Optical Compensation of Differential Mode Delay in MMF Links for 10-Gigabit Ethernet

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Abstract *We propose a dispersion compensating fiber(DCF) to compensate DMD of installed MMF. We show that with 10~30m of DCF, conventional MMF can reach 300m distance@10Gb/s with less than 2dB eye-opening penalty.*

Introduction

The goal of 10-Gigabit Ethernet for the conventional Multimode Fiber (MMF) is to obtain 300m-transmission distance. However, the intermodal dispersion due to Differential Mode Delay (DMD) in MMF channel dramatically limits the bandwidth-distance product to 500MHz-km for 62.5µm-MMF at 1300nm or 50µm-MMF at 850nm and 1300nm.

Recently, some new techniques have been studied to upgrade the data rate of legacy MMF, e.g. CWDM, multilevel modulation, new kind of photodiode receiver and electrical equalization. We propose that the DMD of installed MMF can be compensated by splicing one short span of new kind of MMF, called MMF-DCF. Compared to above-mentioned techniques, we will show that this kind of optical compensation of DMD is a simple, inexpensive and efficient solution.

Theory of compensation DMD of MMF

The graded index profile of conventional MMF can be expressed as

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\dfrac{r}{a}\right)^g\right]^{1/2} & r < a \\ n_1(1-2\Delta)^{1/2} = n_2 & r \ge a \end{cases}$$

Where, n_1, n_2 are the refractive index in the centre of core and the cladding, respectively, a the radius of core, Δ the relative refraction difference, g the index power-law exponent, which is the key parameter determining the DMD as well as the mode group number. The relative propagation delay versus mode group number with different index power-law exponents is schematically shown in Fig. 1, which shows that with power-law exponent $g>g_{opt}$, the propagation delay increases almost linearly with mode group number, which means that 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. [1] 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 available Graded Index MMF (GI-MMF). Instead, we suggest and show that by using new kind of MMF named as MMF-DCF with only about 10~30m, the 10GbE reach of installed MMF can be extended to 300m.

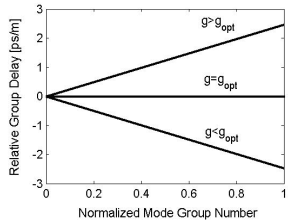

Fig.1: Relative group delay versus mode group number for different power-law exponents

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

1. In terms of diameter and numerical aperture (NA), there are two kinds of MMF: 50µm with NA=0.2 and 62.5µm with NA=0.275. Accordingly, two kinds of MMF-DCF with the two kinds of diameter and NA are suggested to minimize the insertion loss.
2. To maximize the mode conversion efficiency from MMF to MMF-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. MMF-DCF should be capable of compensating DMD for all installed GI-MMF, whose index power-law exponent has two possibilities: $g>g_{opt}$ and $g<g_{opt}$. Consequently, two exponents for MMF-DCF should be used.
4. The shorter the MMF-DCF to compensate 300m installed MMF, the less would be the cost as well as attenuation. Therefore, the maximum DMD of MMF-DCF should be large enough compared to that of installed MMF.

Considerations of all aspects outlined above, specifications of four kinds of MMF-DCF are proposed and listed in Table 1.

Table 1:

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

Simulations and discussions

We take the case of 62.5µm MMF at 1300nm with Overfilled Launch (OFL) bandwidth 500MHz-km as an example. To approach the installed MMF, the index profiles with imperfections including dip and peak at center of core are considered. Six types MMF with OFL 3dB bandwidth-distance product

500MHz-km are examined: ideal index profile, index profile with small dip or peak for $g>g_{opt}$ and $g<g_{opt}$ as well. The delay and electrical field distribution of each LP mode are calculated by solving the mode solver [2]. For modeling MMF channel, mode dependent attenuation is also considered and assumed to be the modified Bessel function of first kind [3]. In addition, mode coupling within the same mode group is assumed to be sufficient. To determine the mode conversion coefficients between MMF and MMF-DCF, the overlap integral given in [1] is used. The following simulations are carried out with PRBS of length 2^9-1 and NRZ line coding.

The relative group delay for conventional MMF (300m, $g>g_{opt}$, ideal index profile) and MMF-DCF (17m, $g=1$) as well as the splicing of both are shown in Fig. 2, from which we can see that group delay for MMF about linearly increases with mode group number and the maximum DMD is about 400ps after 300m transmission distance. With the compensation of 17m MMF-DCF, the group delay distribution approaches the optimum case, which is demonstrated further by the impulse response shown in Fig. 2.

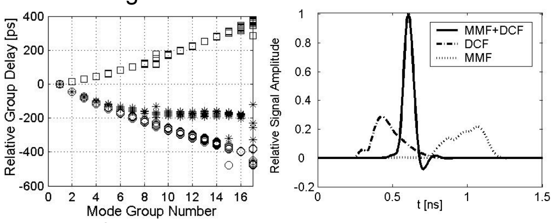

Fig.2: Left: Relative group delay versus mode group number. Square: MMF(300m, ideal), circle: DCF (17m), star: MMF(300m)+DCF(17m). Right: Impulse response of MMF(300m), DCF(17m) and MMF (300m)+DCF(17m).

To find out the optimum length of MMF-DCF($g=1$) to compensate the 300m installed MMF($g>g_{opt}$), the dispersion compensation map is plotted in Fig.3. We can see that with appropriate length of MMF-DCF, less than 2dB EOP (with back-to-back) can be achieved for three kinds of MMF channel. Results for MMF($g<g_{opt}$) with MMF-DCF($g=3$) are shown in Fig.4. Both Fig.3 and 4 exhibit that DMD compensation for the MMF with ideal index profile is more complete in comparison to MMF with imperfect index profile. This is because the dip or peak localized at center of core causes the group delay of those modes with cylindrical mode number zero have larger deviation from others, which can be seen from the group delay shown in Fig. 5.

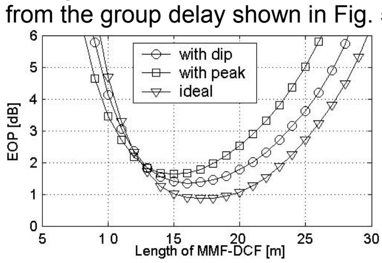

Fig.3: EOP versus the length of MMF-DCF. MMF($g>g_{opt}$, 300m), DCF($g=1$).

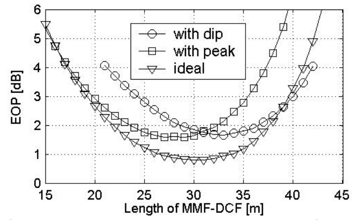

Fig.4: EOP versus the length of MMF-DCF. MMF($g<g_{opt}$,300m),DCF($g=3$).

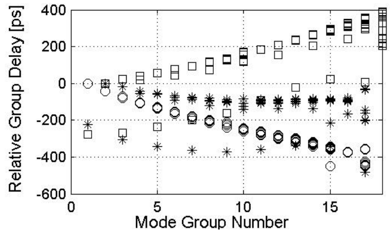

Fig.5: Relative group delay versus mode group number. Square: MMF($g>g_{opt}$,300m,with dip), circle: DCF($g=1$,16m), star: MMF(300m)+DCF(16m).

All above results are for OFL condition. Since the standardization of Gigabit Ethernet, Restricted Mode Launch (RML) [4,5] scheme based on the partial mode excitation by using directly modulated laser has been recommended and developed. The dispersion map for RML condition under the assumption of laser with spot FWHM=7µm by offset 24µm is shown in Fig. 6, which illustrates that due to subset of modes excited for RML condition, more improvement can be obtained. Moreover, dispersion map for RML is much wider than that for OFL condition. With the criterion of 2dB-EOP, length of DCF has the tolerance of 20m for RML as comparison to 8m for OFL condition.

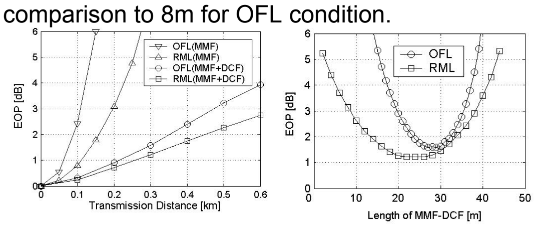

Fig.6: Left: EOP versus transmission distance for OFL as well as RML with and without DCF. MMF($g<g_{opt}$,with peak),DCF($g=3$),L_{DCF}: L_{MMF}=22:300 for RML, L_{DCF}: L_{MMF}=27:300 for OFL. Right: EOP versus length of MMF-DCF. MMF($g<g_{opt}$, 300m, with peak), DCF($g=3$).

Conclusions

New kinds of MMF-DCF are suggested to compensate the DMD of installed MMF in optical domain. Computer simulations on six types typical MMF channels for the OFL as well as RML condition have shown that with 10m~30m MMF-DCF, less than 2dB EOP can be achieved for 300m transmission distance for installed MMF @10Gb/s.

References

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