



Performance enhancement of Absolute Polar Duty Cycle Division Multiplexing with Dual-Drive Mach–Zehnder-Modulator in 40 Gbit/s optical fiber communication systems

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ABSTRACT

We modeled and analyzed a method to improve receiver sensitivity of the Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) transmission system by using Dual-Drive Mach–Zehnder-Modulator (DD-MZM). It is found that by optimizing the bias voltage in DD-MZM, the sensitivity of the AP-DCDM can be improved. The optimizations lead towards the larger eye opening. As opposed to the previous work, in terms of receiver sensitivity and dispersion tolerance, similar performance for all channels was achieved. In comparison to the previously reported AP-DCDM system, this work resulted in almost 3.6 dB improvement of the receiver sensitivity, came together with acceptable chromatic dispersion tolerance.

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1. Introduction

Various techniques have been proposed to improve the Wavelength Division Multiplexing (WDM) transmission performance, which include the implementation of advanced modulation formats [1,2] and advanced dispersion management [3–5]. The use of Return-to-zero (RZ) line codes has also been proven to improve the performance at the cost of larger spectral width [6,7]. In general, ideal modulation format for long-haul, high speed WDM transmission links is the one with compact spectrum and good dispersion tolerance [8].

Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) is an electrical multiplexing technique which enables to increase the spectral efficiency and the dispersion tolerance of WDM systems [9,10]. To date, the spectral efficiency of 0.64 bit/s/Hz on a single polarization state has been achieved using AP-DCDM technique [10]. These characteristics are quite interesting in order to overcome the chromatic dispersion limits of standard RZ schemes as well as to reach closer channel spacing in dense WDM systems. AP-DCDM system has intrinsic sensitivity penalty as compared to the binary signals, due to

fragmentation of the main eye to smaller eyes. At the same received power, these small eyes have different qualities; therefore causing different AP-DCDM channels to have different performances, which is not desirable in telecommunication systems [9].

In this paper, Dual-Drive Mach–Zehnder-Modulator (DD-MZM) is used in AP-DCDM setup at 40 Gbit/s data rate to improve the performance of AP-DCDM system. It is shown by numerical simulation that by optimum adjustment of the bias voltage at both ports, the sensitivity of the worst channel in AP-DCDM can be improved by 3.6 dB due to the larger eye opening.

Mach–Zehnder modulators have the important feature that the chirp of the transmitted signal is a function of the electro optic properties of the p-i-n waveguide, the splitting ratios of the two branch waveguides, the differential length between the two arms of the interferometer, and the format of the modulating voltages applied to the arm electrodes [11–13]. The suitability of this type of modulator for 2.5 Gbit/s and 10 Gbit/s transmissions over non-dispersion shifted fiber has been demonstrated in several experiments using both discrete modulators and modulators integrated with a DFB laser [14]. An important property of DD-MZM is that, due to the quantum confined stark effect, the attenuation and phase constants of an optical signal propagating in the p-i-n waveguide are nonlinear functions of the applied voltage.

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Since these constants determine the modulator extinction ratio and chirp, the bias and modulation voltages can be optimized to yield the minimum degradation in receiver sensitivity due to fiber dispersion and self-phase modulation.

2. AP-DCDM

As reported in [9,10], AP-DCDM uses different RZ duty cycles and bipolar signaling to differentiate the channels. In this technique, for n number of users, the symbol duration or period T_s ($=1/\text{Bit rate}$) is divided over n slots. These slots are assigned to different i th users, whereby the pulse duration, T_i for each user is defined as

$$T_i = i \times \frac{T_s}{n}. \tag{1}$$

The first user has the shortest pulse width (smallest duty cycle) when $i = 1$ and the n th user has the largest pulse width (100% duty cycle) when $i = n$. Note that, each user transmits bit ‘0’ with zero volts and bit ‘1’ with +A volts (for odd numbered users), and –A volts (for even numbered users) by using different duty cycles. Therefore, different channels share the communication medium to transmit in the same time period (T_s) over the same carrier wavelength, but with different duty cycles [9,10].

Fig. 1 shows the system over a single wavelength channel. Data1, Data2, Data3 and Data4, each at 10 Gbit/s rate with PRBS of $2^{10}-1$, are carved with four electrical RZ pulse carvers at $1/4 T_s$, $2/4 T_s$, $3/4 T_s$ and T_s duty cycles to represent User1 (U1), User2 (U2), User3 (U3) and User4 (U4) respectively. The aggregate transmission rate is 40 Gbit/s. At the multiplexer input, the voltages for all users are identical. All users’ data are multiplexed via a power combiner (electrical adder) resulting in a bipolar signal. Subsequently, the absolute circuit is used to produce an absolute polar signal. The signals are used to modulate a laser diode (LD), which operates at 1550 nm wavelength using an amplitude modulator (AM). At the receiver side, the optical signal is detected by a photodiode and passed through a low-pass filter (LPF) and a Clock-and-Data-Recovery (CDR) unit to recover the data for each user [9,15]. The generated eye diagram of this technique is shown in Fig. 2(a). As illustrated in Fig. 2(a) and reported in [9,10,15], the generated eye diagram for 4-channel AP-DCDM system contains 6 small eyes. Eyes 1, 2, 3 and 4 (slots 1 and 2) correspond to the performance of channel 1, eyes 2, 4 and 5 (slots 2 and 3) are related to performance of channel 2, eyes 5 and 6 (slots 3 and 4) influence the performance of channel 3, and eye 6 (slot 4) is related to channel 4.

As illustrated in Fig. 2(a), at –31 dBm received power, Q-factor of all four eyes located at the first level is more than 6, which are higher than that of the eyes located at the second level (around 3.65 and 3.88 for eyes 1 and 2, respectively). The eye openings at different levels are almost similar but have different Q-factors due to different standard

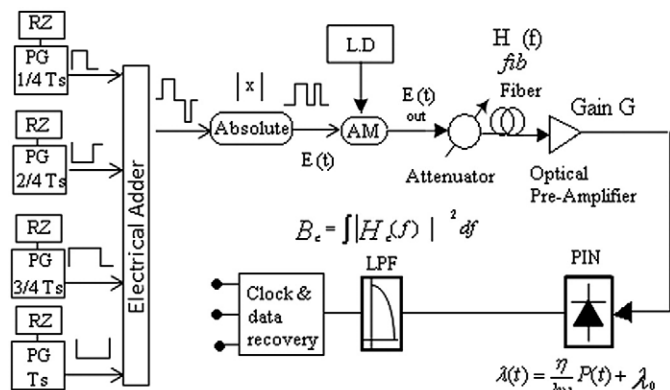


Fig. 1. AP-DCDM system over a single wavelength channel.

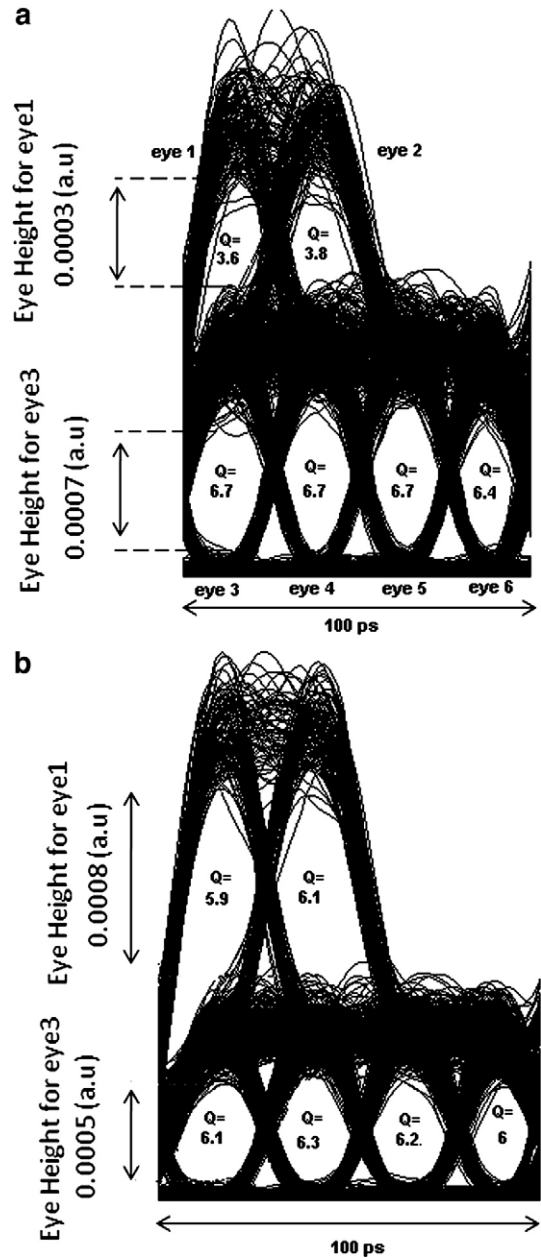


Fig. 2. Received eye diagrams (a) AP-DCDM (AM) and (b) Proposed AP-DCDM (optimized DD-MZM).

deviation of the noise variation at each level. Therefore, at the same received power, channel with minimum variation of noise has the best performance (e.g. channel 4) and the channel with maximum variation has the worst performance (channel 1).

3. The implementation of DD-MZM

Referring to Section 2, the improvement in the system performance can be obtained by having optimum amplitude distribution among the AP-DCDM signal level. This can be achieved by optimization in amplitude control of the level. To satisfy that requirement, we implement DD-MZM, which consists of an input Y-branch splitter, two arms with independent drive electrodes, and an output Y-branch combiner, in our setup as a replacement to conventional single-drive amplitude modulator (AM).

The CW optical signal incident on the input Y-branch is split into the two arms of the interferometer. The on-state is achieved when

there is constructive interference while off-state is achieved when there is destructive interference. The output signal from the modulator is, to a good approximation, the sum of the fields at the outputs of the two arms. For a modulator with the same input and output Y-branch splitting ratios, this signal is given by [16,17]

$$E(V1, V2) = \frac{E_0}{1 + SR} \left[SR \cdot \exp\left(-\left(\frac{\Delta\alpha_\alpha(V1)}{2} + j\Delta\beta(V1)\right)L\right) \right] + \exp\left(-\left(\frac{\Delta\alpha_\alpha(V2)}{2} + j\Delta\beta(V2)\right)L - j\Phi_0\right) \quad (2)$$

$$= \sqrt{I(V1, V2)} \exp(j\phi_0(V1, V2))$$

where $SR = P_1/P_2$ is a Y-branch power splitting ratio; $\Delta\alpha_\alpha/2$ is attenuation constant; $\Delta\beta$, phase constant; Φ_0 , '0' radian for conventional modulator and ' Ω ' radians for a Ω phase shift modulator; V_1 and V_2 are voltages applied to arms 1 and 2 respectively; I is the intensity of the optical signal; and ϕ is the phase.

For $i = 1, 2$

$$V_i(t) = V_{bi} + V_{modi}V(t) \quad (3)$$

where V_{bi} is the bias voltage; V_{modi} peak-to-peak modulation voltage; $V(t)$ modulation waveform with a peak-to-peak amplitude of one and an average value of zero.

The dependence of the attenuation and phase constants on the applied voltage can be obtained either by direct measurement of a straight section of waveguide cut from one arm of a modulator [16] or by using measurements of the voltage dependence of the intensity of the output signal for each arm with the other arm strongly absorbing [18]. As illustrated in Fig. 3 for a DD-MZM module, the absorption (and, hence, $\Delta\alpha_\alpha$) and the change in phase $\Delta\beta$ are nonlinear functions of the applied voltage.

4. DD-MZM optimization

As discussed in Section 2 we need to have almost similar Q-factor for all 6 eyes to achieve similar performance for all channels. This can be done by improving the eye quality in second level. In order to change the eye high in second level while maintaining the maximum power, the bias voltages 1 (V_{b1}) and 2 (V_{b2}) in DD-MZM need to be optimized so that the eye high in first level is reduced while increasing the eye high of the second level.

The optimum bias voltages are considered for two different conditions as shown in Fig. 4a and b. The dependence of Q-factor for all 6 eyes on the V_{b2} is shown in Fig. 4a, at the fixed received power of -31 dBm (receiver sensitivity of best channel), fixed V_{b1} (-2.8 V) and splitting ratio of 1.3.

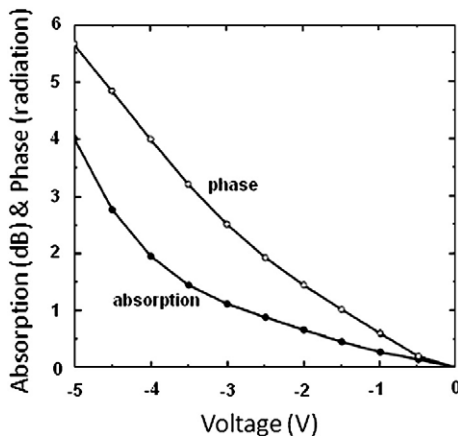


Fig. 3. Characteristics of absorption and phase in the simulated DD-MZM.

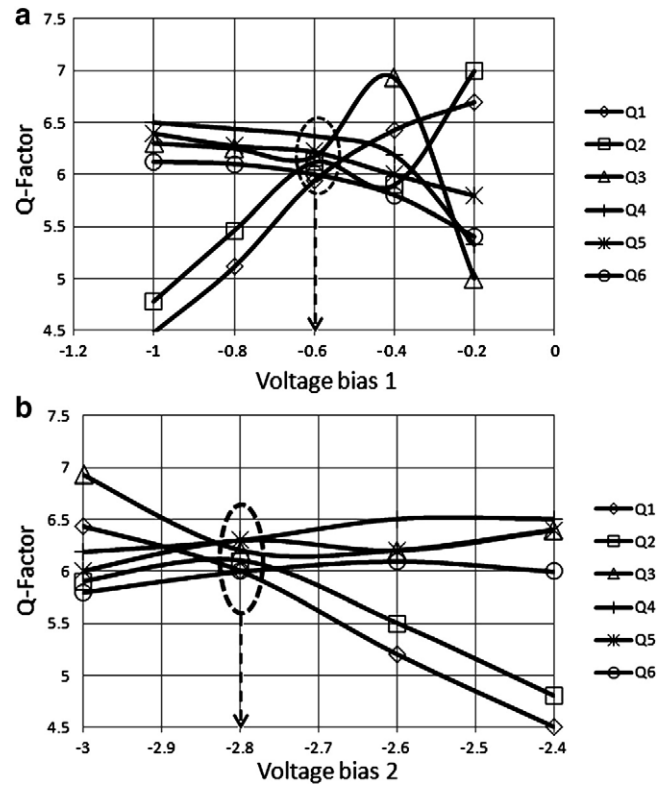


Fig. 4. (a) Dependence of Q-factor on the applied bias voltage 1 (V_{b1}). (b) Dependence of Q-factor on the bias voltage 2 (V_{b2}).

It can be seen from Fig. 4a that the optimum V_{b2} is around -0.6 V where eye1 to eye6 have almost similar Q-factors of 5.9, 6.1, 6.1, 6.3, 6.2 and 6, respectively.

Fig. 4b shows the variation of Q-factor for different values of the V_{b1} with fixed V_{b2} (-0.6 V). The received power is maintained at -31 dBm. As illustrated in Fig. 4b, the optimum V_{b1} is around -2.8 where all eyes have similar Q-factor. The optimum point for V_{b1} and V_{b2} from Fig. 4a and b, and conventional modulator are summarized in Table 1 under optimized voltage biased conditions, the variation in the Q-factor is quite small and it is expected that the optimum sensitivity is essentially similar for all multiplexed channels.

5. AP-DCDM system performance using optimized DD-MZM

5.1. Receiver sensitivity

The simulation results are obtained by replacing AM in Fig. 1 by DD-MZM. The DD-MZM was fixed with splitting ratio (SR) of 1.3, V_{b1} of -2.8 V and V_{b2} of -0.6 V. Fig. 2(b) shows the generated eye diagram at fixed received power of -31 dBm. As illustrated, although the eye highs are different, the Q-factors are almost the same. Compared to AP-DCDM with AM, Q-factors related to the second level are greatly improved (from 3.6 and 3.8 to 5.9 and 6.1 for eye 1 and 2, respectively). Note that the maximum amplitude values for AM and DD-MZM eye diagrams are the same. By improving the quality of the second level eyes, the performance of channels 1 and 2 are

Table 1
DD-MZM optimization process.

Setup	Q1	Q2	Q3	Q4	Q5	Q6
Conventional AP-DCDM	3.6	3.8	6.7	6.7	6.7	6.4
MZM, optimized V_{b1} and V_{b2}	5.9	6.1	6.1	6.3	6.2	6

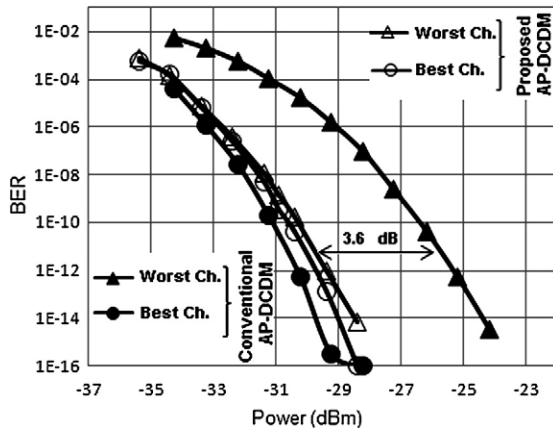


Fig. 5. Receiver sensitivity comparison between proposed AP-DCDM and AM-AP-DCDM.

significantly improved. In addition to that, we can have almost the same performance for all channels. Fig. 5 shows and compares the receiver sensitivity of both AP-DCDM with AM and the one with optimized DD-MZM. It can be seen that the proposed solution improves the receiver sensitivity by 3.6 dB for the worst channel and less than -0.5 dB penalty for the best channel. The reason for this receiver sensitivity improvement can be realized by looking and comparing the received eye diagrams depicted in Fig. 2(a) and (b).

5.2. Dispersion tolerance

Fig. 6 shows the dispersion tolerance of proposed technique and conventional RZ-OOK at 40 Gbit/s. Using DD-MZM, AP-DCDM, all users show almost similar dispersion tolerance of around 136 ps/nm, at BER of 10^{-9} . In comparison to previously reported AP-DCDM (using AM) which has 196 ps/nm dispersion tolerance [10], AP-DCDM using DD-MZM shows around 30 ps/nm reduction in dispersion tolerance. However, as illustrated in Fig. 4 it is still more robust to dispersion in comparison to 40 Gbit/s RZ-OOK, which has the dispersion tolerance of 100.4 ps/nm. This is because of smaller spectral width of the former technique. In addition to that, we can have almost the same performance for all channels in terms of receiver sensitivity and dispersion tolerance.

6. Conclusion

We have presented the performance of AP-DCDM technique when drive voltages of DD-MZM are optimized. In comparison to the

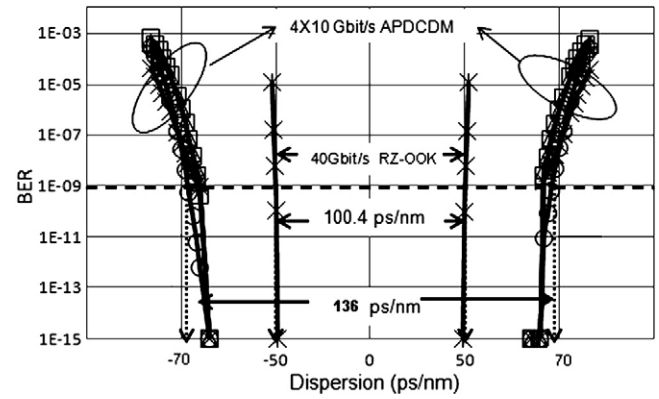


Fig. 6. Chromatic dispersion tolerance comparison between 4×10 Gbit/s DD-MZM-AP-DCDM and 40 Gbit/s RZ-OOK at the same transmission power.

previous report [10], considerable receiver sensitivity improvement (3.6 dB) was achieved with acceptable chromatic dispersion tolerance. The improvement is due to the eye high increment, which leads towards Q-factor enhancement. These results are impactful in the exploration for the optimum AP-DCDM transmission system.

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