Performance Enhancement of AP-DCDM over WDM with Dual Drive Mach-Zehnder-Modulator in 1.28 Tbit/s Optical Fiber Communication Systems

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***Abstract*— We modeled and analyzed a method to improve the performance of Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) over Wavelength Division Multiplexing (WDM) system by using Dual-Drive Mach-Zehnder-Modulator (DD-MZM). It is found that by optimizing the bias voltage in DD-MZM, the receiver sensitivity of 1.28 Tbit/s (32 x 40 Gbit/s) AP-DCDM-WDM over 320 km fiber can be improved. The optimizations leads towards stabilization of timing jitter and, subsequently, result in larger eye opening. In comparison to the previously reported AP-DCDM-WDM system, almost 4.1 dB improvement of receiver sensitivity is achieved.**

***Index Terms*—AP-DCDM, Wavelength division multiplexing, Mach-Zehnder-Modulator**

I. Introduction

To improve the WDM transmission performance, various techniques have been proposed, which include the implementation of advanced modulation formats, new fiber types, and advanced dispersion management. Among these techniques, the use of advance modulation formats has been demonstrated as an effective solution [1, 2]. The use of Return-to-zero (RZ) line codes has also been proven to improve the performance at the cost of larger spectral width [3, 4]. In general, ideal modulation format for long-haul, high speed WDM transmission links is the one with compact spectrum and good dispersion tolerance [5].

Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) is an alternative multiplexing technique which is able to support many users per WDM channel [6, 7]. Therefore, as reported in [8] the capacity of the WDM channels can be increased tremendously by using this technique. AP-DCDM enables us to use narrow optical filters that will provide spaces to increase the channel count. AP-DCDM system has intrinsic sensitivity penalty as compared to the binary signal, due to fragmentation of the main eye to smaller eyes. At the same received power, these small eyes have different quality; therefore cause different AP-DCDM channels to have different performances, which is not desirable in telecommunication systems [6, 8].

In this paper, Dual-Drive Mach-Zehnder-Modulator (DD-MZM) is used in AP-DCDM setup at 1.28 Tbit/s AP-DCDM-WDM transmission system in order 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 4.1dB. The optimization leads towards stabilization of timing jitter and, subsequently, resulted in 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 [9, 10]. 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. 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.

II. Conventional 32-Channel AP-DCDM-WDM Transmission

As shown in Fig.1 the evaluation starts with four AP-DCDM channels (4 x 10 Gbit/s) with PRBS of 2^{10}-1 (Fig. 1a) and followed by 32 WDM channels (32 x 4x 10 Gbit/s)(Fig.1b). In this Figure four OOK channels were multiplexed by using AP-DCDM, whose outputs are multiplexed by using WDM technique (Each WDM channel contains 4 x 10 Gbit/s with PRBS of 2^{10}-1 as shown in Fig. 1(a)).

62.5 GHz (0.5 nm) channel spacing was used. As a result, 128 AP-DCDM channels (32 x 4) are multiplexed in 32 WDM channels (λ_1 to λ_{32}) within ~ 15.5 nm (1550-1565.5 nm) EDFA band. WDM spectral efficiency of 0.64 bit/s/Hz was achieved without polarization multiplexing [8]. The transmission line was 4 spans of 80 km Standard Single

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Mode Fiber (SSMF) followed by a 13.4 km Dispersion Compensation Fiber (DCF). The length ratio between SSMF and DCF is optimized so that the overall second-order dispersion reaches zero. For the SSMF, the simulated specifications for dispersion (*D*), dispersion slop (*S*), attenuation coefficient (α), effective area (A_{eff}) and nonlinear index of refraction (n_2) are 16.75 ps/nm/km, 0.07 ps/nm^2/km, 0.2 dB/km, and 80 µm^2 and 2.7 x 10^{-20} m^2/W respectively. For DCF, *D* of ~ -100 ps/nm/km, *S* of -0.3 ps/nm^2/km, α of 0.5 dB/km, A_{eff} of 12 µm^2 and n_2 of 2.6 x 10^{-20} m^2/W are used.

For Booster and pre-amplifier, an erbium-doped fiber amplifier (EDFA) with a flat gain of 30 dB and a noise figure (NF) of 5 dB was used. The total power to the booster is 8.35 dBm and launch power into SSMF is + 15 dBm (~0 dBm/channel) .The Self Phase Modulation (SPM) effect in the link could be neglected since the launched power into the SSMF and DCF was less than the SPM threshold.

Figs. 1c and 1d show the optical spectra of 32 WDM channels before and after transmission respectively. The effect of Four Wave Mixing (FWM) is negligible due to the phase mismatch in the highly dispersive transmission line [11].

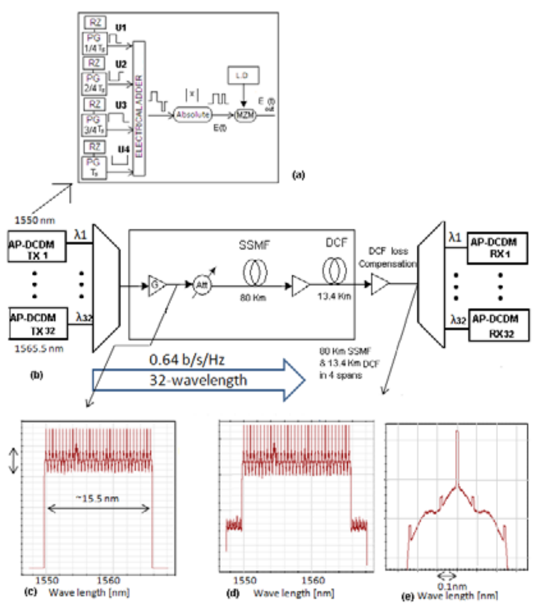

Fig.1. (a) 4 x 10 Gbit/s AP-DCDM transmission system (b) Simulation Setup of 1.28 Tbit/s (32 x 4 x 10 Gbit/s) AP-DCDM-WDM transmissions (c) Optical spectrum before transmission (d) Optical spectrum after transmission (e) single channel AP-DCDM spectrum

Fig. 2 shows the exemplary eye diagrams taken after the 320 km SSMF (4 span of 80 km SSMF + 13.4 km DCF) for channel 16 of WDM system which contains 4 x 10 Gb/s AP-DCDM. As illustrated in Fig. 2 and reported in [8], the generated eye diagram for channel 16 which contains 4-channel of AP-DCDM system contains 6 small eyes. Eyes 1, 2, 3 and 4 (slots 1 and 2) correspond to the performance of AP-DCDM channel 1, eyes 2, 4 and 5 (slots 2 and 3) are related to performance of AP-DCDM channel 2, eyes 5 and 6 (slots 3 and 4) influence the performance of AP-DCDM channel 3, and eye 6 (slot 4) is related to AP-DCDM channel 4. As illustrated in Fig. 2, at -25 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 3.6 and 3.8 for eyes 1 and 2, respectively). The eye openings at different levels are almost similar but have different Q-factors due to different standard 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).

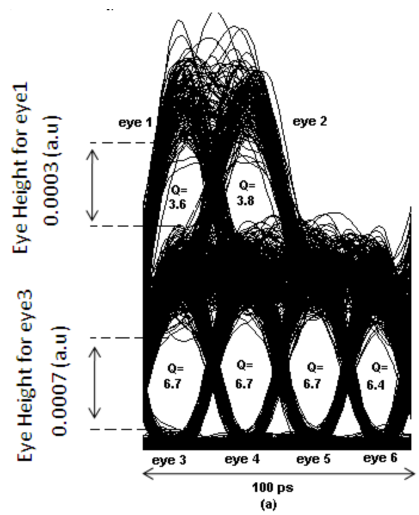

Fig.2 Received eye diagram for channel 16 in 32-channel AP-DCDM-WDM system

III. The Implementation of DD-MZM

Referring to Sect. II, 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 [10]

$$E(V1,V2) = \frac{E_0}{1+SR}\left[SR.\exp\left(-\left(\frac{\Delta\alpha_\alpha(V1)}{2}+j\Delta\beta(V1)\right)L\right)\right]+ \exp\left(-\left(\frac{\Delta\alpha_\alpha(V2)}{2}+j\Delta\beta(V2)\right)L-j\Phi_0\right)= \sqrt{I(V1,V2)}\exp(j\phi_0(V1,V2)) \quad (1)$$

where SR=P_1 / P_2 is a Y-branch power splitting ratio; $\Delta\alpha_\alpha/2$

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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 $i= 1, 2$

$$V_i(t) = V_{bi} + V_{\mathrm{mod}\,i}\, v(t) \tag{2}$$

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 [9] or by using measurements of the voltage dependence of the intensity of the output signal for each arm with the other arm strongly absorbing [10].

IV. DD-MZM OPTIMIZATION

As discussed in Sect. II 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 voltage 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. Table I shows the Q-factor for all 6 eyes with different value of V_{b2} at the fixed receive power of -25 dBm (receiver sensitivity of best channel) and fixed bias voltage 1 (V_{b1}) to -2.8 V. It can be seen from Table I that the optimum V_{b2} is around -0.6 V and the corresponding Q-factors are 5.94, 6.12, 6.17, 6.37, 6.22 and 6.00 for eye 1 to eye 6 respectively. As indicated in Table I, there are a lot of suboptimum Q-factors around the optimum point (-0.6 V), which can be optimized.

Table I
DD-MZM Optimization Process

Setup	Q1	Q2	Q3	Q4	Q5	Q6
Conventional AP-DCDM	3.65	3.88	6.71	6.73	6.75	6.40
MZM, V_{b2}= - 1 v	4.48	4.78	6.3	6.5	6.4	6.12
MZM, V_{b2}= -0.8 v	5.11	5.46	6.25	6.44	6.28	6.1
MZM, V_{b2}= -0.6 v	5.94	6.12	6.17	6.37	6.22	6
MZM, V_{b2}= -0.4 v	6.43	5.90	6.93	6.19	6	5.8
MZM, V_{b2}= -0.2 v	6.7	7	5	5.33	5.8	5.4

V. RESULTS AND DISCUSSION

The simulation results are obtained by replacing AM in Fig. 1 by optimized DD-MZM. The optimized 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. 3 shows the exemplary eye diagrams taken after the 320 km SSMF (4 span of 80 km SSMF + 13.4 km DCF) for Channel 16.

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 worse users (user 1 and 2) in middle WDM channel (Ch. 16) is significantly improved. In addition to that, we can have almost the same performance for all channels.

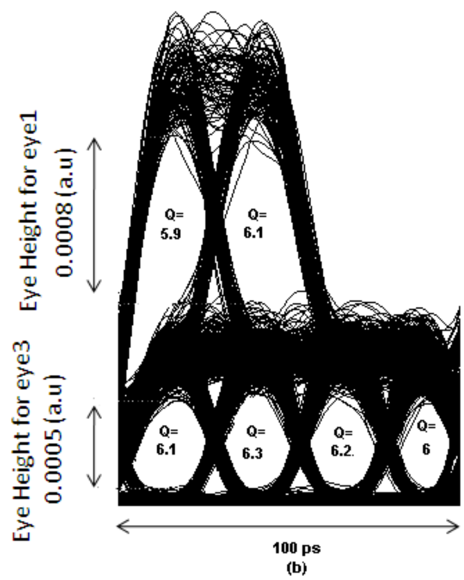

Fig.3 Received eye diagram for channel 16 in 32-channel AP-DCDM-WDM system using optimized DD-MZM

Fig. 4 shows and compares the receiver sensitivity of both AP-DCDM-WDM with AM and the one with optimized DD-MZM.

The degradation of receiver sensitivity is caused by the accumulated spontaneous emission light from each LD through the multiplexing process and by noise figure (NF) of the pre-amplifier. As shown in Fig. 4, the receiver sensitivity was around -21 dBm for conventional AP-DCDM-WDM system and the variation between the channels was around 1.5 dB. As illustrated in Fig.4 the receiver sensitivity of proposed AP-DCDM-WDM system was improved to around -25.1 dBm compare to conventional AP-DCDM-WDM system. Therefore the proposed solution improves the receiver sensitivity by around 4.1 dB.

Fig.5 shows the improvement of OSNR for proposed AP-DCDM-WDM system compare to conventional AP-DCDM-WDM at BER of 10^{-9}. The reason for this receiver sensitivity and OSNR improvement can be realized

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by looking and comparing the received eye diagrams depicted in Fig. 2 and Fig.3.

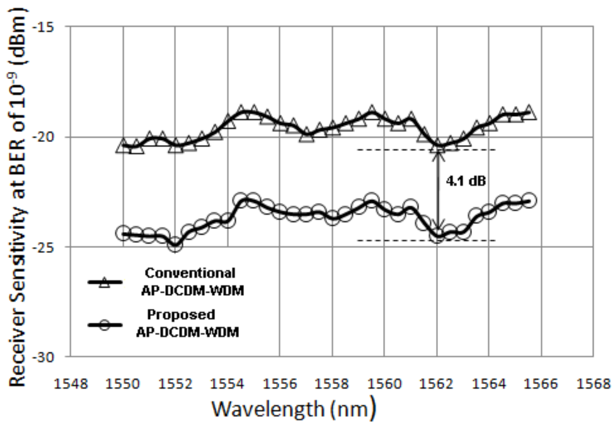

Fig.4 Pre-amplified receiver sensitivity versus signal wavelength for 32 channels

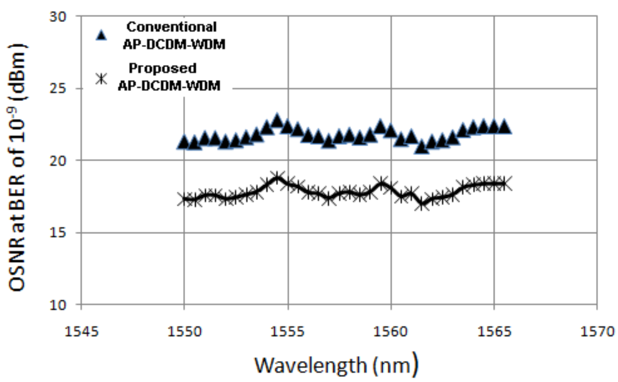

Fig.5. OSNR versus signal wavelength for 32 channels

VI. Conclusion

We have presented the performance of 1.28 Tbit/s AP-DCDM over WDM technique when drive voltages of DD-MZM are optimized. In comparison to the previous report ([8]), considerable receiver sensitivity improvement (4.1 dB) was achieved. 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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