Design and Optimization of Strained-Layer-Multiquantum-Well Lasers for High-Speed Analog Communications

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Abstract—**We report on how the contributions from spatial hole burning, gain suppression, and relaxation oscillations to the chirp and harmonic distortion of SL-MQW DFB lasers can be calculated and minimized. It is shown how, by taking into account the specific properties of strained-layer-multiquantum-well (SL-MQW) lasers, simple solutions of the rate equations point the way to a chirp reduction and an increase of the useful bandwidth for analog communications. In such lasers, the absorption is only weakly dependent on the carrier density and therefore the harmonic distortion at lower modulation frequencies is mainly caused by spatial hole burning. Our numerical simulations indicate that in many cases this distortion is reduced by the same measures that reduce the chirp and increase the bandwidth.**

I. Introduction

SUBCARRIER multiplexing using analog intensity or amplitude modulation of the carriers [1] is one of the interesting advanced optical communication schemes and has potential applications in cable television distribution and in wireless telephony. DFB lasers that can operate in a stable, single longitudinal mode are the desired light sources here as they can have a small intensity noise and give a reduced chromatic fiber disperion. Most important for analog communication is a high linearity or a small distortion in the AM response of the laser diode. Also, the maximum usable bandwidth is limited by harmonic distortion, which is caused by intrinsic nonlinearities and often increases rapidly in the vicinity of the resonance frequency corresponding with the relaxation oscillations [2]. This bandwidth is significantly smaller than the 3-dB small-signal bandwidth; it is proportional with the resonance frequency and affected little by the damping of the relaxation oscillations. At low modulation frequencies, other nonlinearities such as gain suppression, spatial hole burning, etc., are the main causes.

Er-doped fiber amplifiers can be used to relax the requirements on modulation depth and to reduce the intermodulation distortion in this way. The use of a fiber amplifier, however, requires that wavelengths around 1.55 μm be used. In this wavelength region, conventional fibers show a considerable dispersion, causing any chirping of the laser to result in signal distortion at the receiver side and in a sensitivity degradation. Although dispersion-shifted fiber exists, a reduction of the chirp of the laser diode allowing the use of conventional fiber is preferred because of the cost issue.

Chirp, harmonic distortion, and modulation bandwidth have been the subject of many previous studies. Analytical expressions for the chirp and the intrinsic bandwidth of a laser diode were derived several years ago [3], [4]. From the small-signal rate analysis of the rate equations, it follows that the resonance frequency f_r is given by $(2\pi f_r)^2 = G' \times G_{\text{th}} S$ with S the photon density, G_{th} the threshold gain ($= \Gamma g_{\text{th}} v_g$) and $G' = dG/dN$. The damping of the relaxation oscillations is caused mainly by gain suppression and also increases with increasing photon density. The damping rate γ varies linearly with $(f_r)^2$ as the power increases and this means that the intrinsic 3-dB bandwidth is limited to a value proportional with the so-called K-factor, being the proportionality constant between γ and $(f_r)^2$. An expression for K has been derived for bulk lasers [4]; $K = 4\pi^2(G_{\text{th}}^{-1} + \epsilon(dG/dN)^{-1})$ in which ϵ is the gain compression coefficient. It must be slightly modified for quantum wells. It has recently been shown by Nagarajan *et al.* [5], [6] how transport effects need to be included in the expressions and how these effects can limit the 3-dB small-signal bandwidth. The main implication of transport effects is that the differential gain in both the expressions for resonance frequency and K must be divided by a factor $\chi = 1 + \tau_s/\tau_e$ with τ_s the transport time over the separate confinement heterostructure and τ_e the escape time from the quantum wells.

Studies of harmonic distortion have been reported in recent years. Stubkjaer *et al.* [7] and Lau *et al.* [8] have reported on the effect of relaxation oscillations that become important at high modulation frequencies. At lower modulation frequencies, distortion is caused predominantly by gain suppression and by longitudinal spatial hole burning in DFB lasers. It was recently shown by the author [9] that, for bulk MQW lasers and at higher bias levels, a dominant contribution to the low-frequency harmonic distortion comes from the increase in absorption when the carrier density increases as a result of gain suppression. Since the absorption in strained-layer-multi-

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quantum-well material shows a very weak dependence on the carrier density, this contribution becomes unimportant and this generally gives a smaller distortion in SL-MQW lasers. Spatial hole burning then becomes one of the dominating distortion causes. The influence of longitudinal spatial hole burning has been studied by, for example, Takemoto *et al.* [10], Morthier *et al.* [11], and Kawamura *et al.* [13], but only for some typical laser structures and without taking into account the specific properties of SL-MQW material. SL-MQW material can also give low linewidth enhancement factors and thus low chirp and is therefore to be preferred for analog communications. We assume that the lateral/transverse laser structure is such that leakage currents have no influence on chirp and harmonic distortion. A treatment for some laser structures in which leakage could be important has been given by Lin *et al.* [14].

In this paper, we assume SL-MQW material and compare different laser structures with respect to the harmonic distortion, the chirp and the "high" frequency behavior. By high frequencies we will denote frequencies of several hundreds of MHz in the following. We will give analytical approximations for the chirp and the distortion at high modulation frequencies and show how the laser can be optimized for this high-frequency operation. We will then discuss the harmonic distortion at low modulation frequencies and show how several measures taken to reduce the high-frequency distortion and chirp also reduce the static distortion and chirp. We limit ourselves to rather simple structures with uniform grating, but demonstrate numerical results for different κ and L values and look at the influene of HR and AR coatings. The optimizations are largely based on the specific sublinear gain versus carrier density relation of SL-MQW material and we therefore first present some of the adopted assumptions and a justification.

It will be shown how one can usually benefit from a small-signal-threshold carrier density that can be obtained by using a large number of wells or thick wells, by considering long cavities and rather high facet reflectivities. However, increasing the κL-value or the facet reflectivities normally also result in a reduced efficiency. Furthermore, the spatial-hole-burning contribution to the distortion decreases with decreasing κL-value. Theoretically, a small κL-value and high facet reflectivities are favorable for the dynamic operation, but one has to compromise in order to obtain an acceptable side mode suppression and efficiency. It is therefore better to increase the cavity length in order to get a small threshold gain.

Our theory explains the good results (small harmonic distortion and chirp) of SL-MQW lasers that have been reported recently [15], [16].

II. Assumptions

The basic differences between bulk or MQW material and SL-MQW material have the origin in the very small dependence of the absorption on the carrier density [17], [18] and the sublinear nature of the gain–carrier density relationship in SL-MQW lasers. We have approximated the unsaturated gain for SL-MQW by the following relation:

$$g(N) = a \ln (N) - b \tag{1}$$

with g the gain and N the average carrier density in the quantum wells. Theoretical and experimental evidence for this dependence has been given in recent literature [19]. It also follows from measurements of the differential gain on cleaved and AR-coated lasers [20]. The main implications of (1) are that the differential gain dg/dN and the linewidth enhancement factor α depend on the carrier density N:

$$dg/dN = a/N \tag{2}$$

$$\alpha = (4\pi/\lambda)\ (dn_w/dN)(N/a). \tag{3}$$

It is assumed that the refractive index n_w of the quantum wells still depends linearly on the carrier density in the quantum wells. In reality, there will also be a contribution from the carrier density N_B in the barriers. We assume that this contribution is included in dn_w/dN in (3). Evidence for this assumption comes from measurements of the α-factor on cleaved and AR-coated lasers that seem consistent with (3) [20]. We furthermore assumed that the gain suppression is independent of the carrier density.

$$g = g_0(N)(1 - \epsilon S) = (a \ln (N) - b)(1 - \epsilon S). \tag{4}$$

TABLE I

Parameter	Value
Gain Parameter a [cm^{-1}]	573
Gain Parameter b [cm^{-1}]	7209
Refractive Index Parameter dn_w/dN [cm^3]	$-1.54 \cdot 10^{-18}$
Gain Suppression ϵ [cm^3]	$3 \cdot 10^{-17}$
Active Layer Width w [μm]	2
Active Layer Thickness d [μm]	0.032
Confinement Factor Γ	0.04
Internal Loss α_{int} [cm^{-1}]	20
Recombination Coefficient A [ns^{-1}]	1
Bimolecular Coefficient B [cm^3/s]	$2 \cdot 10^{-10}$
Auger coefficient [cm^6/s]	10^{-28}

Table I gives an overview of the different nominal parameters that will be used in the numerical simulations. The active layer dimensions only include the wells, and not the barriers. The internal loss has been assumed to be independent of the carrier density. With the assumed parameters one finds a threshold current of 16 mA for a typical cleaved DFB laser with $\kappa L = 1$ and $L = 600$ μm.

In our calculations of the harmonic distortion, we do not take into account the nonlinearity of the gain–carrier density relationship except for the dependence of the differential gain on the threshold carrier density. This is justified by the fact that even under strong modulation the carrier density remains rather clamped and only small carrier density variations occur (compared to the carrier density variation from one device to another).

III. The Chirp and the Harmonic Distortion: Theoretical Discussion

A. Analytical Approximations and Optimization

For the derivation of analytical approximations we start from the rate equations for quantum-well lasers as given in [6], but we only take into account the transport over the separate confinement heterostructure. In most lasers, the influence of spatial hole burning decreases with decreasing bias level. We will neglect spatial hole burning here and the results that we will find will therefore be more accurate at high bias levels. Analytical expressions can be obtained by expanding the number of photons S and the carrier densities N and N_B as

$$\begin{aligned} S &= S_0 + \mathrm{Re}\,\{S_1 \exp(j\Omega t) + S_2 \exp(2j\Omega t)\} \\ N &= N_0 + \mathrm{Re}\,[N_1 \exp(j\Omega t) + N_2 \exp(2j\Omega t)\} \\ N_B &= N_{B0} + \mathrm{Re}\,\{N_{B1} \exp(j\Omega t) + N_{B2} \exp(2j\Omega t\} \end{aligned} \tag{5}$$

and by substitition in the rate equations:

$$\begin{aligned} \frac{dS}{dt} &= \{G(N, S) - G_{\mathrm{th}}\} S \\ \frac{dN}{dt} &= \frac{N_B}{\tau_s}\frac{V_{\mathrm{SCH}}}{V_W} - \frac{N}{\tau_e} - R(N) - \frac{G(N, S) S}{V_W} \\ \frac{dN_B}{dt} &= \frac{I}{qV_{\mathrm{SCH}}} + \frac{N}{\tau_e}\frac{V_W}{V_{\mathrm{SCH}}} - \frac{N_B}{\tau_s} \\ \Delta\omega &= \frac{\alpha}{2}\frac{dG}{dN}\Delta N \end{aligned} \tag{6}$$

$$\frac{S_2}{S_1} = \frac{1}{2}\,\frac{j\Omega V\left\{2j\Omega\left(1 + \frac{\tau_s}{\tau_e}\right) + \frac{dR}{dN}\right\}\exp\left(\frac{b}{a}\right)\exp\left(\frac{G_{\mathrm{th}}}{\Gamma a v_g}\right)}{S_0(\Gamma a v_g)^2\left(\frac{G_{\mathrm{th}}}{\Gamma a v_g}\right)}\,\frac{S_1}{S_0} \tag{9}$$

with $G = \Gamma g v_g$, G_{th} the threshold gain equal to the total (constant) loss, R the total spontaneous carrier recombination in the wells consisting of linear, bimolecular, and Auger recombination, V_{SCH} and V_W the volumes of the separate confinement layers, respectively, of the quantum wells, τ_s the transport time over the separate confinement layers and τ_e the escape time from the wells. For the chirp Δf one then finds

$$\begin{aligned} \Delta f &= \frac{\alpha}{4\pi}\left\{j\Omega\frac{S_1}{S_0} + G_{\mathrm{th}}\epsilon S_1\right\} \\ &= \frac{\alpha_0}{4\pi}\exp\left(\frac{G_{\mathrm{th}}}{\Gamma a v_g}\right)\left\{j\Omega\frac{S_1}{S_0} + G_{\mathrm{th}}\epsilon S_1\right\}. \end{aligned} \tag{7}$$

Writing α as $\alpha_0 N$ and expressing N in terms of the threshold gain G_{th} gives the last expression. This final expression shows that the chirp strongly increases with increasing threshold gain and that it is proportional with the ac-power S_1. There is also a strong dependence on the confinement factor, which for simplicity can be assumed to depend linearly on the active layer width and thickness. Hence, minimum chirp will result for minimum threshold gain and for largest possible active-layer dimensions. An increase of the active layer dimensions (restricted by requirements on far-field pattern and by the desired single-mode behavior of the waveguide) will also decrease the photon density S_1 corresponding to a certain ac-power. If a certain ac-power is required, one can also increase the bias power in order to decrease the dynamic contribution in (7). It can be noticed that, even if the carriers in the barrier layers contribute to the chirp, it can be argued that the chirp decreases with decreasing carrier density since the carrier density in the barriers will be proportional to the carrier density in the wells. An expression for the second-order distortion at high modulation frequencies can be obtained by further neglecting the gain suppression

$$\frac{S_2}{S_1} = \frac{1}{2}\,\frac{j\Omega\left\{2j\Omega\left(1 + \frac{\tau_s}{\tau_e}\right) + \frac{dR}{dN}\right\}V}{G_{\mathrm{th}}\frac{dG}{dN}S_0}\,\frac{S_1}{S_0} \tag{8}$$

in which $V = V_W$. We have neglected the frequency dependence of the denominator in (8). For a well-designed laser, the resonance frequency is of the order of several GHz and very large with respect to a modulation frequency of several hundreds of MHz. Expressing again the differential gain in terms of the threshold gain gives an expression that as a function of G_{th} shows a minimum for $G_{\mathrm{th}} = \Gamma a v_g$. With the numerical parameters that we chose, this minimum corresponds with facet losses of 3 cm^{-1} and it will be of a same order of magnitude for other sensible choices of the material parameters. This very small value for the optimum facet loss implies that in practice the expression (9) will decrease with decreasing facet loss. There is an additional decrease with increasing steady-state photon number and, under the assumption that the time constants τ_s and τ_e do not change, with increasing confinement factor Γ or increasing active layer width and thickness.

B. The Harmonic Distortion at Small Modulation Frequencies

As was mentioned previously, SL-MQW lasers have a considerable advantage over bulk and unstrained MQW lasers because of the very weak dependence of the absorption on the carrier density. This implies that the harmonic distortion at small modulation frequencies will be determined mainly by spatial hole burning and by the influence of the gain suppression on the carrier recombination $R(N)$. It is, in principle, possible to have both contributions canceling each other [11], though this effect only occurs for some lasers and for a particular biasing and it would not be an easy task to design lasers where this effect occurs for a certain predicted bias for most of the fabricated lasers. We therefore consider it more interesting to obtain a reduction of both contributions separately.

The contribution from the gain suppression, which causes a carrier density increase with increasing power level and therefore an increase of the effective threshold current, can be calculated analytically:

$$\frac{S_2}{S_1} = -\frac{1}{2} \frac{\dfrac{dR}{dN} + \dfrac{G_{th}}{2(dG/dN)} \dfrac{d^2R}{dN^2}}{\dfrac{1}{V} \dfrac{dG}{dN}} \epsilon^2 S_1 \tag{10}$$

This distortion increases with increasing ac power, but is in general very small for SL-MQW lasers. With the material parameters assumed here and for a typical 600-μm-long DFB laser with $\kappa L = 1$ and both facets cleaved, one finds a value of -95 dBc for a modulated output power of 1 mW (which corresponds to an optical modulation depth of 10 percent, respectively; 20 percent at a bias output power of 10 mW, respectively, 5 mW). Under the assumption that the gain compression ϵ is independent of the carrier density, the contribution (10) decreases rapidly with decreasing threshold gain due to the dependence of the differential gain and $R(N)$ on the carrier density. If a weak dependence of the absorption of the carrier density is assumed for SL-MQW material, a larger value for the gain suppression contribution will result. For example, for a ratio of $3 \cdot 10^{-17}$ cm^2 between absorption in the active layer and the carrier density, one would find -70 dBc and less for a modulated ac power of 1 mW.

The contribution from spatial hole burning is difficult to assess analytically. It obviously depends on the nonuniformity of the optical power inside the cavity and thus on the coupling strength and the facet reflectivities, but also on the threshold gain and the differential gain. The optical power is usually more uniform in lasers with high facet reflectivities (and, e.g., better for cleaved lasers than for AR-coated lasers) and a small κL constant. A compromise is needed though since a minimum value for κL is required in order to obtain an acceptable single-mode yield. For lasers with cleaved facets, an acceptable single-mode yield (e.g., 30 percent) can be obtained for rather small κL-values (e.g., $\kappa L > 0.5$) [21] and this is even more valid if rather high bias powers are considered. Lasers with small κL-value and rather high facet reflectivities suffer less from instabilities caused by spatial hole burning at higher bias levels than lasers with larger κL and one or two AR-coated facets.

The influence of spatial hole burning comes from the change of the facet loss as a result of the nonuniformity of the refractive index and the carrier density. The nonuniformity of the carrier density caused by the nonuniformity of the optical power can be estimated from a rate equation for the local carrier density $N(z)$ using local photon densities $S(z)$ (number of photons per unit length). Such an expression has been derived in [12]; with the notation used here the nonuniform carrier density $\Delta N(z) = N(z) - N_0$ as a function of the nonuniform power $\Delta S(z) = S(z) - S_0$ is

$$\Delta N(z) = -\frac{G(N_0)\,\Delta S(z)}{\dfrac{dR}{dN} wd + \dfrac{dG}{dN} S_0} \tag{11}$$

with S_0 and N_0 being the average photon and carrier density. It can also be assumed that the longitudinal power profile is independent of the bias level so that $\Delta S(z) = S_0 f(z)$, i.e., $f \equiv \Delta S(z)/S_0$ is independent of S_0 as is the case in many lasers. Equation (11) describes the total variation in the carrier density at a particular bias level; for the change of this variation with changing bias level one finds

$$\delta[\Delta N(z)] = -\frac{G(N_0) f(z)\, \delta(S_0)}{\dfrac{dR}{dN} wd + \dfrac{dG}{dN} S_0} \left\{ 1 - \frac{\dfrac{dG}{dN} S_0}{\dfrac{dR}{dN} wd + \dfrac{dG}{dN} S_0} \right\} \tag{12}$$

At very low bias levels the bias dependence of the denominators and of the factor between braces can be neglected; from (12) one can then see that the nonuniformity of the carrier density becomes weaker with decreasing threshold gain. At relatively low bias levels, the carrier density variations are also proportional with the small-signal carrier lifetime $(dR/dN)^{-1}$, which will weaken the decrease of ΔN with decreasing threshold gain somehow. Obviously, the contribution of spatial hole burning not only depends on the magnitude of the carrier density variations, but also on the influence of the carrier density variations on refractive index and distributed feedback loss. The influence of carrier density variations on the feedback loss can be quite different from one structure to another and depends, e.g., on the length and the coupling strength.

At very high photon densities the second term in the denominators will dominate and the factor between braces approaches zero. It follows that the longitudinal carrier density distribution becomes fixed at very high bias levels and hence the small-signal spatial hole burning will disappear. As the photon density increases, the damping of the carrier density variations by the denominators of (12) increases and this damping is larger for larger differential gain. In our numerical examples we will use a constant optical modulation depth m for all bias levels and the power variation δS_0 then increases with increasing bias level ($\delta S_0 = m S_0$). This will result in an initial increase of the nonuniformity of the carrier density and of the harmonic distortion.

From the previous discussion, it follows that the distortion caused by spatial hole burning will, in general, decrease with increasing bias level and that a high bias level is advantageous. This decrease with increasing bias level is faster if a larger differential gain exists, i.e., again when a small-threshold carrier density is obtained, e.g., by maximizing the active layer volume. Since the carrier density variations are proportional with the threshold gain, the distortion caused by spatial hole burning can be expected to decrease with decreasing internal loss.

IV. Some Case Studies: Numerical Results and Discussion

We will focus mainly on the influence of spatial hole burning on the harmonic distortion. The chirp is mainly caused by gain suppression and relaxation oscillations and can be described analytically fairly well. The same holds for the contributions from gain suppression and relaxation oscillations to the harmonic distortion. It is, of course, not possible to describe the behavior of all possible DFB lasers and therefore we will limit ourselves to some special structures that do, however, illustrate and extend the above theory. We only consider relatively simple structures with uniform grating.

All our numerical results are obtained with the longitudinal laser model CLADISS [11], [12], in which spatial hole burning is taken into account in detail in both the static and the dynamic calculations. Transport effects are not taken into account in the numerical calculations, but their effect is easily estimated from (8).

A. Comparison Between Cleaved and Coated Lasers

In general, the axial variations in the optical power become more important as the facet reflectivities become smaller and the coupling coefficients become larger. The ideal laser with the least spatial hole burning is a laser with high facet reflectivities and very weak (if not zero) distributed feedback, but such a laser would have a bad external efficiency and a poor side mode rejection. A compromise needs to be found and we will show that such a compromise must be searched for among lasers with relatively high facet reflectivities and rather low κL-values.

We have calculated the harmonic distortion due to spatial hole burning for several lasers with either both facets cleaved, one cleaved and one AR-coated facet (with a 5 percent reflectivity) and one cleaved and one HR-coated facet (with a 90 percent reflectivity), and considered several values for the coupling strength κL and the facet reflectivity phases. All devices here are 600 μm long. We illustrate the results here for the choice $\phi_1 = 0$, $\phi_2 = \pi/2$ of the facet phases, but emphasize that a similar behavior is found for other choices. Fig. 1 shows the second-order distortion for the laser with both facets being cleaved. This figure shows that the smallest distortion is obtained for the smallest κL-values. This is partly because the axial power variations decrease (the power in an F-P laser with cleaved facets is relatively uniform), but partly

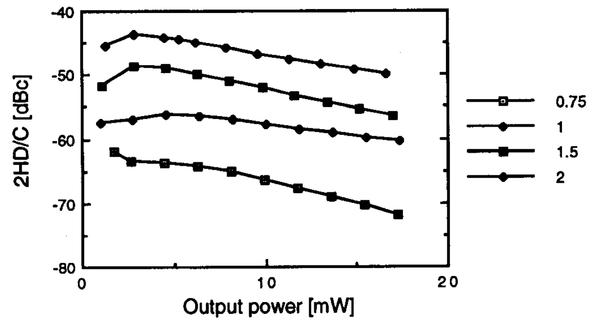

Fig. 1. Static second-order distortion of a 600-μm-long cleaved laser with facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$ for different κL-values and for an OMD of 35 percent.

also because the distributed feedback becomes less important in comparison with the feedback from the facets (which implies a smaller influence of the carrier density variations on the loss). This type of behavior is found for most DFB laers with cleaved facets. For reasonable values of κL, one always has a superlinear behavior of the power–current relation and hence a distortion with phase zero. (The devices with κL-value of 1.5 and 2 also became multimode at bias power levels of 10 mW due to the stronger spatial hole burning.)

Fig. 2 shows the distortion for the same laser but now with the right facet being AR coated. The larger axial power variations and the larger influence of the distributed feedback results in a considerably larger distortion for all κL-values. The strong asymmetry of the longitudinal power profile and the strong spatial hole burning for these lasers can also result in significant changes of the power profile with increasing bias, which can cause additional distortion. Expression (12) is in this case only valid at low bias levels, while the prediction of the distortion at higher bias levels becomes difficult. The change of the longitudinal power profile can also lead to very small distortion at higher bias levels. This is illustrated in Fig. 3 for a 600-μm-long laser with one cleaved and one AR-coated facet and with facet phases $\phi_1 = 0$, $\phi_2 = 7\pi/4$, where for $\kappa L = 1.5$ a very small distortion is obtained. Such an effect, however, only occurs for a few facet phases and in a small κL-range. On average, AR-coated lasers seem to have a larger distortion at small modulation frequencies than cleaved lasers. The same holds for DFB lasers with one HR and one AR coating, again because of the strong asymmetry and nonuniformity of the longitudinal power profile. Lasers with one cleaved and one HR-coated facet give on average similar small distortion as lasers with two cleaved facets. Such lasers have a smaller threshold current and a higher single-facet efficiency than lasers with both facets cleaved and could thus be more interesting. However, the increased importance of the facet reflectivities seems to give these lasers a smaller gain margin and thus a smaller single-mode yield.

Since the distortion caused by spatial hole burning has a phase 0 for lasers with cleaved facets and since, accord-

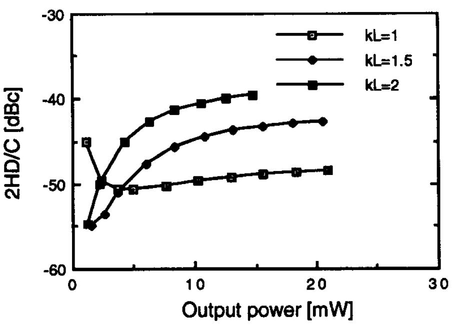

Fig. 2. As in Fig. 1, but with the right facet being AR coated (5 percent), for different κL-values and for an OMD of 35 percent.

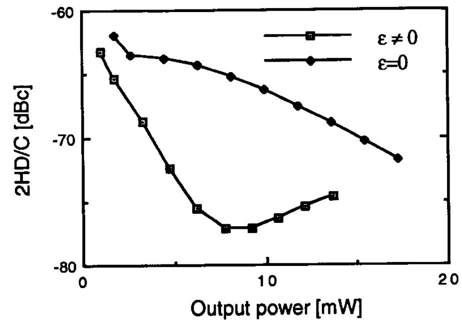

Fig. 4. Static second-order distortion of a 600-μm-long laser with κL = 0.75, with cleaved facets with phases $\phi_1 = 0$, $\phi_2 = \pi/2$ with and without taking gain suppression into account.

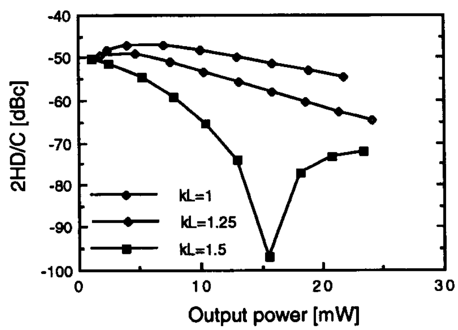

Fig. 3. Static second-order distortion of a 600-μm-long laser with one cleaved and one AR-coated facet, with facet phases $\phi_1 = 0$, $\phi_2 = 7\pi/4$, for different κL-values and for an OMD of 35 percent.

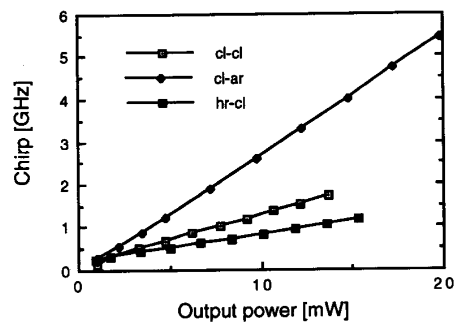

Fig. 5. Chirp at 50 MHz of a 600-μm-long laser with κL = 1 and with facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

ing to (10), the distortion caused by the gain suppression has a phase π, one can expect that both contributions cancel each other to some extent. Because of the relatively small distortion caused by gain suppression, this will only occur at high bias levels and for weak spatial hole burning i.e., small κL-value. This canceling is illustrated in Fig. 4 for a 600-μm-long cleaved DFB laser with $\kappa L = 0.75$ and with facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$. If a dependence of the absorption on the carrier density is taken into account, the canceling will occur at lower bias levels and also for larger κL-values.

Lasers with cleaved or HR-coated facets clearly have a smaller chirp and a better high-frequency behavior. This follows from the expressions (7) and (9) and the strong decrease of these expressions with decreasing theshold gain. The chirp of the 600-μm-long DFB laser with κL = 1 and with facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$ is depicted in Fig. 5 for both facets cleaved, for one cleaved and one HR-coated facet and for one cleaved and one AR-coated facet. The value $\kappa L = 1$ is chosen as a good compromise between single-mode yield and small distortion. The chirp almost always decreases with increasing facet reflectivities.

B. Influence of the Geometrical Parameters

The effect of the laser length is twofold: a decreasing carrier density and thus an increasing differential gain with increasing length, but also a larger influence with increasing length of the axial carrier density variations on the distributed feedback. The first effect results in a smaller chirp, a smaller distortion at high modulation frequencies and a faster decrease of the spatial-hole-burning-induced distortion with bias level, as can easily be seen from the expressions (7), (9), and (12). The second effect can be understood by noticing that in lasers not emitting at the Bragg wavelength, spatial hole burning has its influence mainly through the axial variations of the Bragg deviation and their influence on the reflection loss. The total reflection of a grating with coupling coefficient κ is maximum for zero Bragg deviation and decreases away from that point with a slope that is approximately proportional with the inverse of κ (the width of this reflection curve is proportional with κ). For a constant κL-value, the change of the reflection (and of the transmission) of the grating with changing Bragg deviation will be proportional with the length. Although, according to (12), the variations in carrier density and thus in Bragg deviation, decrease with decreasing threshold gain they are not proportional to the inverse length (as the threshold gain) because the denominator (dR/dN at low bias levels) also decreases with increasing length. This means that the change of transmission of the grating and thus of the output power due to spatial hole burning will be faster with increasing length.

The spatial-hole-burning-induced distortion is shown

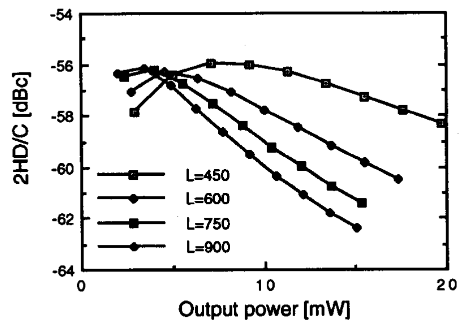

Fig. 6. Influence of laser length on the spatial-hole-burning-induced second-order distortion for a cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

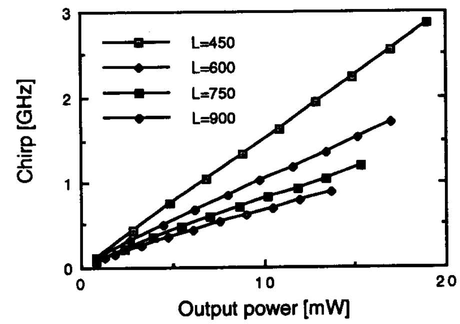

Fig. 8. Influence of the laser length on the low-frequency chirp for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

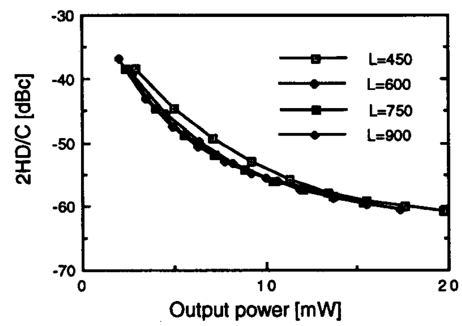

Fig. 7. Influence of laser length on the second-order distortion at 450 MHz for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

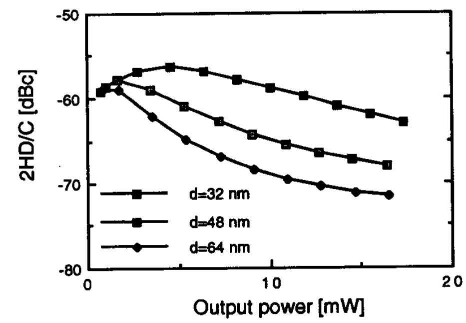

Fig. 9. Influence of active layer thickness on the spatial-hole-burning-induced second-order distortion for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

for different values of the length in Fig. 6 for the cleaved laser with $\kappa L = 1$ and with facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$. Long lasers seem to give better results for output powers of 5 mW or more because of the faster decrease of the spatial hole burning as a result of the larger differential gain. Fig. 7 shows the second-order distortion for a modulation frequency of 450 MHz for the same lasers and Fig. 8 shows the chirp at a modulation frequency of 50 MHz. The chirp at a modulation frequency of 450 MHz has the same value for power levels above 5 mW. From Fig. 7, it follows that the laser length has little influence on the contribution of the relaxation oscillations. The reason is that the minimum of (9) is not very sharp.

The effect of active layer width or thickness (or number of wells) can be predicted from (7), (8), (10), and (12). Increasing the active layer dimensions increases the differential gain substantially and therefore leads to a reduction of the chirp and the harmonic distortion at high modulation frequencies. The increasing differential gain also results in a faster decrease of the spatial-hole-burning-induced distortion with bias level, but does not affect the spatial-hole-burning-induced distortion at low bias level. With increasing active layer width or thickness, one also obtains a smaller photon density for the same power level. This gives an additional decrease of the chirp, but an increase of the distortion at high modulation frequencies.

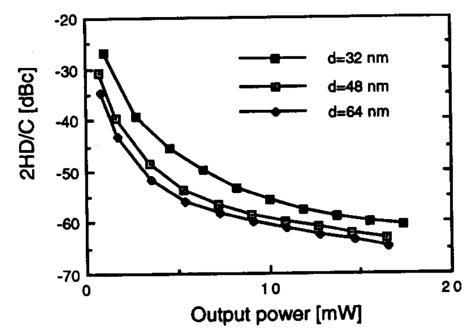

Fig. 10. Influene of active layer thickness on the second-order distortion at 450 MHz for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

The influence of the active layer thickness d on the harmonic distortion is illustrated in Fig. 9 (for a modulation frequency of 50 MHz) and Fig. 10 (modulation frequency of 450 MHz) for the 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$. Notice also that the contribution of gain suppression to the distortion will decrease due to the increase of the differential gain. Fig. 11 shows the chirp for the same lasers and the results again show a decreasing chirp with increasing active layer thickness.

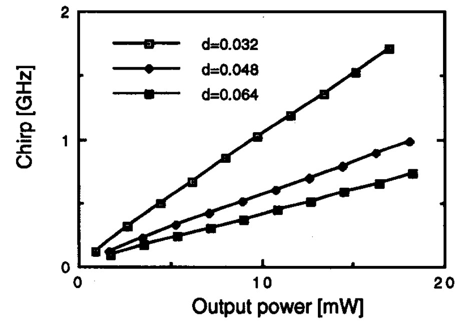

Fig. 11. Influence of active layer thickness on the low-frequency chirp for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

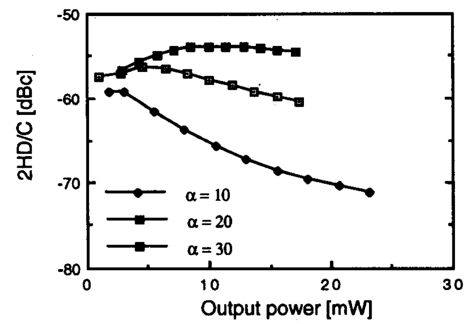

Fig. 12. Influence of the internal absorption α on the spatial-hole-burning-induced second-order distortion for a 600-μm-long cleaved laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$.

C. *Influence of the Internal Absorption*

Besides the influence of the carrier density dependence on the absorption there is also a large influence on distortion and chirp of the value of the absorption itself. This influence is trivial for what concerns the chirp and the contribution of the relaxation oscillations and can be derived from (7) and (9). The influence of the spatial-hole-burning-induced second-order distortion is shown in Fig. 12 for the 600-μm-long cleaved DFB laser with $\kappa L = 1$ and facet phases $\phi_1 = 0$, $\phi_2 = \pi/2$. Increasing absorption reuslts in larger values for the distortion at low bias level, but also makes the decrease of the distortion with increasing bias level considerably slower. The increase of the distortion can, of course, be explained by the increase of the threshold gain with increasing absorption, which according to (12) gives a larger nonuniformity of the carrier density. At the same time, the differential gain decreases and the recombination dR/dN increases, which according to (12) will cause the decrease of the distortion with increasing bias level to occur at a higher bias level and also cause it to be weaker.

V. Conclusion

We have described the factors that determine the chirp and the harmonic distortion of SL-MQW DFB lasers, both at low and moderate modulation frequencies. It was shown how these factors can be minimized by choosing appropriate structural and geometrical parameters. The absorption in such lasers shows a weak dependence on the carrier density and the distortion is therefore caused mainly by spatial hole burning and the intrinsic (dynamic) nonlinearity. The chirp is mainly caused by gain suppression and its value depends strongly on the threshold gain and on the linewidth enhancement factor.

Our optimization has been based partly on the assumption of a sublinear gain–current density relation and more particularly on a logarithmic relation. There exists some evidence for this. It was shown theoretically and numerically that the chirp and the distortion generally decrease with increasing active layer dimensions. Furthermore, lasers with small κL-values and both facets cleaved seem to give the weakest spatial hole burning and thus the smallest distortion.

On the basis of several theoretical arguments given in the text, it can be concluded that lasers with the smallest threshold carrier density will generally give the smallest chirp and the smallest harmonic distortion. One exception is that the threshold carrier density should not be reduced by increasing the κL-value, which should be as small as practically possible (limited, e.g., by the single-mode yield requirement).

We have assumed that the lateral/transverse laser structure is such that the influence of leakage currents can be neglected.

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Geert Morthier, photograph and biography not available at the time of publication.