by the effective coupling coefficient $\kappa = |\kappa|exp(i\phi) = \kappa_m + \zeta_2$. As a result of the complex coupling, the longitudinal mode degeneracy that would occur in a uniform, pure index coupled, 1st order grating, is broken leading to natural single mode behavior [4].

An important feature of complex coupling in high-order gratings is that the sign of the imaginary part of the coupling coefficient depends on the grating shape and can be either positive or negative (partial gain and loss coupling, respectively). It is highly desirable that $Im(\kappa) > 0$ in order to improve single mode yield in coated back facet lasers [9,10]. Uniquely, high-order grating LC-DFB laser can be engineered specifically to have a positive imaginary part of the effective coupling coefficient, while providing sufficiently high coupling between the lasing mode and the grating.

A model of a LC-DFB cavity, based on Streifer's theory [7], has been developed to optimize the longitudinal mode selection by analyzing the effect of the LC grating shape on the complex effective coupling coefficient κ . It allows arbitrary shaped grating profiles so that the features like etch tilt or corner rounding can be included. Typical dependences of the real and imaginary parts of κ on a duty cycle γ , calculated for a grating profile like that shown in Fig. 1 c), are given in Fig. 2. It is seen, that for this particular structure, the LC-DFB laser is loss coupled when $0.53 < \gamma < 0.74$ and gain coupled if $\gamma > 0.74$.

III. RESULTS AND COMPARISON WITH EXPERIMENT

To verify the model described above, 3rd order LC-DFB lasers were fabricated with a structure and configuration similar to those described in [4-6] but with two different duty cycles corresponding to the loss and gain coupled regions in Fig.2. Following fabrication, the DFB lasers were cleaved into bars and antireflection coated. Subsequently, the grating complex coupling coefficient was extracted from a nonlinear least squares fit of the measured subthreshold ASE spectra, according to the procedure that is described in [11].

Typical subthreshold ASE spectra of the fabricated LC DFB lasers are shown in Fig. 3 together with the numerical fit. It is seen that the extracted complex coupling coefficients are in excellent agreement with the theoretical predictions shown in Fig.2. Moreover, the spectra clearly indicate the effect of duty cycle on the coupling coefficient: that is, when γ= 0.55 loss coupling results and DFB lases on the short side of the stopband, whereas, when γ= 0.85 the DFB becomes gain coupled and therefore lases on the long wavelength side of the stopband.

IV. CONCLUSION

In conclusion, a physical model to analyze the longitudinal mode selection in high-order LC-DFB lasers was developed and then used to optimize the grating shape in a way that insures positive imaginary part of the complex coupling coefficient and results in a "gain-coupled-like" performance. The model is verified by comparing with measurements of the 3rd order grating lasers actually designed by using this model, which suggests that the surface-etched high-order grating shape indeed is a powerful tool for optimizing LC-DFB lasers.

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