Inter-Channel FWM Mitigation Techniques for O-band WDM Based 800G/1.6T LR and 5G Fronthaul Applications

Xiang Liu and Qirui Fan
Huawei Hong Kong Research Center, Hong Kong, China
xiang.john.liu@huawei.com; remi.fanqirui@huawei.com

Abstract: We review recent advances in the mitigation of inter-channel four-wave-mixing (FWM) based on the "XYYX" input polarization alignment and unequal channel spacing to enable high-performance O-band WDM transmission for 800G-LR4, 1.6T-LR8 and bidirectional 5G fronthaul.

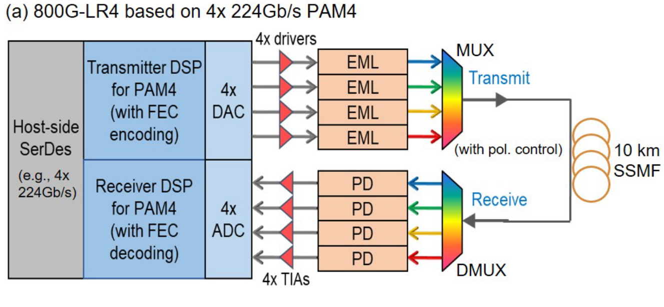
1. Introduction

For short-distance data center interconnections and 5G fronthaul links, cost-effective and energy-efficient optical transceivers based on simple intensity-modulation and direct-detection (IM/DD) are commonly used [1]. With the increase of modulation speed to 100Gbaud and beyond, the dispersion tolerance of DD receivers become highly limited. Thus, WDM transmission in the O-band that includes the zero-dispersion wavelength (ZDW) window of standard single-mode fiber (SSMF), i.e., between 1300 nm and 1324 nm, is being considered for both 800Gb/s long-reach (LR) [2] and LAN-WDM based 5G fronthaul transmission [3]. However, inter-channel four-wave-mixing (FWM) was found to impose a severe limitation on the performance of WDM transmission in the O-band [4-6]. To mitigate the FWM impairment, polarization interleaving [4,5] and unequal channel spacing [6] had been proposed. More recently, an innovative polarization alignment based on "XYYX" has been proposed [7,8] and experimentally verified [9] to effectively suppress the FWM impairment in 800G-LR4. In addition, the FWM impairment was shown to be effectively suppressed in a bidirectional 12-channel LAN-WDM fronthaul transmission system (L-WDM) that achieves unequal channel spacing in each direction without scarifying the spectral efficiency [10]. In this paper, we review these effective FWM mitigation techniques for O-band WDM based 800G-LR4, 1.6T-LR8 and bidirectional 5G fronthaul transmission.

2. 800G-LR4 and 1.6T-LR8

Fig. 1(a) shows the schematic of an 800G-LR4 IM/DD transceiver with four 224Gb/s PAM4 channels. The wavelength plan can be based on the longest four wavelengths of LAN-WDM, as shown in Fig. 1(b), or 400GHz-red-shifted [8]. The input polarization alignment of "XYYX" is illustrated in Inset (a). For typical transmission fibers, the random birefringence model (RBM), where the fiber polarization axes and birefringence strength vary randomly with distance, is applicable [11]. Under the RBM, the first three wavelength channels with polarizations "XYY" will not generate any non-degenerate FWM component at the 4th channel under the ideal case of zero polarization-mode dispersion (PMD) [12]. The physical reason for this remarkable effect is that the phase of the generated FWM component $\varphi_{FWM}(z)=2\varphi_y(z)-\varphi_x(z)$ is fast varying with transmission distance z due to the very short fiber beat length of a few meters typically, so that the phase-matching condition for FWM is quickly destroyed [8]. Moreover, the degenerate FWM from the center two co-polarized channels generates side tones that are orthogonal to the two edge channels in polarization, so the degenerate FWM-induced penalty is also negligibly small [7].

(a) 800G-LR4 based on 4x 224Gb/s PAM4



(b) Four LAN-WDM wavelengths in or near the ZDW window

LAN-WDM index	Center frequency (THz)	Center wavelength (nm)	Dispersion after 10km (ps/nm)
Ch1	231.4	1295.56	-26.16 ~ -4.08
Ch2	230.6	1300.05	-22.03 ~ 0.05
Ch3	229.8	1304.58	-17.87 ~ 4.21
Ch4	229.0	1309.14	-13.67 ~ 8.41

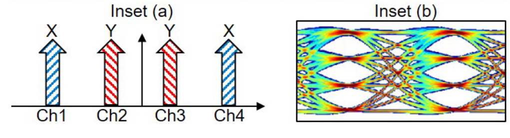


Fig. 1. (a) Schematic of an 800G-LR4 IM/DD transceiver with four 224Gb/s PAM4 channels; (b) A wavelength plan based on LAN-WDM. Inset (a): Illustration of the "XYYX" input polarization alignment. Inset (b): An exemplary eye diagram of a 224Gb/s PAM4 signal.

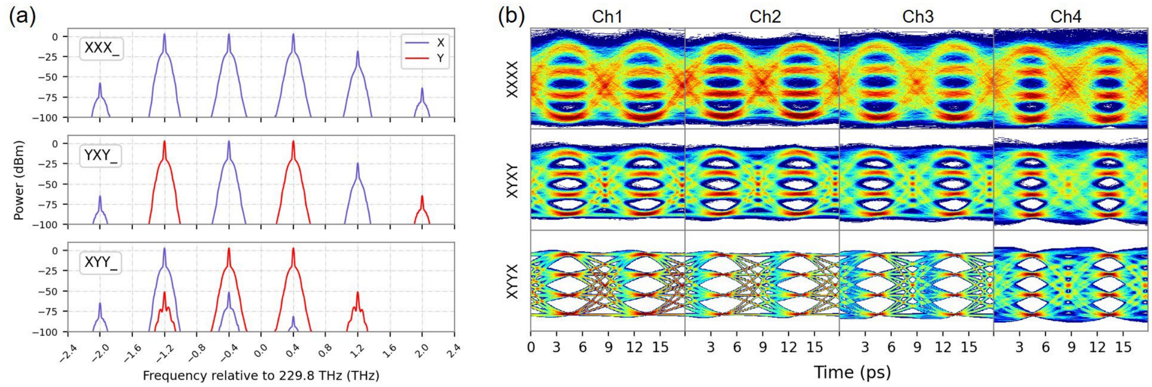


Fig. 2. (a) Simulated optical spectra after 10-km SSMF transmission with three 800GHz-spaced input signals having “XXX”, “YXY”, and “XYY” input polarization alignments; (b) Simulated signal eye diagrams after 10-km SSMF transmission with four 800GHz-spaced input signals having “XXXX”, “XYXY”, and “XYYX” input polarization alignments. Launch power per channel: 6dBm; Fiber ZDF: 229.8 THz.

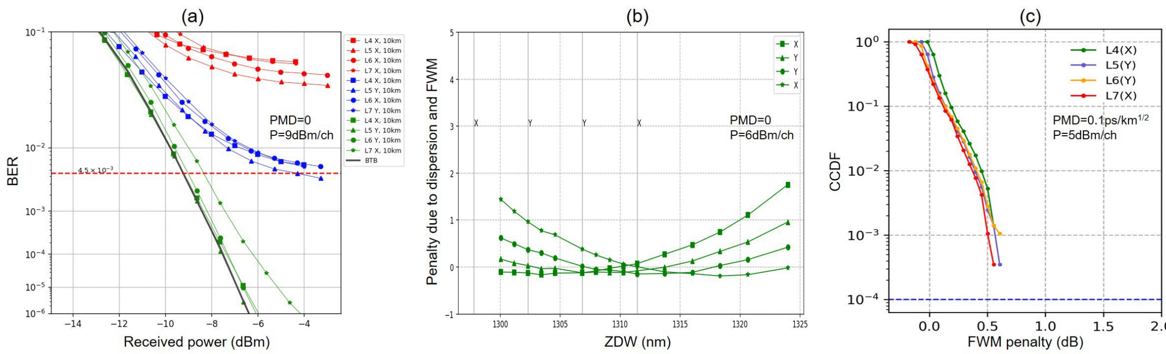
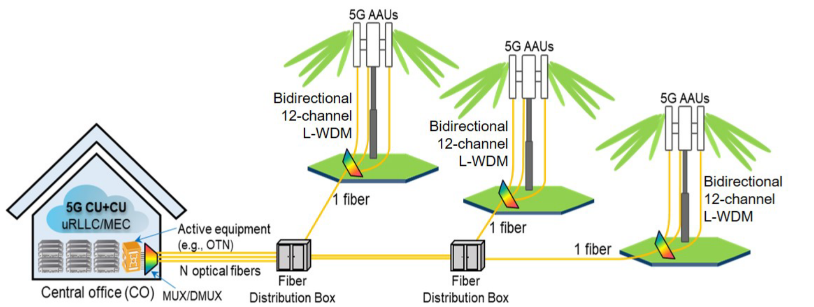


Fig. 3. (a) Simulated BER performance after 10-km SSMF transmission for “XXXX”, “XYXY”, and “XYYX” input polarization alignments; (b) The receiver sensitivity penalty due to dispersion and FWM as a function of the fiber ZDW for the “XYYX” case; and (c) CCDF of the simulated FWM penalty with over 2,800 PMD realizations. Fiber ZDF: exactly at the center of the four 800GHz-spaced channels.

Numerical simulations are performed to quantify the effectiveness of the FWM suppression. Fig. 2 (a) shows the simulated optical spectra after 10-km SSMF transmission with three 800GHz-spaced input signals having “XXX”, “YXY”, and “XYY” input polarization alignments under zero PMD. Evidently, the FWM interference on the 4th channel in the “XYY” case is the weakest. Fig. 2(b) shows the simulated signal eye diagrams of 224Gb/s PAM4 signals (with a chirp of 0.5) after 10-km SSMF transmission with four 800GHz-spaced input signals having “XXXX”, “XYXY”, and “XYYX” input polarization alignments. Consistently, the FWM-induced eye closure is minimized in the “XYYX” case.

Fig. 3(a) shows the BER performances for “XXXX”, “XYXY”, and “XYYX” input polarization alignments under zero PMD and 9dBm signal launch power per channel, clearly showing the effective FWM suppression in the “XYYX” case. Fig. 3(b) shows the receiver sensitivity penalty at a FEC BER threshold of $4.5\text{x}10^{-3}$ due to dispersion and FWM as a function of the fiber ZDW for the “XYYX” case, indicating unnoticeable FWM penalty for all relevant ZDW values. Fig. 3(c) shows the complementary cumulative distribution function (CCDF) of the FWM penalty with over 2,800 fiber PMD realizations, indicating that under the alignment of ZDW and laser frequencies, the FWM-induced “outage” is $\sim 10^{-3}$ for a 1dB penalty and a signal launch power of 5dBm per channel. Further assuming that the fiber ZDW distribution is uniform over 1300nm~1324nm, the chance of “FWM wavelength matching” was found to be 0.563% [13]. Due to the laser frequency tolerance of Δf=100GHz, the probability of the FWM being within the receiver bandwidth is approximately $B/2\Delta f$, or 0.56 according to Ref. [5]. Thus, the FWM-induced overall outage probability becomes $\sim 3.2\times 10^{-6}$ [8], which is reasonably low, given that the PMD-induced outage probability specified in OIF 400ZR is 4.1×10^{-6}. The actual FWM-induced overall outage probability may be much lower when considering (1) the realistic SSMF ZDW distribution [13], (2) fiber cable slicing induced randomization of ZDW in field-deployed fiber segments that are typically 3 km in length [14], and/or (3) longitudinal fluctuations of fiber ZDW due to non-uniform fiber fabrication conditions [15]. With the FWM impairment being effectively suppressed, 800G-LR4 with four 800GHz-spaced 224Gb/s PAM4 channels on the LAN-WDM grid is expected to be technical feasible [13,16]. For future 1.6T-LR8, eight 400GHz-spaced 224Gb/s PAM4 channels with “XYYXXYYX” input polarization alignment may be used [7].



Inset (a)

Central frequencies of all the 12 channels	f_m=237.0 - 0.8 x m (THz), m = 1 to 12
Central frequencies of the DL channels	f_1, f_3, f_5, f_8, f_9, f_{11}
Central frequencies of the UL channels	f_2, f_4, f_6, f_7, f_{10}, f_{12}

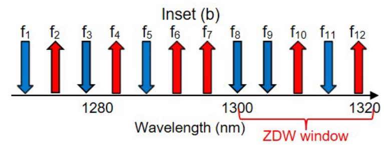


Fig. 4. Illustration of a 5G fronthaul transmission system that uses a single fiber to connect each cell site via bidirectional 12-channel L-WDM. Inset (a): The center frequencies of the downlink (DL) and the uplink (UL) wavelength channels. Inset (b): Illustration of the unequal channel spacing for both the DL and the UL wavelength channels in the ZDW window of the SSMF.

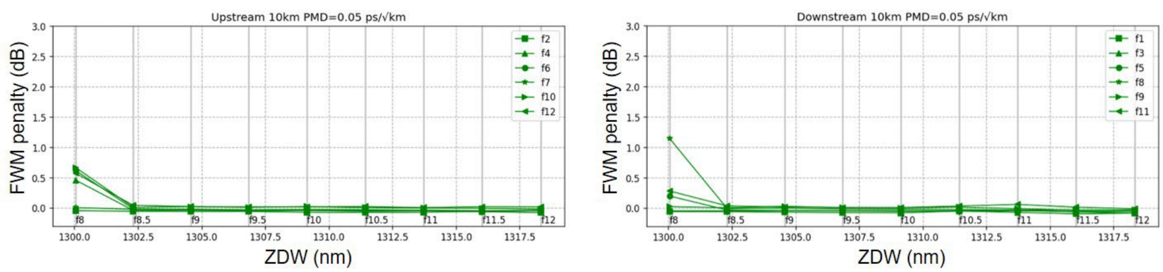


Fig. 5. Simulated receiver sensitivity penalty at BER=5×10^{-5} due to FWM vs. the fiber ZDW. Signal launch power: 5.5 dBm/channel.

3. Bidirectional 12-channel L-WDM based fronthaul

Fig. 4 illustrates a 5G fronthaul transmission system that uses a single fiber to connect each cell site via bidirectional 12-channel L-WDM [1]. With the use of unequal channel spacing in the ZDW window for each of the DL and UL directions, as shown in Insets (a) and (b), the FWM penalty can be effectively suppressed [10]. Fig. 5 shows that the receiver sensitivity penalties due to FWM for all the relevant fiber ZDW values are smaller than the allocated optical path penalty of 2 dB [10].

4. Conclusion

We have reviewed recent advances in mitigating the inter-channel FWM impairments for O-band WDM based 800G-LR4, 1.6T-LR8, and bidirectional fronthaul. With the effective mitigation of the FWM impairments, IM/DD is expected to continue to be a viable technology for future high-speed short-reach applications.

5. References

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