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Performance Evaluation of a High-Birefringence Linearly Chirped Grating for PMD Compensation in WDM/ IM-DD Transmission System

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Abstract - We analytically evaluated the performance of an adjustable polarization mode dispersion compensator based on a 2-cm long high-birefringence linearly chirped fiber Bragg grating and simulated a 4-channel WDM /IM-DD system using this compensator. The device can adjust differential group delay in a linearly continuous way without affecting wavelength outside the bandwidth. The various properties of the device such as relative group delay, reflectivity, differential group delay etc. are investigated in terms of wavelength and stretching ratio. Results show that under stretched condition; the device generates a time-delay between fast and slow polarization axes that is adjustable from 0 ps to 55 ps and is tunable within 2.4 nm wavelength range. Through simulation, it is also found that the power penalty is reduced from 7.10 db to 4.5 dB at a mean DGD 40 ps for a 4-channel 10 Gb/s WDM system when no stretched is applied on the grating.

I. Introduction

Polarization mode dispersion (PMD) has become one of the most difficult issues in implementing next-generation high-bit rate 10 Gb/s and beyond transmission systems. PMD is a serious problem, because a large amount of the installed fibers exhibit PMD values that are several times that of current state-of-art fibers. Degrading effects that tended to cause catastrophic events even at lower bit rates have become critical concerns of high-performance networks. First-order PMD compensation is the simplest technique to compensate PMD and it is realized by delaying one state-of-polarization (SOP) with respect to other. There have been several experiments and/or simulation work to demonstrate first-order PMD compensation [1]-[4]. Conventionally to compensate PMD in a WDM system, channels have to be demultiplexed and compensated individually resulting in increased cost and complexity.

Chirped fiber gratings are useful for PMD and chromatic dispersion compensation [5]-[7]. The linearly high-birefringence (Hi-Bi) chirped FBG has a large refractive index difference (Δn) between its fast and slow polarization axes. The birefringence, Δn causes the orthogonal polarization modes to experience two different couplings with the grating and the Bragg reflection from the birefringence chirped grating for a given signal wavelength occurs at different locations for different polarizations. The Hi-Bi fiber provides different time delay for different SOPs and the chirp of the grating provides the selectability of varying amounts of differential polarization time delay when the FBG is stretched or compressed [8]. Z. Pan *et al* [9], experimentally demonstrated chirp-free tuneable PMD compensation for a 10 Gb/s signal by using an adjustable highly-birefringence nonlinearly-chirped FBG in a novel dual-pass configuration that significantly reduces the induced chirp of the FBG. It is shown that a 45-km link interacting with the FBG induced chirp is reduced from 4.0 to 0.5 dB. X. Kun *et al* [10], based on numerical simulations reported that the efficiency of a sampled Bragg grating PMD compensator is assessed for the 10 Gb/s NRZ transmission system with 58.6 and 106 ps differential group delay (DGD), respectively by applying transverse and uniform distributed force.

In this paper, we have developed analytical formulations and evaluate the performance of a Hi-Bi linear chirped fiber Bragg grating (LCFBG) based WDM-PMD compensation device and simulation is done to investigate the feasibility to compensate several channels at the same time for a 4-channel WDM/IM-DD transmission system using this device. The reflection point inside the grating can be moved by several millimeters by stretching the grating by few microns. It is found that a 2 cm long LCFBG allows the DGD to be adjusted from 0 ps to 55 ps in a continuous way within a 2.4 nm wavelength range by stretching it by 0.2%. Simulation results show that the power penalty for a 4-channel 10 Gbps system with 40 ps average DGD is reduced from 7.10 dB to 4.5 dB.

II. LCFBG based PMD compensator

The system model of a LCFBG based PMD compensator is shown in Fig.1. The proposed delay element consists of a 4-port polarization beam splitter (PBS) and a 2 cm length Hi-Bi LCFBG. The PBS splits the incoming optical signal into two orthogonal polarizations. The fast axis polarization signal (P_f) enters the Hi-Bi LCFBG from the longer wavelength port and slow one (P_s) from the shorter wavelength port. The polarization states of the signal (λ_i) within the bandwidth of the grating will be reflected and differently delayed by the grating. By properly tuning the LCFBG, we can adaptively generate required DGD ($\Delta\tau$) for the PMD compensation. The two orthogonally polarized optical signals are then combined without interference and the compensated signal is directed to output port 1 of the PBS. An optical circulator can be used to separate the input signal and the PMD compensated output signal. All light (λ_0) outside the reflection bandwidth of the grating will not be affected and detected to output port 2.

II. WDM-PMD compensation system model

Fig.2 shows the typical module of the compensation scheme using the LCBG based compensator. It shows the power penalty (at the input and output) for different DGD values when the input power is evenly divided between the two PSPs. The power penalty for small (such as 10 ps) DGD is usually negligible or within the power margin of the system and therefore be tolerated. It is the high values that cause significant degradation when signal power splits almost equally between the two PSPs. At the input 4-channels (bit rate, 10 Gbps per channel) with wavelength λ_1, λ_2, λ_3 and λ_4 are multiplexed and fed to fiber link. In our simulation, we take two span of 200 km length fiber link. The LCFBG compensators are placed after 200 km fiber link length where fiber loss is totally compensated by EDFA. Finally, the channels are demultiplexed at the receiving end and eye diagram is monitored without and with compensator to assess the deterioration and amount of compensation of each channel.

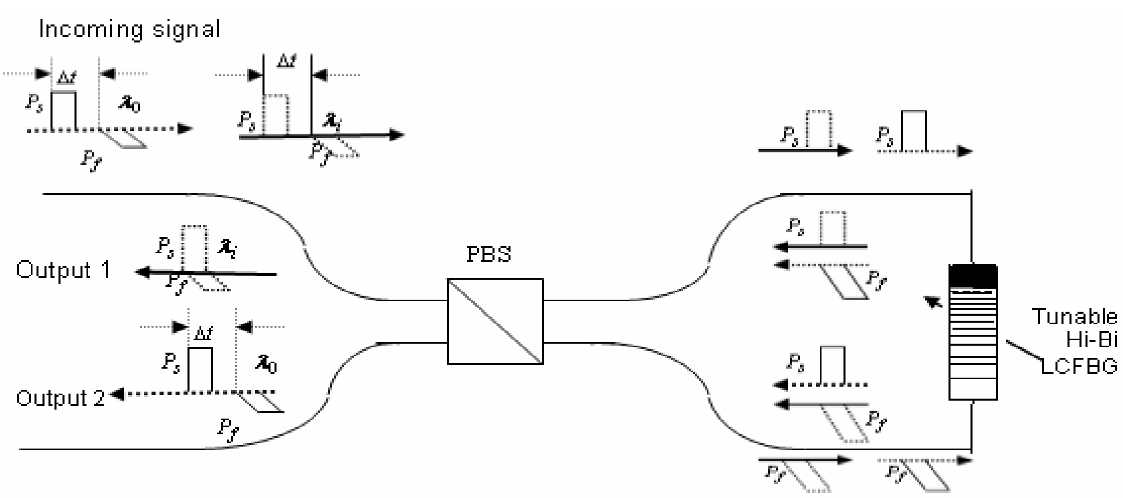

Fig.1: System model of the LCFBG based PMD compensator. The incoming signal has polarization components along both the fast- (P_f) and slow (P_s)axis. The LCFBG generates the required DGD for the Bragg reflected signal (λ_i), while it does not affect the signal (λ_0) outside the grating bandwidth

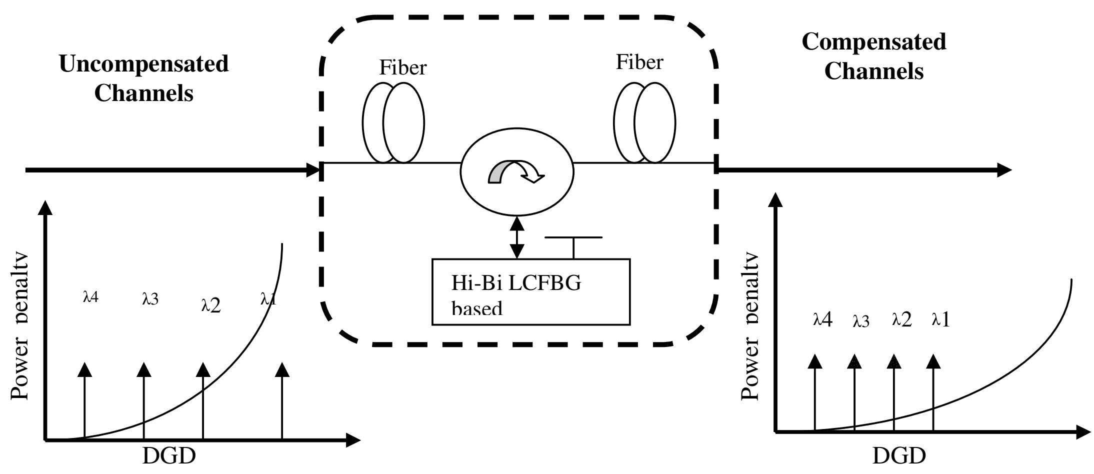

Fig.:2 Hi-Bi LCFBG based WDM-PMD compensation module

IV. Theoretical analysis

A. Characteristics of Hi-Bi LCFBG

Let us assume that a Bragg grating in a single mode fiber consists of a refractive index that is varied with the period, Λ and the modulation amplitude is added to the initial refractive index in the fiber. The perturbation to the effective refractive index n_{eff} of the guided mode(s) of interest given by,

$$\delta n(z) = \delta n_{eff}\left[1 + v(z)\cos(Kz + \phi(z))\right] \quad (1)$$

Where, $\delta n_{eff} = n_{av} - n_{co}$ is the average index change over one period, v is the fringe visibility of the index change, $0 \le v \le 1$. $\cos(Kz + \phi(z))$ is the index perturbation, which has a constant spatial frequency with an additional position dependent phase variation $\varphi(z)$ that represents the change in periodicity.

Birefringence in optical fibers is defined as the difference in refractive index Δn between a pair of orthogonal modes (called slow- and fast modes) and results from the presence of circular asymmetries in the fiber section. The refractive index for both the slow- and fast-mode is defined as

$$n_{eff,s} = n_{eff} + \frac{\Delta n}{2}\ ; \qquad n_{eff,f} = n_{eff} - \frac{\Delta n}{2} \quad (2)$$

Where n_{eff} is the fiber effective index. To denote the refractive index of both modes from now on we will use notation $n_{eff,\,f(s)}$.

B. The effect of strain on Hi-Bi LCFBG

The penetration depth in reflection and the distance traversed in transmission in response to an applied axial strain or temperature changes, because there is a redistribution of the period as well a change in the refractive index due to photo-elastic or photo-thermal effect [11]. Both of these effects influence the Bragg condition (*i.e.,* $\lambda_B = 2n_{eff,f(s)}\Lambda$). Suppose at constant temperature, under the influence of axial strain (+ve) $\varepsilon(z)$, at the grating position *z*, the FBG will experience a physical elongation of grating period, Λ and a change of refractive index, $n_{eff,\,f(s)}$ due to the photo-elastic effect. The grating period can be written as,

$$\Lambda(z, \varepsilon(z)) = (\Lambda_0 + C_0 z)(1 + \varepsilon(z)) \quad (3)$$

Where, Λ_0 is the grating period at position, $z = 0$ without strain. Constant C_0 denotes the initial chirp of the grating and represented as, $C_0 = d\Lambda/dz\big|_{z=0}$. The induced change in the fiber index $dn_{eff,\,f(s)}(z)$ that is due to the photo-elastic effect is expressed as [12], $\frac{dn_{eff,\,f(s)}}{n_{eff,\,f(s)}} = -\rho_e\ \varepsilon(z)$, where we assumed the photo-elastic contributions into ρ_e, which is defined by $\rho_e = \frac{n_{eff,\,f(s)}}{2}\left[p_{12} - \mu(p_{11} + p_{12})\right]$ in terms of Pockel's coefficients p_{ij} and μ is the Poisson ratio. Together with the Bragg condition the resonance condition can be approximated and becomes dependent on local strain. Thus Bragg wavelength $\lambda_{f(s)}$ at grating position z becomes,

$$\lambda_{f(s)}(z) = 2n_{eff,\,f(s)}\left[(\Lambda_0 + C_0 z) + (\Lambda_0 + C_0 z)(1 - \rho_e)\varepsilon(z)\right] \quad (4)$$

From (4), it is straightforward to observe that the reflection wavelength shift of the grating is proportional to the applied strain. If strain gradient is added to a FBG, the Bragg wavelength varies linearly along the fiber length because of the change in the effective grating period.

C. Modeling of the fiber Bragg grating

Coupled-mode theory is a good tool for obtaining quantitative information about the diffraction efficiency and spectral dependence of fiber grating. Generally, Bragg reflection is the interaction between the optical signal and its medium. The wave formulation for forward and backward wave amplitudes *F(z)* and *B(z)* can be expressed as,

$$\begin{aligned} \frac{dF^+(z)}{dz} &= -i\hat{\sigma}_{f(s)}\ F^+(z) + i\kappa_{f(s)}(z)\ B^+(z) \\ \frac{dB^+(z)}{dz} &= -i\hat{\sigma}_{f(s)}\ B^+(z) - i\kappa^*_{f(s)}(z)\ F^+(z) \end{aligned} \quad (5)$$

Where, $F^+(z) = F(z)\,e^{(i\delta z - \varphi/2)}$, $B^+(z) = B(z)\,e^{(-i\delta z + \varphi/2)}$; $F^+(z)$ (reference) represents the forward propagating mode, $B^+(z)$ (signal) is the identical backward (counter) propagating mode, $\hat{\sigma}_{f(s)}$ and $\kappa_{f(s)}$ are the general dc (period averaged) self-coupling and ac coupling coefficients respectively and can be expressed as,

$$\begin{aligned} \hat{\sigma}_{f(s)} &= \delta_{f(s)} + \sigma_{f(s)} - \frac{1}{2}\frac{d\varphi(z)}{dz} \\ &= \delta_{f(s)} + \frac{2\pi}{\lambda_{f(s)}}\delta n_{eff,\,f(s)} - \frac{1}{2}\frac{d\phi(z)}{dz} \end{aligned} \quad (6)$$

$$\kappa_{f(s)} = \frac{\pi}{\lambda_{f(s)}}\delta n_{eff,\,f(s)}v \quad (7)$$

$$\delta_{f(s)} = \beta - \beta_B = 2\pi\, n_{eff,\,f(s)}\left(\frac{1}{\lambda_{f(s)}} - \frac{1}{\lambda_B}\right) \quad (8)$$

Where $\delta_{f(s)}$ is the detuning (which is independent of z for all gratings) from the Bragg wavelength λ_B related to period Λ_0; $\delta n_{eff,\,f(s)}$ is the dc index spatially averaged over a grating period. $\sigma_{f(s)}$ is the dc coupling coefficient and The derivative $1/2\left(d\varphi(z)/dz\right)$ describes the possible chirp of the grating.

The coupled mode equations for the forward and the backward propagating modes can be solved using appropriate boundary conditions. The boundary conditions assume a forward propagating mode with $F^+(0)=1$ and that the backward propagating mode, at the end of the grating, will be zero, $B^+(L_g)=0$ as there are no perturbing beyond the end of the grating.

The solution of the coupled mode equation (5) can be best expressed by,

$$\begin{bmatrix} F^{+}(0)=1 \\ B^{+}(0) \end{bmatrix} = [T] \begin{bmatrix} F^{+}(L_g) \\ B^{+}(L_g)=0 \end{bmatrix} \qquad (9)$$

where T is the transfer matrix and given by,

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \qquad (10)$$

Where, $T_{11} = \cosh(\gamma L_g) - i\dfrac{\hat{\sigma}_{f(s)}}{\gamma}\sinh(\gamma L_g)$ (11)

$$T_{12} = -i\frac{\kappa_{f(s)}}{\gamma}\sinh(\gamma L_g) \qquad (12)$$

$$T_{22} = \cosh(\gamma L_g) + i\frac{\hat{\sigma}_{f(s)}}{\gamma}\sinh(\gamma L_g) \qquad (13)$$

$$T_{21} = i\frac{\kappa_{f(s)}}{\gamma}\sinh(\gamma L_g) \qquad (14)$$

γ is the parameter relating to coupling coefficient as $\gamma = \sqrt{\kappa_{f(s)}^2 - \hat{\sigma}_{f(s)}^2}$.

Reflectivity is the percentage of light reflected at the Bragg wavelength, the wavelength outside of the reflected bandwidth is transmitted without disturbance. For the case of uniform grating, the complex amplitude reflection coefficient at the beginning of the FBG at $z = 0$ is defined as,

$$\rho_{f(s)}(\lambda) = \frac{B^{+}(\hat{\sigma}_{f(s)})}{F^{+}(\hat{\sigma}_{f(s)})} = \frac{T_{12}}{T_{11}} \qquad (15)$$

$$\rho_{f(s)}(\lambda) = -\frac{\kappa_{f(s)}\sinh(\gamma L_g)}{\hat{\sigma}_{f(s)}\sinh(\gamma L_g) + i\gamma\cosh(\gamma L_g)} \qquad (16)$$

And the reflectivity *or* the power reflection coefficient, $R_{f(s)}(\lambda)$ is given by,

$$R_{f(s)}(\lambda) = \left|\rho_{f(s)}(\lambda)\right|^2 = \frac{\sinh^2(\gamma L_g)}{\cosh^2(\gamma L_g) - \hat{\sigma}_{f(s)}^2 / \kappa_{f(s)}^2} \qquad (17)$$

The group delay of the reflected light can be determined from the phase of the complex amplitude reflection coefficient $\rho_{f(s)}(\lambda)$. If we denote $\varphi_\rho \equiv phase(\rho_{f(s)}(\lambda))$, then the time delay τ_R for light reflected off of a grating is,

$$\tau_{R,f(s)} = \frac{d\varphi_\rho}{d\omega} = -\frac{\lambda_{f(s)}^{\ 2}}{2\pi c}\frac{d\varphi_\rho}{d\lambda_{f(s)}} \qquad (18)$$

Where, $\tau_{R,f(s)}$ is usually given in picoseconds, ω is the angular frequency and *c* is the velocity of light. Thus an optical wave traveling through a medium of length L and refractive index *n* will undergo a phase change, $\varphi_\rho = (2\pi n_{eff,f(s)}L_g)/\lambda$; The derivative of the phase with respect to wavelength is an indication of the delay experienced by the wavelength component of the reflected light;

$$\frac{d\varphi_\rho}{d\lambda_{f(s)}} = -\frac{2\pi n_{eff,f(s)}L_g}{\lambda_{f(s)}^2} \qquad (19)$$

The reflected spectrum is characterized by a main peak at the wavelength defined as, $\lambda_{\max,f(s)} = 2(n_{eff,f(s)} + \delta n_{eff,f(s)})\Lambda(z)$. Thus, with a large refractive-index difference Δn between the fast and slow polarization axes; that results in a shift in Bragg wavelength $\Delta\lambda_B = \left|\lambda_{\max,s} - \lambda_{\max,f}\right| = 2\Delta n\Lambda_0$ at the same location for two polarizations. Therefore, the Hi-Bi linearly chirped FBG can be seen as two different chirped FBGs because of the birefringence. The position difference of the reflection produces a DGD:

$$DGD(\lambda) = \left|\tau_{R,f}(\lambda) - \tau_{R,s}(\lambda)\right| \qquad (20)$$

V. Results and Discussion

Following the analytical formulations, at first the performance of a 2 cm long LCFBG is investigated in terms of relative group delay, DGD, stretching to determine the tuning range and maximum amount of PMD that can be compensated. To demonstrate its capability simulation is carried out for a 4-channel WDM system using this LCFBG compensator at unstretched condition. The different parameters used in the simulation are shown in Table 1. To avoid the power loss due to the leakage of the grating, the reflectivity was greater than 99% within the grating bandwidth is assumed.

Fig.3 shows the relative time delay for the fast- and slow axis polarization reflected signals inputting from the long- and short wavelength ports of the unstressed FBG respectively as a function of wavelength. From the plots, it is seen that the group delay of the grating reveals good linearity and the delay curves for the two polarization axes are shifted by 0.25 nm at wavelength 1550.5 nm relative to each other due to the high birefringence of the fiber. Since the group delay of the grating is shifted to longer or shorter wavelength by stretching or compressing the grating, the DGD between fast- and slow axes are increased or decreased for a given wavelength. The linear variation makes it easy for the adjustment of the DGD to any given value.

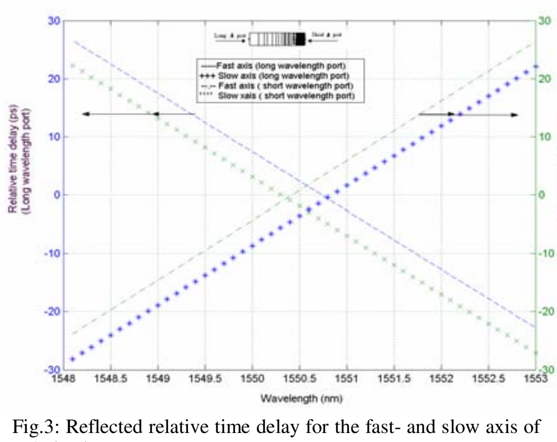

Fig.3: Reflected relative time delay for the fast- and slow axis of polarization

The reflection spectrum of the grating is shown in Fig.4. It is observed that the bandwidth of the grating is 1549 nm to 1551.02 nm at unstretched condition. When the grating is stretched, the amplitude and the group delay spectrum shifts to longer wavelength. Note that due to tuning, though the passband shifts to shorter or longer wavelength but the polarization of the reflected signal remains same. S. Lee *et.al,* [8] experimentally achieved reflection wavelength ranging from 1547.2 nm to 1550.5 nm at unstressed condition and a tuning range of 2.32 nm for a 5 cm long nonlinearly chirped grating. The simulation work in Ref. 7 obtained a bandwidth ranging from 1548.2 nm to1550.5 nm and 2.1 nm of tuning range using a 1cm LCFBG.

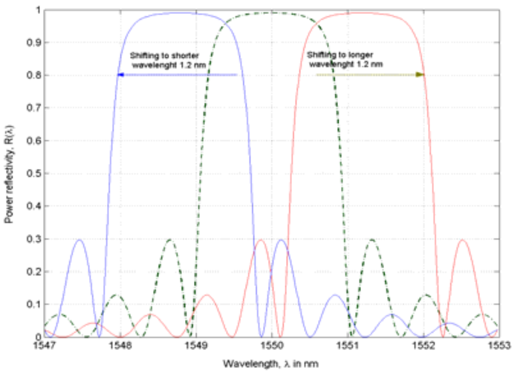

Fig.4: Reflection spectrum for the LCFBG under stretching and compression. Wavelength tuning shifts the passband to longer- or shorter wavelength regime without changing the shape of the spectrum

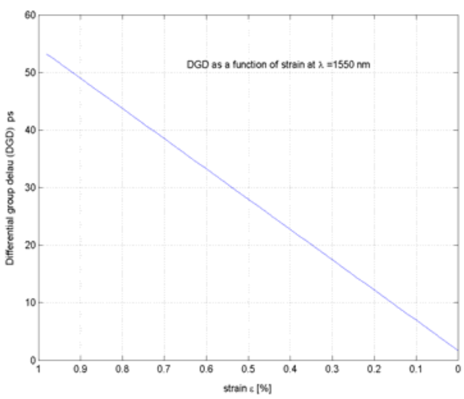

Fig.4: Variation of the DGD between two polarizations as the LCFBG stretched (the stretching ratio is the change in the length of the fiber grating divide by its original length ($\varepsilon = \Delta L/L$)

Fig. 5 shows the change in the differential time delay (ps) as a function of the grating stretching ratio. By changing the strain ε from 0% to 0.2% the DGD can be continuously adjusted from 3 ps to 58 ps. As mentioned earlier, all light outside the reflection bandwidth λ_0 can be directed to the output port without adding any PMD. For this system we have a residual DGD of 3 ps. It is also observed that a maximum DGD is varied over a 55 ps range by a 0.2 % stretch of the grating at 1552.2 nm. Ref. [15] experimentally demonstrates a variable polarization delay line exhibits an adjustable amount of PMD within its operating bandwidth that the DGD can be continuously adjusted from 0 to 80 ps (from 1330.4 nm to 1531 nm wavelength range) under mechanical strain applied by a piezo driven translator.

From the above results we found that stretching the LCFBG adjust the differential time delay without altering the polarization and thus this device has the potential for compensation variable PMD for a long-distance high-speed optical WDM transmission system. Through simulation, we investigate the impact of PMD on the WDM system in terms eye diagram without applying any stress on the LCFBG. At the receiving end we demultiplexed all the 4-channel and monitor their eye diagram without and with applying the PMD compensation scheme. A typical measurement of the eye diagram of the accumulated DGD for 4-channels before and after compensation is shown in Fig. 6. At 10 Gb/s data rate each channel produces (200 km span) about 28 ps of DGD and our designed LCFBG compensator can compensate only 25 ps DGD without any external strain. We observe that channel 4 has been improved significantly after compensation without impacting the other channels and about 6 ps DGD of each channel remain uncompensated which is also within tolerance level or power margin of the system.

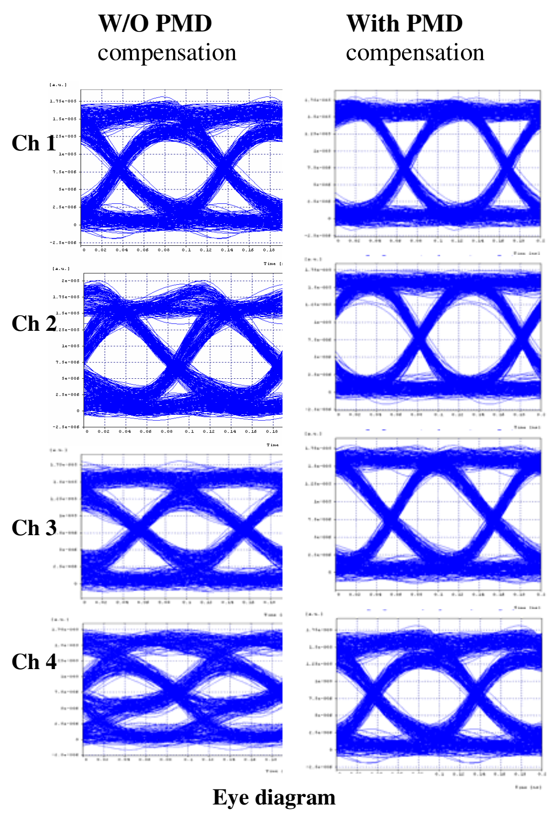

Fig.:6 Eye diagram for a 4-channel (each channel at 10 Gbps, NRZ modulation) with and without WDM-PMD compensation. The output signal is received after 400 km transmission

Finally, we calculate the average eye-opening penalty (EOP) due to PMD for the 4-channel WDM system. Here, we define the parameter of the eye-opening penalty (EOP) s,

$$EOP = -20 \log\left(\frac{B}{B_0}\right) \tag{21}$$

Where, B is the eye opening without PMD effect and B_0 is the eye-opening with PMD. Fig.7 shows a comparison of EOP penalty between our 4-channel simulated transmission system and with single change LCFBG based compensation system as a function of DGD. From the curve we found that about 2.6 dB (reduced from 7.10 dB to 4.5 dB) of EOP reduction is obtained at 40 ps by the compensation scheme. The performance of the single channel is 0.55 dB better for mean DGD > 40 ps and this happens due to inter-channel crosstalk.

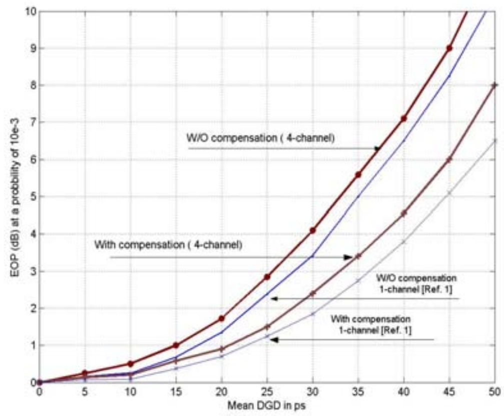

Fig.: 7: Eye opening penalty (EOP) at a probability of 10^{-3} in the dependence of the mean DGD for 4-channel and single transmission system

Parameters/description	**values**
Fiber loss (dB/km)	0.25
Dispersion (ps/km-nm)	0
Effective core are (μm^2)	80
Fiber length (2-span of 200 km)	400
PMD co-efficient (ps/√km)	2
Birefringence of the Hi-Bi LCFGB	$3.77x10^{-4}$
Bit rate of each channel (Gb/s)	10
No. of channels	4
Comp. BW w/o strain (nm)	2
Channel spacing (nm)	0.4
Working wavelength range (nm)	1549 nm -1551 nm
Receiver sensitivity (at 10^{-9})	-24
Transmitter power (dBm) /ch.	-10
Booster EDFA output (dBm)	9

Table 1: Simulation parameters of Hi-Bi LCFBG based PMD-WDM compensation scheme

VI. Conclusion

The performance analysis of a novel PMD using a 2-cm long LCFBG compensator and 4-channel PMD-WDM simulation is carried out. The various properties of reflectivity, relative group delay and DGD of the Hi-Bi LCFBG have been discussed in detail. The PMD compensation capability of the device mainly determined by the characteristics of the Hi-Bi LCFBG and improved capability can be achieved by adopting higher chirp ratio phase mask to fabricate the Hi-Bi grating. The performance of the simulated compensation scheme achieved a significant improvement in quality of eye pattern of the received signal for a link length of 400 km at a bit rate of 10 Gb/s and it compensates about 50 ps of DGD per channel. It is also observed that the amount eye power penalty for a single channel is about 0.55 dB less than that of 4-channel WDM system (at 40 ps of DGD) and that happens due to absence of channel crosstalk in a single channel system. It is an all fiber PMD compensation solution, which is inexpensive, compact, absence of nonlinear effects and feasible for continuously adjustable DGD.

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