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Monomode Operation of Direct Modulated GaAlAs DHS Injection Lasers from 260 Mbit/s up to 1.4 Gbit/s

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Monomode emission of DHS lasers with stripe-geometry is demonstrated for 260 Mbit/s, 1.25 Gbit/s, and 1.4 Gbit/s. No structural difference between the cw spectra and the spectra during modulation can be observed for a defined range of operating parameters.

Numerical studies confirm the measured time dependence of the light output at high bit rates.

Monomodaler Betrieb direkt modulierter GaAlAs DHS Injektionslaser von 260 Mbit/s bis zu 1,4 Gbit/s

Monomodale Emission von DHS-Lasern mit Streifengeometrie wird für Bitraten von 260 Mbit/s, 1,25 Gbit/s und 1,4 Gbit/s demonstriert. Strukturunterschiede zwischen den CW-Spektren und den Spektren bei Modulation können in den Grenzen bestimmter Betriebsparameter nicht beobachtet werden.

Numerische Untersuchungen bestätigen den gemessenen Zeitverlauf der Lichtleistung bei hohen Modulationsraten.

1. Introduction

Direct PCM modulation of injection lasers at bit rates above 100 Mbit/s becomes difficult because of pattern effects, i.e. the dependence of the light pulses on the PCM pattern of the modulating current. Three effects are important: the lasing delay time, the prepumping effect, and the ringing caused by relaxation oscillations.

The initial delay after application of an injection current step until the onset of the laser oscillation [1] can be eliminated by a bias current near threshold.

If the laser is biased below threshold and modulated with two subsequent pulses, then the second pulse becomes biased at a higher level, because excess charge remains in the junction after cessation of the first pulse. Therefore the second light pulse will have a higher peak power than the first one. Reduction of this pattern effect by a prepulse preceding each modulation pulse which follows a logical zero was shown at a PCM rate of 200 Mbit/s [2]. If the modulation current has both forward and reverse swings, then the excess charge can be removed by the reverse swing. With a bias slightly below threshold an equivalent modulation rate of 500 Mbit/s was achieved [3].

For still higher bit rates up to the GHz-range the relaxation oscillations, which decay about with the electron lifetime, distort the optical pulses severely. Danielsen et al. [4], [5] proposed to choose the height and the width of the modulation pulse in such a way, that the laser would emit only its first spike of the relaxation oscillation. He gave approximate formulae for the condition, that after cessation of the modulating pulse the photon and electron density will reach quickly their stationary values defined by a bias near threshold. Most probably this optimum condition was fulfilled in former experiments [6]–[8], where bit rates up to 2.3 Gbit/s could be achieved.

So far only the time dependence of the laser light output was regarded. But to reduce the pulse dispersion in glass fibres at wavelengths of about 850 nm a narrow spectral output is imperative, together with a narrow pulse width for maximum information transfer. For this purpose injection locking techniques [9]–[14] are useful, but unfortunately, the optical arrangement is complicated and not easily adjusted. An alternative method is to bias the laser above threshold where, with selected devices, a monomode spectrum may exist and a kind of self-irradiating results. The advantage of retaining the stationary spectrum during modulation [15]–[17] is partly compensated, however, by the drawback of a not negligible light output during the zeros of a PCM signal. A bias below threshold is not advisable, for [15] and [18] show, that a delay time of up to 20 ns exists, until a monomode spectrum will develop. To the author's knowledge the maximum monomode modulation rate achieved up to now is 250 Mbit/s [15]. In this paper monomode modulation rates of 260 Mbit/s, 1.25 Gbit/s, and 1.4 Gbit/s are reported [16]. A numerical analysis of the monomode laser rate equations confirms the experiments.

2. Experimental Setup

The investigated DHS laser chips on a diamond heatsink inside a package with low parasitics (AEG-Telefunken, CQX 20 special) were mounted in a modified circuit as described in [19] having added

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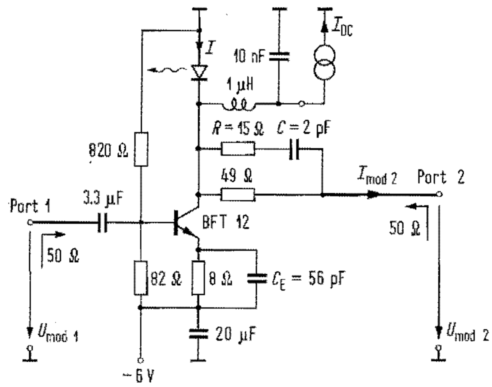

Fig. 1. Embedding network for modulation of injection current I with a voltage $U_{mod\,2}$.

a DC input, Fig. 1. Only port 2 was used for the various modulation experiments. The transistor was biased for a collector current below 1 mA. The temperature of the laser heatsink could be controlled electronically by means of a Peltier-element and a NTC-resistor. The modulation at 260 Mbit/s (Fig. 3) was produced using a gated HP 8082A as a word generator. The test signal with a bit pattern 11001 or 1101 (Figs. 4, 5) was derived from a mercury-relay generator [19], modified by the use of a very small position-independent relay (Hamlin MTHG-2), and a combination of power dividers with delay lines.

As detector an APD (AEG-Telefunken, BPW 28 special) was used with a multiplication factor of 14 and a risetime of 240 ps [20].

The laser light output was fed via a magnifying optical system to the entrance slit of a monochromator (Jobin-Yvon HRP, Czerny-Turner layout, focal length 600 mm, first order ruled grid with 1200 lines/mm and blaze wavelength 1 µm on a square of 70 mm × 70 mm). If the grid were fully illuminated by the entering beam, a transit time difference $\Delta\tau$ of rays at the extremities of the grid would exist, e.g. at $\lambda = 820$ nm $\Delta\tau = 130$ ps, resulting in an approximate overall risetime of the detector output voltage of 270 ps. In practice no significant increase of the overall risetime could be observed moving the grid from zero to first order reflection, Figs. 4, 5, indicating nonideal illumination of the grid.

3. Experimental Results

Only two lasers were available for measurements. Typical data at $T = 20$ °C heatsink temperature are summed up in Table 1. In the following text P_0 stands for the DC injection current and P_1 for the total peak current, normalized to the threshold current $I_{th} = 170$ mA.

Fig. 2 shows a typical cw spectrum at the highest available resolution of the monochromator, $\Delta\lambda = 0.1$ Å, indicating the existence of a monomode spectrum at $P_0 = 1.1$. With a measured width of $\Delta\lambda_{meas} = 0.13$ Å the laser line width $\Delta\lambda_{m\,cw}$ of the fundamental transversal mode can be estimated to be $\Delta\lambda_{m\,cw} \approx \Delta\lambda_{meas} - \Delta\lambda \approx 0.03$ Å.

Table 1. Typical parameters of investigated lasers at $T = 20$ °C heatsink temperature [16], [21]–[23].

recombination volume	0.5 µm × 17 µm × 500 µm
threshold current (cw) I_{th}	170 mA
saturation voltage of device	≈ 2 V
lifetime of electrons τ_s	1.5 ns
lifetime of photons τ_p	≈ 1 ps
wavelength of emission	≈ 820 nm
linewidth of spontaneous emission $\Delta\lambda_{sp}$	≈ 300 Å
cw monomode emission linewidth $\Delta\lambda_{m\,cw}$ between 5% and 13% above threshold (Fig. 2)	< 0.1 Å
pulsed monomode emission linewidth $\Delta\lambda_{m\,p}$	< 0.5 Å
factor of spontaneous emission Q_{sp} below threshold, measured from dc light-current characteristic	≈ 10^{-2}
factor of spontaneous emission $Q = Q_{sp}\,\Delta\lambda_m/\Delta\lambda_{sp}$ for monomode operation	< 10^{-5}
longitudinal mode distance	1.9 Å
transversal mode distance	≈ 0.1 Å
thermal resistance	52 K/W
thermal time constant	2.6 µs
thermal shift of a resonator mode	0.55 Å/K
thermal shift of the spontaneous emission line	2.4 Å/K
thermal shift of the threshold current (cw)	0.9 mA/K
thermal shift of the device voltage at constant injection current	≈ − 2 mV/K

Table 2. Results of modulation experiments.

bit rate (of light output)		0.26		1.25	1.7 (1.4)	Gbit/s
bit pattern (of light output)		11111111		11001	1101 (111)	
number of figure		3		4	5	
normalized bias current P_0		1.09		1.055	1.1	
normalized peak current P_1		1.24		1.11	1.16	
duty cycle of modulation word		$2 \cdot 10^{-3}$		10^{-6}	$5 \cdot 10^{-5}$	
length of modulation word		30		4	2.2	ns
heatsink temperature	16	20	24	20	20	°C
main spectral line	8215	8225	8227	8225	8225	Å
most prominent secondary line(s)	8213, 8217	8223, 8227	8225, 8229	8221	8221	Å
observed line width		< 0.5		< 0.5	< 0.5	Å
width of optical pulse		3.8		0.25	0.25	ns
linewidth due to switching of laser		≈ 0.006		≈ 0.1	≈ 0.1	Å
NRZ modulation possible		yes		no	no	
sensitivity to changes in bias current, modulation current and temperature		moderate		strong	strong	

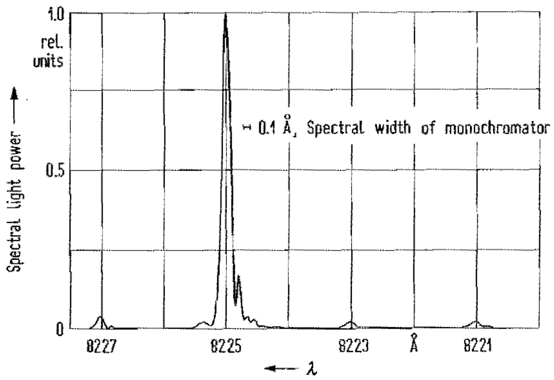

Fig. 2. Monomode cw spectrum at $P_0 = 1.1$. Spectral width of the monochromator $\Delta\lambda = 0.1$ Å. Measured emission line width $\Delta\lambda_{meas} = 0.13$ Å. Estimated laser line width $\Delta\lambda_{m\,cw} \approx 0.03$ Å.

The results of the modulation experiments are given in Table 2. Because of the low duty cycle of the superimposed modulation current the average temperature rise of the junction above its stationary value remained negligible. Due to the large thermal time constant the momentary temperature increase during a single 260-Mbit/s word stayed below 15 mK, resulting in a calculated mode shift of 0.01 Å and in a shift of the spontaneous emission line of 0.05 Å at the end of the pulse train, Table 1. Because of the shorter wordlength these temperature effects were even less important for the higher modulation rates.

Fig. 3a shows the laser current at a bit rate of 260 Mbit/s. A bias current $P = 1.09$ caused emission of a monomode spectrum at $\lambda = 8227$ Å. In Fig. 3b the optical power at the main wavelength 8227 Å and in Fig. 3c the optical power at the most prominent secondary lines 8229 Å, 8225 Å are displayed. The total optical power is nearly equal to the one at 8227 Å confirming monomode emission, the linewidth being less than 0.5 Å. Because the word generator does not completely return to zero between two pulses, because of a residual thermal displacement of the spectrum at the end of the modulation word, and because of charge storage effects in the lasing junction, the light power does not completely return to its stationary value between successive pulses and at the end of the pulse train.

A broadening of the spectral line when modulating the laser could not be observed. It was possible to reduce the modulation current amplitude from 25 mA ($P_1 = 1.24$) to zero ($P_1 = P_0 = 1.09$) without any change in the structure of the spectrum. Variation of the heatsink temperature from 16 °C to 24 °C caused mode jumping, Table 2. Apart from this shift the spectrum remained unchanged. Variation of the DC current by 15 mA from $P_0 = 1.07$ to $P_0 = 1.17$ at $T = 20$ °C caused similar mode jumps because of the different heating of the junction. In other respects the spectrum remained unchanged, if the peak current of $P_1 = 1.24$ was not exceeded; otherwise spontaneous fluctuations occurred.

Fig. 4a shows the laser modulation voltage $U_{mod\,2}$ at a bit rate of 1.25 Gbit/s. A bias current $P_0 = 1.055$ caused emission of a monomode spectrum at $\lambda = 8225$ Å.

Fig. 4b shows the total optical power, Fig. 4c the optical power at the main wavelength 8225 Å and Fig. 4d the optical power at the most prominent secondary line 8221 Å. The total optical power is nearly equal to the one at 8225 Å confirming monomode emission, the linewidth being less than 0.5 Å.

A small residual prepumping effect can be observed. Variation of the modulation amplitude from 2.6 mA ($P_1 = 1.07$) to 16 mA ($P_1 = 1.15$) caused stronger pattern effects for the higher amplitudes. At $P_1 = 1.07$ no pattern effect was observable, at $P_1 = 1.15$ a stronger prepumping effect and a 20% ripple at the logical zeros of the PCM word was recorded, but no change in the monomodal structure of the spectrum occurred.

Fig. 5a shows the laser modulation voltage $U_{mod\,2}$ at a bit rate of 1.7 Gbit/s. A bias current $P_0 = 1.1$

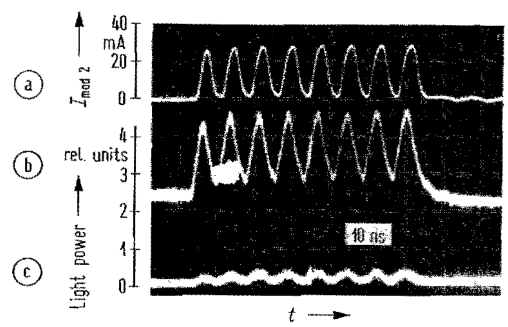

Fig. 3. Monomode emission at 260 Mbit/s. Spectral width of the monochromator $\Delta\lambda = 0.5$ Å, $T = 24$°C, $P_0 = 1.09$, $P_1 = 1.24$;
(a) injection current,
(b) light power at $\lambda_0 = 8227$ Å, virtually equal to total light power,
(c) light power at most prominent secondary modes, $\lambda_1 = 8229$ Å, $\lambda_2 = 8225$ Å.

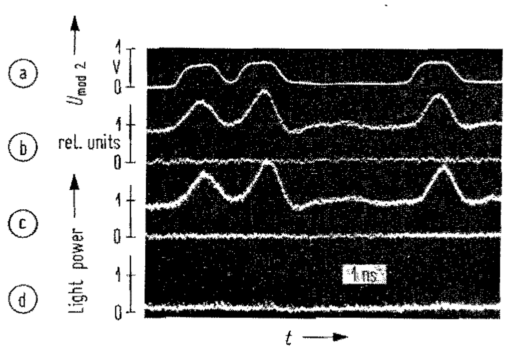

Fig. 4. Monomode emission at 1.25 Gbit/s. Spectral width of the monochromator $\Delta\lambda = 0.5$ Å, $T = 20$°C, $P_0 = 1.055$, $P_1 = 1.11$;
(a) input voltage at port 2,
(b) total light power, monochromator grid in zero order position,
(c) light power at $\lambda_0 = 8225$ Å,
(d) light power at most prominent secondary mode, $\lambda_1 = 8221$ Å.

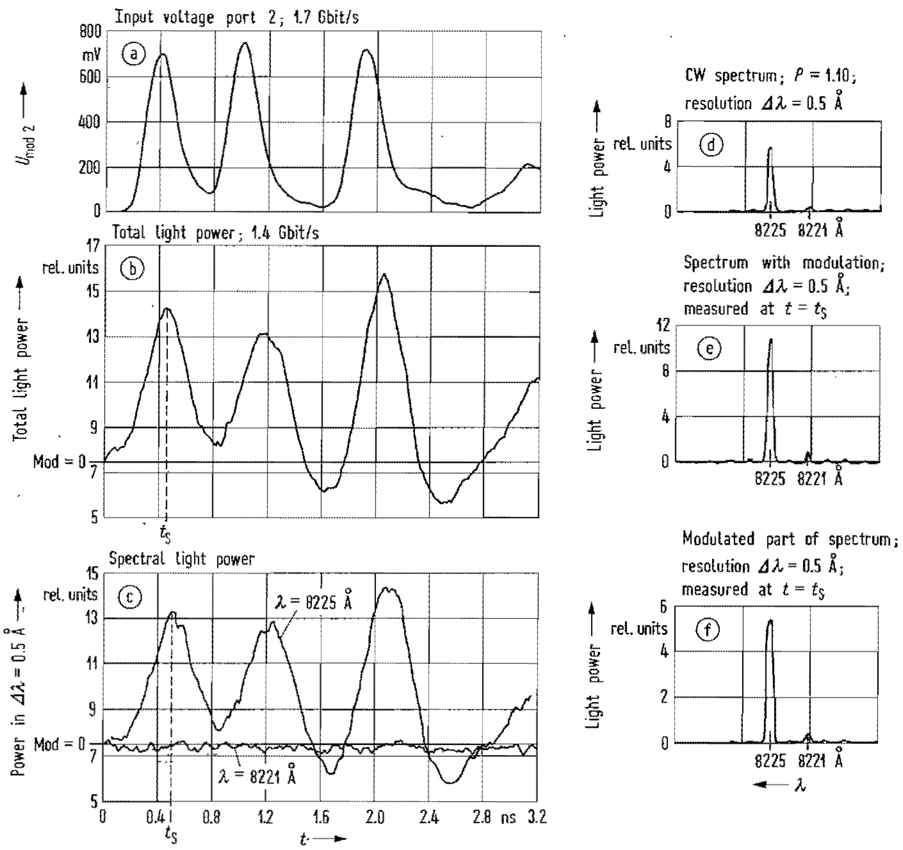

Fig. 5. Monomode emission at 1.4 Gbit/s. Spectral width of the monochromator $\Delta\lambda = 0.5$ Å, $T = 20$°C, $P_0 = 1.1$, $P_1 = 1.16$;
(a) input voltage at port 2,
(b) total light power, monochromator grid in zero order position,
(c) light power at $\lambda_0 = 8225$ Å and at most prominent secondary mode $\lambda_1 = 8221$ Å,
(d) cw spectrum,
(e) spectrum at time t_s including dc part,
(f) spectrum at time t_s excluding dc part.

caused emission of a monomode spectrum at $\lambda = 8225$ Å, Fig. 5d.

Fig. 5b shows the total optical power, Fig. 5c the optical power at the main wavelength 8225 Å and at the most prominent secondary line 8221 Å. In Fig. 5e the time resolved spectrum as measured at time t_s (Fig. 5b, c) is displayed, and in Fig. 5f the corresponding AC part of the spectrum is seen.

The equivalent bit rate of the light pulses is measured to be 1.4 Gbit/s instead of the expected 1.7 Gbit/s due to a delay of the second bit, a pre-pumping effect which could be observed in numerical calculations, too; so 1.4 Gbit/s seems to be a natural maximum bit rate for this type of laser.

The optical pulse width at the modulation rates 1.25 Gbit/s and 1.4 Gbit/s is measured to be 400 ps. If the detector switching time of 240 ps is considered, an original pulse width of $\Delta\tau \approx 250$ ps results, Fig. 6; this corresponds to a bandwidth $\Delta f \approx 1/\Delta\tau = 4$ GHz of the switched sinusoidal carrier, i.e. a broadening of $\Delta\lambda = 0.1$ Å at $\lambda = 8225$ Å. A certain broadening of the monomode emission line is observed, indeed. With a monochromator bandwidth $\Delta\lambda = 0.1$ Å (as used in cw experiments) the detected power was significantly less than for $\Delta\lambda = 0.3$ Å, so the standard resolution of $\Delta\lambda = 0.5$ Å (as used on modulation experiments) was chosen; but this increase of $\Delta\lambda$ had far less influence than the step from 0.1 Å to 0.3 Å.

For maintaining monomodal emission with small pattern effects no variation of the bias current, the modulation amplitude, and the temperature could be tolerated for the higher bit rates. NRZ modulation is impossible, for strong relaxation oscillations would result. For the 260-Mbit/s modulation rather large changes of the above mentioned operating parameters are allowable. NRZ modulation is possible.

4. Influence of Modulation Current Distortion

The impressed modulation voltage as shown in Figs. 4a and 5a becomes distorted by the differentiating network at input port 2 of Fig. 1 and the residual laser package parasitics. The switching times of the voltage pulse at port 2 are reduced by 25 ps to 85 ps, Fig. 6. In numerical studies no strong influence of the network parameters R and C could be observed in agreement with theory [4], because

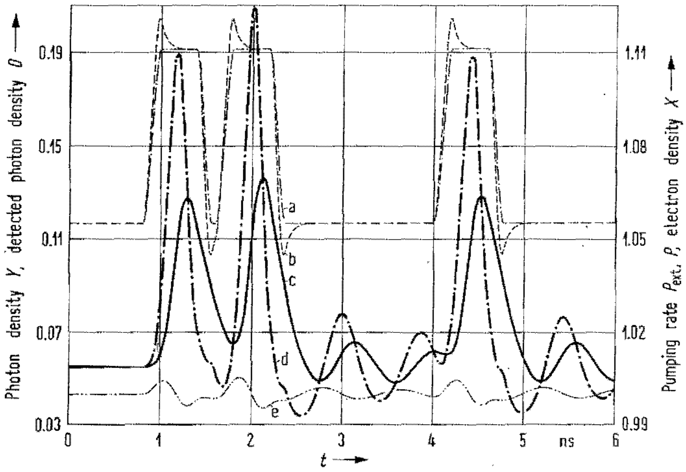

Fig. 6. Computed monomode laser response to a 1.25 Gbit/s modulation pattern; $P_0 = 1.055$, $P_1 = 1.11$, $\tau_s = 1.5$ ns $\tau_p = 1$ ps, $\tau_d = 240$ ps, $Q = 10^{-5}$, $n = 1.5$;
curve a: pumping rate P_{ext} without and
curve b: pumping rate P with differentiating network of Fig. 1;
curve c: detected normalized photon density $D = y_{det}/0.3 \cdot 10^{15}\,cm^{-3}$,
curve d: normalized photon density $Y = y/0.3 \cdot 10^{15}\,cm^{-3}$,
curve e: normalized electron density $X = x/0.4 \cdot 10^{18}\,cm^{-3}$.

the delivered charge and not the time function of the modulation pulse is of prime importance. Parasitic resonances could have an advantageous influence on the modulation behaviour of injection lasers, as was demonstrated recently [24]. This is not the case here, because long current pulses produced strong spiking.

5. Restrictions and Further Considerations

So far only two lasers could be investigated which behaved very similar. It is believed that all lasers with low-parasitic mounting and the lifetimes of Table 1 will exhibit high-speed monomode operation, if a broad range of the bias current exists, where the cw spectrum is monomodal.

Because of relatively large tolerances of the operating parameters a monomode transmission of PCM signals from 139 Mbit/s up to 280 Mbit/s seems to be feasible. Maximum monomode bitrates up to 1.4 Gbit/s can be used only for laboratory purposes, for the operating parameters have to be closely controlled.

Knowledge and stabilization of the laser chip temperature would be very helpful for many experiments. Having measured the thermal resistance R_{th} of the laser, Table 1, the temperature of the device $T_D = T_H + R_{th} N$ can be calculated by simple analogue means, if the heatsink temperature T_H and the electrical input power N is sensed. An alternative method uses the temperature dependence of the device voltage U, mainly due to the NTC-like characteristic of the spreading resistance R_s [16], [22]. For operation above threshold the junction voltage U_j saturates in the range of about 1.72 V (−20 °C) down to 1.55 V (+40 °C) because the electron density stays nearly constant by induced recombination, independent from the injection current I, Fig. 6. Preliminary measurements of the I-U-characteristic showed that in the temperature range from $T = 253$ K up to $T = 313$ K R_s can be fitted by the function $R_s(T) = R_s(T_0) \cdot \exp[B(1/T - 1/T_0)]$ with the resistance $R_s(T_0) = 2\,\Omega$ at the reference temperature $T_0 = 273$ K and the constant $B = 1500$ K. For comparison a typical NTC-resistor (Siemens K 17) yields

$$R_{NTC}(T_0) = 20\,k\Omega \quad \text{and} \quad B_{NTC} = 3000\,K.$$

If in a closed loop system the laser temperature is stabilized U_j remains constant, so R_s can be measured by computing $R_s(T) = (U - U_j)/I$. One of the common linearization schemes is useful to derive a temperature-proportional voltage as an error signal. Both measurement methods mentioned are investigated now.

6. Numerical Results

To study the dynamical behaviour of the investigated lasers a monomode rate equation approach [25]–[27] was used,

$$\tau_s \frac{dX}{dt} = P - X - Y X^n, \qquad (1)$$

$$\tau_p \frac{dY}{dt} = Y(X^n - 1) + Q(P)\,X, \qquad (2)$$

$$\tau_d \frac{dD}{dt} = Y - D. \qquad (3)$$

τ_s is the spontaneous lifetime of electrons, τ_p the photon lifetime, τ_d the APD time constant. $X = x/(\tau_s p_{th})$ represents the normalized electron density x, $Y = y/(\tau_p p_{th})$ the normalized photon density y, $D = y_{det}/(\tau_p p_{th})$ the normalized low-pass-filtered photon density y_{det} as indicated by a detector. The optical gain $g(x)$ is approximated by $g(x) = a x^n$ where a and n are constants. $p_{th} = i_{th}/(q w) = 1/(a \tau_p)^{1/n}/\tau_s$ is the threshold pumping rate with the injection current density i, the electron charge q and the width of the active layer w. $P = P(t) = P_0 + P_m(t) = p/p_{th}$ stands for the normalized pumping rate $P = i/i_{th}$. The exponent $n = 1.5$ of the optical gain and the factor $Q(P)$ of the spontaneous emission are both measured from the dc light-current characteristic, to which the function $Y = Y(P, dY/dt = dX/dt = 0)$ derived from eqs. (1), (2) was fitted. Far below threshold ($P_0 < 0.6$) $Q_{sp} = 10^{-2}$ was typically measured, and because $Q \sim \Delta\lambda_m/\Delta\lambda_{sp}$ holds [25] where $\Delta\lambda_m$ is the width of the laser spectrum and $\Delta\lambda_{sp}$ the spontaneous line width, Table 1, the Q-factor of monomode emission $Q = Q_{sp}\Delta\lambda_m/\Delta\lambda_{sp} \approx 10^{-5}$ could be determined.

Eqs. (1) to (3) were solved on a digital computer using a predictor/corrector method (Euler/Newton).

$P_m(t)$ was defined by computing the short circuit current response of the network at port 2 of Fig. 1 to cosine-edged pulses as shown in Fig. 4a. The calculated photon density as seen by a detector with 240 ps risetime, Fig. 6, agrees quite well with the recorded light power of Fig. 4b, remembering the very strong dependence of high bit rate performance on measured parameters like lifetime, bias and modulation current amplitude.

7. Conclusion

For DHS stripe-geometry injection lasers monomode operation at a bit rate of 260 Mbit/s was demonstrated. NRZ modulation is possible. The parameters temperature, bias and modulation current amplitude are not sensitive.

Monomode operation at bit rates of 1.25 Gbit/s and 1.4 Gbit/s could be achieved only with RZ modulation, and for a very limited set of parameters. A maximum rate of 1.4 Gbit/s seemed to be a final limit for the investigated lasers.

A significant structural change of the bias dependent cw spectra could not be observed when modulating the laser.

Numerical studies based on the monomode rate equations with consideration of the spontaneous emission confirmed the experiments.

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