Basic Analysis of AR-Coated, Partly Gain-Coupled DFB Lasers: The Standing Wave Effect

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***Abstract*—A theoretical analysis of DFB lasers with mixed gain and index coupling (partly gain-coupled DFB) is given for perfect antireflection (AR) coatings. Analytical expressions for the threshold gain, facet loss, and the relative depth of the standing wave pattern are derived. At the same time the importance of the standing wave effect and its consideration by the coupled mode equations are shown. For purely gain-coupled DFB lasers, simple expressions for the effective linewidth enhancement factor and the longitudinal spontaneous emission factor are derived. In addition, various approximations, describing the performance of purely gain-coupled DFB lasers, are given.**

I. Introduction

In "ordinary," i.e., index-coupled DFB lasers, the feedback necessary for laser operation is provided by reflections at periodic refractive index variations along the laser cavity. If periodic gain variations are responsible for this feedback a gain-coupled DFB laser is obtained. These gain-coupled DFB lasers have recently received considerable experimental [1]–[3] and theoretical [4]–[6] attention, the reason being some remarkable properties. As Kogelnik and Shank [7] (hereafter denoted as KS) already showed, the degeneracy problem of AR-coated index-coupled DFB lasers is lifted by the introduction of pure gain coupling and one finds the lasing mode exactly at the Bragg frequency. For a special value of κ_{gain} (gain-coupling coefficient), one gets a perfectly flat longitudinal, optical power density [8] (no longitudinal spatial hole burning). In devices with mixed index and gain coupling (hereafter called partly gain-coupled DFB lasers), a significant improvement in terms of reduced spatial hole burning and increased threshold gain difference as compared with index-coupled DFB lasers is still reported [8], [9]. This allows large side-mode suppression ratios up to large output powers. Even for imperfect antireflection (AR) coatings and cleaved facets, relevant improvements of the threshold gain difference [3], [10], [11] and even the spatial hole burning [4], [6] are found. This shows that AR coatings are not indispensable for gain-coupled DFB lasers. In addition, first experimental [2] and theoretical [4] results show a potential for lower feedback sensitivity compared with other DFB lasers. Finally, low linewidth has been found, both experimentally [3] and theoretically [13].

Purely index or gain-coupled, perfectly AR-coated DFB lasers have already been studied theoretically by KS and some important results will be summarized in Section II. Kapon *et al.* [9] numerically extended this investigation to partly gain-coupled DFB lasers. They presented results for the threshold gain, Bragg deviation, and longitudinal optical power density. In both papers a negative threshold gain was found for sufficiently large κ_{gain} values. First analytical and physical explanations for this fact can be found in [5] and [6], respectively, and are extended here.

It is more difficult to understand the properties of gain-coupled and partly gain-coupled devices because the standing wave pattern, formed by the forward and backward traveling waves, "sees" a different gain in the presence of a gain grating than would a simple traveling wave. To our knowledge very few analytical expressions that ease this understanding have been presented in literature for the properties of such a laser.

This paper presents analytical expressions for partly gain-coupled DFB lasers with AR-coated facets and gives a physical explanation for these expressions. The paper is organized as follows. In Section II we summarize some results from KS. We analytically derive the standing wave effect, which can explain a negative threshold gain, in Section III. In Section IV we study purely gain-coupled DFB lasers. Simple expressions for the longitudinal spontaneous emission factor and the effective linewidth enhancement factor are derived. In addition, approximations relating important device characteristics to the gain-coupling coefficient are given. We give numerical results for the partly gain-coupled DFB laser in Section V. A brief summary is given in Section VI.

II. Summary of Coupled-Mode Solutions from KS

For the reader's convenience, and to establish our notation, we briefly summarize some results of KS [7] that are relevant for our further analysis. Starting from the scalar wave equation and using small-gain and perturbation assumptions, the following coupled-mode equations were

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given by KS:

$$-\frac{dR(z)}{dz} + (\alpha - j\delta)R(z) = j\kappa_{RS}S(z)$$
$$\frac{dS(z)}{dz} + (\alpha - j\delta)S(z) = j\kappa_{SR}R(z) \quad (1)$$

where $R(z)$ is the complex mode amplitude of the wave traveling to the right and $S(z)$ to the left. κ_{RS} and κ_{SR} are the coupling coefficients, α is the threshold gain for the field, and $\delta(\delta = \beta - \beta_0)$ gives the Bragg deviation. β and β_0 are the mode and Bragg-propagation constants, respectively. For perfect AR coatings symmetry arguments can be used to find the general solution of (1):

$$R(z) = \sinh \gamma \left(z + \tfrac{1}{2} L\right) \quad (2)$$

$$-S(z) = \pm\sinh \gamma \left(z - \tfrac{1}{2} L\right) \quad (3)$$

where L is the length of the laser cavity and the complex propagation constant $\gamma = \gamma' + j\gamma''$ is obeying the dispersion relation

$$\gamma^2 = \kappa^2 + (\alpha - j\delta)^2 \quad (4)$$

where $\kappa^2 \equiv \kappa_{RS}\kappa_{SR}$. γ is the solution of the eigenvalue equation

$$\kappa = \pm j\gamma/\sinh \gamma L \quad (5)$$

and the resulting threshold gain α and Bragg deviation δ are found from

$$-\alpha + j\delta = \pm j\kappa \cosh \gamma L = -\gamma \coth \gamma L. \quad (6)$$

Numerical results for α, δ, and the optical power density are then discussed by KS and for the mixed cases by Kapon *et al.* [9]. Note that (3) and (6) have additional minus signs in comparison to the equations in KS. The physical meaning of this and the sign ambiguity will be discussed in Section IV.

The preceding analysis, as our investigations further on show, are correct at threshold. However, in partly gain-coupled DFB lasers longitudinal spatial burning is low [6], [8] and the performance above threshold should be similar and not considerably changed as in $\lambda/4$-shifted DFB lasers, for example.

III. The Standing Wave Effect

From the coupled-mode equations (1) the rate of the net power flux change can be derived as being proportional to

$$\frac{d}{dz}(RR^* - SS^*) = 2\alpha(RR^* + SS^*) + 2\,\mathrm{Im}\,\{SR^*(\kappa_{RS} - \kappa_{SR}^*)\}. \quad (7)$$

Equation (7) was given by Kapon *et al.* [9]. They interpreted the first term on the right-hand side as the total power change experienced by each mode due to the gain along the cavity and the second term as the power change due to coupling. Because of power conservation it follows [9], for a pure index grating, that

$$\kappa_{RS} = \kappa_{SR}^* \quad (8)$$

and for a pure gain grating

$$\kappa_{RS} = -\kappa_{SR}^*. \quad (9)$$

In Appendix A we show that for most partly gain-coupled DFB lasers κ_{SR} and κ_{RS} can be written as

$$\kappa_{SR} = \kappa_{RS} = \kappa_{\text{index}} + j\kappa_{\text{gain}} \quad (10)$$

with κ_{index} and κ_{gain} being real numbers describing the coupling strength of the index and gain grating, respectively. This is the case for a situation where the index and gain grating are both caused by the same geometric grating. This situation was also considered in KS.

A deeper understanding of partly gain-coupled DFB lasers is derived now. The units of $R(z)$ and $S(z)$ are chosen in such a way that the total photon number in the cavity P_{tot} is given as

$$P_{\text{tot}} = \int_{-L/2}^{L/2} (RR^* + SS^*)\, dz. \quad (11)$$

In the laser cavity two counterpropagating waves exist, forming a standing wave pattern (for the electric field and its intensity). The relative depth of the standing wave pattern, denoted as $\mathbf{f}_{\text{st}}$ hereafter, can be written as

$$\mathbf{f}_{\text{st}} = \frac{\mathrm{Re}\left\{2 \int_{-L/2}^{L/2} RS^*\, dz\right\}}{P_{\text{tot}}}. \quad (12)$$

In a DFB laser the counterpropagating waves have, in general, different electric field amplitudes and therefore $\mathbf{f}_{\text{st}}$ is smaller than 1. The photon loss per facet $\alpha_{\text{end}}L$ can be calculated from the photon flux at the facet divided by the total photon number in the cavity. Integrating (7) over the cavity length L, dividing by P_{tot}, and using (10), (11), and (12) gives

$$2\alpha L = 2\alpha_{\text{end}}L - 2\kappa_{\text{gain}}L\mathbf{f}_{\text{st}}. \quad (13)$$

Equation (13) is valid for partly gain-coupled DFB lasers and is one important result of this paper. An intuitive reasoning [6] about a basic mechanism in partly gain-coupled DFB lasers is as follows. The consideration of the interaction between the standing wave along the laser cavity and the periodic variation of the gain—the standing wave effect—is essential. This effect "enhances" the gain because the standing wave pattern has maxima at the points of high gain and minima at the points of low gain, see Fig. 1(a) and Section IV. This explains why the required threshold gain for a traveling wave ($2\alpha L$) can be lower than the facet loss ($2\alpha_{\text{end}}L$) in the cavity and even be negative. This reasoning is analytically expressed by (13). It can easily be seen that this standing wave effect is not present in purely index-coupled DFB lasers because, for this case, $\kappa_{\text{gain}} = 0$. α_{end} is always positive and therefore the threshold gain has to be positive in this laser.

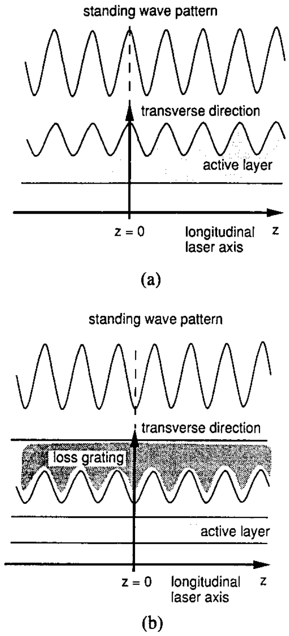

Fig. 1. Schematic drawing showing the standing wave effect. (a) For a gain grating. (b) For a loss grating.

It is a known fact [6], [7], [9] that gain-coupled DFB lasers have significantly larger threshold gain differences than index-coupled DFB lasers. This can partly be described by the standing wave effect: The side modes have a different field distribution than the lasing mode and hence they do not "profit" as effectively as the lasing mode from the periodic gain variation. This effect, not present in index-coupled DFB lasers, gives rise to an extra threshold gain difference.

It is useful to mention that a similar standing wave effect as described above has been recognized to be important in vertical surface-emitting lasers with several quantum well active layers spaced by half a wavelength. In this device the feedback provided by the periodic gain is very weak, however [12].

When we use (2) and (3) for the mode amplitudes R and S the results for P_{tot}, $\mathbf{f}_{st}$, and $\alpha_{end}L$ can be given analytically:

$$P_{tot} = \frac{\sinh 2\gamma' L}{2\gamma' L} - \frac{\sin 2\gamma'' L}{2\gamma'' L} \tag{14}$$

$$\mathbf{f}_{st} = \frac{\frac{1}{\gamma'' L}\cosh \gamma' L \sin \gamma'' L - \frac{1}{\gamma' L}\sinh \gamma' L \cos \gamma'' L}{\frac{\sinh 2\gamma' L}{2\gamma' L} - \frac{\sin 2\gamma'' L}{2\gamma'' L}} \tag{15}$$

$$\alpha_{end}L = \frac{\sinh^2 \gamma' L + \sin^2 \gamma'' L}{\frac{\sinh 2\gamma' L}{2\gamma' L} - \frac{\sin 2\gamma'' L}{2\gamma'' L}}. \tag{16}$$

Equations (14) and (16) are equal to (10) and (14) in [14], respectively. Before we proceed with the study of partly gain-coupled DFB lasers, we first look at purely gain-coupled DFB lasers because of the simplicity of the results for this case.

IV. Purely Gain-Coupled DFB Lasers

Basically, two possibilities exist for realizing gain coupling, i.e., a periodic gain variation along the laser cavity: a periodic gain or a periodic loss variation. Both gratings have been realized experimentally [15], [3], [10]. We will now show the relation between these two grating types and the sign ambiguity in (3), (5), and (6). We assume a sinusoidal first-order gain grating, which is similar to the situation discussed by KS. The field gain $g(z)$ is then given as ((2) in KS):

$$g(z) = \alpha \pm 2\kappa_{gain} \cos 2\beta_0 z. \tag{17}$$

Fig. 1(a) sketches the standing wave pattern and the gain grating for the positive sign of all equations with a sign ambiguity. For this case $S(z) = -R(-z)$, which represents the symmetric solution. The maximum overlap between gain and optical power can clearly be seen. A periodic loss variation corresponds to considering the minus sign (shown in Fig. 1(b)). Now the periodic losses and the standing wave pattern show minimal overlap. This interpretation shows that the sign ambiguity in (3), (5), (6), and (17) expresses a physical meaning and not merely a mathematical symmetry.

Besides this sign difference there is another difference between gain and loss gratings: how the internal losses have to be changed as a function of the gain-coupling coefficient [16]. This adaptation of the internal losses also gives the mathematical link if the complex part of the coupling coefficient is caused by radiation losses of DFB lasers with a second-order index grating [13].

From (6) it follows directly that for purely gain-coupled DFB lasers the Bragg deviation becomes zero for all nonzero κ_{gain} values. In addition, it can easily be verified that the complex eigenvalue γ is either purely imaginary or real, i.e., $\gamma'' L = 0$ for $\kappa_{gain}L < 1$ and $\gamma' L = 0$ for $\kappa_{gain}L > 0$. For $\kappa_{gain}L = 1$ the eigenvalue γL equals zero and the mode amplitudes become linear functions of z. $|\gamma L|$ as a function of $\kappa_{gain}L$ can be seen in Fig. 2. Using the fact that γL is either purely imaginary or real, it is simple to prove (13) by direct substitution of (6), (15), and (16). For a periodic gain variation, a gain grating, the coupling coefficient $\kappa_{gain}L$ depends on the carrier density [6], [16]. Note that for this case the coupling strength at the transition of real to imaginary γL values $\kappa_{gain}L = 1$ represents the largest possible $\kappa_{gain}L$ value if all losses in the laser are zero [16].

The relative depth of the standing wave pattern $\mathbf{f}_{st}$, as given by (15), is shown in Fig. 3. The intensity threshold gain $2\alpha L$ is shown in Fig. 4. Note that, for $\kappa_{gain}L > \pi/2$, $2\alpha L$ becomes negative. Fig. 5 shows the intensity facet loss $2\alpha_{end}L$. Approximations for these four quantities are

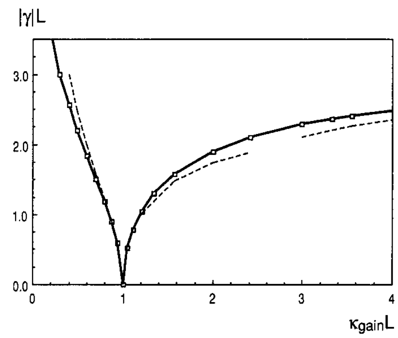

Fig. 2. The absolute value of the complex propagation constant γL as a function of $\kappa_{gain}L$. The dashed lines give approximate results for $\kappa_{gain}L \sim 1$ and large $\kappa_{gain}L$ values.

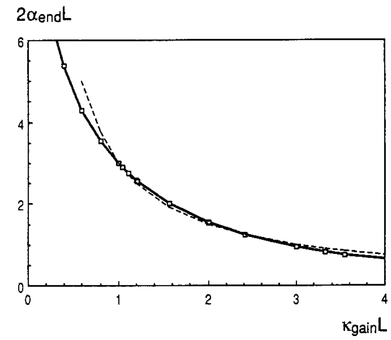

Fig. 5. The intensity facet loss $2\alpha_{end}L$ as a function of $\kappa_{gain}L$. The dashed line gives the approximate result for $\kappa_{gain}L \sim 1$.

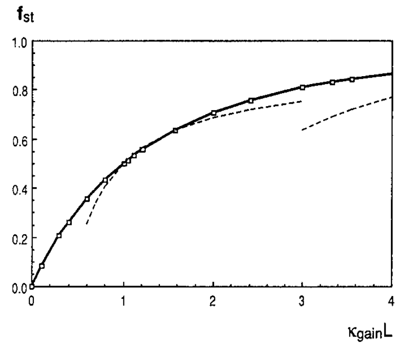

Fig. 3. The relative depth of the standing wave pattern f_{st} as a function of $\kappa_{gain}L$. The dashed lines give approximate results for $\kappa_{gain}L \sim 1$ and large $\kappa_{gain}L$ values.

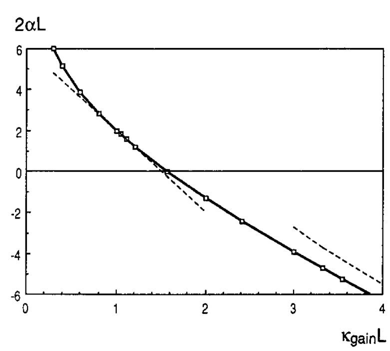

Fig. 4. The intensity threshold gain $2\alpha L$ as a function of $\kappa_{gain}L$. The dashed lines give approximate results for $\kappa_{gain}L \sim 1$ and large $\kappa_{gain}L$ values.

TABLE I
SOME SIMPLE, EXACT SOLUTIONS FOR PURELY GAIN-COUPLED DFB LASERS

$\kappa_{gain}L$	γL	$2\alpha L$	f_{st}	$2\alpha_{end}L$	Remarks
0	∞	∞	0	∞	Amplifier limit
1	0	2	$\frac{1}{2}$	3	Linear mode amplitudes
$\frac{\pi}{3}$	$j\frac{\pi}{6}$	$\frac{\pi\sqrt{3}}{3}$	$\frac{6-\pi\sqrt{3}}{2\pi-3\sqrt{3}}$	$\frac{\pi}{2\pi-3\sqrt{3}}$	
$\frac{\pi}{4}\sqrt{2}$	$j\frac{\pi}{4}$	$\frac{\pi}{2}$	$\frac{4-\pi}{2\pi-4}\sqrt{2}$	$\frac{2\pi}{2\pi-4}$	
$\frac{2\pi}{9}\sqrt{3}$	$j\frac{\pi}{3}$	$\frac{2\pi}{9}\sqrt{3}$	$\frac{6\sqrt{3}-2\pi}{4\pi-3\sqrt{3}}$	$\frac{6\pi}{4\pi-3\sqrt{3}}$	
$\frac{\pi}{2}$	$j\frac{\pi}{2}$	0	$\frac{2}{\pi}$	2	No spatial hole burning
$\frac{4\pi}{9}\sqrt{3}$	$j\frac{2\pi}{3}$	$-\frac{4\pi}{9}\sqrt{3}$	$\frac{4\pi+6\sqrt{3}}{8\pi+3\sqrt{3}}$	$\frac{12\pi}{8\pi+3\sqrt{3}}$	
$\frac{3\pi}{4}\sqrt{2}$	$j\frac{3\pi}{4}$	$-\frac{3\pi}{2}$	$\frac{3\pi+4}{6\pi+4}\sqrt{2}$	$\frac{6\pi}{6\pi+4}$	
$\frac{5\pi}{3}$	$j\frac{5\pi}{6}$	$-\frac{5\pi}{3}$	$\frac{6+5\pi\sqrt{3}}{10\pi+3\sqrt{3}}$	$\frac{5\pi}{10\pi+3\sqrt{3}}$	
∞	$j\pi$	$-\infty$	1	0	Unphysical limit

given in the following two sections. A summary of simple, exact solutions is given in Table I.

Laser structures with significant facet loss are subject to enhanced spontaneous emission, given by the parameter K_z. The significance of this factor for the linewidth was experimentally shown in [17]. For the theoretical derivation of this factor see references in [17]. In [18], this parameter has been calculated for index-coupled and phase-shifted DFB lasers and was given as

$$K_z = \frac{P_{tot}^2}{\left|2\int_{-L/2}^{L/2} R(z)S(z)\,dz\right|^2} \tag{18}$$

which can be written as

$$K_z = \frac{P_{tot}^2}{\left|\frac{\sinh \gamma L}{\gamma L} - \cosh \gamma L\right|^2}. \tag{19}$$

For purely gain-coupled DFB lasers as well as index-coupled DFB laser structures with zero Bragg deviation, like the $\lambda/4$-shifted DFB, γ is either purely real or imaginary. Hence RS is purely real and, using (12), K_z can be written as

$$K_z = \frac{1}{\mathbf{f}_{st}^2}. \tag{20}$$

For partly and purely gain-coupled DFB lasers, K_z as a function of $|\kappa|L$ differs only a few percent from the results of purely index-coupled DFB lasers, see Fig. 3 in [18].

For a DFB laser it has been shown that the linewidth enhancement factor for the material α_{mat} should be replaced by a structure-dependent effective linewidth enhancement factor α_{eff}, which takes the spatial dependencies of the field intensity and the electron density into account and was given as [19]

$$\alpha_{eff} = \frac{\alpha_m \int_{-L/2}^{L/2} \Gamma'(z)I(z)\,dz - \int_{-L/2}^{L/2} \Gamma''(z)I(z)\,dz}{\alpha_m \int_{-L/2}^{L/2} \Gamma''(z)I(z)\,dz + \int_{-L/2}^{L/2} \Gamma'(z)I(z)\,dz} \tag{21}$$

where $I(z) = RR^* + SS^*$. $\Gamma'(z)$ and $\Gamma''(z)$ are given as

$$\Gamma'(z) = -\mathrm{Re}\,\frac{RS}{\int_{-L/2}^{L/2} RS\,dz} \quad \text{and}$$

$$\Gamma''(z) = -\mathrm{Im}\,\frac{RS}{\int_{-L/2}^{L/2} RS\,dz}. \tag{22}$$

For the same class of lasers as above, α_{eff} becomes identical to α_{mat}.

A. Approximate Results of $\kappa_{gain}L \sim 1$

For $\kappa_{gain}L$ near 1, approximate results are discussed here. These approximations directly relate the performance of a purely gain-coupled DFB to its coupling strength $\kappa_{gain}L$. From (4) and (6) we obtain the propagation constant γL as

$$\gamma L \approx \sqrt{6}\sqrt{\frac{1}{\kappa_{gain}L} - 1} \tag{23}$$

see Fig. 2. Using (15) and (23) the relative depth of the standing wave pattern $\mathbf{f}_{st}$ can be approximated by

$$\mathbf{f}_{st} \approx \frac{1}{2}\left[1 - \frac{3}{4}\left(\frac{1}{\kappa_{gain}L} - 1\right)\right]. \tag{24}$$

With (6) the intensity threshold gain $2\alpha L$ becomes

$$2\alpha L \approx 6 - 4\,\kappa_{gain}L \tag{25}$$

and with (16) and (23) the facet loss $2\alpha_{end}L$ can be approximated by

$$2\alpha_{end}L \approx \frac{3}{\kappa_{gain}L}. \tag{26}$$

As can be seen in Fig. 2–5 these approximations give quite accurate results for $\kappa_{gain}L \sim 0.5$–2. For large $\kappa_{gain}L$ values, approximations are given in the next section.

B. Approximate Results for Large $\kappa_{gain}L$ Values

For large $\kappa_{gain}L$ values we find with (4) and (6) for the propagation constant:

$$\gamma L \approx j\pi\left(1 - \frac{1}{\kappa_{gain}L}\right). \tag{27}$$

Using this result and (15) the approximate result for $\mathbf{f}_{st}$ is

$$\mathbf{f}_{st} \approx 1 - \frac{\pi^2}{2(\kappa_{gain}L)^2} + \frac{\pi^2}{2(\kappa_{gain}L)^3}. \tag{28}$$

Because of the gain enhancement by the standing wave effect it is intuitively clear that $2\alpha L$ has to be proportional to $-\kappa_{gain}L$ for large coupling coefficients. Using (6) and (27) we find, indeed, that

$$2\alpha L \approx \frac{\pi^2}{\kappa_{gain}L} - 2\kappa_{gain}L. \tag{29}$$

With (16) and (27) we finally obtain

$$2\alpha_{end}L \approx 2\frac{\pi^2}{(\kappa_{gain}L)^2}\left(1 - \frac{1}{\kappa_{gain}L}\right). \tag{30}$$

Note that the first term in (30) is the same approximation as given for the purely index-coupled DFB laser in KS. It is evident that the relative depth of the standing wave pattern is limited to 1. This explains the "saturation" effect and hence γL, $2\alpha L$, and $2\alpha_{end}L$ have to become constant or proportional to $\kappa_{gain}L$. The limiting results for infinite $\kappa_{gain}L$ values can be found in Table I.

V. Partly Gain-Coupled DFB Lasers

For partly gain coupled DFB lasers the solution of (5) becomes more difficult because γL has real and imaginary parts at the same time. In Appendix B it is shown that for a purely index-coupled DFB laser the real part of γL runs from infinity to zero and the imaginary part from $\pi/2$ to π, for increasing $\kappa_{index}L$, see Fig. 6. The full lines in this figure give the real parts of γL and the dashed lines the imaginary parts for three DFB lasers: the purely index-coupled, the purely gain-coupled, and a partly gain-coupled DFB with $\kappa_{gain}L = 0.6$. The $\gamma' L$ and $\gamma'' L$ of the latter structure lie between the limiting values of pure gain and index coupling.

Fig. 7 shows the relative depth of the standing wave pattern $\mathbf{f}_{st}$ for these three cases, as obtained from (15). It can be seen that $\mathbf{f}_{st}$ of the partly gain-coupled DFB laser can be increased by increasing $\kappa_{gain}L$. From this fact and (13) it follows that the benefits of gain coupling in partly gain-coupled DFB lasers are improved, just by increasing $\kappa_{index}L$. This is seen in Fig. 8, which shows the intensity threshold gain $2\alpha L$ for the three cases. Fig. 9 gives the intensity facet loss $2\alpha_{end}L$ obtained from (16). Note that for pure index coupling the results in Figs. 8 and 9 are identical, as expected from (13).

VI. Conclusion

The performance of AR-coated partly gain-coupled DFB lasers has been investigated theoretically. Analytical

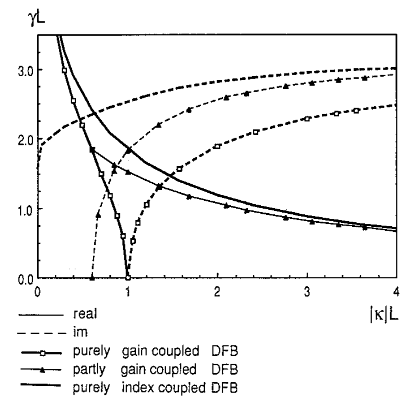

Fig. 6. The complex propagation constant γL as a function of $|\kappa|L = ((\kappa_{\mathrm{gain}}L)^2 + (\kappa_{\mathrm{index}}L)^2)^{0.5}$. The full lines give the real and the dashed lines the imaginary parts of γL. The partly gain-coupled DFB has $\kappa_{\mathrm{gain}}L = 0.6$ and for this case the curve starts for $|\kappa|L = 0.6$.

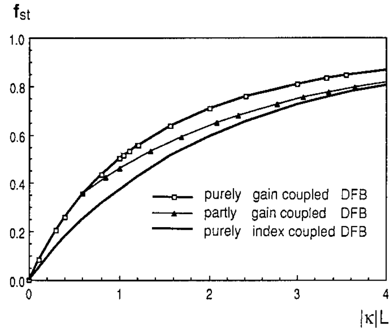

Fig. 7. The relative depth of the standing wave pattern $\mathbf{f}_{st}$ as a function of $|\kappa|L$. The partly gain coupled DFB has $\kappa_{\mathrm{gain}}L = 0.6$ and for this case the curve starts for $|\kappa|L = 0.6$.

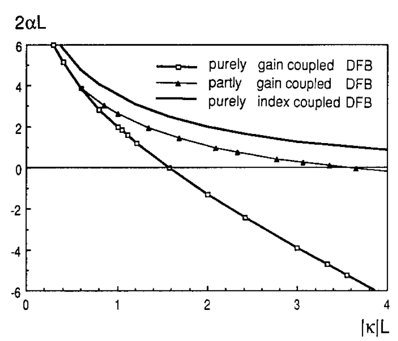

Fig. 8. The intensity threshold gain $2\alpha L$ as a function of $|\kappa|L$. The partly gain coupled DFB has $\kappa_{\mathrm{gain}}L = 0.6$ and for this case the curve starts for $|\kappa|L = 0.6$.

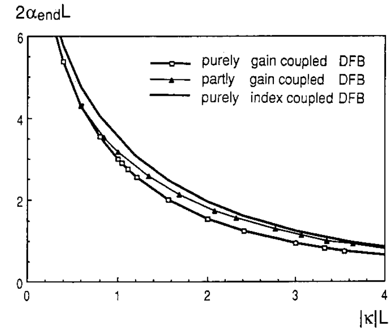

Fig. 9. The intensity facet loss $2\alpha_{\mathrm{end}}L$ as a function of $|\kappa|L$. The partly gain coupled DFB has $\kappa_{\mathrm{gain}}L = 0.6$ and for this case the curve starts for $|\kappa|L = 0.6$.

expressions are given for the threshold gain, facet loss, and relative depth of the standing wave pattern $\mathbf{f}_{st}$. The relevance of the standing wave effect is shown analytically, an effect that is of major importance for the improved device characteristics of partly gain-coupled DFB lasers. For pure gain coupling the longitudinal spontaneous emission factor K_z is found to be $\mathbf{f}_{st}^{-2}$, and the material α_{mat} and the effective linewidth enhancement factor α_{eff} are identical. Next, simple approximations are given that describe the performance of the laser as a function of the gain-coupling coefficient. For partial gain coupling these characteristics are given numerically.

Appendix A
General Form of the Coupling Coefficient

The coupling coefficient of the index grating κ_{index} can be chosen real, without loss of generality, by choosing the origin of the x axis. In addition we choose κ_{gain}, giving the coupling strength of the gain grating, to be a real number. The general form of κ_{RS} can then be written [6]:

$$\kappa_{RS} = \kappa_{\mathrm{index}} + j\kappa_{\mathrm{gain}}e^{j\Theta} \tag{A.1}$$

where Θ defines the phase between gain and index grating. κ_{SR} is given by

$$\kappa_{SR} = \kappa_{\mathrm{index}} + j\kappa_{\mathrm{gain}}e^{-j\Theta}. \tag{A.2}$$

It can easily be verified that (A.1) and (A.2) satisfy (8) and (9). It is straightforward to numerically analyze partly gain-coupled DFB lasers with any Θ value and some results can be found in [6]. In cases where κ_{index} and κ_{gain} are caused by the "same" geometric grating, Θ is either π or 0. From an experimental viewpoint these are the two most likely cases. In addition, these two situations are the ones where partly gain coupling is most advantageous [6] and the last case has been considered in this paper. To study the case with $\Theta = \pi$ all that has to be changed is an appropriate minus sign in front of κ_{gain}. In addition, a change of the sign of the Bragg deviation of the lasing mode results.

Appendix B
Useful Relations for Purely Index-Coupled DFB Lasers

With $\kappa = \kappa_{\mathrm{index}}$ we can write (5) as

$$\kappa_{\mathrm{index}}L \sinh \gamma' L \cos \gamma'' L = -\gamma'' L \tag{B.1}$$

$$\kappa_{\mathrm{index}}L \cosh \gamma' L \sin \gamma'' L = \gamma' L \tag{B.2}$$

and the real part of (6) as

$$\alpha L = \kappa_{\mathrm{index}}L \sinh \gamma' L \sin \gamma'' L. \tag{B.3}$$

Equations (B.1), (B.2), and (B.3) give

$$\coth \gamma' L = \frac{\gamma' L}{\alpha L} \tag{B.4}$$

$$\cot \gamma'' L = -\frac{\gamma'' L}{\alpha L}. \tag{B.5}$$

Equations (B.4) and (B.5) have been derived in a different way in [20]. From them it follows for $\kappa_{\text{index}} \epsilon [0, \infty[$ that $\gamma' L \epsilon]\infty, \pi/2]$ and $\gamma'' L \epsilon [0, \pi]$.

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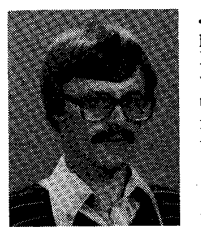

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