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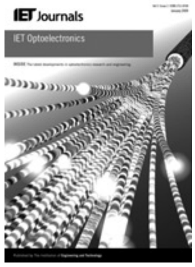

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Electronic distortion equalisation by using decision-feedback/feed-forward equaliser for transient and adiabatic chirped directly modulated lasers at 2.5 and 10 Gb/s

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Abstract: A thorough study on the beneficial use of electronic distortion equalisation (EDE) in the transmission performance enhancement of conventional low-cost directly modulated lasers (DMLs) is provided. The studies focus first on the compensation of the chromatic dispersion effect and then on the compensation of cascaded filtering effects of DML generated transmission signals in a system, by means of the feed-forward and decision-feedback equalisers (FFE/DFE). The reported studies consider DMLs with different chirp characteristics operating at 2.5 and 10 Gb/s, using parameters that have been extracted from real lasers, previously verified by simulations and experiments. The performance efficiency of EDE is evaluated in terms of eye-opening penalty degradation associated with the signal transmission over a standard single mode fibre. Extensive simulations reveal significant performance improvement for all the examined cases by using the FFE/DFE. Furthermore, the results show that the equalisation efficiency strongly depends on the chirp characteristics of DMLs.

1 Introduction

A critical factor that affects the cost of metro/access networks is the cost of terminal equipment. In this concept, one solution is the use of effective low-cost transmitters such as directly modulated lasers (DMLs). Additional characteristics of DMLs that make them suitable for metro/access networks are their low-driving voltage, small size and high-output power, compared with externally modulated lasers (EMLs). However, the transmission distance that can be achieved with most of DMLs without dispersion compensation over standard single mode fibre (SSMF) is limited to 10 km at 10 Gb/s [1] and 100 km at 2.5 Gb/s, because of the frequency chirp characteristics of DMLs. Furthermore, another limitation in designing transparent metro networks is the signal degradation because of transmission through multiple filtering elements in the system. This effect is more pronounced when transmitters with large optical spectral bandwidth are used. This paper addresses these issues, exploring the beneficial use of electronic equalisation in the transmission performance enhancement of conventional low-cost DMLs as well as the compensation of cascaded filtering effects of DML transmission signals in a system.

To enhance the transmission distance of DMLs, several different solutions have been proposed. One approach was suggested in [1], where the use of a special fibre with negative dispersion characteristics was proposed as a solution for the mitigation of the chirp problem. However, this is not a practical solution as SSMFs are massively deployed in metro networks today. Another promising approach is based on the development of special laser modules able to reach up to 560 km at 2.5 Gb/s by using either special DML designs, for example, buried heterostructure gain coupled DFB semiconductor laser [2] or new techniques, for example, chirped managed lasers, that have been proposed for longer distances [3, 4]. On the other hand, the use of electronic distortion equalisation (EDE) in transmission performance enhancement has been extensively studied and demonstrated for several different types of EML transmitters [5–7]. However, the use of EDE in combination with a DML transmitter has only been reported in [8]. In that study, it was shown that the use of a feed-forward equaliser (FFE) (5) can double the transmission distance at 10 Gb/s, but the influence of different types of laser chirp characteristics was not studied. To the best of our knowledge, no thorough studies have been reported for all the different types of low-cost DML-based transmitters at 2.5 and 10 Gb/s associated with EDE performance enhancement.

With respect to filter concatenation effects, there are many studies that have explored the effects of filter cascading on signal quality and its spectral narrowing. Most of these studies have considered EML transmitters [9, 10], whereas also a few studies have focused on the effects of filter concatenation for DML transmitters [11, 12]. Furthermore, the use of EDE technologies for the mitigation of the distortion that is caused by filtering effects introduced by narrowband optical filtering in EML-based systems have been examined in [13–15]. However, to the best of our knowledge, there are no studies focusing on the mitigation of the filter concatenation effect with the use of EDE technologies on DML-based transmitters.

The work presented in this paper provides detailed studies on the impact of FFE and decision-feedback equaliser (DFE), for the mitigation of transmission distortion effects (because of chromatic dispersion) and filter concatenation effects, when these equalisation schemes are applied in transient and adiabatic chirped DML-based transmission systems at 2.5 and 10 Gb/s. Some preliminary work related only with the electronic mitigation of chromatic dispersion has been presented in [16], which proves some of the findings in [8]. Here, further results are presented and discussed in more detail. The extracted parameters of DMLs that are used in this work have been previously verified by simulations and experiments in [17]. Additionally, it should be noted that the prime focus of this work is on the performance improvement of conventional DMLs (transient and adiabatic chirped) and not the advanced types of DMLs [2–4]. It is clear to realise that if EDE is used for the newly developed DMLs, further improvement is expected, as it was shown in [18].

This paper is organised as follows. In Section 2, the simulation models and the laser parameters used in the studies are presented and analysed. Section 3 shows the experimental simulation set-ups used in this work to obtain the results. In Sections 4 and 5, the results for the mitigation of the chromatic dispersion and filter concatenation effects by means of FFE/DFE electronic equalisation are discussed in detail and presented.

2 Simulation models and parameters

The performance of DMLs strongly depends on the characteristics of the laser frequency chirp. The chirp $\Delta\nu(t)$ of a DML is related to the laser output power $P(t)$ through the expression

$$\Delta\nu(t) = \frac{\alpha}{4\pi}\left(\frac{\mathrm{d}}{\mathrm{d}t}[\ln(P(t))] + \kappa P(t)\right) \tag{1}$$

where α is the linewidth enhancement factor and κ the adiabatic chirp coefficient [12]. In (1), the first term is related with 'transient' chirp and the second term with 'adiabatic' chirp [12]. Transient chirp is caused by pulse transitions, whereas adiabatic chirp is related to the frequency difference between the '1' and '0' levels. Depending on their design parameters, some DMLs exhibit strong adiabatic chirp, whereas others strong transient chirp characteristics and therefore are classified accordingly. The laser rate equation parameters for transient and adiabatic chirp dominated DMLs used in this paper were reported in [17] and have been extracted from various commercially available DMLs. These parameters have also been verified both by simulations and experiments [17]. For the transmission part of our studies, the VPI transmission maker tool was used. The various laser models (adiabatic and transient chirped) were implemented in the same tool [19] by selecting the appropriate parameters of DMLs and verifying the laser output characteristics with those in [17], to achieve a perfect match between them. The laser models were deterministic. The power versus current curves have been depicted analytically in [17]. The chirp and power waveforms for each case are presented in Fig. 1. For the case of 10 Gb/s, the peak-to-peak chirp is ~50 and 30 GHz for the case of adiabatic and transient chirp dominated DMLs, respectively, whereas for 2.5 Gb/s, the peak-to-peak chirp is ~20 and 25 GHz for adiabatic and transient chirp dominated DMLs, respectively. The parameters used in the studies for all cases of DMLs are presented in Table 1. According to this, λ is the transmission wavelength, n_{opt} the optical coupling efficiency into the fibre, a the linear material gain coefficient, N_0 the transparency carrier density, α the linewidth enhancement factor, τ_{p} the photon lifetime, ε the nonlinear gain, β the spontaneous emission factor, V the volume of the active layer and Γ the optical confinement factor. The assumed Γ and V are in fact dummy parameters and their selection will not affect the resultant output field from the DMLs [17]. The only exception where the parameters have not been previously verified is for the case of a 10 Gb/s adiabatic chirp dominated DML. In this case, the

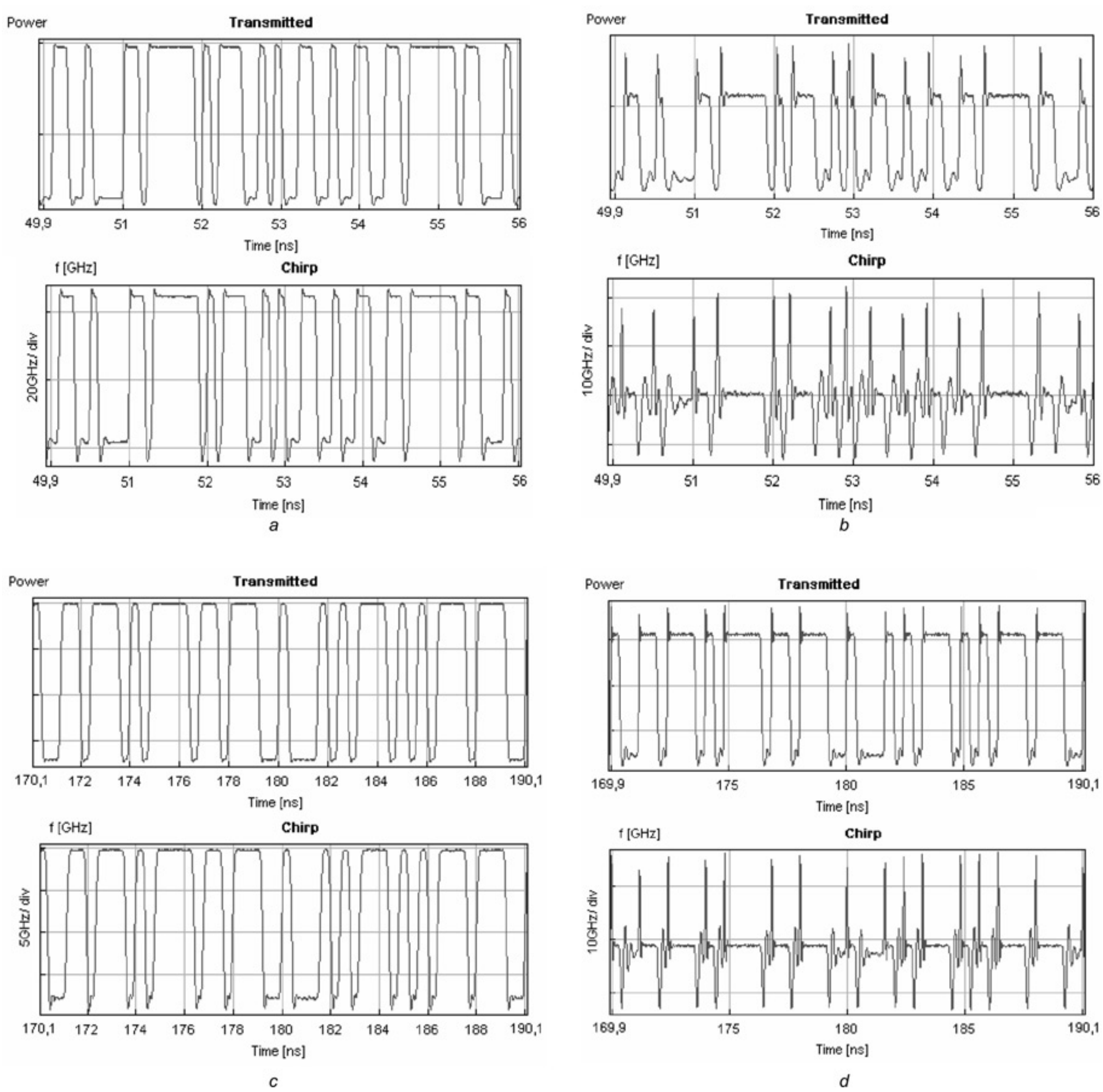

Figure 1 *Power and chirp waveforms for*

a 10 Gb/s adiabatic chirp dominated DML
b 10 Gb/s transient chirp dominated DML
c 2.5 Gb/s adiabatic chirp dominated DML
d 2.5 Gb/s transient chirp dominated DML

parameters of a 2.5 Gb/s adiabatic chirp dominated DML were used with small differences, as presented in Table 1 and with the purpose to present a more complete comparison. It was a hypothetical adiabatic chirp dominated DML. This laser was chosen for comparison reasons. A technique that can be used in order to design such a type of DML source at 10 Gb/s is by using complex-coupled DMLs, for which the very large difference in threshold gain between the main mode and the side mode suppresses the mode competition even near the threshold and produces a damped relaxation oscillation such that the laser chirp is dominated by the adiabatic chirp. Note that for these studies, the focus is on the characteristics of the output waveform of the DML and how this is affected by using an equaliser and not how this behaviour is generated. The corresponding bias electrical currents for the case of an adiabatic chirp dominated DML was 33.9 mA (with Ith = 8.2 mA) with a 100 mA peak-to-peak driving current at 10 Gb/s and 14.95 mA (with Ith = 4.66 mA) with a 58 mA peak-to-peak driving current at 2.5 Gb/s, whereas for the case of a transient chirp dominated DML the bias electrical current was 24.27 mA (with Ith = 15.25 mA) with a 37 mA peak-to-peak driving current at 10 Gb/s, and 23.66 mA (with Ith = 17.34 mA) with a 35 mA peak-to-peak driving current at 2.5 Gb/s. The bias current according to the VPI simulation tool that we used corresponds to the level of the ‘0’s. The rise/fall times of the driver signal for the case of 10 Gb/s is 25 ps for both the cases of DMLs. At 2.5 Gb/s, the rise/fall times is 80 and 132 ps for the

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Table 1 Parameters of DMLs in VPI transmission maker tool

Parameter	Value	DML 10G (transient)	DML 2.5G (transient)	DML 2.5G (adiabatic)	DML 10G (adiabatic)
λ	nm	1541.35	1544.51	1554.62	1554.62
n_{opt}		0.145	0.057	0.12	0.12
A	m^2	141.29×10^{-21}	62.208×10^{-21}	106.445×10^{-21}	106.445×10^{-21}
N_0	$1/m^3$	0.4359×10^{24}	0.8059×10^{24}	0.059×10^{24}	0.4×10^{24}
α		2.7	5.6	2.2	2.1
τ_p	ps	6.1236	9.6908	3.6364	3.6364
ε	$1/m^3$	0.9693×10^{-23}	0.4473×10^{-23}	7.5826×10^{-23}	8×10^{-23}
β		0.0001	0.1955×10^{-4}	0.28149×10^{-4}	0.28149×10^{-4}
V	m^3	2.7×10^{-17}	2.7×10^{-17}	2.7×10^{-17}	2.7×10^{-17}
Γ		0.1	0.1	0.1	0.1

transient and adiabatic chirp dominated DMLs, respectively. Finally, the models for the FFE and DFE equalisers have been developed analytically in Matlab and introduced in VPI in a co-simulation mode. The accuracy of these models has also been verified in the past in accordance with available experimental results for various EML transmitters [7].

3 Simulation set-ups

For the simulations, 10 and 2.5 Gb/s modulation signals with a non-return-to-zero format and $2^{23}-1$ pseudo random bit sequence (PRBS) was assumed. For the benchmarking case of EML transmission, a realistic chirp-free Mach–Zehnder modulator with an extinction ratio of 15 dB was used both at 10 and 2.5 Gb/s. For both types of DML transmitters at 10 and 2.5 Gb/s, an extinction ratio of 8.2 dB was used. It is important to note that although this extinction ratio value is difficult to be achieved in the case of the 10 Gb/s DMLs and with the majority of commercially available DMLs, it was chosen in order to coincide with the ITU-T standards.

The simulation set-up for the case of chromatic dispersion effect is presented in Fig. 2*a*. The transmission channel was an SSMF with a dispersion coefficient of $D = 16$ ps/km/nm. An erbium-doped fibre amplifier (EDFA) with a 6 dB noise figure (NF) was used after 80 km and for longer spans. No optical dispersion compensation was considered. Variable optical attenuators were used in order to control the launched power into the fibre links, which was set at 0 dBm with the purpose to minimise the nonlinear impairments. A 40 GHz second-order Gaussian optical band-pass filter was used at the input of the receiver in order to filter out the ASE noise before detection. Also, a Bessel electrical low-pass filter, with a 3 dB bandwidth of 0.7 times the bit rate, was applied before the equaliser.

For the simulations of the filter concatenation effect (Fig. 2*b*), a circulation loop set-up was used containing an arrayed waveguide grating (AWG) module, an optical attenuator and an EDFA in order to emulate the operation of an optical add-drop multiplexing node. With each loop circulation, the concatenated filtering effect was experienced through the AWG module, which was simulated using a fourth-order Bessel filter that matches the AWG transfer function according to [20]. The optical attenuator emulates the losses in the node, and the EDFA (with NF = 6 dB) restores the optical power at the output. The signal wavelength in each case was aligned to the centre wavelength of the filters. In the simulations, the behaviour of the equaliser was observed, by detuning the centre frequency of the filter from the central laser frequency. The 3 dB filter bandwidth was assumed at 65% of the 50 GHz channel spacing (i.e. 32.5 GHz). Furthermore, in the simulations, the wavelength detuning range of the laser around the centre wavelength was ± 0.25 nm.

The interaction of the laser chirp with chromatic dispersion was the dominant source of distortion in the simulations of the chromatic dispersion effect, whereas the interaction of the laser chirp with filter concatenation was the dominant source of distortion in the simulations of the filter concatenation effect. The performance criterion used in all cases to evaluate the performance of the received signals was the eye-opening penalty (EOP). An EOP limit of 1 dB was used in this study as a nominal threshold for the maximum acceptable signal degradation.

The EDE module used at the receiver end was based on the techniques of FFE and DFE [7, 21]. The FFE is the simplest structure and provides the most cost-effective solution. It consists of a delay line filter with filter coefficients that are adaptively adjusted to the channel impairments. The algorithm that was used in order to calculate the optimum tap coefficients for each case was the

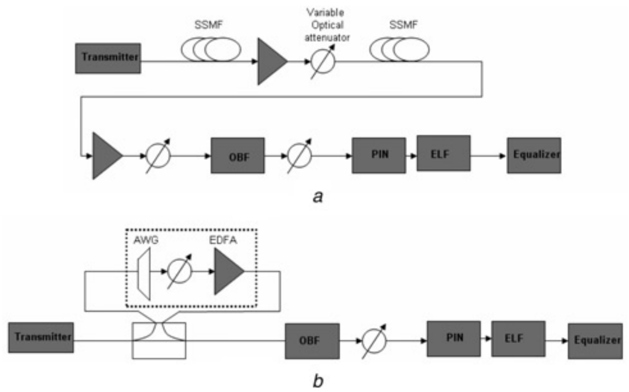

Figure 2 *System set-up for*

a Chromatic dispersion effect
b Filter concatenation effect

least mean square. The goal of that algorithm is to minimise the mean squared error between the desired equaliser output and the actual equaliser output. The DFE version of the equaliser is a nonlinear process that uses the same algorithm but it subtracts the interference by the already detected data offering advanced performance characteristics at the cost of some added complexity. The equalisers that were used were fractionally spaced equalisers ($T/2$). For the simulation studies, an analytical model has been developed for the equalisers and introduced in the VPI tool for co-simulation.

4 Simulation results for the mitigation of CD

The first studies were related with the identification of the optimum DFE design that offers the best performance at minimum design complexity, defined by the number of taps. Fig. 3 illustrates the effect of varying the number of FFE taps after transmission over the SSMF for all cases of DML transmitters (including EML transmission for comparison purposes). The transmission distances that were selected are closely related with the distance limits of EDE for a penalty of 1 dB for each case, which is presented later. As observed in Fig. 3*a*, when simple FFE is used, an increase in the number of taps by more than five offers no adequate additional improvement (although in some cases even three taps are enough). For the FFE and DFE combination, the optimum performance is observed for the DFE (5,1) case (Fig. 3*b*), where 5 denotes the feed-forward taps and 1 the decision feedback. Extended simulation studies revealed that the addition of more taps in the DFE part did not improve the performance significantly for any transmission distances and for any laser that was used in this simulation study. The only exception is for the case of an adiabatic chirp dominated DML at 2.5 and 10 Gb/s for 800 and 50 km, respectively, where the saturation in the performance improvement exists after six and seven taps in the FFE part, respectively, for each case. According to the studies shown in Fig. 3, the combination of a five-tap FFE

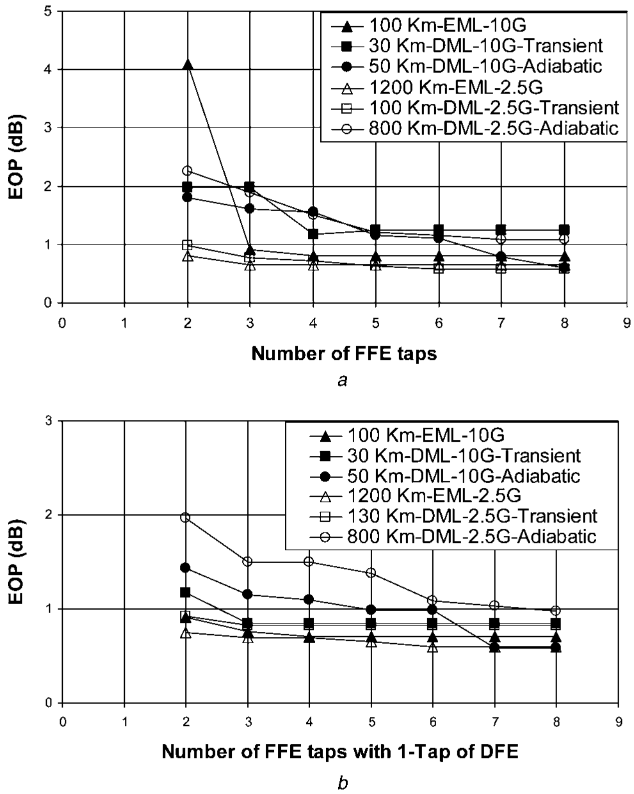

Figure 3 *EOP against number of FFE taps after SSMF transmission for various FFE and DFE configurations*

a FFE only
b FFE with 1 tap DFE

and one tap of DFE was selected as the optimum equaliser in terms of performance against complexity and this was used for the rest of the studies presented in the following.

Fig. 4 illustrates the EOP in terms of the transmission length for transient and adiabatic chirped DMLs at 2.5 Gb/s (Fig. 4*a*) and 10 Gb/s (Fig. 4*b*), respectively, with and without optimum DFE (5,1) equalisation; the case of EML is also included for comparison. The received eye diagrams, before the equaliser, for distances that correspond to an EOP of 1 dB, are presented in Fig. 5, together with the back-to-back eye diagram. The solid symbols in Fig. 4 denote the cases without equaliser, whereas the open symbols represent the cases with a DFE (5,1). The distances achieved for EMLs and DMLs correspond to a penalty of 1 dB and the results on the percentage improvement for each case are summarised in Table 2 for FFE (5) and DFE (5,1).

According to these studies, it is observed that the transmission distance (without equalisation) that can be achieved for the case of adiabatic chirp dominated DMLs is higher than the case of transient chirp dominated DMLs; this is in agreement with the results published in [22, 23]. According to Fig. 4, it is evident that when using adiabatic chirp dominated DMLs, the transmission efficiency enhancement because of the use of EDE and in

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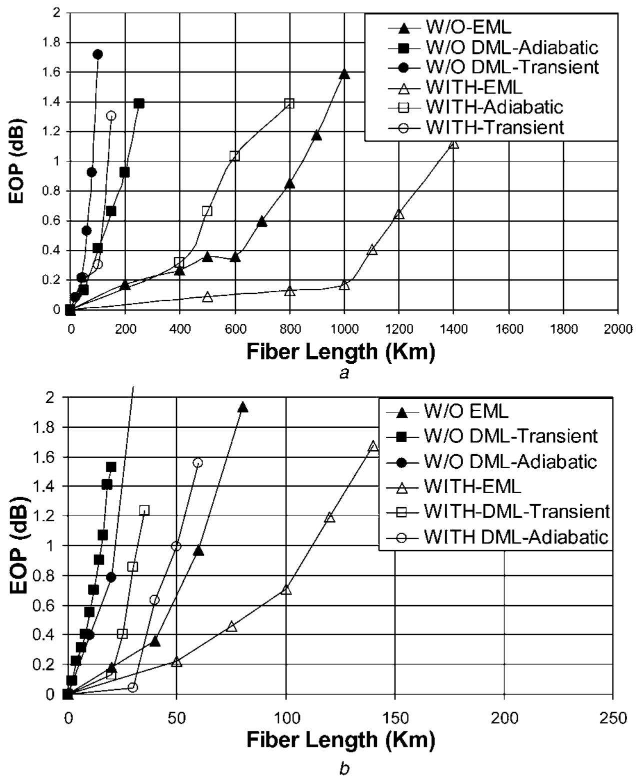

Figure 4 *EOP against fibre length without and with equaliser of DFE (5,1) for*

a 2.5 Gb/s and
b 10 Gb/s
Trendlines in figures are drawn as a guide for the eye

terms of EOP against distance is better than the case of transient chirp dominated DMLs (112–200% over 100–68% in transmission distance improvement). The 'kink' in the transmission performance of a 10 Gb/s adiabatic chirp dominated DML (shape of the EOP against fibre length curve characteristics) can be explained by the characteristics of this laser, which leads to a particular pulse shape and chirp characteristics that interact with the chromatic dispersion during the signal propagation in the fibre and may lead to such peculiar behaviours. Another observation is that the performance improvement of the DFE over the FFE is not so pronounced for the case of the adiabatic chirped DML.

The reason why the equaliser performs better for the case of the adiabatic chirp dominated DML than that of the transient chirp dominated DML is because of the fact that the pattern dependence is significantly lower in the former case; in terms of eye diagrams, this is also depicted and marked in Fig. 5*a*. Since the transient chirp is proportional to the derivative of the power, whereas the adiabatic chirp is proportional to the power waveform (1), it is expected that for the case of the transient chirp dominated DML, any variations in the power waveform caused because of the various bit-by-bit transitions will cause a large number of chirp patterns resulting, after transmission, in larger pattern dependent effects (i.e. nonlinear behaviour). Consequently, this will affect the ability of the equaliser to correct the signal based on the knowledge of the previously received bits. It is also observed that the improvements are different for the cases of 2.5 and 10 Gb/s. This is mainly because the DMLs are different (different characteristics) and therefore no direct comparisons can be provided. Besides, the purpose of this study was to investigate and compare different types of lasers at different rates.

5 Simulation results for the mitigation of filter concatenation

In the simulations of the filter concatenation effects, no fibre waveguide propagation effects were present, as the main focus was on the studies of the filter concatenation effects only. Additionally, it is well known that the spectrum of the adiabatic chirp dominated DML has two distinct peaks, because of the wavelength shift when the data signal alters between the bit levels of the '1's and the '0's [17]. It is important to note that in this case (adiabatic chirp dominated DMLs), the central wavelength of the filter was defined according to the corresponding frequency of '1's in order to achieve the optimum performance. If the central frequency of the filter coincides with the frequency of '0's, then the signal degrades rapidly and an EOP of 1 dB or more is observed even after one passage.

The simulations consisted of two parts. First, the performance behaviour of EDE was investigated by measuring the EOP as a function of the number of loops for all cases of transmitters. Secondly, the filter concatenation effect was examined by detuning the laser wavelength around the centre wavelength of the filters within a range of ± 0.25 nm.

The first studies were related with the identification of the optimum equaliser (FFE or DFE) that offers the best performance at minimum complexity and cost, and is defined by the number of taps. Extensive simulation studies revealed that the optimum FFE equaliser for the mitigation of the filter concatenation effect is FFE (5) (further increase in the tap number showed negligible improvement). Relative to the DFE case and based on the trade-off between performance and complexity, the optimum performance was observed for the DFE (5,1). Additional simulation studies demonstrated that the DFE scheme did not offer significant performance improvement in comparison with the FFE. Thus, in order to keep cost and complexity at a minimum, there was no need to use the DFE, and the simulations presented here consider only the performance improvement of FFE (5) for the mitigation of the filter concatenation effect.

Fig. 6 illustrates the EOP in terms of the number of loops and equally the number of cascaded filters, for DMLs and EMLs at 2.5 Gb/s (Fig. 6*a*) and 10 Gb/s (Fig. 6*b*), respectively. The solid symbols in Fig. 6 denote the cases without an equaliser, whereas the open symbols represent the cases with the FFE (5) equaliser. The received eye

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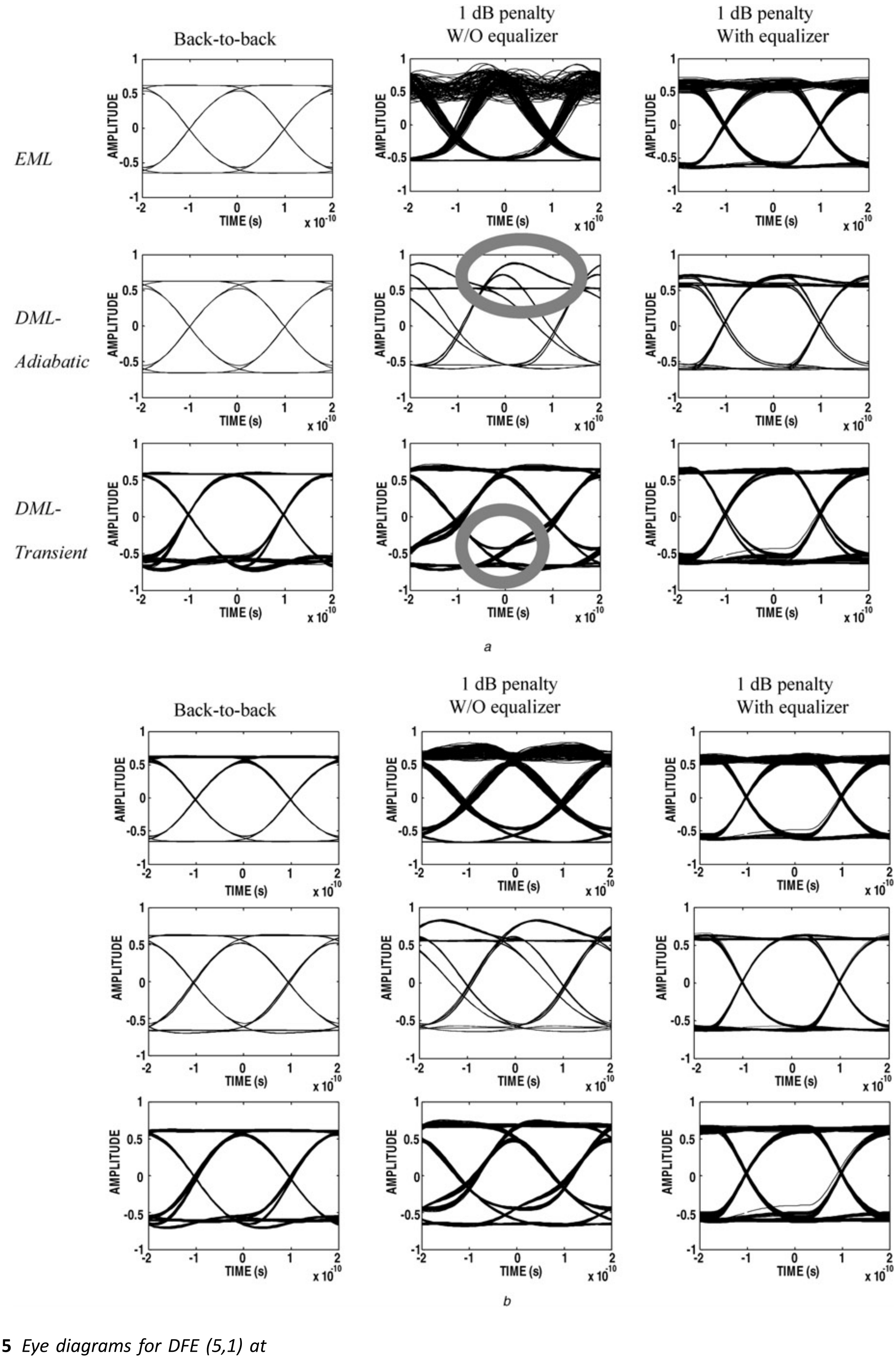

Figure 5 *Eye diagrams for DFE (5,1) at*

a 2.5 Gb/s for the mitigation of chromatic dispersion
b 10 Gb/s for the mitigation of chromatic dispersion

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Table 2 Performance improvement at 1 dB penalty for the mitigation of chromatic dispersion effect

Type	Transmission distance (km) W/O equaliser (1 dB penalty)	Improvement (FFE), km-(%)	Improvement (DFE), km-(%)
EML (10G)	60	100-(67)	110-(83)
EML (2.5G)	870	1320-(52)	1350-(55)
DML-10G (adiabatic)	23	48-(108)	52-(126)
DML-10G (transient)	16	28-(75)	32-(100)
DML-2.5G (adiabatic)	200	600-(200)	600-(200)
DML-2.5G (transient)	80	120-(50)	135-(68)

diagrams, before the equaliser corresponding to the number of loops that result in an EOP of 1 dB, are presented in Fig. 7, together with the back-to-back eye diagrams. The number of loops achieved for EMLs and DMLs corresponding to an EOP of 1 dB and the percentage improvement in each case is summarised in Table 3. According to this, it is evident that the mitigation of the filter concatenation effect in terms of the EOP against the number of loops by using EDE is more pronounced (i.e. higher percentage improvement) for the case of the adiabatic chirp dominated DMLs compared with the transient chirp dominated DMLs and also the case of the EMLs. On the other hand, it is noted that it is not safe to provide any direct comparison between the 2.5 and 10 Gb/s DMLs because of the different laser characteristics.

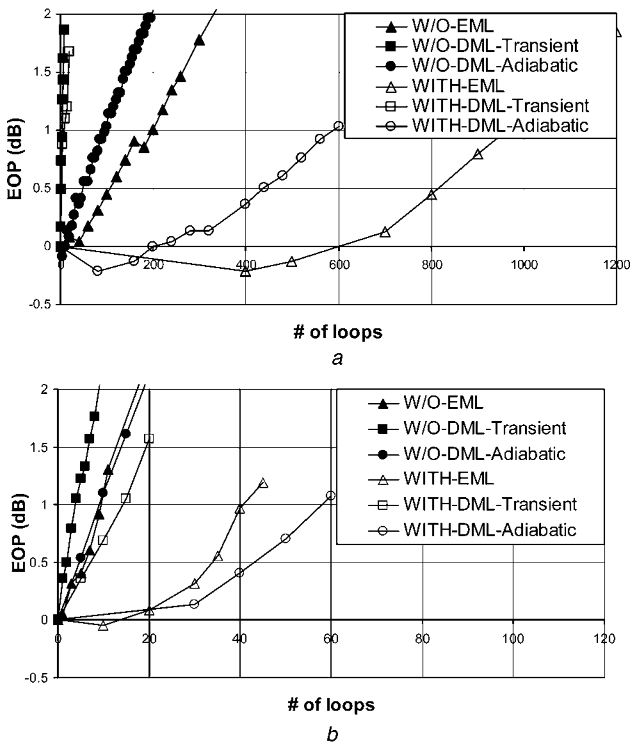

Figure 6 *EOP against the number of loops without and with equaliser of FFE (5) for*

a 2.5 Gb/s
b 10 Gb/s
Trendlines in figures are drawn as a guide for the eye. In both cases a 50 GHz filter was used

The higher performance improvement, by means of equalisation, of the adiabatic chirp DMLs compared with that of the transient chirp DMLs, is observed both for the mitigation of the filter concatenation effect and the chromatic dispersion effect, and also independent of the operating rate. In both cases, the nature of the generated chirp characteristics for the adiabatic or transient chirped DMLs (as it was discussed is Section 4) is the issue that affects the performance of the equaliser. Therefore the type of the laser used as the DML source is particularly important when combined with electronic equalisation. The difference in performance improvement (in percentage) that is observed between the mitigation of the filter concatenation effect and the chromatic dispersion effect can be explained by comparing the eye diagrams for the two cases (the marked part of Fig. 5*a* with the marked part of Fig. 7*a*). According to these, the pattern dependent effects (i.e. nonlinear behaviour) for the case of the filter concatenation effect are lower than the case of the chromatic dispersion effect, and as explained before, the performance of the equaliser is better for signals that have more predictable bit-by-bit variations. More specifically, filter concatenation causes only amplitude distortion (as the filter assumed in the simulations has linear phase and therefore no phase distortion is expected), whereas chromatic dispersion causes phase distortion which is translated to amplitude distortion after photo-detection, where the phase information is lost.

A second set of measurements illustrated in Figs. 8 and 9 examine the EOP in terms of laser wavelength detuning from the centre wavelength of the filters, for all cases of the transient and adiabatic chirp dominated DMLs and the benchmarking case of EMLs at the operating rates of 2.5 Gb/s (Fig. 8) and 10 Gb/s (Fig. 9). For all cases, the results are presented after passage through four filters. The solid symbols in Figs. 8 and 9 denote the cases without equaliser, whereas the open symbols represent the cases with the FFE (5) equaliser.

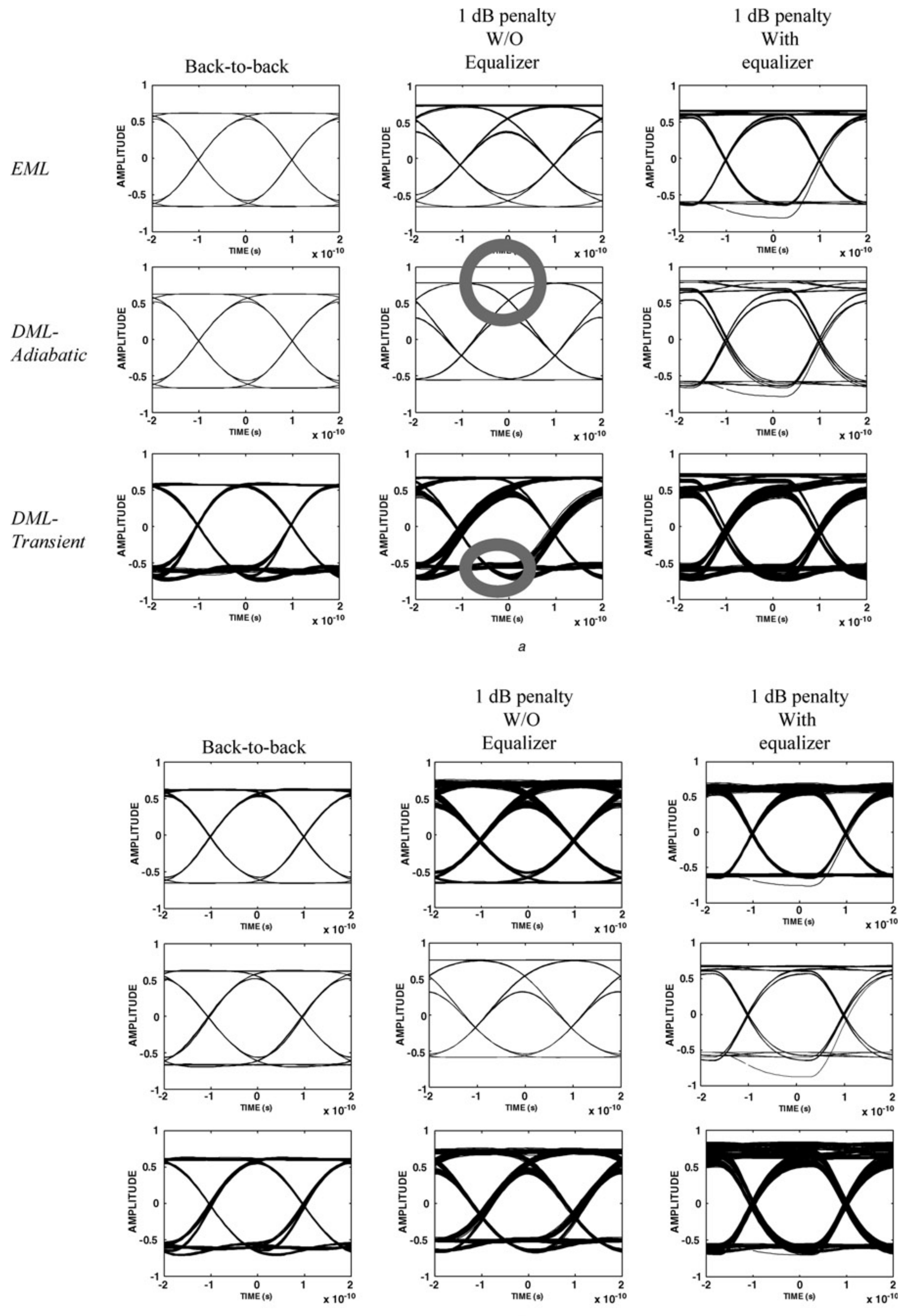

Figure 7 *Eye diagrams for FFE (5) at*

a 2.5 Gb/s for the mitigation of filter concatenation effect
b 10 Gb/s for the mitigation of filter concatenation effect

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Table 3 Performance improvement at 1 dB penalty for the mitigation of filter concatenation effect

Type	Number of loops W/O equaliser (1 dB penalty)	Improvement (FFE)-loops	Improvement, %
EML (10G)	9	40	344
EML (2.5G)	200	950	375
DML-10G (adiabatic)	10	58	480
DML-10G (transient)	4	15	275
DML-2.5G (adiabatic)	100	600	500
DML-2.5G (transient)	4	8	100

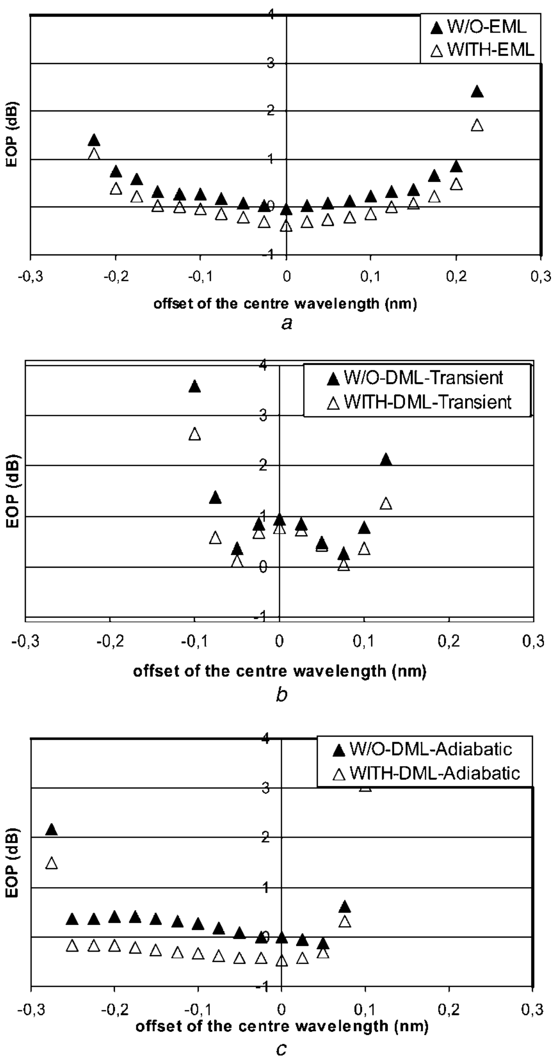

Figure 8 *EOP at 2.5 Gb/s after passage through four filters designed to support 50 GHz channel spacing against the detuning from the centre wavelength of the filters without and with equaliser of FFE (5)*

a EML
b Transient dominated DML
c Adiabatic dominated DML

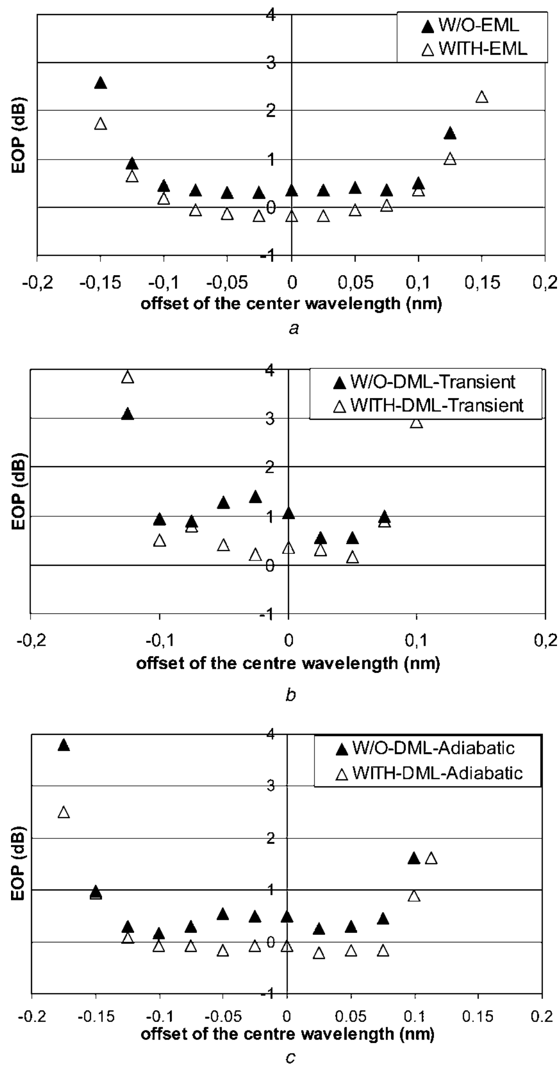

Figure 9 *EOP at 10 Gb/s after passage through four filters designed to support 50 GHz channel spacing against the detuning from the centre wavelength of the filters without and with equaliser of FFE (5)*

a EML
b Transient dominated DML
c Adiabatic dominated DML

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Examining first the filter detuning effects without equalisation, it is observed that for the case of the adiabatic chirp dominated DML and in contrast to the cases of the transient DML and EML, the results show a definite asymmetry with respect to the sign of the laser frequency offset in terms of the EOP. This is because of the two distinct peaks in the laser spectrum of the adiabatic chirped DML corresponding to the frequencies of the bits of '0's and '1's. Therefore negative filtering detuning (i.e. towards lower wavelengths) results in further rejection of the spectral components that correspond to bits of '0's, leading to higher tolerances in terms of performance and, consequently, to an almost flat performance over 0.25 and 0.15 nm for the cases of 2.5 and 10 Gb/s, respectively. On the other hand, the effect of detuning primarily affects the performance of the transient chirped DMLs causing large EOP variations (~0.8 dB) around the central wavelength (±0.075 nm).

When EDE is applied, the purpose is to examine the achievable performance improvement for various detuning ranges and, hence, estimate the tolerances of the system in terms of filtering detuning effects. More specifically, when EDE is applied for the transient chirp dominated DML operating at 2.5 Gb/s, there is little EOP advantage from EDE with the laser wavelength around the centre wavelength of the filter (Fig. 8*b*). However, for the same type of DML at 10 Gb/s (Fig. 9*b*), a significant performance improvement is achieved around the central wavelength where the EOP is almost eliminated. For the case of the adiabatic chirp dominated DMLs, EDE offers noticeable EOP improvement at both the operating rates, almost eliminating any EOP variations around the central wavelength (Figs. 8*c* and 9*c*). This increases the design tolerances of the system, relaxing the need for lasers with high central frequency accuracy and/or filters with strict bandwidth characteristics. Finally, it should be noted that in all cases, EDE does not affect the detuning dynamic spectral range.

6 Conclusion

The study presented in this paper highlights the effectiveness of the FFE and DFE equalisers in conjunction with DMLs, providing a cost-effective way to significantly increase the transmission distance of DMLs and mitigate the effect of filter concatenation. The transmission distance limits of the 2.5 Gb/s and 10 Gb/s DMLs using EDE are reported as well as the limits for the filter concatenation effects. The characterisation is based on real parameters verified by simulations and experiments. The simulation results revealed that the equalisation efficiency is higher for the case of the adiabatic chirp dominated DML than for that of the transient chirp dominated DML. The better performance improvement by using an equaliser for the case of the adiabatic chirp dominated DMLs is based on the fact that the pattern dependence is significantly lower than for the case of the transient chirp dominated DML. In terms of filtering effects, it is shown that EDE can offer significant performance improvement for both the transient and adiabatic chirp dominated DMLs at 10 Gb/s when the signal is in the centre area of the filter. The elimination of EOP variations caused by filter detuning increases the system design tolerance, offering a more economical solution. Finally, the use of EDE in DML-based systems is particularly attractive for metro/access networking applications at high data rates that require moderate signal improvement and low cost as it significantly improves the distortions induced from the limited transmission characteristics of DMLs.

7 References

[1] TOMKOS I., HALLOCK B., ROUDAS I., *ET AL.*: '10-Gb/s transmission of 1.55-μm directly modulated signal over 100 km of negative dispersion fibre', *IEEE Photon. Technol. Lett.*, 2001, **13**, (3), pp. 735–737

[2] NELSON L., WOODS I., WHITE J.K.: 'Transmission over 560 km at 2. 5 Gb/s using a directly modulated buried heterostructure gain-coupled DFB semiconductor laser'. OFC 2002, 2002, pp. 422–423

[3] MAHGEREFTEH D., CHO P.S., GOLDHOR J., MANDELBERG H.I.: 'Penalty-free propagation over 600 km of non-dispersion-shifted fibre at 2.5 Gb/s using a directly laser modulated transmitter'. IEEE CLEO, May 1999, vol. 2, p. 182

[4] MAHGEREFTEH D., LIAO C., ZHENG X., *ET AL.*: 'Error-free 250 km transmission in standard fibre using compact 10 Gbit/s chirp-managed directly modulated lasers (CML) at 1550 nm', *Electron. Lett.*, 2005, **41**, (9), pp. 543–544

[5] WINTERS J.H., GITLIN R.D.: 'Electrical signal processing techniques in long-haul fibre-optic systems', *IEEE Trans. Commun.*, 1990, **38**, (6), pp. 1439–1453

[6] BULOW H.: 'PMD mitigation by optic and electronic signal processing'. IEEE LEOS, November 2001, vol. 2, pp. 602–603

[7] WATTS P.M., MIKHAILOV V., SAVORY S., *ET AL.*: 'Performance of single mode fibre links using electronic feed forward and decision feedback equalizers', *IEEE, Photon. Technol. Lett.*, 2005, **17**, (10), pp. 2206–2208

[8] FEUER M.D., HUANG S.-Y., WOODWARD S.L., COCKUN O., BORODITSKY M.: 'Electronic dispersion compensation for a 10-Gb/s link using a directly modulated laser', *IEEE Photon. Technol. Lett.*, 2003, **15**, (12), pp. 1788–1790

[9] KHRAIS N.N., ELREFAIE WAGNER R.E., AHMED S.: 'Performance of cascaded misaligned optical (de) multiplexers in multiwavelength optical networks', *IEEE Photon. Technol. Lett.*, 1996, **8**, pp. 1073–1075

doi: 10.1049/iet-opt:20070077

[10] CASPAR C., FOISEL H., FREUND R., KRUGER U., STREBEL B.: 'Cascadability of arrayed-waveguide grating (de) multiplexers in transparent optical networks'. OFC'97, Paper TUE2, 1997, pp. 19–20

[11] TOMKOS I., RHEE J.-K., IYDROOSE P., HESSE R., BOSKOVIC A., VODHANEL R.: 'Filter concatenation penalties for 10-Gb/s chirped transmitters suitable for WDM metropolitan area networks', *IEEE Photon. Technol. Lett.*, 2002, **14**, (4), pp. 564–566

[12] DOWNIE J.D., TOMKOS I., ANTONIADES N., BOSKOVIC A.: 'Effects of filter concatenation for directly modulated transmission lasers at 2.5 and 10 Gb/s', *IEEE J. Lightwave. Technol.*, 2002, **20**, pp. 218–228

[13] DOWNIE J.D., HURLEY J., SAUER M., LOBANOV S., RAGHAVAN S.: 'Experimental measurements of the effectiveness of MLSE against narrowband optical filtering distortion'. OFC'07, 2007, pp. 1–3 (paper OMG4)

[14] RUBSAMEN M., WINZER P.J., ESSIAMBRE R.-J.: 'MLSE receivers for narrow-band optical filtering'. Optical Fibre Communication Conf. Exhibition and The National Fibre Optic Engineers Conf. CD-ROM (Optical Society of America, Washington, D.C., 2006), paper OWB6

[15] XIA C., ROSENKRANZ W.: 'Electrical dispersion compensation for different modulation formats with optical filtering'. Optical Fibre Communication Conf. Exhibition and The National Fibre Optic Engineers Conference on CD-ROM (Optical Society of America, Washington, D.C., 2006), paper OWR2

[16] PAPAGIANNAKIS I., XIA C., KLONIDIS D., ROSENKRANZ W., BIRBAS A.N., TOMKOS I.: 'Performance of 2.5 Gb/s and 10 Gb/s transient and adiabatic chirped directly modulated lasers using electronic dispersion compensation'. ECOC'O7, 2007 paper Th. 9.3.5

[17] TOMKOS I., ROUDAS I., HESSE R., ANTONIADES N., BOSKOVIC A., VODHANEL R.: 'Extraction of laser rate equations parameters for representative simulations of metropolitan-area transmission systems and networks', *Opt. Commun.*, 2001, **194**, pp. 109–129

[18] CHANDARSEKHAR S., DOERR C.R., BUHL L.L., *ET AL.*: 'Flexible transport at 10-Gb/s from 0 to 675 km (11,500 ps/nm) using a chirp managed laser, no DCF, and a dynamically adjustable dispersion-compensating receiver'. Proc. OFC 2005, PDP30, 2005

[19] AHMED M., YAMADA M., SAITO M.: 'Numerical modeling of intensity and phase noise in semiconductor lasers', *IEEE J. Quantum Electron.*, 2001, **QE-37**, pp. 1600–1610

[20] WANGENHEIM L.: 'Active filter in RC- und SC-technic' (Heidelberg, 1991)

[21] PROAKIS J.G., SALEHI M.: 'Communication systems engineering' (Prentice-Hall, Englewood Cliffs, NJ, 1994)

[22] CORVINI P.J., KOCH T.L.: 'Computer simulation of high-bit-rate optical fibre transmission using single-frequency lasers', *J. Lightwave Technol.*, 1987, **LT-5**, (11), p. 1591

[23] BINDER J., KOHN U.: '10 Gbit/s-dispersion optimized transmission at 1.55 um wavelength on standard single mode fibre', *IEEE Photon Technol. Lett.*, 1994, **6**, (4), p. 558