Further Considerations on Analyzing FWM Effect on 200G/lane IMDD for LR

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Outline

- **Introduction**
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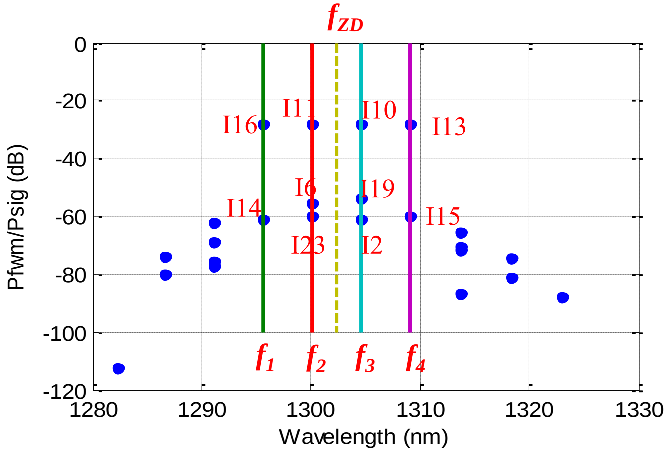
- **Statistical Analysis of Polarization**
- **Conclusion**

Challenges using 200G-PAM4 for 800G 10km Application

- In the objective of IEEE 802.3df, the technology for 800G 10km remains an open case. The traditional technology of choice, IM-DD, faces challenge on power budget for 200G-PAM4 signaling.
- Simulation analysis on chromatic dispersion has shown possibility of 200G-PAM4 for 800G-LR4 if using wavelength grid of LWDM or narrower(kuschnerov_b400g_01_210503).
- This however raises another concern, the probability of FWM effect from equally spaced, co-polarized wavelengths near the zero-dispersion wavelength of fiber and its resulting crosstalk penalty.
- Proposals have been made to mitigate the FWM effect, either using un-even wavelength spacing (rodes_3df_01a_220329) or breaking the co-polarization state (yu_3df_01a_220329.pdf).

Problem Definition

- Consider a worst choice of wavelength for LWDM4, with 4 wavelengths evenly distributed aside of the ZDW of fiber.
- A total of 24 idler lights can be generated due to FWM.. Only the four strongest idler lights (I11, I10, I13, I16) which fall into the band of operating wavelength need to be considered.
- Probability of occurrence of a worst case FWM impairment has been discussed in johnson_3df_optx_01_220414.
- We further investigate the PMD influence to FWM by building a detailed fiber link polarization state model, considering three different wavelength spacing (800GHz, 1.6THz, 2.4THz).



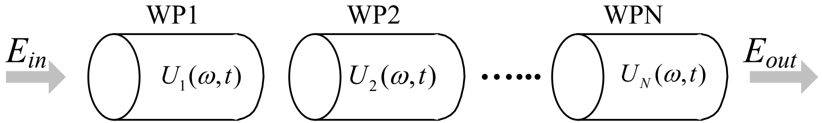
Idler number	Pump	Signal	Idler
I10	f_1、f_4	f_2	$f_1+f_4-f_2$
I11	f_1、f_4	f_3	$f_1+f_4-f_3$
I13	f_2、f_3	f_1	$f_2+f_3-f_1$
I16	f_2、f_3	f_4	$f_2+f_3-f_4$

Factors affecting the FWM effect

- Tx:
  - Selection of wavelength
  - Polarization state
  - Line width
  - Average launch power
- MUX-DMUX
  - Phase difference
  - Filter bandwidth
  - Loss difference/lane
- **Fiber link**
  - ZDW
  - Fiber Bi-rigrengence/PMD
  - Composition/span(engineered link)

Modeling the Polarization Walk-off in a Fiber Link

Using Waveplate (WP) PMD model [1]:



$$U_i(\omega,t) = R(-\theta_i,-\phi_i)\begin{pmatrix} \exp(-j\omega\Delta\tau_i/2) & 0 \\ 0 & \exp(j\omega\Delta\tau_i/2) \end{pmatrix} R(\theta_i,\phi_i)$$

- Phase retardance (DGD) [2]

$$\Delta\tau_i = \sqrt{\frac{3\pi}{8N}}\langle \mathrm{DGD}\rangle(1+\sigma x_i)$$

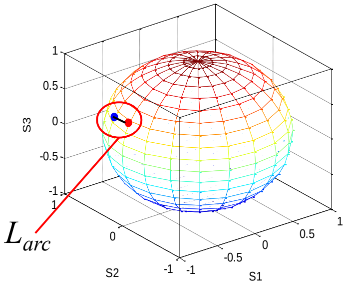
Mean DGD of the fiber (PMD, typical value: 0.1ps*sqrt(L);
DGD of each segment ： a perturbation around mean value

- Angle rotation(SOP) [1]

$$R(\theta_i,\phi_i) = \begin{pmatrix} \cos\theta_i & \sin\theta_i \exp(j\phi_i) \\ -\sin\theta_i \exp(-j\phi_i) & \cos\theta_i \end{pmatrix}$$

θ_i and ϕ_i: rotation angles, uniformly distributed random variables in the range of [0, 2π]

- Polarization walk-off can be quantitatively represented by the arc length on Poincare Sphere between any two polarization states
- We can use the polarization walk-off as an indicator of the relative polarization state of any two wavelengths contributing to the FWM effect of interest.
  - Parallel ： $L_{arc} = 0$;
  - Orthogonal： $L_{arc} = \pi$;
  - Using orthogonal polarization states brings benefits of reduced FWM Idler signal strength and FWM penalty as pointed out in liuxiang_3ca_1a_0517 and johnson_3df_optx_01_220414.



[1] Xie C ,et.al. Dynamic Performance and Speed Requirement of Polarization Mode Dispersion Compensators[J]. Journal of Lightwave Technology, 2006, 24(11):3968-3975.
[2] Marks B S , et.al . Autocorrelation function for polarization mode dispersion emulators with rotators[J]. Optics Letters, 2002, 27(13):1150-1152.

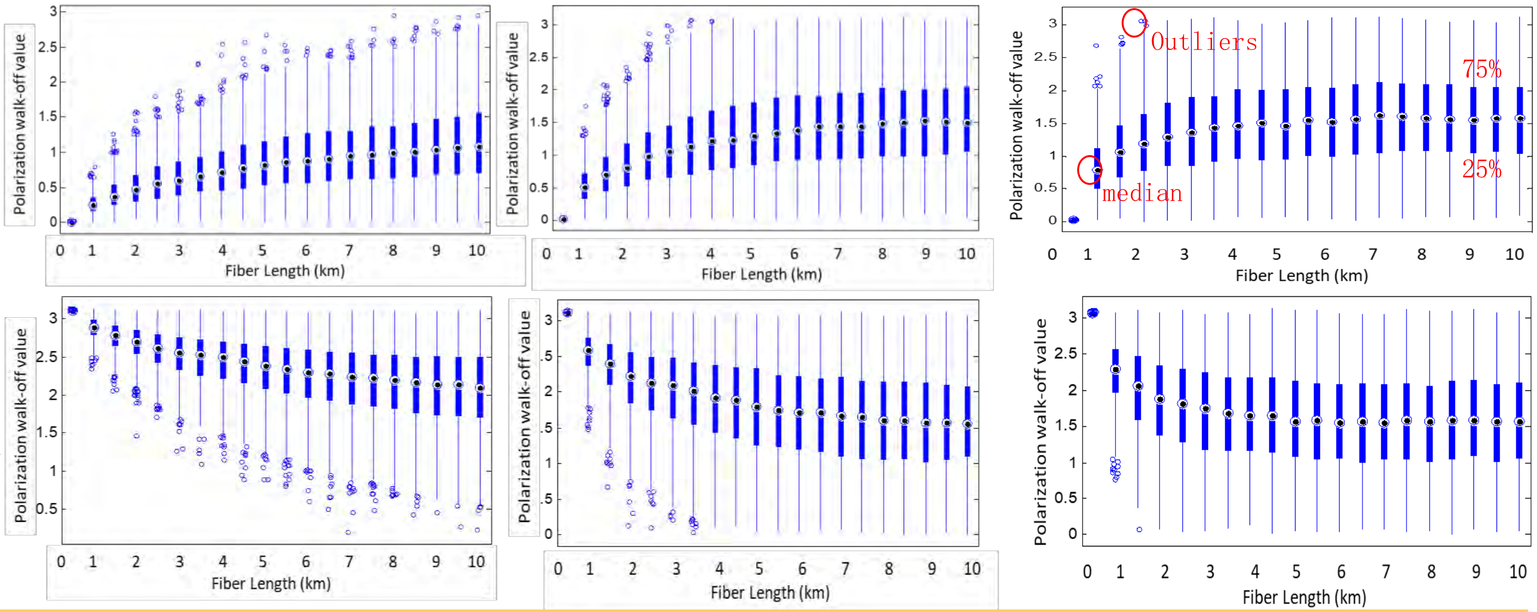
Statistical Analysis of Polarization Walk-off in a Fiber Link

- We performed statistic analysis of the impact of DGD/PMD on polarization walk-off using Monte Carlo method .
- Simulation condition： PMD = 0.1 ps/sqrt(km) , length of fiber segment is 1m. 1000 iterations.

frequency spacing: **800GHz** | frequency spacing: **1600GHz** | frequency spacing: **2400GHz**

Parallel @ Launch Point

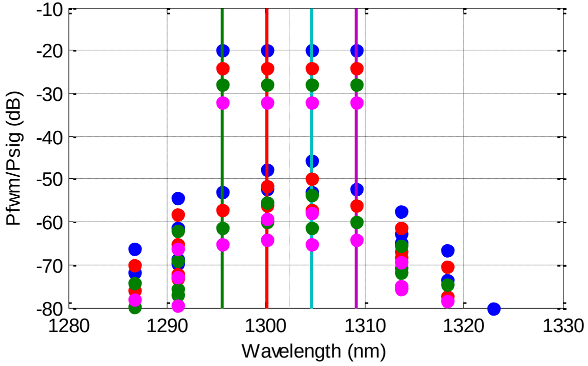
Orthogonal @ Launch Point



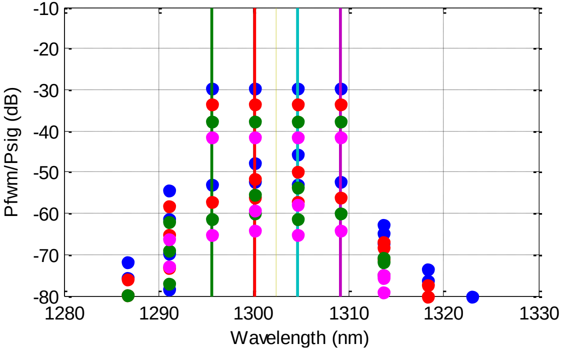
- The polarization walk-off shows a random distribution.
- Its median value varies as the two wavelengths propagate along the fiber link.
- As the wavelength spacing expands, the change in polarization walk-off becomes larger, while reaches a stable value faster.

How will Polarization Walk-off Influence FWM

Parallel



orthogonal



Interpretation:

- FWM idler power is proportional with pump and signal Power :P_{FWM}~P^3
- Signals launched in parallel polarization causes the worst case of FWM. Signals launched in interleaving orthogonal polarization provides benefit of reduced Idler power.
- As the signals transmitting through the fiber link, the interleaved channels have probability walking off from their ideal orthogonal polarization state, due to PMD of the fiber. Even considering the worst case of polarization walk-off at 10km, the optical link will still benefit from employing orthogonal polarization, due to the reduced optical power in the aligned polarization states.

Conclusions

- We investigate the PMD influence to FWM during fiber transmission based on a wave plate PMD model and Monte Carlo analysis.
  - Wavelength spacing of 800GHz, 1.6THz and 2.4THz are considered to cover the wavelength combination inducing the worst case of Idler power.
  - Mote Carlo analysis of polarization walk-off between two wavelengths considering co-polarization and orthogonal polarization at launch point.
- **Co-polarization at launch point:** The walk-off from co-polarization state in the fiber link brings reduction to the Idler strength of the worst case FWM.
- **Interleaving Cross Polarization at launch point:** Even taking into account the polarization walk-off along the fiber link, 800G-LR4 profits from launching signals in orthogonal polarization by weakening FWM effect in the strongest contributing section of the fiber link.
- Further analysis is undergoing to support 800G-LR4 baseline accommodating the FWM effect including
  - Investigation on the sensitivity of FWM penalty under various FEC scheme, to provide input on the decision of FEC.
  - Investigation on penalty allocation with combined CD and FWM effect and their trade-off.

HUAWEI

THANK YOU

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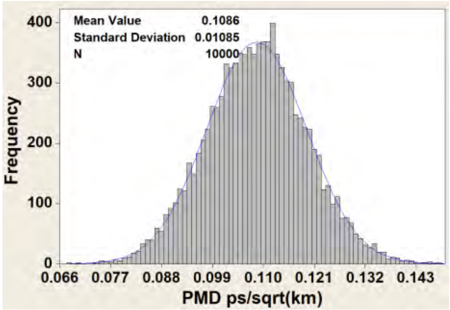
PMD Model Detail

1. Phase retardance[1]:

$$\tau_i = \sqrt{\frac{3\pi}{8N}}\langle \mathrm{DGD}\rangle(1+\sigma x_i)$$

- : $\langle \mathrm{DGD}\rangle$ mean DGD of the fiber;
  - Here $\langle \mathrm{DGD}\rangle = \mathrm{PMD_{coeff}}\sqrt{L}$
  - Typical $\mathrm{PMD_{coeff}}$ value of SMF can be 0.1ps/sqrt(km) [2]
- x_i: gaussian random distribution (0,1)
- σ: DGD variance of the sections
  - Represent randomization of the sections' DGD values
  - Typical value of σ can be set as 10%[3]
  - This model is suitable for the case of 1 single 10km fiber or a collection of fibers used to build the 10km link



Probability distribution of PMD on each segment

2. Angle rotation[3]

$$R(\theta_i,\phi_i)=\begin{pmatrix} \cos\theta_i & -\sin\theta_i \exp(-j\phi_i) \\ -\sin\theta_i \exp(-j\phi_i) & \cos\theta_i \end{pmatrix}$$

- θ_i and ϕ_i : rotation angles, uniformly distributed random variables in the range of [0, 2π];

$$\theta_i(t+\Delta t)=\theta_i(t)+d\theta_i$$
$$\phi_i(t+\Delta t)=\phi_i(t)+d\phi_i$$

- $d\theta_i$ and $d\phi_i$: uniformly distributed variables in the range of [−α/2, α/2] ;

  Δt: PMD update time

  α: PMD variation speed. Here we set α=0.5°

[1] Marks B S , et.al . Autocorrelation function for polarization mode dispersion emulators with rotators[J]. Optics Letters, 2002, 27(13):1150-1152.
[2] anslow_3cu_adhoc_051519
[3] Xie C ,et.al. Dynamic Performance and Speed Requirement of Polarization Mode Dispersion Compensators[J]. Journal of Lightwave Technology, 2006, 24(11):3968-3975.

PMD Model Detail

3. Quantitative analysis of polarization walk-off

Arbitrary two orthogonal elliptical polarization states[1] :

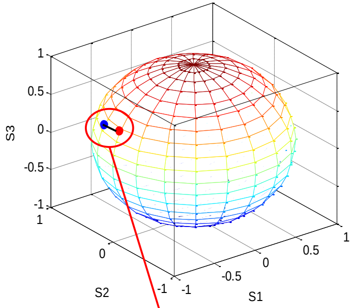
$$\vec{E}_1 = \begin{pmatrix} \cos\alpha \\ \sin\alpha e^{j\delta} \end{pmatrix}, \quad \vec{E}_2 = \begin{pmatrix} -\sin\alpha e^{-j\delta} \\ \cos\alpha \end{pmatrix}$$

Satisfy the relationship: $\vec{E}_1 . \vec{E}_2^* = \begin{pmatrix} E_{x1} & E_{y1} \end{pmatrix} \begin{pmatrix} E_{x2}^* \\ E_{y2}^* \end{pmatrix} = 0$

Convert to Stokes Vector：

$$\begin{cases} S_{11} = \cos^2\alpha - \sin^2\alpha \\ S_{12} = \sin 2\alpha \cos\delta \\ S_{13} = -\sin 2\alpha \sin\delta \end{cases} \qquad \begin{cases} S_{21} = \sin^2\alpha - \cos^2\alpha \\ S_{22} = -\sin 2\alpha \cos\delta \\ S_{23} = \sin 2\alpha \sin\delta \end{cases}$$

For arbitrary two light: stokes vector are symmetrical about the center of the Poincaré sphere. Length difference (arc length) of the two Stokes vectors on Poincaré sphere surface is π.



Polarization walk-off

- Polarization walk-off can be quantitatively represented by the arc length L_{arc}:

  Parallel : $L_{arc} = 0$;
  Orthogonal: $L_{arc} = \pi$;

[1] Nan C ,et al. Two-parameter-SOP and three-parameter-RSOP fiber channels: problem and solution for polarization demultiplexing using Stokes space[J]. Optics Express, 2018, 26(16):21170.