A New DFB-Laser Diode with Reduced Spatial Hole Burning

G. MORTHIER, K. DAVID, P. VANKWIKELBERGE, AND R. BAETS

Abstract—**A novel index-coupled AR-coated DFB-laser diode, which theoretically exhibits a longitudinally uniform power density is proposed. The proposed structure contains an amplitude modulated grating and is far more efficient in reducing spatial hole burning than for example multiphase-shift lasers.**

I. Introduction

IT IS well known that ordinary DFB-lasers exhibit relatively strong longitudinal spatial hole burning, i.e., a nonuniform carrier density resulting from a nonuniform power density. This nonlinearity is generally more important in lasers with a large length and/or a large coupling coefficient and limits the performance of laser diodes. It has been found both experimentally [1] and theoretically [2] that lasers can become multimode already at low or moderate power levels due to strong spatial hole burning. Moreover, longitudinal spatial hole burning in DFB-lasers can also result in a less flat FM-response [3], an increased linewidth [4], intermodulation distortion [5] (an unwanted effect in analog communication) and chirp.

For this reason, special laser structures with reduced spatial hole burning have been and are still intensely investigated. Up to now, multiple-phase-shifted lasers have been considered as the best solution to this problem [6], [7]. It was also recently pointed out that the introduction of gain coupling may lead to lasers with high threshold gain difference and a reduced spatial hole burning [8], but the fabrication of such lasers is very complicated.

It is shown in this letter that complete elimination of spatial hole burning in AR-coated DFB-lasers can theoretically be achieved by the introduction of a grating with an amplitude that varies in the longitudinal direction. The required amplitude variation can be approximated by a number of fabrication methods.

II. Theory

Index-coupled DFB-lasers can be described by the standard coupled wave equations [9]:

$$\frac{dR^+}{dz}+(j\delta-\alpha)R^+=\kappa(z)R^- \quad (1.a)$$

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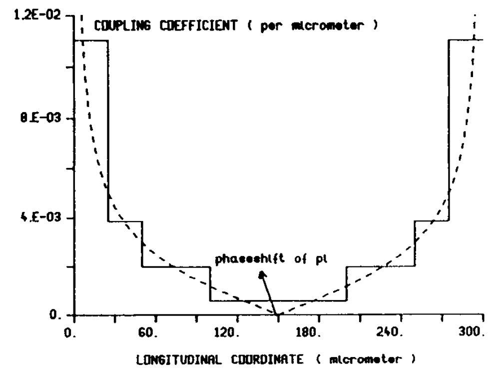

Fig. 1. Variation of the coupling coefficient resulting in a uniform power density (---) and a stepwise constant approximation (——) used for numerical calculations.

$$\frac{dR^-}{dz}-(j\delta-\alpha)R^-=\kappa^*(z)R^+ \quad (1.b)$$

in which R^+ and R^- are the slowly varying amplitudes of the forward and backward propagating fields, δ is the Bragg deviation, and α is the net amplitude gain. z is the longitudinal coordinate and the coupling coefficient κ is taken z-dependent to take into account a slow variation of the grating amplitude.

It can be easily verified that a uniform power is obtained in a perfectly AR-coated laser of length L if κ varies as

$$\kappa(z)=\frac{\left(1-2\frac{z}{L}\right)}{2\sqrt{z(L-z)}} \quad \text{with} \int_0^L \kappa(z)\,dz=1. \quad (2)$$

Lasing occurs at the Bragg wavelength in this case ($\delta = 0$) and the threshold gain α_{th} is given by

$$\alpha_{th}=1/L. \quad (3)$$

The power of forward and backward propagating waves varies linearly:

$$P^+=|R^+|^2\sim z \quad (4.a)$$

$$P^-=|R^-|^2\sim L-z \quad (4.b)$$

The function (2) is displayed in Fig. 1 for a 300 μm long DFB-laser, together with a stepwise constant approximation. We have used the laser diode simulator CLADISS [2], [3] to calculate the properties of a laser diode with this stepwise constant κ. Fig. 2 shows the longitudinal variation of the

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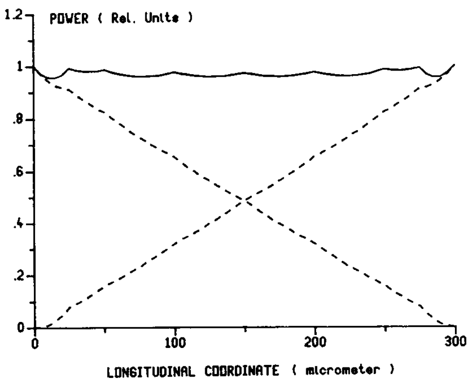

Fig. 2. Longitudinal variation of the power density for the stepwise constant coupling coefficient from Fig. 1.

power density for the approximate structure. The threshold gain difference has the value $2\Delta\alpha L = 0.34$. From this value and the uniform power, it can be expected that a large SMSR up to high power levels will result.

III. Fabrication and Approximations

The stepwise constant coupling coefficient of Fig. 1 can only be obtained if gratings are produced by e-beam lithography. Two options exist: the production of gratings with a variable amplitude and the production of gratings with a variable duty cycle. However, the variation of the coupling coefficient will in general be accompanied by a variation of the effective refractive index and of the Bragg deviation (which was assumed to be zero in II), if the last method is used.

A second approximation can be formed by the double exposure of a photoresist to form two holographic interference patterns of slightly different periods Λ_1 and Λ_2 [10], [11]. This results in a cosine variation of the coupling coefficient:

$$\kappa = \kappa_0 \cos \left[(\Lambda_1 - \Lambda_2) \frac{2\pi z}{\Lambda_1 \Lambda_2} \right] . \tag{5}$$

A linear variation can be obtained if Λ_1, Λ_2, and L are chosen appropriately, i.e., when

$$\left(\frac{L}{\Lambda_1} - \frac{L}{\Lambda_2} \right) \ll 1. \tag{6}$$

It must be noticed that the variation of the coupling coefficient will again be accompanied by an effective refractive index variation. The relation between the longitudinal variation of the coupling constant and that of the effective refractive index depends on the lithography and etching process. One possible structure is shown in Fig. 3, in which case the effective index variation can be estimated as

$$\Delta n_e(z) = 0.5\kappa(z). \tag{7}$$

The case of a linearly varying coupling coefficient, accompanied by a linear refractive index variation has been modelled numerically for a 300 μm long DFB-laser. The linear variations have been approximated by stepwise constant functions and the value of κ_0 has been optimised for minimum spatial hole burning. The longitudinal variation of the power for the optimised value $\kappa_0 L = 2.25$ is shown in Fig. 4. The power variations are still restricted to about 10% and the threshold gain difference is $2\Delta\alpha L = 0.14$, so that a good mode discrimination can be expected. The reduction of $2\Delta\alpha L$ is found to be mainly due to the effective index variation.

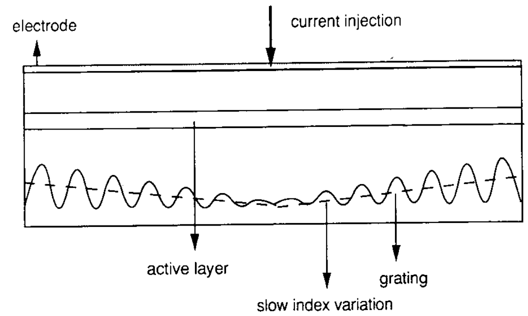

Fig. 3. Grating with a nonuniform amplitude, obtained by the double exposure of a photoresist to form two holographic interference patterns of slightly different periods Λ_1 and Λ_2.

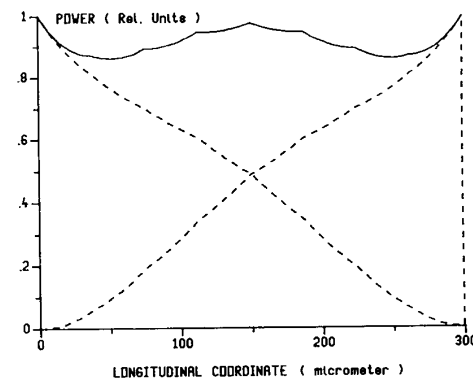

Fig. 4. Longitudinal variation of the power for the case of a linearly varying coupling coefficient, where an additional refractive index variation is taken into account.

IV. Conclusion

It has been shown how a longitudinally uniform power density in AR-coated index-coupled DFB-lasers can theoretically be obtained by a longitudinal variation of the coupling coefficient. A few practical implementations, which still exhibit very little spatial hole burning (less than, e.g., multiphase-shifted DFB-lasers) and a large threshold gain difference, have been discussed. A restriction of the longitudinal power variation to a few percent can be obtained for gratings produced by e-beam lithography.

Such lasers can be expected to be single mode up to high power levels. They can be of interest when long lasers with a reduced linewidth and a flat FM-response are to be used or as lasers with small modulation distortion in analog communication.

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References

[1] H. Soda, Y. Kotaki, H. Sudo, H. Ishikawa, and S. Yamakoshi, "Stability in single longitudinal mode operation in GaInAsP/InP phase-adjusted DFB-laser," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 804-814, 1987.

[2] P. Vankwikelberge, G. Morthier, and R. Baets, "CLADISS, a longitudinal, multimode model for the analysis of the static, dynamic and stochastic behavior of diode lasers with distributed feedback," to be published.

[3] P. Vankwikelberge, F. Buytaert, A. Franchois, R. Baets, P. Kuindersma, and C. Frederiksz, "Analysis of the carrier induced FM response of DFB lasers: Theoretical and experimental case studies," *IEEE J. Quantum Electron.*, vol. QE-25, pp. 2239-2254, 1989.

[4] G. Morthier, P. Vankwikelberge, F. Buytaert, R. Baets, and P. Lagasse, "Linewidth of single mode DFB lasers in the presence of spatial and spectral hole burning," in *Proc. European Conf. Opt. Commun.-ECOC'89*, Sweden, Gothenburg, 1989.

[5] A. Takemoto, H. Watanabe, Y. Nkajima, Y. Sakakibara, S. Kakimoto, H. Namizaki, J. Yamashita, T. Hatta, and Y. Miyake, "Low harmonic distortion distributed feedback laser diode and module for CATV systems," *Tech. Dig. OFC,* 1990, p. 214.

[6] G. Agrawal and A. Bobeck, "Modelling of distributed feedback semiconductor lasers with axially varying parameters," *IEEE J. Quantum Electron.*, vol. QE-24, pp. 2407-2414, 1988.

[7] T. Kimura and A. Sugimura, "Linewidth reduction by coupled phase shift distributed feedback laser, *Electron. Lett.*, vol. 23, pp. 1014-1015, 1987.

[8] G. Morthier, P. Vankwikelberge, K. David, and R. Baets, "Improved performance of AR-coated DFB-lasers by the introduction of gain coupling," *IEEE Phot. Tech. Lett.*, pp. 170-172, Mar. 1990.

[9] H. Kogelnik and C. V. Shank, "Coupled-wave theory of distributed feedback lasers," *J. Appl. Phys.*, vol. 43, pp. 2327-2335, 1972.

[10] G. Heise, R. Matx, and U. Wolff, "Phase-shifted holographic gratings for distributed feedback lasers," *SPIE,* vol. 651, 1986.

[11] D. C. J. Reid, C. M. Ragdale, I. Bennion, D. J. Robbins, J. Buus and W. J. Steward, "Moiré Fibre Grating Resonators," *MOC/GRIN '89, PD5,* Tokyo, Japan, 1989, pp. 19-22.