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Nonlinearities of GaAlAs Lasers—Harmonic Distortion

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***Abstract*—Narrow stripe lasers (2–6 μm) and transverse junction lasers exhibit excellent linearity. The dependence of relative second- and third-harmonic distortion is investigated as a function of modulation frequency and modulation current. Relative second- and third-harmonic distortion of −50 and −70 dB is observed for an optical signal of 4 mW p-p (f_m = 60 MHz). Intermodulation products are compared with the harmonic distortion and good agreement is obtained between the two quantities when the relations for a simple nonlinearity without memory are used. The measured distortion is in agreement with distortion calculated from rate equations.**

I. Introduction

LINEARITY of the emission characteristic is a highly desired property for most applications of semiconductor lasers. Therefore, nonlinearities have been subject to much work in order to understand how they originate. Earlier investigations have shown that transverse motion of the near field [1] or guiding properties of the laser [2] can give rise to kinks.

Reduction of stripe width is found to be an effective way to improve the stability of the near field and consequently the linearity [3], [4]. Also, the devices with built-in confinement of carriers and light have been reported to exhibit good linearity of the emission characteristics [5], [6].

The fact that kinks can be eliminated from the emission characteristic makes it interesting to perform a more detailed measurement of small instabilities still present when the laser is modulated. Measurements of harmonic distortion are a convenient method for such investigations because of the high sensitivity of available measurement equipment. These distortion measurements are also convenient to characterize the possibility of high quality analog optical transmission systems using semiconductor lasers as light sources.

Detailed investigations of nonlinearities in light emitting diodes indicate that they are suitable light sources for analog systems [7]-[9]. So far, only a few results have been published on harmonic distortion in semiconductor lasers [6], [10]-[13] and especially on third-order distortion [11]-[13], which is of importance to system applications.

In this paper experimental results on harmonic distortion obtained for various laser structures are presented. The minimum

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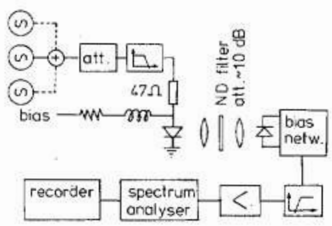

Fig. 1. Schematic diagram of the measurement system.

distortion level which can be obtained was shown to decrease for decreasing stripe width. For narrow stripe lasers ($S < 6\ \mu$m) and transverse junction lasers, excellent linearity is seen in the frequency range from a few megahertz up to 100-200 MHz. Thermally induced mode jumping induces increased nonlinearity at frequencies below 3 MHz.

Third-order intermodulation products measured for narrow stripe lasers and transverse junction stripe (TJS) lasers fulfill the requirements for high quality analogue transmission.

In addition, the investigation shows that the laser behaves as a simple nonlinearity without memory if: 1) the difference between bias current and modulation current amplitude is higher than the threshold current, and 2) the modulation frequency is well below the resonance frequency of the laser.

A theoretical analysis of distortion properties based on rate equations is made. The calculated dependence of distortion on bias current, modulation current, and frequency is found to be in quantitative agreement with the measurements performed on lasers with a narrow active region.

II. Experimental

DH GaAlAs stripe geometry lasers and TJS lasers were used for the experiments. The stripe geometry lasers had stripe widths from 2.6 to 20 μm. Most of them were proton insulated with both deep and shallow implantation. The 2.6-μm laser was oxide insulated. All the devices used for the measurements were well behaved with respect to near field and spectral properties. Spectral width of the laser was 10-25 Å.

The TJS lasers were of the type described in [5], with height and width of active area ~0.4 and ~2 μm, respectively. These lasers have only a single longitudinal mode when biased a little above threshold. However, the fine structure of the spectra clearly indicated that higher order transverse modes were present.

The experimental setup for the linearity measurements is shown in Fig. 1. In some of the measurements, a low pass filter was inserted in the signal circuit to avoid the distortion from the input signal itself. In the same way a high pass filter was inserted in the detector circuit to avoid harmonic distortion from the preamplifier (B & E type DC-3002) and the spectrum analyzer (HP 8552 B). The distortion from the photodiode (BPW 28) was lower than the distortion of the lasers. This was ensured by measurements of the intermodulation products created by the APD when light from two different sources was present [14]. Insertion of additional neutral density filters in the optical beam were also used to ensure that the photodiodes did not contribute to the distortion.

The third-order intermodulation product was measured without filters to suppress the unwanted signals. But by insertion of attenuators in signal and detector circuits it was possible to ensure that the measured intermodulation originated from the laser itself. However, intermodulation products from the signal generators do limit the available measurement range. The measurements were performed with the heatsink temperature of 18°C.

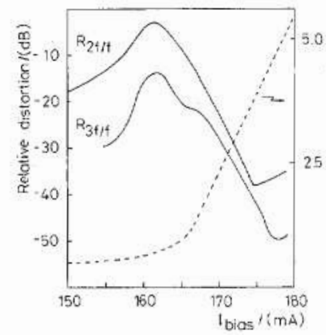

Fig. 2. Relative second- and third-harmonic distortion for a 20-μm stripe laser (———). The modulation current is 13 mA p-p and the modulation frequency is 100 MHz. The static emission characteristic is also shown (– – –).

III. Experimental Results

The signal level response of the fundamental frequency was flat up to the laser resonance for all the lasers used.

The relative second- and third-harmonic distortion (abbreviated to $R_{2f/f}$ and $R_{3f/f}$, respectively, as used in [21]) is shown in Fig. 2 for a shallow proton implanted laser with a stripe width of 20 μm. The modulation frequency is 100 MHz and modulation current is 13 mA p-p. The corresponding optical signal is 4 mW p-p, which is reasonable for an optical communication system assuming 50 percent coupling efficiency [15]. The curves show that the distortion reaches minimum levels of -38 and -50 dB for $R_{2f/f}$ and $R_{3f/f}$, respectively, and the distortion increases slowly at higher bias current.

Measurements of $R_{2f/f}$ and $R_{3f/f}$ for lasers with stripe widths from 2.6 to 20 μm indicate a correlation between minimum harmonic distortion and stripe widths (compare Figs. 2-4). The best results were obtained for stripe widths less than 6 μm. For these lasers, the minimum levels for $R_{2f/f}$ were ~-50 dB and those for $R_{3f/f}$ were -60 to -70 dB for output signals of 4 mW p-p.

In [1] it is concluded that in order to ensure a linear light current characteristic, the stripe width of the laser must be less than or comparable to the carrier diffusion length. On the background of our measurements it is reasonable to suggest that this also must be fulfilled in order to obtain low distortion.

A. Narrow Stripe Lasers

Figs. 3 and 4 give $R_{2f/f}$ and $R_{3f/f}$ as a function of bias current for a laser with a stripe width of 2.6 μm, which was the narrowest stripe width investigated. The modulation frequency is 60 MHz and the three modulation currents used correspond to optical signals of 2.0 mW p-p, 3.6 mW p-p, and 6 mW p-p. From Fig. 3 it is seen that the relative second-harmonic distortion obtained for an optical signal of 3.6 mW p-p is ~-49 dB when the laser is biased well above threshold. Before this level of $R_{2f/f}$ is reached, a narrow minimum with

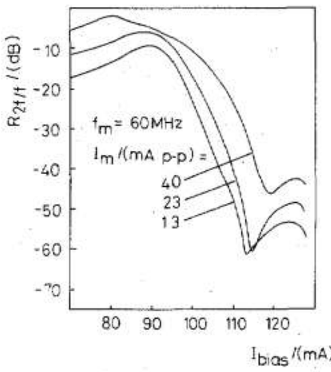

Fig. 3. Relative second-harmonic distortion for a 2.6-μm stripe laser. The modulation currents used are 13, 23, and 40 mA p–p, respectively. The modulation frequency is 60 MHz.

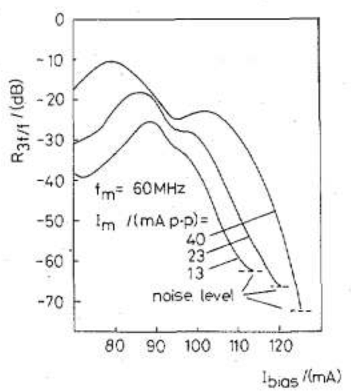

Fig. 4. Relative third-harmonic distortion for the same laser as shown in Fig. 3. Modulation currents and modulation frequency used correspond to those in Fig. 3. The measurement range is limited by the noise of the detection system.

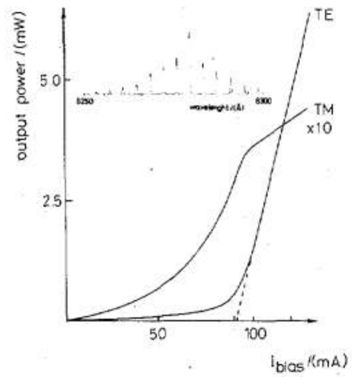

Fig. 5. Light–current characteristics for TE and TM light for the laser investigated in Figs. 3 and 4. Threshold current is 91 mA and slope efficiency is 0.15 mW/mA. The TM characteristic is magnified ten times. The spectrum for an output power of 3.5 mW is also given in the figure.

the depth of −60 dB occurs, corresponding to a zero crossing of the second derivative of the light–current characteristic.

The relative third-harmonic distortion decreases monotonically as a function of bias current when the laser is biased above threshold. The curve for $R_{3f/f}$ corresponding to a 6 mW p-p optical signal is limited at −72 dB by the noise of the detection system. The levels at which the other curves are limited by noise, are higher because of the smaller fundamental signals. No attempt has been made to decrease the noise bandwidth (10 kHz) of the detection system, since, as discussed later, an $R_{3f/f}$ of −72 dB is sufficient, from a system's point of view. Higher harmonics in the optical signal were less than, or comparable to, the third harmonic.

The distortion properties can be compared with other properties of the device. First, the light-current characteristics for TE and TM light are shown in Fig. 5. As can be seen, the TE characteristic is linear without kinks. Threshold current for the laser is 91 mA ($t_{heatsink}$ = 18°C) and slope efficiency is 0.15 mW/mA. The TM characteristic increases linearly with bias current above threshold. The nonsaturation of the TM light is caused by a lateral current spread and lateral carrier diffusion.

The laser is multilongitudinal moded with a halfwidth of ~10 Å, as seen from the insert in Fig. 5, which gives the static spectrum corresponding to an output power of ~3.5 mW.

The noise properties of the laser are investigated as a function of frequency and bias current since even small instabilities can be detected by such measurements. A detailed discussion of noise measurements can be found in [16]. The noise measured as a function of bias current for various frequencies exposed a 5 dB, almost frequency independent, noise peak at I_{bias} = 113 mA. It is interesting to notice that the minima of $R_{2f/f}$ in Fig. 3 for small modulation currents are found for this bias current. Similar frequency independent noise peaks have also been reported by Kobayashi *et al.* [17] for lasers with extremely narrow stripes. Noise resonance peaks of 4–5 dB indicate strongly damped relaxation properties. This can be explained by the high fraction of spontaneous emission present in the laser. The resonance frequency at I_{bias} = 125 mA was 2.6 GHz, which is much higher than the modulation frequency used in the distortion measurements. The influence of the resonance properties of the laser on harmonic distortion will be discussed later.

B. Transverse Junction Lasers

Distortion properties were also investigated for transverse junction lasers, whose built-in carrier confinement should improve spatial stability of the emitted light. Excellent dynamic properties have been reported for this structure [18].

Fig. 6(a) gives $R_{2f/f}$ and $R_{3f/f}$ for a TJS laser as a function of bias current. The modulation frequency is 60 MHz. Two values of modulation current have been used: 4 and 13 mA p-p corresponding to optical signals of ~1.2 and 4 mW p-p, respectively. For an output signal of 4 mW p-p, the lowest values observed for $R_{2f/f}$ and $R_{3f/f}$ are in the range of −52–60 dB and −60 to −65 dB, respectively.

It is known that feedback to the laser from an external cavity (e.g., microscope objectives, fibers, or mirrors) can induce instabilities resulting in kinks and pulsations [19]. Feedback will also influence the minimum levels obtained for the harmonic distortion. Thus, we found that the minimum levels for $R_{2f/f}$ in some cases increase 5–8 dB and $R_{3f/f}$ 1–3 dB relative to those in Fig. 6(a) when reflection from a partially reflecting mirror or the microscope objectives was present. Consequently, the second-harmonic distortion was found to be more sensitive to feedback than the third-harmonic distortion. The measurements indicate that great care should be taken to

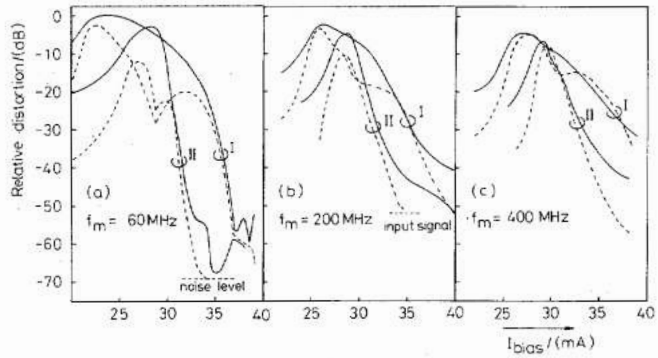

Fig. 6. Relative second- and third-harmonic distortion for a TJS laser. (———) is used for $R_{2f/f}$ curves and (- - -) for $R_{3f/f}$ curves. The modulation currents used are: curve I 13 mA p-p and curve II4 mA p-p. The modulation frequency is 60, 200, and 400 MHz for (a), (b), and (c), respectively. In (a) the measurement range is limited by noise in the detection system and in (b) it is limited by the distortion of the input signal.

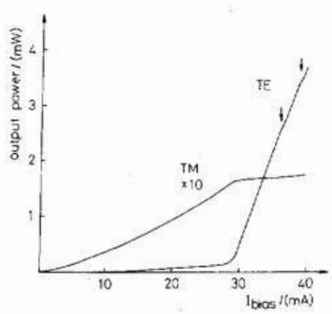

Fig. 7. Light-current characteristic for TE and TM light for the laser investigated in Fig. 6. Threshold current is 29 mA and slope efficiency is 0.3 mW/mA. The TM characteristic is magnified ten times.

avoid feedback, especially in analog signaling where only small distortion is tolerated.

For a detailed investigation of the device, the distortion measurements should be compared with other measurements, as was done for the 2.6-μm stripe laser. The light-current characteristic for TE and TM light is shown in Fig. 7. Threshold current is ~29 mA ($t_{heatsink} = 18°C$) and slope efficiency is ~0.3 mW/mA. It is noticed that small kinks (marked with an arrow) are seen in the TE characteristics. These kinks, which are present in all the TJS lasers investigated, are found to be associated with a sudden shift of the emitted light from one longitudinal mode to the neighbor mode with increasing current. Since the laser has only one longitudinal mode, the differential efficiency is very sensitive to mode shifts. Also in the TM characteristic, which is saturating above threshold, small changes can be seen where the mode shifts occur.

The distortion (see Fig. 6) was low in spite of the kinks seen in Fig. 7. This is because the thermal heating is responsible for the mode shifts [18] and the thermal time constant is much larger than one period of the modulation current. However, using a lower modulation frequency of 2-3 MHz, the temperature can reach to change during a period and the kink becomes effective. An increase of approximately 20 dB in the distortion has been measured in the bias current region where kinks appear.

The longitudinal mode shifts could also be seen in the noise measurements performed on the laser. The height of the noise resonance peaks was 10-12 dB, which is a little higher than the result for the narrow stripe laser, in agreement with the sharper increase of the characteristic seen for the TJS laser in the threshold region. The resonance frequency of the laser investigated in Figs. 6 and 7 was 2.6 GHz at $I_{bias} = 30$ mA. Since this is high compared to the modulation frequency, the resonance will not contribute seriously to the distortion.

At a higher modulation frequency the harmonic frequencies approach the resonance frequency of the laser with the consequence that the distortion is increased. This is illustrated in Fig. 6(b) and (c), where the distortion is shown for the modulation frequencies 200 and 400 MHz, respectively. The modulation currents are the same as those used in Fig. 6(a). It is seen that the increase in distortion at 200 and 400 MHz is ~15 and ~25 dB, respectively, relative to the distortion at 60 MHz, when the laser is biased well above threshold. In addition, for high modulation frequencies the second- and third-harmonic components will no longer be the only ones contributing to the total distortion because of the resonance peak. Therefore, the bandwidth, in which the linearity is good enough for analogue transmission of an optical signal with acceptable amplitude, will be limited to 100-200 MHz. The exact bandwidth will depend on the maximum bias current I_{bias} that can be tolerated due to the well-known proportionality between the squared laser resonance frequency f_{res}^2 and $(I_{bias} - I_{th})$.

C. Intermodulation Products

In analog systems, third-order intermodulation products are significant because they will fall within the frequency band of interest. It will be shown by comparison of measured second- and third-order products with second and third harmonics, that the lasers, when biased well above threshold and modulated at frequencies far below the resonance frequency, behave as simple nonlinearities without memory, i.e., the input-output transfer characteristic can be expressed as a power series. Therefore, the measurements of harmonic distortion are sufficient for characterization of the laser nonlinearities and the more complicated measurements of intermodulation products can be avoided.

If the laser acts as a simple nonlinearity without memory, the following relations hold for the second- and third-order distortion [21]:

$$L_{2a} = K_2 + 2L_a - 6 \text{ dB} \tag{1}$$

$$L_{ab} = K_2 + L_a + L_b \tag{2}$$

$$L_{3a} = K_3 + 3L_a - 15.5 \text{ dB} \tag{3}$$

$$L_{abc} = K_3 + L_a + L_b + L_c \tag{4}$$

where L_i (in decibels) represents the modulation amplitude of the ith frequency component relative to some fixed reference level, and K_2 and K_3 represent characteristic constants (in decibels) for nonlinearities.

The standard modulation scheme used for the measurements is shown in Fig. 8 [20], where f_1, f_2, and f_3 are frequencies of the three free-running oscillators used. From (1) and (2) the difference between the second-order intermodulation product at $f_3 - f_1$ relative to the amplitude at f_3, $R_{f_3-f_1/f_3}$, and the

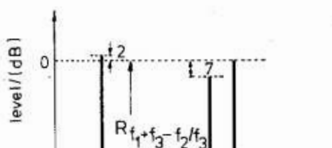

Fig. 8. Scheme for measurements of intermodulation products. The frequencies used are f_1 = 38.0 MHz, f_2 = 42.4 MHz, and f_3 = 43.5 MHz. Intermodulation products were measured at $f_3 - f_1$ = 5.5 MHz, and $f_1 + f_3 - f_2$ = 39.1 MHz.

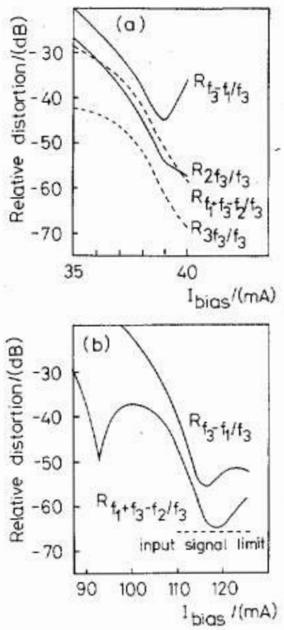

Fig. 9. (a) Relative second- and third-order distortion for the TJS laser investigated in Fig. 6. The modulation currents for the three modulation frequencies (see Fig. 8) are f_1: 9.1 mA p-p, f_2 3.3 mA p-p, and f_3 7.3 mA p-p. (———) is used for the R_{2f_3/f_3} and $R_{f_3-f_1f_3}$ curves, and (- - -) is used for R_{3f_3/f_3} and $R_{f_1+f_3-f_2/f_3}$. (b) $R_{f_3-f_1/f_3}$ and $R_{f_1+f_3-f_2/f_3}$ for the narrow stripe laser investigated in Figs. 2 and 4. The modulation currents are (see Fig. 8): f_1: 16.2 mA p-p, f_2; 5.8 mA p-p, and f_3; 12.9 mA p-p.

relative second harmonic R_{2f_3/f_3} is 8 dB when the modulation scheme mentioned is used. Similarly, from (3) and (4), the difference $R_{f_1+f_3-f_3/f_3} - R_{3f_3/f_3}$ is 10.5 dB.

Experimental results on $R_{f_1+f_3-f_2/f_3}$ and $R_{f_3-f_2/f_3}$ as a function of the bias current for the TJS laser treated above are shown in Fig. 9(a). The peak-peak modulation currents used for f_1, f_2, and f_3 are 9.14, 3.25, and 7.25 mA, respectively, which correspond to the peak-peak modulation optical powers 2.7, 1, and 2.2 mW, corresponding to a maxima of ~6 mW p-p. The minimum measured value of $R_{f_1+f_3-f_2/f_3}$ is -58 dB at 40 mA, which is less than our requirements of -56 dB for analogue video systems. The distance between $R_{f_1-f_3/f_3}$ and R_{2f_3/f_3} curves and $R_{f_1+f_3-f_2/f_3}$ and R_{3f_3/f_3} curves are 7 and 10 dB, respectively, in most of the bias current range, which deviates from the theoretical values mentioned by less than the experimental uncertainties. At $I_{bias} < 36$ mA, $R_{f_1+f_3-f_2/f_3} - R_{3f_3/f_3}$ is higher than prescribed by the nonmemory nonlinearity. The reason is that the third harmonic in this region is amplified by the laser resonance. At $I_{bias} > 39$ mA, $R_{f_3-f_1/f_3} - R_{2f_3/f_3}$ is higher than prescribed by the nonmemory nonlinearity. This comes probably from the mode jumping instability appearing at this current as mentioned earlier.

Similar experimental results [Fig. 9(b)] are also found for the narrow stripe laser treated in Figs. 3 and 4. A minimum value of $R_{f_1+f_3-f_2/f_3} = -65$ dB is found at $I_{bias} = 120$ mA, using a total optical signal of 5 mW p-p, which is also well below our requirements. $R_{f_3-f_1/f_3}$ and $R_{f_1+f_3-f_2/f_3}$ are, in this case, compared with the corresponding values at 60 MHz derived from the harmonics in Fig. 3. The agreement is within the experimental error of 2 dB in the range I_{bias} = 105–111 mA. Below 105 mA, the laser resonance creates larger deviation and above 111 mA deviation from the nonmemory behavior is also found. We assume the reason to be the diffusion created nonlinearity at high bias currents as treated in [22].

From (1) and (3) it is seen that for a simple nonlinearity the relative second-harmonic distortion increases proportionally to the modulation amplitude and the relative third-order harmonic increases proportionally to the square of the modulation amplitude. These relations were verified for the narrow stripe laser and the TJS laser within the experimental error of 0.3 dB for modulation current amplitudes up to 60 percent of $(I_{bias} - I_{th})$ and a deviation below 3 dB at 100 percent of $(I_{bias} - I_{th})$. Thus, we conclude that the distortion of the laser can be described by (1)–(4) when the modulation frequencies used are small compared to the resonance frequency and the laser is biased well above threshold. Therefore, the intermodulation products can be calculated from the measured harmonic distortion.

It should be emphasized that in spite of these excellent linearity results of these lasers, the applicability of these lasers in analog systems could be limited by the maximum power ratings. In fact some of the best results were obtained at powers above the maximum power ratings specified by the manufacturer, and hence can give increased long term degradation.

IV. Calculation of Harmonic Distortion

Rate equations have successfully described the transient behavior of a pulse modulated laser. The distortion properties of the laser can also, to a certain degree, be predicted from the simple rate equations having the following form:

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_s} - G(n)\,S \tag{5}$$

$$\frac{dS}{dt} = G(n)\,S + \frac{\beta n}{\tau_s} - \frac{S}{\tau_p} \tag{6}$$

where

$$G(n) = a\,(n - n_0) \tag{7}$$

J is the injected current density, n and S are the electron and photon density, τ_s is the electron lifetime, τ_p is the photon lifetime, β is the spontaneous emission factor, and a and n_0 are gain parameters. The distortion is calculated by Fourier transformation of the calculated stationary response from the laser when it is modulated with a sine function. The time response is obtained by direct numerical solution of (5) and (6).

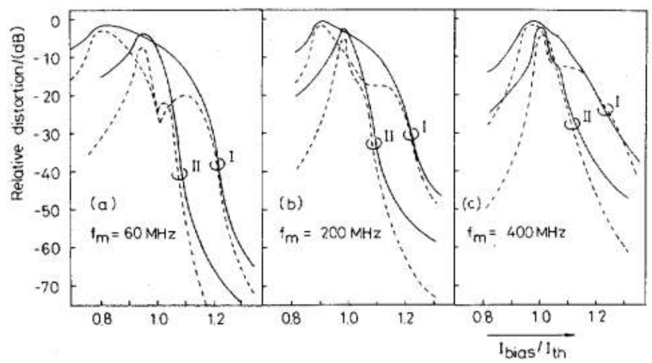

Fig. 10. Calculated relative second- and third-harmonic distortion. (———) is used for $R_{2f/f}$ and (- - -) for $R_{3f/f}$. The modulation currents are curve I $0.22 \times I_{th}$ and curve II $0.07 \times I_{th}$, which corresponds to the modulation currents used in Fig. 6. Calculations are performed for the modulation frequencies 60, 200, and 400 MHz in (a), (b), and (c), respectively. The laser parameters used are: $\tau_s = 1.2$ ns, $\tau_p = 2$ ps, $\beta = 2 \cdot 10^{-4}$, $a = 10^{-12}$ $m^3 \cdot s^{-1}$, and $n_0 = 10^{24}$ m^{-3}.

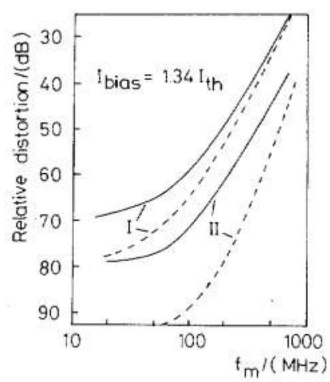

Fig. 11. Calculated relative second (———) and third (- - -) harmonic distortion as a function of modulation frequency. The bias current is $1.34 \times I_{th}$ and the modulation currents are: curve I; $0.22 \times I_{th}$ and curve II; $0.07 \times I_{th}$. The laser parameters are the same as those in Fig. 10.

From various measurements the parameters, which will have to be inserted in (5) and (6) for the TJS laser, have been estimated. $\tau_s = 1.2$ ns was determined from pulse delay measurements. This value is realistic since diffusion terms are not included in the model used. τ_p and an_0 were estimated to 2 ps and 1 ps, respectively, from measurements of the resonance frequency. With these values for τ_s, τ_p, and an_0, β was estimated to be $2 \cdot 10^{-4}$ using the halfwidths of the resonance peak. These parameters are in reasonable agreement with those published in [18]. In addition, n_0 was assumed to be 10^{24} m^{-3}.

Calculated curves for $R_{2f/f}$ and $R_{3f/f}$ are shown as a function of bias current in Fig. 10(a)–(c) for the modulation frequencies 60, 200, and 400 MHz, respectively. The modulation currents are the same as those used in the measurements shown in Fig. 6.

From Fig. 10(a) it is noticed that the agreement with measurements is within 5 dB when we neglect the effects measured at the distortion levels where minima occur. The calculated distortion for $f_{mod} = 200$ MHz and $f_{mod} = 400$ MHz are also in good agreement with the measured curves, although at high bias currents there is a tendency for the calculated distortion to be ~7–10 dB lower than the measured quantities. This is especially seen for $f_{mod} = 200$ MHz.

Calculated curves for $R_{2f/f}$ and $R_{3f/f}$ are shown in Fig. 11 as a function of modulation frequency for $I_{bias} = 1.34\, I_{th}$ for two different modulation current amplitudes. The curves clearly illustrate a tradeoff between maximum modulation frequency and modulation amplitude when the bias current is kept constant.

V. Conclusions

Distortion measurements are found to be a convenient way to investigate the stability of emission transfer characteristics for semiconductor lasers because of the high dynamic range of the measurement equipment.

Measurements of second- and third-harmonic distortion in the frequency range 50–100 MHz showed that the distortion was improved when the stripe width of the laser is reduced to 2–6 μm, which is comparable to the diffusion length of carriers. This indicates that diffusion is an important factor for obtaining good stability of the emitted light as concluded in [1]. Contributions to the distortion due to thermal heating properties are found to be of little significance for the modulation frequencies used. However, comparison of harmonic distortion at lower frequencies to distortion at 50–100 MHz might be a way to obtain information about thermally induced instabilities, giving rise to nonlinearity with memory.

The relaxation phenomena in the laser will contribute to the distortion when the modulation frequency is raised to more than ~5–10 percent of the resonance frequency of the laser. Therefore, the maximum modulation frequency which can be used for optical signals of 2–4 mW p-p will be in the range 100–200 MHz depending on the bias current that can be allowed for the laser.

The relations between the curves for third-order intermodulation products and the third-harmonic distortion are described by the expressions for distortion in a simple nonlinearity without memory, when the bias current relative to threshold is chosen so that it is higher than the amplitude of the modulation current.

Measurements show that narrow stripe lasers and lasers with current confinement for output powers of 4 mW p-p and modulation frequencies of 40–60 MHz have third-order intermodulation products, which are lower than those specified for analog transmission systems. In spite of these promising results it is of importance to mention that when light is transmitted through a fiber, as verified by a graded index fiber [23], additional distortion will occur due to transmission properties of the fiber. This extra distortion is related to the modal noise reported by Epworth [24]. It is found that lasers with a broad spectrum and consequently short coherence time are required to avoid this extra distortion. Details on this matter are left for a coming publication [23].

The distortion properties of the laser can be precisely described by simple rate equations, when realistic laser parameters are used in the equations. Therefore, since the calculations are relatively simple, the rate equations can be useful for prediction of the dependence of distortion on various laser parameters.

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