Combination of optical and electrical compensation of differential mode delay in MMF links for 10-Gigabit ethernet

Chunmin Xia[a], Mahesh Ajgaonkar[b], Werner Rosenkranz[a]

[a]Chair for Communications, University of Kiel, Kaiserstrafle 2, D-24143 Kiel, Germany
[b]Discovery Semiconductors Inc., 119 Silvia Street, Ewing, NJ 08628, USA

ABSTRACT

We present both optical and electrical compensation of Differential Mode Delay (DMD) in Multimode Fiber (MMF) links. Based on the rigorous analysis of optical compensation of DMD, a new kind of Dispersion Compensating Fiber (DCF) is proposed. We show that 10Gb/s Ethernet reach for conventional MMF can be extended to 300m by splicing 10~35m of this DCF. We prove that ISI resulting from DMD can be mitigated with electrical compensation by using linear or nonlinear equalizers. Moreover, we demonstrate that combination of optical and electrical compensation can dramatically enhance the bandwidth of installed MMF. Simulations carried out on six types of typical installed MMF for Overfilled Launch (OFL) as well as Restricted Mode Launch (RML) condition exhibit that transmission distance for conventional MMF with bandwidth-distance product 500MHz-km can be extended to 1000m or beyond with 2dB Eye-Opening Penalty (EOP).

Keywords: 10-Gigabit Ethernet, Differential Mode Delay (DMD), Multimode Fiber (MMF), electrical equalization, Overfilled Launch (OFL), Restricted Mode Launch (RML).

1. INTRODUCTION

The goal of 10-Gigabit Ethernet for the conventional Multimode Fiber (MMF) is to obtain 300m-transmission distance [1,2]. However, the intermodal dispersion induced by the Differential Mode Delay (DMD) in MMF dramatically limits the bandwidth-distance product to only about 500MHz-km for 62.5μm-MMF at 1300nm or 50μm-MMF at 850/1300nm.

Although the next generation laser-optimized MMF has been produced and can be used to reach the requirement of 10-Gigabit Ethernet [2], however, in consideration of the cost and practicability, replacing installed MMF with new fiber is not an ideal solution. Meanwhile, some new techniques have been studied to upgrade the data rate of installed MMF [3-7], as e.g. CWDM, multilevel modulation, new kind of photodiode receiver, mode group diversity multiplexing and polarization multiplexing.

In this work, we present the combination of optical and electrical compensation of DMD in MMF links. We show that each of the two techniques can compensate DMD effectively and improve the bandwidth of installed MMF. Moreover, computer simulations reveal that combining the two compensations, the installed MMF with bandwidth-distance product 500MHz-km can be extended to 1000m or beyond with 2dB Eye-Opening Penalty (EOP) for Overfilled Launch (OFL) condition as well as for Restricted Mode Launch (RML) condition. To testify the results, six types typical installed MMF with different refractive index profiles including imperfections such as dip or peak located at center of core are examined simultaneously.

The organization of this paper is as follows. Firstly, the whole MMF link model is introduced. Secondly, Based on the rigorous analysis of optical compensation of DMD in MMF, a new kind of Dispersion Compensating Fiber (DCF) is proposed. Electrical equalization on DMD mitigation is discussed as the third part. Finally, the combination of optical and electrical compensation of DMD is presented.
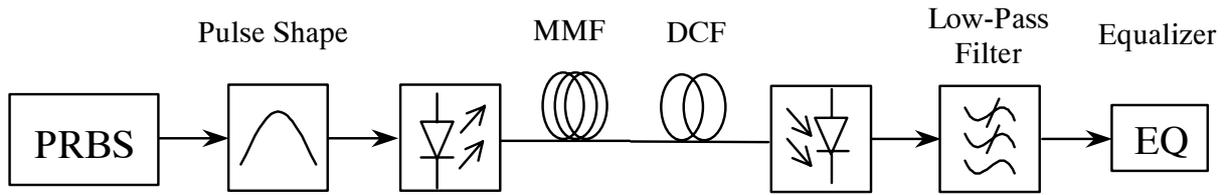
2. THE MODEL OF MMF LINK

Fig.1. The MMF link with dispersion compensating fiber DCF and electrical equalization

The whole simulation model of MMF link including DMD compensating fiber DCF and electrical equalization is schematically illustrated in Fig.1. PRBS with length 2^9-1 and NRZ line coding are assumed. Considering the cost-effective MMF link, the directly modulated laser like Fabry-Perot laser or VCSEL is employed and modeled as the linear laser without considering chirp.

The MMF channel is modeled as the superposition of the power P_m carried by each mode m (from 1 to M, where M the maximum mode number), which has different delay τ_m. The impulse response is expressed as,

$$h(t)=\sum_{m=1}^{M}P_m\delta(t-\tau_m)$$

The different mode delay as well as the electrical field distribution for each LP mode is examined by calculating a numerical mode solver [8].

The mode selective loss is also considered. We assume the mode dependent attenuation satisfies the modified Bessel function of the first kind [9] and the parameters suggested in [9] are presumed. To complete the MMF model, mode coupling is also taken into account. We know that power will couple from one mode to another due to imperfections in practical MMF during the transmission. However, strong mode coupling only happens when the transmission distance is long enough, e.g. more than 100m. In addition, mode coupling between different mode groups is much smaller compared to that of within the same mode group [10]. Therefore, in our model, mode coupling within the same mode group is assumed to be complete during the transmission in MMF (>100m) but absent in the DCF, whose length is much shorter than MMF.

In the following discussions, we take the case of 62.5μm MMF at 1300nm wavelength with Overfilled Launch (OFL) bandwidth-distance product 500MHz-km as an example. The conclusions can be derived straightforwardly to other cases such as 50μm MMF at 1300nm as well as at 850nm.

To approach the installed MMF, the refractive index profiles with imperfections including dip and peak at core center are considered simultaneously. Six typical types of 62.5μm MMF with different index profile configurations including undercompensated power-law exponent $g=2.03>g_{opt}$ (≈1.98) and overcompensated power-law exponent $g=1.88<g_{opt}$ listed in Table.1 are examined. The dip or peak is assumed to be Gaussian shape with diameter 4% of core diameter and depth or height 20% of ideal relative index difference between the core and cladding.

Table.1. Six MMF with different refractive index profiles considered for analysis

MMF	#1	#2	#3	#4	#5	#6
Index profile	g=2.03 with dip	g=2.03 with peak	g=2.03 ideal	g=1.88 with dip	g=1.88 with peak	g=1.88 ideal

As one example, the relative group delay for MMF #1 is illustrated in Fig.2 (a), which shows that there are about 19 mode groups and the maximum DMD is about 2ps/m. It is important to note that it is the small dip located at the center of core that causes those lower LP modes with azimuthal number zero have larger deviation from others. We scale the group delay for each MMF listed in Table.1 to approach the 3dB OFL bandwidth-distance product of 500MHz-km. The OFL bandwidth is calculated by assuming uniform excitation of all fiber modes, i.e. by assigning a power value of 4 to the modes with azimuthal mode number $\nu\neq0$ (fourfold degeneracy) and 2 to the modes with $\nu=0$ (twofold degeneracy).

Since the standardization of Gigabit Ethernet, Restricted Mode Launch (RML) scheme based on the partial mode excitation has been recommended. However, RML bandwidth is not always larger and even worse than that of OFL case owing to the imperfection of refractive index profile [11,16]. Subsequently offset RML technique is developed to overcome this problem. The Mode Power Distribution (MPD) can be obtained by solving the overlap integral between the electrical field of light source and each LP mode [10,11]. Under the assumption of Gaussian beam spot with FWHM=9μm and offset launch 18μm, the MPD for MMF #1 is calculated and drawn in Fig.2 (b). From Fig.2 (b) we can see that under this RML condition, only middle order mode groups (about from 4 to 12) are excited and larger bandwidth can be achieved by avoiding those mode groups with lower or higher order, whose group velocities have larger deviation from others.
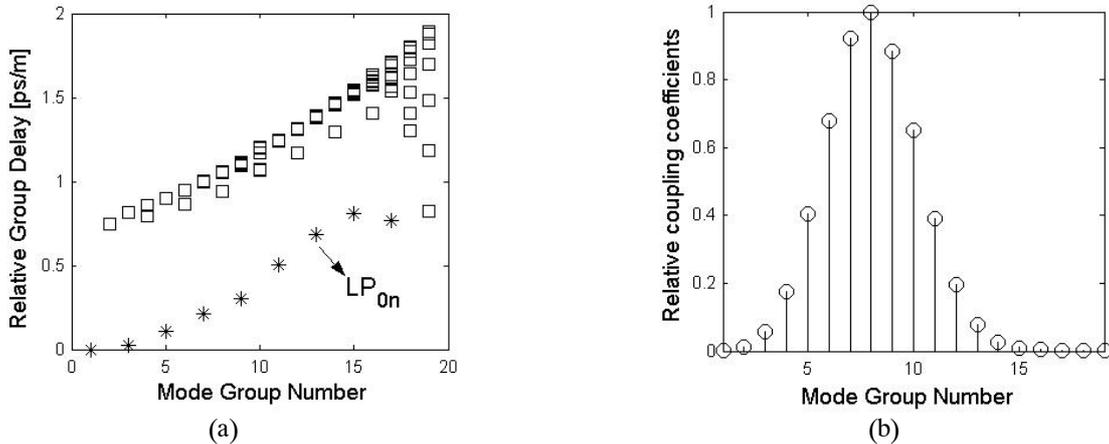

Fig.2. (a) Relative mode group delay versus mode group number for MMF #1. (b) Mode power distribution for MMF #1. Gaussian beam spot with FWHM=9μm and offset launch 18μm.

3. OPTICAL COMPENSATION OF DMD

For the graded index profile of conventional MMF, with power-law exponent g>g_{opt}, the modes with higher order move slower than those with lower order. On the contrary, with power-law exponent g<g_{opt}, modes with higher order move faster than those with lower order. Therefore, splicing the two kinds of MMF can result in the compensation of DMD. [12] shows that splicing two fibers with opposite deviations from the optimum index profiles can improve the bandwidth. However, this solution is impractical for the installed MMF. For this case, to achieve 300m transmission distance @10Gb/s for installed MMF, approximately equal length of 300m for the compensating MMF should be spliced due to the small difference of power-law exponent for all installed graded index MMF. Instead, we suggest and show that by using new kind of MMF named as DCF with only about 10~35m, the 10GbE reach of installed MMF can be extended to 300m.

For the introduction of the DCF suggested by us, the following conditions should be taken into account simultaneously.

(1) In terms of diameter and Numerical Aperture (NA), installed graded index MMF can be classified into two groups: 50μm with NA=0.2 and 62.5μm with NA=0.275. Accordingly, two kinds of DCF are suggested to minimize the insertion loss.
(2) To maximize the mode conversion efficiency from MMF to DCF, the difference of the mode group number as well as the electrical field distribution of LP mode between them can not be large.
(3) The power-law exponents for installed graded index MMF have two possibilities: g>g_{opt} and g<g_{opt}. Consequently, two kinds of power-law exponents for DCF should be used.
(4) The shorter the DCF to compensate at least 300m installed MMF, the less would be the cost as well as the attenuation.

With all above aspects taken into account, specifications of four kinds of DCF are proposed and listed in Table 2.

We take the 62.5μm MMF operated at 1300nm as the example. The mode conversion coefficients from MMF to DCF are calculated by the overlap integral of electrical fields for each two LP modes between MMF and DCF [10,12].

Table.2. Specifications of DCF proposed

MMF	62.5μm, NA=0.275		50μm, NA=0.2	
	g>g$_{opt}$	g<g$_{opt}$	g>g$_{opt}$	g<g$_{opt}$
DCF	62.5μm, NA=0.275		50μm, NA=0.2	
	g=1	g=3	g=1	g=3

The relative group delay for the conventional MMF (300m, MMF #6, g=1.88, ideal) and DCF (31m, g=3) as well as splicing of both are shown in Fig. 3(a), from which we can see that the group delay for MMF about linearly decreases with mode group number and the maximum DMD is about 600ps after 300m transmission distance (marked with square). By splicing 31m DCF (marked with circle), the group delay distribution becomes much flat and approaches the optimum case (marked with star), which is demonstrated further by the impulse response shown in Fig. 3(b).
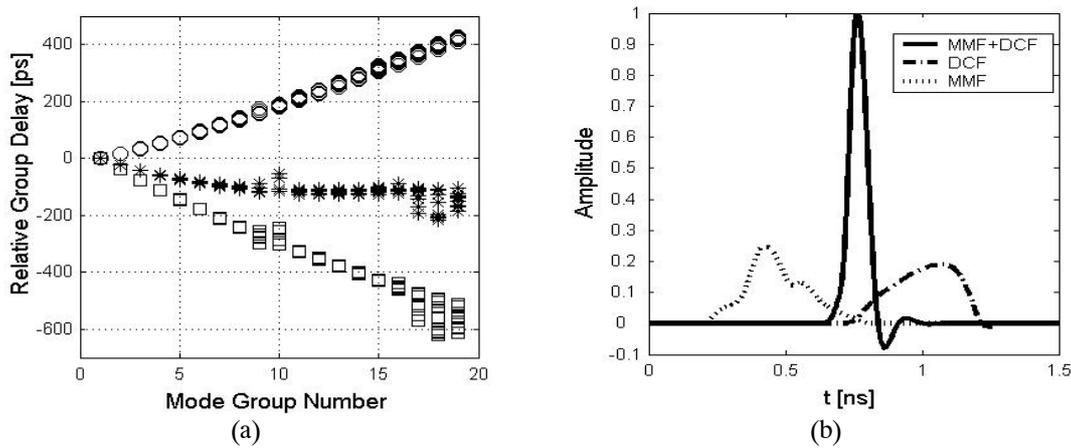

Fig. 3. (a) Relative group delay versus mode group number, MMF #6. Square: MMF, circle: DCF, star: MMF+DCF. (b) Impulse response of MMF (#6, 300m), DCF (g=3,31m) and MMF +DCF.

To find out the optimum length of DCF (g=1) to compensate the 300m installed MMF (#1~#3, g=2.03), the dispersion compensation for OFL as well as for RML condition with Gaussian beam spot size of FWHM=9μm and offset 18μm is plotted in Fig.4. We can see that with appropriate length of DCF, less than 3dB EOP (compared to back-to-back) can be achieved for the three kinds of MMF channel. Fig.4 exhibits that DMD compensation for the MMF with ideal index profile like MMF #3 is more complete in comparison to MMF with imperfect index profiles such as MMF #1 and #2. This is because the dip or peak located at the center of core causes the group delay of those modes with azimuthal mode number zero have larger deviation from others, which can be seen from the group delay shown in Fig. 5. It is important to note that the DCF used to compensate the DMD of different MMF is assumed to be with ideal graded index profile. Therefore, those MMF channels with non-ideal index profiles with dip or peak cannot be compensated completely with the ideal DCF. In addition, Fig.4 also displays that due to subset of modes excited for RML condition, the required length of DCF to compensate the 300m MMF has the larger tolerance for RML case in comparison to OFL case.

Similar results are obtained for the DMD compensation of MMF (#4~#6, g=1.88) by splicing DCF (g=3). The simulations reveal that by splicing about 30m DCF (g=3), the 300m-transmission reach over MMF (with g=1.88) can be achieved.

The above discussions demonstrate that DMD in both of installed MMF with undercompensated and overcompensated power-law exponents can be compensated by splicing a short span of DCF. By the end of this part, it is important to indicate that the DMD compensation of the MMF with non-ideal index profile can be compensated more completely by concatenating another new kind of DCF with not only opposite power-law exponent but also with opposite imperfections. As one example, using one kind of DCF whose index profile with exponent g=1 and peak at center to

compensate the installed MMF whose index profile with exponent $g>g_{opt}$ and dip at center. However, the complete compensation of DMD is at the cost of more complicated manufacture technique and process of the new fiber.
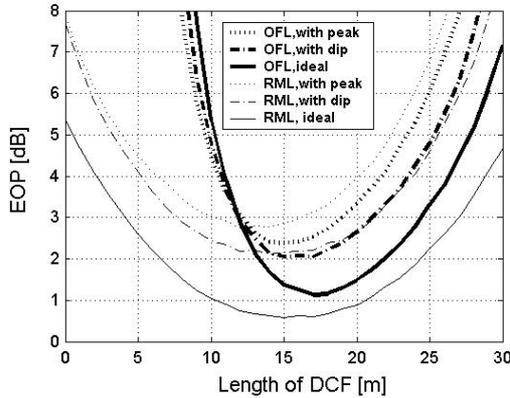

Fig.4. EOP versus the length of DCF (g=1) for OFL and RML. MMF: #1 ~#3 (300m). RML: Gaussian beam spot with FWHM=9um and offset 18um launch.
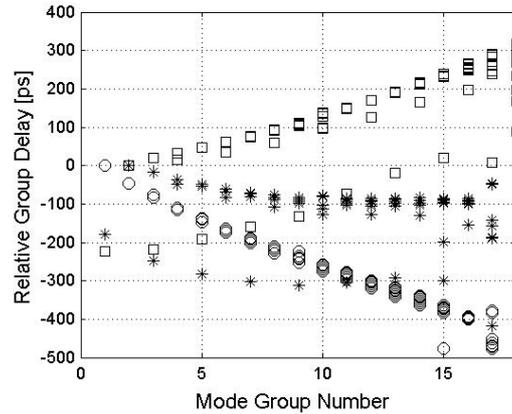

Fig.5. Relative group delay versus mode group number. Square: MMF #1 (300m), circle: DCF (17m, g=1), star: MMF+DCF.

4.   ELECTRICAL EQUALIZATION OF DMD

The electrical equalization technique to mitigate ISI of signal has been used widely in wireless communication and researched broadly in single mode fiber long haul links as well [13]. Recently, equalization is considered as one of possible solution to eliminate ISI caused by DMD of multi-path effect in MMF channel [14,15]. Electrical equalization used in optical communications is generally called Electrical Dispersion Compensation (EDC). In this part, we show that linear equalizer or Decision Feedback Equalizer (DFE) can mitigate ISI resulting from intermodal dispersion and enhance installed MMF bandwidth and thus reach or extend the required 300m-transmission distance of 10-Gigabit Ethernet.

The coefficients for each tap of equalizers are calculated based on minimum mean square error rule without considering noise. Equalization can be performed either in the sampled discrete domain or in the analog domain. In our case, we assume the latter.

EOP of received signal with and without using EDC for MMF #1 for OFL condition is shown in Fig.6 (a). From Fig.6 (a) we can see that without equalization, the transmission distance is limited to only about 85m at 2dB EOP. By using linear equalizer, only when the order is increased to 14, the transmission distance can reach 300m at 10Gb/s with EOP less than 2dB. In contrast to linear equalizer, Decision Feedback Equalizer, which employs previous decisions to eliminate the postcursors, can eliminate ISI resulting from DMD more effectively, especially when transmission is larger or ISI is more serious. Fig.6 (a) displays that by using DFE with order 4 feedforward filter and order 3 feedback filter, more than 350m-transmission distance can be achieved at target 2dB EOP.

More simulations have been carried out on equalizations for MMF #1 for RML condition. EOP of received signal output from equalizer for RML case with Gaussian beam spot size of FWHM=9μm and offset 18μm is shown Fig.6 (b). The results shown in Fig.6 (b) reveal that due to only the subset of mode group excited for RML condition, equalization exhibits better performance compared to OFL case. Even only with order 6 linear equalizer FIR (6), the transmission distance can be extended from about 120m to more than 400m with 2dB EOP. The comparison of linear equalizer and DFE for RML case demonstrates further that DFE exhibits superior performance.

Although, sometimes, linear equalizer with higher order can achieve equivalent performance to DFE, however, the basic limitation of linear equalizer is that it performs poorly on channels having spectral nulls [15]. For most installed MMF
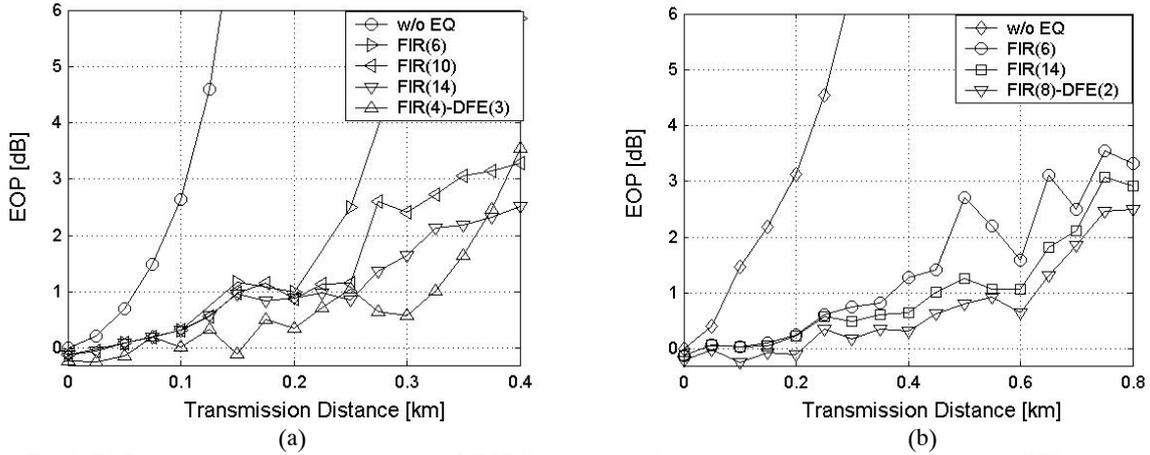
Fig.6. EOP versus transmission distance for MMF #1 with or without using electrical equalization. (a) OFL conditon.(b) RML condtion. Guassian beam spot with FWHM=9μm and offset launch 18μm.

operated at high data rate or longer transmission distance, the spectrum exhibits some zeros points in the data rate bandwidth, which limits the performance of linear equalizer. As one example, with the incident beam spot size of FWHM=18μm and the offset launch 24μm, the frequency response for MMF #1 after 300m transmission is plotted in Fig.7(a), which exhibits the first zero point at about 3.5GHz. For this case, the linear equalizer even with very high order can not eliminate the ISI effectively. The received normalized eye-diagram after equalization with order 20 linear equalizer is shown in Fig.7 (b), which exhibits 4.8dB EOP and demonstrates the problem of linear equalizer for a channel having null points. Especially when noise is considered, the linear equalizer will enhance the noise due to the large gain required by the equalizer to compensate the dip in the spectrum. On the contrary, generally, DFE can avoid the influence of zero points and does not enhance the noise. Simulations show that for this case, by using DFE with 8-order feedforward filter and order 2 feedback filter, the EOP of signal after equalization is only about 0.6dB, as shown in Fig.7 (c). Therefore, to guarantee the performance of EDC on variable MMF channels, DFE is suggested.
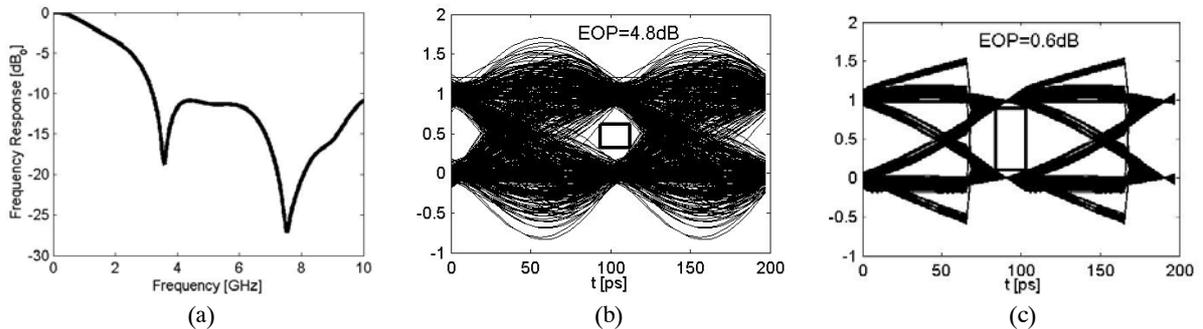

Fig.7. (a) The frequency response of MMF #1 under RML conditon with FWHM of Gaussian beam spot 18μm and offset launch 24μm. (b) Reveived normalized eye-diagram after equalization by using order 20 linear equalizer for the channel with frequency response as shwon in (a). (c) Reveived normalized eye-diagram after equalization by using DFE with order 8 feedforward filter and order 2 feedback filter for the channel with frequency response as shown in (a).

5.   COMBINATION OF OPTICAL AND ELECTRICAL COMPENSATION OF DMD

Optical compensation of DMD by splicing a short span (10~35m) of DCF and electrical compensation by using linear or nonlinear equalizers have been discussed separately above. In this part, we show that superior performance can be achieved by combining the two kinds of compensation technique in MMF links.

The whole simulation model for MMF link including both optical and electrical compensation has been shown in Fig.1. The EOP of the received signal for MMF #1 by using optical compensation, electrical equalization and combination of

both for OFL condition is shown in Fig.8 (a). It is important to note that the proportion of DCF length to MMF is chosen according to the optimum dispersion compensation as shown in Fig.4. From Fig.8 (a), we can see that with the criterion of 2dB EOP, if only optical compensation or electrical equalization with order 6 linear equalizer, each of them alone cannot extend the transmission distance to more than 300m. However, combination of both enhances the bandwidth of MMF dramatically and the transmission distance can reach more than 1000m with 2dB EOP. More simulations are done for the other five kinds of MMF channels listed in Table.1 and the maximum transmission distance at 2dB EOP with different compensation schemes for each MMF is presented in Table.3. From Table.3, we know that the minimum transmission distance for the six MMF by combining optical and electrical compensation is 970m.
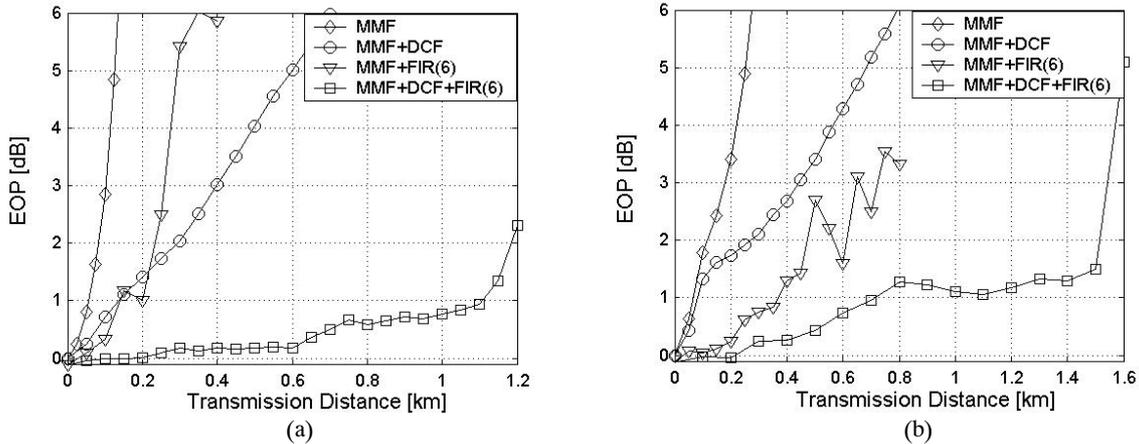

Fig.8. EOP versus transmission distance for MMF #1 with optical, electrical compensation or combination of both. (a) OFL condition. (b) RML condition, Guassian beam spot with FWHM=9μm and offset launch 18μm.

Table.3. The maximum transmission distance at 2dB-EOP with different compensation for OFL condition

MMF	#1	#2	#3	#4	#5	#6
OFL	82m	88m	88m	76m	81m	90m
with DCF	290m	268m	412m	308m	275m	418m
with FIR(6)	230m	253m	225m	275m	373m	420m
DCF+FIR(6)	1180m	1006m	970m	1635m	1437m	1440m

The EOP of the received signal for MMF #1 by using optical compensation, electrical equalization and combination of both for RML condition with offset 18μm and Gaussian beam spot size of FWHM=9μm is shown in Fig.8 (b). In the same way, the maximum transmission distance at 2dB EOP with different compensation schemes for each MMF is presented in Table.4, which shows that for RML condition, more transmission distance (from 1394m to 2400m) can be achieved by combining optical and electrical compensation.

Table.4. The maximum transmission distance at 2dB-EOP with different compensation for RML condition

MMF	#1	#2	#3	#4	#5	#6
RML	116m	124m	203m	110m	109m	198m
with DCF	270m	200m	577m	190m	200m	442m
with FIR(6)	472m	386m	978m	603m	419m	991m
DCF+FIR(6)	1514m	1451m	1394m	1490m	1540m	2400m

For above discussions on combination of optical and electrical compensation of DMD in MMF, linear equalizer with order 6 is assumed. It is straightforward to derive that if higher order linear equalizer or DFE is used, better performance or longer transmission distance can be achieved. Therefore, with combination of optical and electrical compensation of DMD, MMF transmission at 10 Gb/s becomes nearly power limited.

As discussed previously, linear equalizer performs poorly when the channel spectrum has null points. However, when linear equalizer is combined with optical compensation, the null points are shifted to far beyond the data rate bandwidth. The analysis of results shown in Table.3 and 4 has demonstrated that the influence of the zero points on the linear equalization occurs only if the transmission distance reaches about 1000m or beyond. For the same MMF channel under the same launch condition, we show that the zero points will move outside the data rate bandwidth if optical compensation is used. The frequency response for this channel after 1000m-transmission by splicing 53m DCF is shown in Fig.9 (a), which does not exhibit any obvious dip in the spectrum even after 1000m transmission distance. For this case, even linear equalizer of order 6 can mitigate the ISI and recover the eye with only 1.5dB EOP as shown in Fig.9 (b). Therefore, the combination of EDC and optical compensation of DMD can avoid the influence of zero points on linear equalizer.
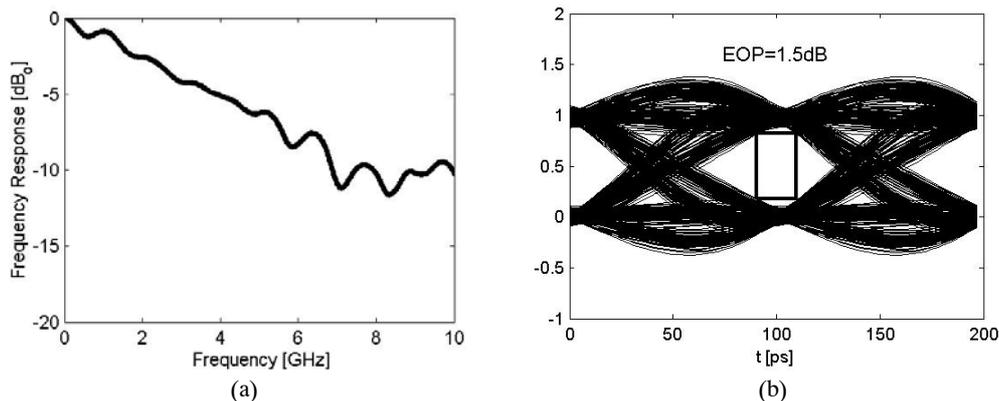

(a)   (b)

Fig.9. (a) The frequency response of MMF #1(1000m)+DCF(g=1,53m) under RML conditon with FWHM of Gaussian beam spot 18μm and offset launch 24μm. (b) Reveived normalized eye-diagram after equalization by using order 6 linear equalizer for the channel with frequency response as shwon in (a).

6.   CONCLUSIONS

Based on analysis of DMD compensation, we propose a new kind of dispersion compensating fiber to compensate differential mode delay in installed multimode fiber. In addition, we demonstrate that by using decision feedback equalizer, the installed MMF with bandwidth-distance product 500Mhz-km can be extended to over 300m at 10Gb/s. The feedforward filter equalizer alone cannot guarantee the EDC performance due to the MMF channel having null points in the spectrum. Especially, we show that excellent performance can be achieved by combining optical and electrical compensation. Based on simulations of six typical types of installed MMF, we demonstrate that transmission distance for conventional MMF can reach one kilometer or beyond at 2dB eye-opening penalty for overfilled launch as well as for restricted mode launch condition with appropriate offset launch. Moreover, we prove that combination of EDC and optical compensation can avoid the influence of the null points on linear equalization.

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