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Cost-Effective Up to 40 Gb/s Transmission Performance of 1310 nm Directly Modulated Lasers for Short- to Medium-Range Distances

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Abstract—This paper presents successful 20 and 40 Gb/s potentially low-cost transmission experiments using 1310 nm directly modulated distributed feedback lasers (DMLs) in the very-short- to medium-range distances. This paper will recommend operating conditions for error-free transmission at these bit rates and distances. Pattern dependencies are identified. General characteristics of direct laser modulation are confirmed by dedicated simulation software and experiments. Unknown laser parameters needed to solve the rate equations are estimated by a given method based on measured and calculated small- and large-signal DML responses.

Index Terms—40 Gb/s, 1310 nm, direct laser modulation, laser characterization, parameter estimation.

I. INTRODUCTION

TO DEVELOP high-speed optical links at low costs, direct laser modulation (DLM) in combination with a simple PIN-photodiode-based receiver is still a very attractive option. The limits of high-speed DLM have been explored extensively in the past [1]–[8]. Recently, a 10 GbE DML was used for successful very-short-range (VSR) transmission experiments at 40 Gb/s [9]. This very high bit rate is the subject of discussion by many researchers [10]–[13]. Our research focus toward 40 Gb/s DLM was motivated by a design study for a very-large-scale next-generation low-frequency radio-antenna array (LOFAR) [14]. Within LOFAR, the Remote Elements Telescope Intelligent Network Architecture (RETINA) project is concerned with the development of a high-bit-rate optical data transport network connecting 168 antenna stations (160 Gb/s each) with the central processor [15].

As approximately 25% of the antenna stations are located within 5 km of the core, VSR links operating at 40 Gb/s in space-division multiplexing (SDM) schemes become a viable option for this part of the network. Transmission at the low-dispersion window of 1310 nm alleviates the need for dispersion-compensating modules, making the SDM schemes more simple and cost-effective. DMLs in combination with wide-band PIN-photodiodes could serve as a potentially low-cost architecture of the VSR links. Many other applications exist for (ultra-)high-speed 1310 nm DMLs such as a broadband interconnect between routers [13], an ultra-high-speed pulse source, video-con-

ferencing links, or OC-192 applications like SONET/SDH add-drop multiplexing.

In general, the performance of DMLs decreases at higher speed in terms of a decrease of the extinction ratio (ER) and enhanced wavelength chirp. Under normal conditions, this cannot be accepted. However, to fully exploit the high-speed properties of the DMLs, they have to be operated at high power conditions. When operated in VSR links using standard single-mode fiber (SSMF), the attenuation is of less importance and a significant reduction in ER can be tolerated. Moreover, when operated in the O-band, the enhanced chirp is far less detrimental, as dispersion is virtually eliminated.

In this paper, we study the properties of high-speed 1310 nm laser diodes for applications in VSR to medium-haul transmission at 40 and 20 Gb/s, respectively. All experiments are done for a laser temperature of 25°, unless noted otherwise. This paper is organized as follows. Section II focuses on the estimation of the device parameters and lists simulation results. Section III describes the characterization of the devices at high bit rates. In Section IV the results of the transmission experiments are presented. Section V concludes and discusses the most relevant findings encountered in the previous sections.

II. PARAMETER ESTIMATION AND SIMULATION

The laser's modulation bandwidth is generally governed by its relaxation oscillation frequency f_{rel} . It is present in the laser's response due to the interaction between carrier and photon densities [16]. The 3 dB bandwidth $f_{3\text{dB}}$ of the DML is related to f_{rel} and the K -factor. The nonlinearity of the gain damps f_{rel} , represented by the damping factor Γ_d . A low K (high f_{rel} , low Γ_d) implies a high $f_{3\text{dB}}$. The bias current I_b is linearly related to the photon density S . As f_{rel} is proportional to $\sqrt{S}$, raising I_b will raise f_{rel} and thus $f_{3\text{dB}}$.

Ultimately, gain suppression and the damping Γ_d set an upper limit to raising f_{rel} . A number of laser design considerations have been reported that lead to higher f_{rel} , e.g., cooling the laser to increase g_0 [10]. Other important bandwidth limiting factors are imposed by parasitic capacitances and inductances introduced by the laser chip, the package, and the mounting assembly of the DML.

The DML's response to a logical 010 transition superimposed on its bias current shows an over- and undershoot. The corresponding rise and fall times (t_{rise} and t_{fall}) are inversely proportional to the relaxation oscillation frequencies of the over- and

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Fig. 1. 40 Gb/s 2^7-1 PRBS for PPG. $\hat{I}_{\text{mod}} = 35$ mA, 100 ps/div. (a) Measured and (b) simulated.

TABLE I
DML DATA SPECIFIED BY PROVIDERS

DML	λ [nm]	I_{th} [mA]	f_{rel} [GHz]
A1	1310.02	11.06	18.14 ($I_{\text{th}} + 30\text{mA}$)
A2	1316.48	18.24	19.85 ($I_{\text{th}} + 30\text{mA}$)
B	1303.34	11.90	>20 ($I_{\text{th}} + 40\text{mA}$)

undershoot. Having the logical 0-level at a lower I_b , it is thus physically impossible that t_{fall} is faster than t_{rise} . By finding a tradeoff between the modulation depth m , $m = \hat{I}/(I_b - I_{\text{th}})$, and the laser's measurable figures of merit, an optimum response has to be realized. The three DMLs studied in this paper are all commercially available 10 GbE 1310 nm multiple quantum-well distributed feedback DMLs [two Agere D1861A (A1 and A2) and one NEL NLK5B5E2KA (B)]. Relevant data measured by the providers are listed in Table I. These data in general did not correspond to the authors' observations.

To confirm and visualize the theoretically stated properties of DMLs, simulation software was written in MATLAB. Given a value for the input current $I(t)$, the rate equations describing the carrier density rate $N(t)$ and the photon density rate $S(t)$ are numerically solved using a Runge-Kutta (RK) scheme [17]. The rate equations that are used by the simulation software are shown in [18].

An ideal nonreturn-to-zero (NRZ) bit sequence is shaped to represent nonideal measured pulse pattern generator (PPG) responses at bit rates of 10, 20, and 40 Gb/s. The (a)symmetrical shape is achieved by using a Butterworth filter concatenation. The measured and simulated 40 Gb/s PPG bit sequences are shown in Fig. 1. The simulated results resemble very well the measured bit sequence.

For unknown reasons, laser providers were unable to release essential data of the laser parameters. Therefore we concentrate on one device, DML A1, to estimate a set parameters for simulation purposes. The parameter estimation is done by comparing

Fig. 2. Subtracted transfer functions DML A1.

and fitting measured small- and large-signal responses with calculated values in principal similar to [18]. Small-signal measurements were carried out at seven different bias currents by using a network analyzer (HP8703A) as described in [19]. Frequency-dependent noise in the transfer functions is removed by subtracting all but one intensity modulation (IM) response with one measured at a low bias current as shown in Fig. 2.

To fit the theoretical model with the measured data of Fig. 2, an iteration based on Newton's method is used and gives very good fits for all six curves. The fits are evaluated in the routine by examining the relative error between subsequent loops Δ_{rel} . The iteration can be said to be converged if Δ_{rel} is negligibly low ($0 \leq \Delta_{\text{rel}} \ll 1$). Typical it takes 11 iteration loops to have $\Delta_{\text{rel}} < 1 \cdot 10^{-12}$ and an average error per data point below 0.02.

Using the results of the fit on the subtracted IM responses, it is possible to plot Γ_d as a function of f_{rel}^2 for DMLs A1 and A2

TABLE II
ESTIMATED K -FACTOR AND f_{3dB} DMLs A1 AND A2

DML	K -factor [ns]	f_{3dB} [GHz]
A1	0.29	30.81
A2	0.22	40.52

TABLE III
LASER PARAMETERS FOR DML A1

Parameter	Unit	Initial	Optimized
V ($\times 10^{-11}$)	cm^3	1.4	1.450
Γ	-	0.1	0.100
g_0	cm^3/s	4.5	4.300
η_0	-	0.4	0.240
ϵ ($\times 10^{-17}$)	cm^3	2.5	3.500
τ_p	ps	1	0.712
τ_n	ns	1.5	1.350
β ($\times 10^{-4}$)	-	1	1.000
N_{tr} ($\times 10^{18}$)	cm^{-3}	1	1.550

[20]. A linear curve fit is used to find the K -factors by which f_{3dB} is calculated. Results are listed in Table II.

The estimated values presented in Table II indicate that the devices could be operated even at 40 Gb/s.

The next step is to estimate the nine device parameters that constitute the rate equations. As a starting point, an initial parameter set is introduced based on values commonly encountered in literature for similar laser structures. After several optimization steps, the parameter set of Table III is found to adequately describe the laser's response.

This set is comparable with reported simulation parameters for high-speed DMLs [21]. Calculating the K -factor and f_{3dB} for the optimized set results in $K = 0.35$ ns and $f_{3dB} = 25$ GHz [22]. The simulated large-signal responses are shown with measured data in Figs. 3 and 4.

Simulated eye patterns at 40 and 20 Gb/s are shown in Figs. 5 and 6. Fig. 5(b) indicates a clear feasibility of 40 Gb/s operation at high bias condition. The simulations also show two important DLM characteristics. Fig. 5 shows that decreasing the modulation depth m by raising I_b improves the laser's response. Fig. 6 shows that decreasing m by lowering $\hat{I}_{mod}$ improves the shape of the eye pattern: it becomes more symmetrical at the expense of ER. The eyewidth remains nearly unchanged.

III. DML CHARACTERIZATION AT HIGH BIT RATES

As discussed in the previous section, frequency parasitics can limit the DML's bandwidth. The mounting assembly of DML A1 is shown in Fig. 7. S_{11} measurements report that reflections from the assembly are less than -27 dB (0.1–20 GHz). The mounting assemblies for DMLs A1 and A2 are originally designed for 20 Gb/s operation. The subminiature A (SMA) connectors have an electrical cutoff frequency of 18 GHz, but the cutoff frequency of the GPO connector (GPO is a trademark of Gilbert Engineering) is specified up to 40 GHz. Even though

Fig. 3. Measured and simulated L-I curve DML A1.

Fig. 4. AC response DML A1. $I_b = 60$ mA, $\hat{I}_{mod} = 17.5$ mA, 50 ps/div. (a) Measured and (b) simulated.

DML A1 should be capable of reaching bit rates over 20 Gb/s (Table II), its mounting assembly is limiting the performance. Modulating directly on the GPO connector should reduce the influence of frequency parasitics.

A 40 Gb/s back-to-back (BTB) experiment did not result in a clear eye pattern (Fig. 8), neither for DML A2 that has a similar mounting.

DML B, however, is equipped with a K connector (K is a trademark of Wiltron) specified up to 40 GHz for a direct connection with the PPG. Measured 40 Gb/s eye patterns for DML B are shown in Fig. 9. The eyes in Fig. 5 are similar to those in Fig. 9. A slow fall time is observed at low bias condition. A comparison between DML A1 and DML B at 20 Gb/s is shown in Fig. 10. All three DMLs are characterized using the same measurement setup.

Fig. 5. 40 Gb/s simulated eye patterns DML A1. $\hat{I}_{\text{mod}} = 35$ mA, 5 ps/div. (a) $I_b = 55$ mA and (b) $I_b = 90$ mA.

Fig. 6. 20 Gb/s simulated eye patterns DML A1. $I_b = 70$ mA, 10 ps/div. (a) $\hat{I}_{\text{mod}} = 35$ mA and (b) $\hat{I}_{\text{mod}} = 11$ mA.

Fig. 7. Mounting assembly of DML A1. DML A2 has no RF cable.

A. ER and Eye-Width Properties

ER and eye-width properties are characterized at 20 Gb/s for DMLs A and B and at 40 Gb/s only for DML B. Similar behavior for all DMLs is observed at these measurements. Fig. 11 shows ER values as a function of the modulation index m for DML B ($m = \hat{I}_{\text{mod}}/(I_b - I_{\text{th}})$, with $\hat{I}_{\text{mod}}$ and I_b defined in Fig. 12). One can observe that the ER increases in a nonlinear way as m also increases. This is due to the fact the value of the ER will go to infinity as the optical power of the logical zero-level goes to zero.

Fig. 8. Eye pattern of time trace shown in Fig. 4(a).

For each $m < 0.4$, different $I_{\text{mod},pp}$ give similar ERs. This is due to the linearity of the L-I curve at low bias currents. For each $m > 0.4$, a smaller $I_{\text{mod},pp}$ gives a larger ER. This is due to the saturation of the L-I curve at high bias currents. A lower I_b is needed to get the same m for smaller $I_{\text{mod},pp}$.

(a)

(b)

Fig. 9. 40 Gb/s eye patterns DML B. $\hat{I}_{\text{mod}} = 35$ mA, 10 ps/div. (a) $I_b = 50$ mA and (b) $I_b = 100$ mA.

(a)

(b)

Fig. 10. 20 Gb/s eye patterns. $I_b = 60$ mA, 20 ps/div. (a) DML A1 and (b) DML B.

Fig. 11. ER versus m at 20 Gb/s for DML B.

The DML needs to be operated at a high bias current to have a high f_{rel} . As a consequence, the ER will decrease, but this is

Fig. 12. Definition of I_b , $\hat{I}_{\text{mod}}$, and $I_{\text{mod,pp}}$.

of less importance when operating the DML in very short links. Fig. 13 shows eye-width values as a function of m . A smaller $I_{\text{mod,pp}}$ does not cause a better eye-width. This observation corresponds with the simulation results in Section II. The eye becomes more symmetrical because of an increase in the value of t_{rise} and a decrease in the value of t_{fall} .

B. Rise- and Fall-Time Properties

A broad range of measurements are done to evaluate the effect of the modulation on rise and fall times. A particular part of the 2^7-1 pseudorandom bit sequence (PRBS) was chosen for evaluation. This part contains a diverse range of logical bit transitions as shown in Fig. 14.

 Fig. 13. Eye-width versus I_b at 20 Gb/s for DML B.

 Fig. 14. Bit transitions at 2^7-1 PRBS (simulation).

Measured 40 Gb/s bit transitions at low and high I_b are shown in Fig. 15.

The total time, defined as $t_{\text{total}} = t_{\text{rise}} + t_{\text{fall}}$ per bit transition is shown in Fig. 16 for DML B at 40 Gb/s. Three different values of $I_{\text{mod},pp}$ are considered at a low and high I_b . Measurement results are sometimes influenced by the onset of f_{rel} in the “0”-state. In this case the measured t_{fall} of a bit transition was lower than the corresponding t_{rise} . To avoid ambiguities, all measurements were restricted to the levels 20%–80%. Pattern dependencies are observed by the peaks in t_{total} at particular bit transitions. In this case, the logical consecutive “1” decreases the performance at 40 Gb/s for DML B. The pattern dependencies vary with the laser and operating conditions such as bit rate.

We observe a number of remarkable dynamical phenomena by varying the modulation depth m at equal bias current I_b . First, the fall times improve at lower m due to the fact that the relaxation oscillation frequency at the logical “0” level increases (associated with higher power during the “0” state). Secondly, the rise time increases as the pulse overshoot decreases. As a result, the t_{total} remains nearly unaffected when lowering $I_{\text{mod},pp}$. These observations are reflected in the values presented in Table IV, showing the measured t_{rise} , t_{fall} , and t_{total} for bit transition 5 at different conditions for all DMLs.

Fig. 17 shows 10 Gb/s bit sequences generated by DMLs A1 and B. Lateral carrier diffusion causes the observed saturation effect at both sequences [16]. This effect is clearly visible by the slow time constant of the rise and fall times at bit transition 5. The parasitics associated with the mounting assembly of DML

 Fig. 15. 40 Gb/s DML B. $I_{\text{mod}} = 35$ mA, 50 ps/div. (a) $I_b = 65$ mA and (b) $I_b = 100$ mA.

A1 cause the ringing as observed in Fig. 17. The simulation does not model parasitics or lateral carrier diffusion.

IV. TRANSMISSION EXPERIMENTS

Error-free 20 Gb/s transmission in the O-band is measured over 37.5 km SSMF using DML A2 with a 10 GHz clock signal in the C-band. Error-free 40 Gb/s transmission is measured over 2.5 km SSMF using DML B. NRZ signals are used at all experiments. DML A2 was chosen for the 20 Gb/s transmission experiment because of its higher P at low I_b than DML A1. No optical preamplification was used. The zero-dispersion wavelength of the transmission link is 1313 nm.

A. 20 Gb/s Transmission With DML A2

Due to the absence of a 20 GHz clock recovery unit that extracts the clock frequency directly from the incoming data, we transmitted a 10 Gb/s data signal on a separate channel (1550 nm) similar to [23]. At the receiver-end, the 20 Gb/s data is separated from the 10 Gb/s data by a 1.3/1.5 μm coarse wavelength-division multiplexer (CWDM) as shown in Fig. 18.

A low impedance front-end (HP11982A) with a sensitivity of -9.3 dBm is used for the O/E conversion of the received 20 Gb/s data signal. A 10 G clock recovery unit (NEL MC240-100A with NEL MOS43CM) with a sensitivity of -17 dBm is used to generate a 10 GHz clock from the 10 Gb/s data signal. Table V lists a link budget for this CWDM scheme. Measured bit error rate (BER) curves for an SSMF length of 37.5 km are shown in Fig. 19.

A pattern-dependent penalty of 0.7 dB is measured for a BTB setup at 20 Gb/s. This penalty is caused by a limited low-frequency response of the O/E converter when a long sequence of “0” or “1” is detected. For error-free transmission over 25 km SSMF, an ER of 5.06 dB ($I_b = 60$ mA, $I_{\text{mod}} = 35$ mA) proved to be sufficient. Observed pattern-dependent penalty at 25 km is 1 dB. The same settings for a SSMF length of 37.5 km resulted in the BER curves given in Fig. 19.

Fig. 16. Total time per bit transition at 40 Gb/s for DML B. (a) $I_b = 65$ mA and (b) $I_b = 100$ mA.

TABLE IV
RISE AND FALL TIMES FOR BIT TRANSITION 5; ALL DMLs

DML	I_b [mA]	$\hat{I}_{mod}$ [mA]	m	Bitrate [Gbit/s]	t_{rise} [ps]	t_{fall} [ps]	t_{total} [ps]
A1	90	35.0	0.44	10	11.43	30.55	41.98
	90	17.5	0.22	10	14.20	25.44	39.64
A2	90	35.0	0.47	10	13.80	25.85	39.65
	90	17.5	0.24	10	16.78	22.99	39.68
B	100	35.0	0.39	40	7.54	13.93	21.47
	100	17.5	0.20	40	7.73	13.48	21.21

For DLM at 1316 nm, the dispersion is not the limiting factor. In the setup the CWDMs introduced an optical loss of approximately 3–4 dB to the received data. This loss decreases substantially the link budget of the system. Using a direct retrieval of the clock signal from the incoming data, an increased link budget of about 3–4 dB is expected for the same receiver performance.

B. 40 Gb/s Transmission With DML B

To avoid the use of components limiting the experiment, the setup is specified for 40 Gb/s transmission. The capacitor of a

65 GHz bias T (SHF 123B) is used as a blocking C, and a photo diode (PD) with a transimpedance amplifier (TIA) (U²T TIA UPRV2020) is used for the O/E conversion. The DML temperature was lowered to 10 °C to increase g_0 . For an ER of 1.81 dB ($I_b = 95$ mA, $\hat{I}_{mod} = 35$ mA) error-free BTB transmission was measured. A BER of $2 \cdot 10^{-11}$ was measured over 2.5 km SSMF. By raising I_b to 100 mA (ER = 1.67 dB), an error-free transmission over the same distance was obtained as shown in Fig. 20.

Fig. 21 shows the eye slightly improved at the end of the transmission link. This is caused by the fact that the operating

Fig. 17. 10 Gb/s sequence. $I_b = 50$ mA, $\hat{I}_{mod} = 35$ mA, 200 ps/div. (a) DML A1 and (b) DML B.

Fig. 18. Experimental setup for 20 Gb/s transmission with DML A2.

TABLE V
LINK BUDGET FOR 20 Gb/s TRANSMISSION WITH DML A2

(Loss) Element	10G Clock (1550 nm)	20G Data (1316 nm)
Laser Source	-4.2 dBm	7.5 dBm
Receiver Sens.	-17.0 dBm	-9.3 dBm
Allowed Loss	12.8 dB	16.8 dB
2 C-WDMs	-3.0 dB	-3.0 dB
37.5 km SSMF	-9.0 dB @0.24 dB/km	-12.0 dB @0.32 dB/km
System Margin	0.8 dB	1.8 dB

wavelength is in the anomalous dispersion region, so optical compression may occur along the link. We observed a slight improvement of the eyes compared with these presented in Fig. 9. The 10 G Precision Timebase used in this experiment came available during the research. The relatively poor receiver sensitivity of 6.2 dBm (Fig. 20) is merely caused by the low electrical output of the PD-TIA front-end. A suitable low-noise high-bandwidth electrical amplifier after the TIA should considerably increase the receiver sensitivity and as such improve the link budget. This is supported by recent 43 Gb/s transmission results reported in [24].

Fig. 19. 20 Gb/s BER curves DML A2. $I_b = 60$ mA, $\hat{I}_{mod} = 35$ mA.

Fig. 20. 40 Gb/s BER curves DML B. $T_{LD} = 10$ °C.

Fig. 21. 40 Gb/s eye patterns. $T_{LD} = 10^\circ\text{C}$, $I_b = 95\text{ mA}$, $I_{mod} = 35\text{ mA}$. (a) Back-to-back and (b) after 2.5 km SSF.

V. DISCUSSION AND CONCLUSIONS

The central issue in high-speed direct laser diode modulation is given by the large discrepancy between the very fast rise time and the much slower fall time in the laser response. This is embedded in the highly nonlinear nature of the laser diode as the rise time is dominated by the relaxation oscillation associated with the logical "1"-state (which is usually at high power level), whereas the fall time is dominated with the relaxation oscillation in the logical "0"-state inherently at a low power level. Pursuing a high extinction ratio (e.g., 8.2 dB in the current 10 Gb Ethernet standard) will always result in relatively slow fall times that restrict the laser to modulation up to 10 Gb/s only.

The key factor to improve the modulation response is to increase the bias current up to a power level where reliable operation is still guaranteed and to decrease the ER. As such the "0"-state power level is pushed to a power level associated with a significantly higher relaxation oscillation frequency (f_{rel} relates to the power with $\sqrt{P}$) resulting in a substantially faster fall time. As a rule of thumb, the sum of the rise and fall time

should not exceed the bit-slot time of 50 ps for 20 Gb/s and should be restricted to 25 ps for 40 Gb/s.

We explored experimentally a number of laser diodes targeted for 10 GbE applications and found that this situation is adequately met at an ER of 5–6 dB for 20 Gb/s and 2 dB for 40 Gb/s. Although reduction of the ER introduces an sensitivity penalty (2.5 dB; respectively, 5 dB), this can be tolerated given the high laser output power level and the limited transmission distances envisioned. Supporting transmission experiments show clear evidence for error-free transmission of 20 Gb/s over 37.5 km SSF and 40 Gb/s transmission over 2.5 km SSF. Improving the receiver sensitivity at 40 Gb/s should at least double this distance.

Within this paper, general improvements and effects in the DML responses due to varying input settings are verified, characterized, and explained for operating bit rates at 10, 20, and 40 Gb/s. Simulation software is tuned to measured DML responses by a given laser parameter estimation based on small- and large-signal DML responses. As confirmed by simulations and experiments, we observe a strong potential for high-speed 1310 nm DMLs in simple and low-cost transmission schemes at bit rates of 20–40 Gb/s for short- to medium-range distances.

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