Improved Performance of AR-Coated DFB Lasers by the Introduction of Gain Coupling

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Abstract—**AR-coated DFB lasers with both gain- and index-coupled distributed feedback are studied numerically with respect to mode losses, mode suppression, and spatial hole burning. The mode losses and the spatial hole burning decrease with increasing gain coupling, while the mode suppression increases. It is shown that a large improvement in performance can already be obtained for small fractions of gain coupling.**

I. Introduction

OPTICAL communication systems require DFB laser diodes with a low linewidth and a stable single-mode behavior. A stable single-mode behavior is generally achieved by the use of cleaved facets, with their associated yield problem, or by single or multiple phase shifts [1], in which case, however, relatively high reflection losses and therefore relatively high linewidths result. Reduction of the losses can be obtained by increasing the laser length, but in many cases the longitudinal nonuniformity in power (spatial hole burning) then causes the laser to become multimode at relatively low power levels.

In this paper, we show that AR-coated DFB lasers without phase shifts can result in low losses, minor longitudinal spatial hole burning, and a large threshold gain difference if gain-coupled distributed feedback is introduced. The results are obtained directly by solving the coupled wave equations. Both the threshold behavior and the above threshold behavior (including spatial hole burning) have been analyzed. A large improvement in performance can already be obtained when the gain coupling is only a few tenths of the index coupling, for which a stable single-mode behavior up to power levels of 50 mW and more is theoretically found.

A general analysis of the effects of complex coupling coefficients on distributed feedback lasers has been given earlier by Kapon [2], who has calculated the threshold characteristics of AR-coated DFB lasers for several values of the normalized coupling coefficient and for varying relative gain coupling. In this paper, the normalized coupling coefficients are optimized for low spatial hole burning and above threshold calculations, taking into account the spatial hole burning, are included to describe the single-mode stability.

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It must be noted that weak gain coupling may often be present in common index-coupled DFB lasers, where the grating in the passive layer modifies the lateral/transverse mode profile and the confinement factor. Above threshold, the cavity standing waves cause a periodic variation of the carrier density, which also results in weak gain coupling. It can be estimated, however, that the gain coupling induced by both effects is less than a percent of the index coupling in a common index-coupled DFB laser. However, DFB lasers with considerably larger gain coupling have already been produced [3] and were reported to have good single-mode properties.

II. Modeling Results

DFB lasers with both index and gain coupling can be described by the set of coupled wave equations [4]:

$$\frac{dR^+}{dz} + (j\delta - \alpha)R^+ = (\kappa_g + j\kappa_n)R^-$$

$$\frac{dR^-}{dz} - (j\delta - \alpha)R^- = -(\kappa_g + j\kappa_n)R^+$$

where R^+ and R^- represent the (complex) amplitudes of the forward and backward propagating waves. $\alpha = 0.5g$ with g being the threshold gain and δ is the Bragg deviation:

$$\delta = 2\pi n_e/\lambda - \pi/\Lambda$$

with Λ being the grating period, n_e the effective refractive index (without the grating being taken into account), and λ the wavelength of the longitudinal mode. The coupling constants κ_g, resp., κ_n represent the gain, resp., the index coupling. The phases of κ_g and κ_n are assumed here to be equal. This is justified for the case where gain and index coupling are caused by one grating (e.g., a modulation of the active layer thickness), where the phase difference between κ_g and κ_n can only take the values 0 or π. It can further be noticed that a phase difference of π between κ_g and κ_n would only cause a change of the sign of the Bragg deviation of the lasing mode. The grating phase at the left facet (which is the origin of the longitudinal axis) is chosen such that κ_g and κ_n are real. Because the facets are AR-coated, this can be done without loss of generality.

The boundary conditions at the AR-coated facets are (L is the laser length):

$$R^+(0) = 0 = R^-(L).$$

We have calculated the threshold gain g, the threshold gain

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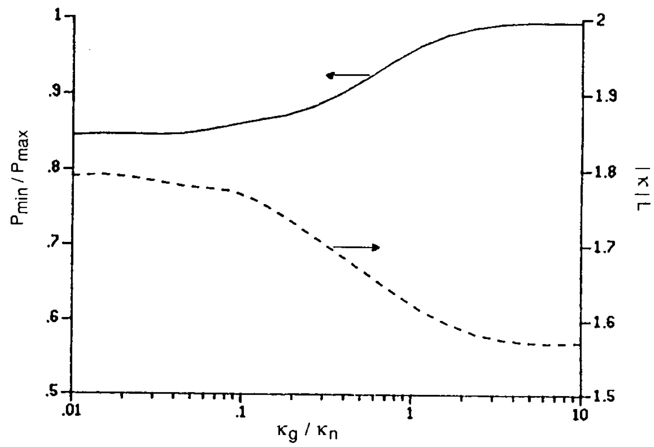


Fig. 1. Optimum value of $P_{\min}/P_{\max}$ (——) and $|\kappa|L$ (- - -) as a function of κ_g/κ_n.

difference ΔgL, the Bragg deviation δ, and the longitudinal spatial hole burning of AR-coated DFB lasers of length 300 μm as a function of the ratio κ_g/κ_n. The value of $|\kappa|$ is chosen so as to obtain minimum spatial hole burning. As a measure for the spatial hole burning, we consider the ratio $P_{\min}/P_{\max}$, with $P_{\min(\max)}$ being the minimum (maximum) value of the power along the longitudinal axis. Above threshold, the power level P_m where the static side-mode suppression (SMSR) drops to below 20 dB has been calculated. Both ΔgL and the spatial hole burning have influence on this power level, and a new longitudinal, multimode model for the analysis of DFB lasers [5], where spatial hole burning is self-consistently taken into account, has been used for this.

Fig. 1 shows the value of $|\kappa|L$ that gives minimum spatial hole burning and the corresponding value of $P_{\min}/P_{\max}$. Little spatial hole burning is obtained in all cases and one can see that the spatial hole burning is completely eliminated for pure gain coupling. $|\kappa|L$ equals the value $\pi/2$ in this case and both g and δ are zero. It can easily be verified that the solution of the coupled wave equations in this case reduces to

$$R^+(z) = \sin(\pi z/2L);\; R^-(z) = \cos(\pi z/2L).$$

The longitudinal variation of forward and backward propagating power, as well as the total power, is depicted in Fig. 2 for three values of κ_g/κ_n (10^{-2}, 0.5, and 10). A relatively uniform power also results for the case of weak gain coupling or almost pure index coupling. The low threshold gain difference in this case makes such a laser unattractive however. As κ_g increases, both R^+ and R^- become more sinusoidal and the power becomes more uniform.

Fig. 3(a) shows the variation of g and δ as a function of κ_g/κ_n. The threshold gain and the Bragg deviation, as well as the spatial hole burning, are slowly decreasing functions of the gain coupling for small values of κ_g/κ_n, but they rapidly approach zero if the gain coupling becomes larger than the index coupling. The threshold gain difference ΔgL [Fig. 3(b)] on the other hand increases considerably for a small fraction of gain coupling. The output power P_m [the dashed curve on Fig. 3(b)] where the SMSR drops below 20 dB also increases rapidly for increasing gain coupling. E.g. for $\kappa_g/\kappa_n = 0.05$

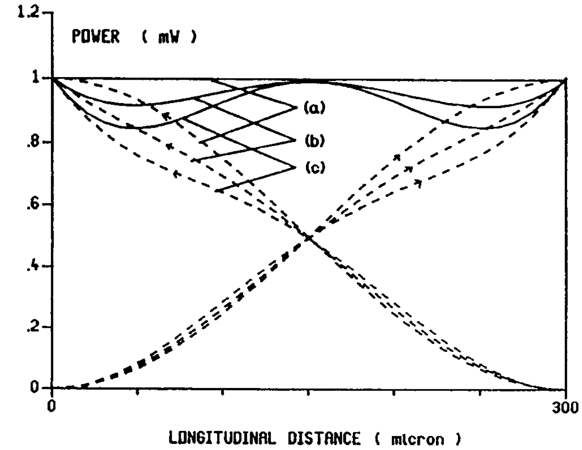


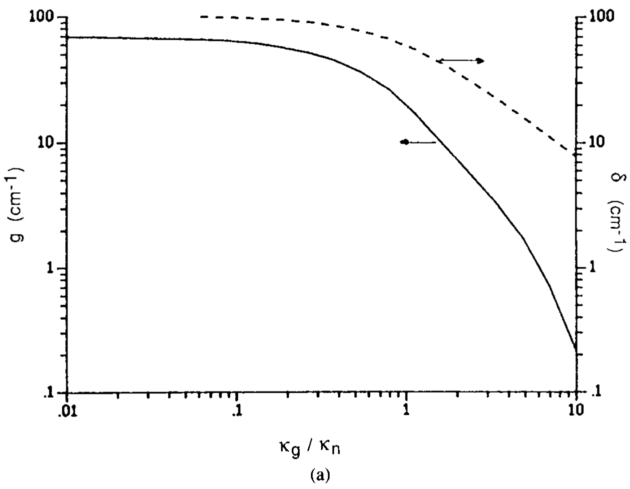
Fig. 2. Longitudinal variation of forward and backward propagating power (- -) and of the total power (__) for $\kappa_g/\kappa_n = 10$ (a), 0.5 (b), and 0.01 (c).

we obtained a genuine single-mode behavior (SMSR > 30 dB) up to an output power level of more than 50 mW.

Due to the gain coupling, the phase resonances occur no longer at wavelengths that are symmetric with respect to the Bragg wavelength (as in index coupled AR-coated DFB lasers). At the same time, a larger effective gain is provided for the cavity mode nearest to the Bragg wavelength. The last effect can be understood from the presence of a standing wave pattern, both in the power of the cavity modes (with a period $\lambda/2n_e$) and in the gain (period Λ). The overlap of both standing wave patterns, which describes the degree of coincidence between points with high gain and points of large optical power, increases for a decreasing difference between mode wavelength and Bragg wavelength. This results in a larger net-to stimulated emission rate. The asymmetry in the phase resonance can be seen from the resonance condition, which is easily derived from the coupled wave equations:

$$e^{2SL} = -\frac{S + \alpha - j\delta}{S - \alpha + j\delta}$$

with $S^2 = (\alpha - j\delta)^2 - (\kappa_g + j\kappa_n)^2$.



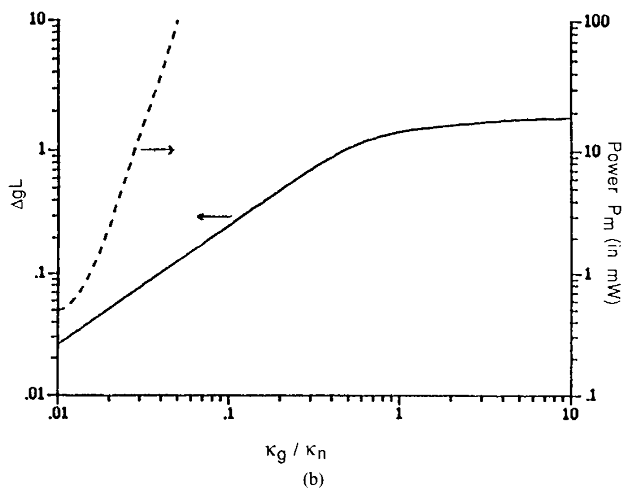


Fig. 3. (a) Variation of g (——) and δ (- - -) with κ_g/κ_n. (b) Variation of ΔgL (——) and of the power P_m (- - -), where multimode operation starts, with κ_g/κ_n.

E.g. in the high gain approximation, $|\alpha - j\delta| \gg |\kappa_g + j\kappa_n|(\kappa_g/\kappa_n < 1)$, one finds the phase resonance condition:

$$\left\{\delta + \frac{[2\kappa_g\kappa_n\alpha + \delta(\kappa_g^2 - \kappa_n^2)]}{2(\delta^2 + \alpha^2)}\right\} L = tg^{-1}(\delta/\alpha) + tg^{-1}(\kappa_n/\kappa_g) + m\pi.$$

From this equation, it can easily be verified that the phase resonances are symmetric with respect to the Bragg wavelength only for $\kappa_g = 0$ or $\kappa_n = 0$.

The calculations shown here are only valid for an optimized value of $|\kappa|L$. In practical implementations, however, the gain coupling and thus $|\kappa|L$ generally will depend on the threshold gain. Such a dependence is not taken into account in our calculations. For values of κ_g not larger than a few tenths of κ_n, there is no influence of κ_g on $|\kappa|L$ and the optimum value depends on the choice of κ_n only. The threshold gain and Bragg deviation remain almost independent of κ_g in this case, and practically, κ_g can be calculated from the threshold gain of the corresponding index-coupled laser. It is interesting to compare the values of g (60 cm^{-1}), ΔgL (0.5), and P_{min}/P_{max} (0.875) that can be obtained in this case ($\kappa_g/\kappa_n = 0.2$) to the corresponding values of a $\lambda/4$-shifted index coupled laser (with $\kappa L = 1.25$): $g = 80$ cm^{-1}, $\Delta gL = 0.7$, and $P_{min}/P_{max} = 0.7$. The introduction of a $\lambda/4$-shift in gain-coupled DFB lasers is found to be disadvantageous. For small values of κ_g/κ_n (≤ 0.1), an increase in threshold gain difference can result, but at the same time an increased spatial hole burning is present. For larger values of κ_g/κ_n, both a decreased threshold gain difference and a increased spatial hole burning result from the introduction of a $\lambda/4$-shift. The presence of $\lambda/4$-shift causes a degeneracy in the spectrum of DFB lasers with strong gain coupling.

Complete elimination of spatial hole burning and zero losses can be obtained when strong gain coupling is introduced. The optimum value of $|\kappa|L$ then strongly depends on κ_g and on the threshold gain (which itself again depends on κ_g) and careful design is required in this case.

Finally, it must be noted that perfect AR-coating has been assumed here, whereas more realistic values for the facet reflection coefficients are of the order of magnitude of 10^{-3}. Our calculations indicate that only a variation of 5% from the results shown here can be expected in this case, and therefore all conclusions still hold.

III. Conclusion

It has been shown that DFB-lasers where both gain and index coupling are present are promising devices from a theoretical point of view. A low threshold gain, a large threshold gain difference, and a reduced spatial hole burning result at the same time when the fraction of gain coupling is increased. For values of κ_g/κ_n more than about 5%, a stable single-mode operation up to an output power level of more than 50 mW results for a laser length of 300 μm. Because of the low spatial hole burning, this stable single-mode operation can also be expected for longer lasers (e.g., with length ~1000 μm). Such lasers would therefore combine low linewidth with stable single-mode behavior and no facet-related yield problem.

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