Four Wave Mixing in Near Zero Dispersion Regions

Eugene (Yuxin) Dai

Cox Communications

IEEE 802.3ca 100G EPON TF

November, 2016

San Antonio, Texas, USA

Background

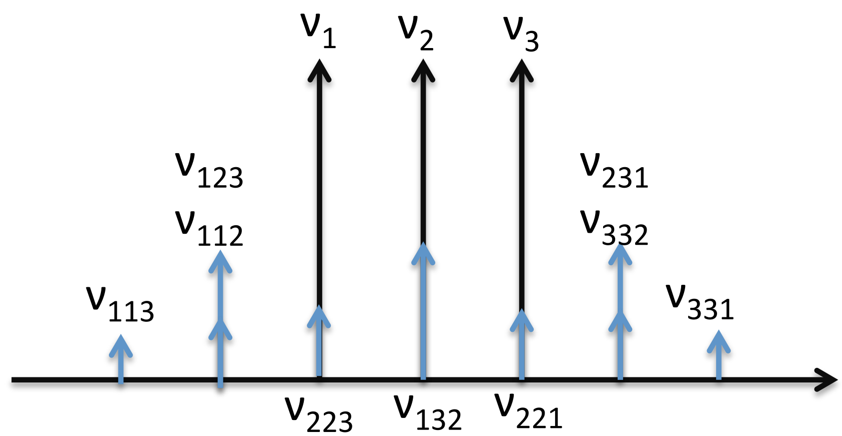
- Wavelength plans have been discussed in several interim and plenary meetings
- A all O band wavelength plan A "johnson_3ca_1a_0916.pdf" was presented Dallas interim meeting
- In contribution "dai_3ca_1(a)_1116.pdf" for San Antonio meeting, the FWM issues with Huawei's simulation on plan A were discussed
- This contribution further addresses the origins of the FWM and other nonlinear impairments when placing DWDM channels in zero dispersion regions

Outline

- FWM in near zero dispersion regions with DWDM
- Origins of the FWM and other nonlinear phenomenon in zero dispersion regions observed in simulations
- FWM Issues with the all O band wavelength plan A

Four Wave Mixing (FWM)

- FWM is an nonlinear effect which is linked to 3rd electric susceptibility in optical fiber.
- In a WDM system, FWM manifests as an optical signal interested with pump signals (other optical signals), creating a new optical signal that falls into the frequency band of information carrying signals.



DWDM channels	FWM Products
2	2
3	9
4	24
8	224

- The FWM noise generated on the source wave may not fully be discussed/understood
- The Quantum nature of FWM may need to be considered in order to understand some observations

FWM Generated Signal Power

$$\frac{P_{FWM}}{P_S} \sim \eta \left(\frac{P\, n^2}{\Delta\lambda A_{eff}} \right)^2 e^{-\alpha L}$$

- FWM efficiency (η)
- Power per WDM channel (P)
- Nonlinear refractive index (n)
- WDM channel Wavelength spacing ($\Delta\lambda$)
- Mode Field Effective Area (A_{eff})
- Coherent length (L)

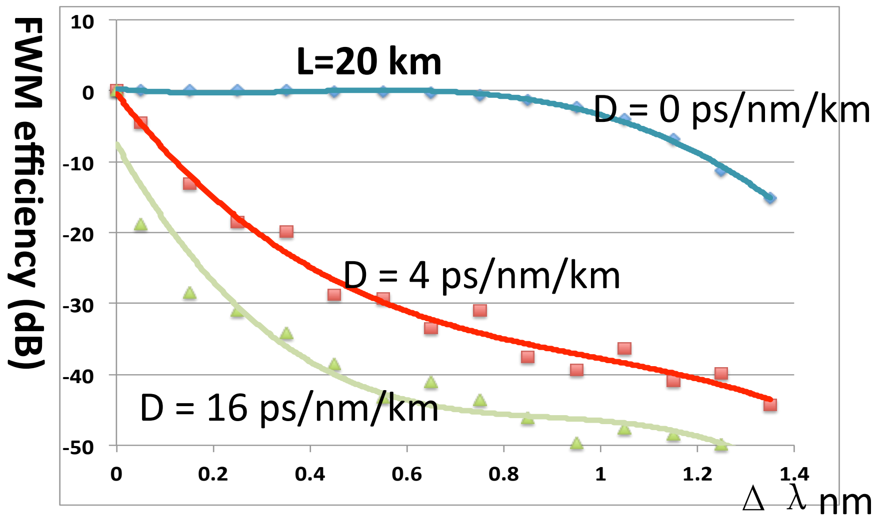
$$\eta = \left| \frac{1 - \exp[-(\alpha + i\Delta\beta)L]}{(\alpha + i\Delta\beta)L} \right|^2$$

$$\eta = \begin{cases} 1, & \Delta\beta \to 0 \\ \sim 0, & \Delta\beta >> 1 \end{cases}$$

Where α is real part of propagation constant and β is the imaginary part.

Factors that Impact FWM

1. FWM efficiency η



2. Phase match condition

$\beta_m = \beta_{p1} + \beta_{p2} - \beta_s$ (FWM);

$\beta_m = 2\beta_p - \beta_s$ (DFWM).

3. WDM channel optical power

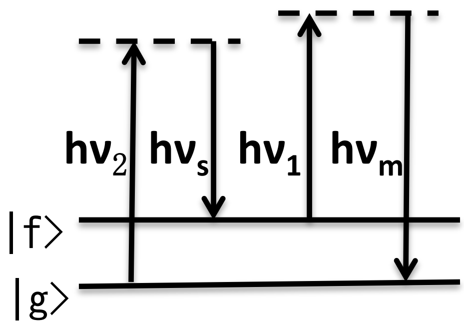
In near zero dispersion region:

- FWM efficiency is high;
- When the zero dispersion is at the center of a WDM channel or at the middle of WDM channels the phase matching conditions are satisfied → **η = 1**

Take precautions if WDM channels are placed near zero dispersion regions

Four Wave Mixing

Frequency match condition (energy conversation)



$\nu_m = \nu_1 + \nu_2 - \nu_s$ (FWM)

$\nu_m = 2\nu_1 - \nu_s$ (DFWM)

h = 6.626x10^{-34} J •s is Plank's constant

Phase match condition (momentum conversation)

$\beta_m = \beta_{p1} + \beta_{p2} - \beta_s$ (FWM);

$\beta_m = 2\beta_p - \beta_s$ (DFWM).

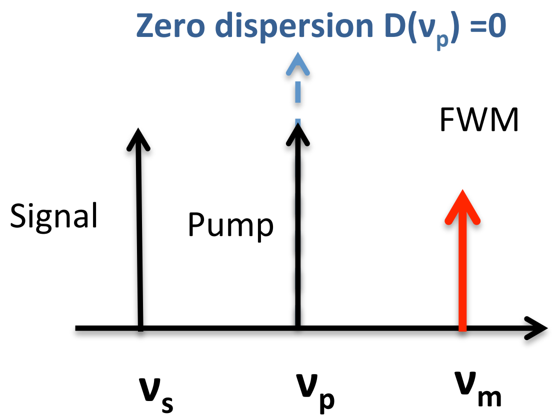
If phases mismatch, then

$$\Delta\beta = \beta_m - 2\beta_p + \beta_s = \frac{8\pi\nu_p^2}{c} D(\nu_p)(\nu_p - \nu_s) \qquad \text{(DFWM)}$$

$$\Delta\beta = \frac{2\pi\lambda^2}{c}\,\Delta\nu_{ik}\,\Delta\nu_{jk}\left(D + \frac{\lambda^2}{2c}\left(\Delta\nu_{ik} + \Delta\nu_{jk}\right)\frac{dD}{d\lambda}\right) \qquad \text{(FWM)}$$

Degenerated FWM in Zero Dispersion Regions

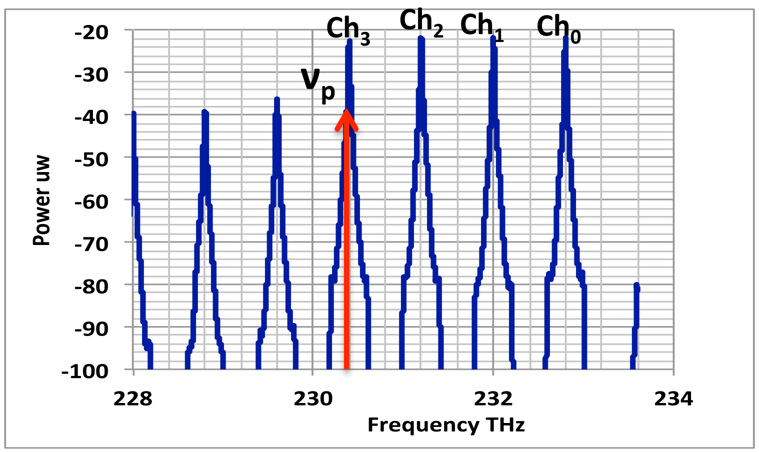
Degenerated FWM phase matching condition

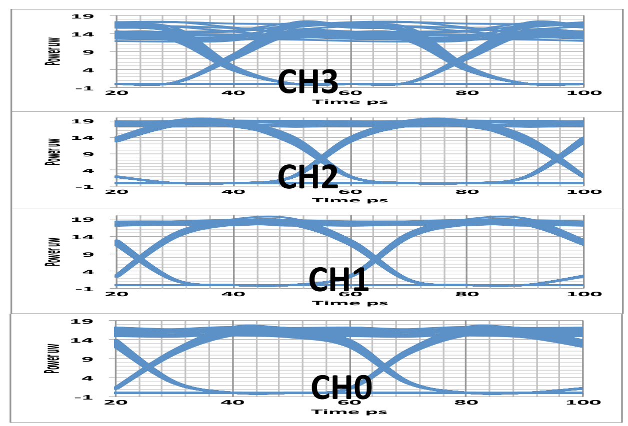


$$\beta_m = 2\beta_p - \beta_s \quad \text{(DFWM)}.$$

$$\Delta\beta = \beta_m - 2\beta_p + \beta_s = \frac{8\pi\nu_p^2}{c} D(\nu_p)(\nu_p - \nu_s)$$

If $D(\nu_p) = 0$, phased matched FWM signal is created.

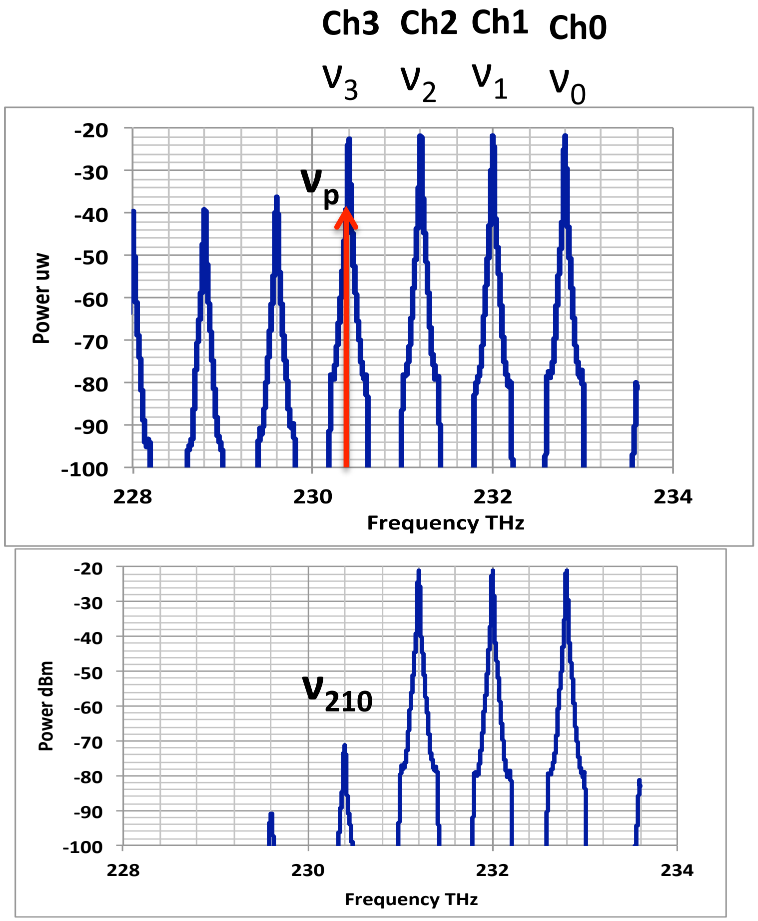


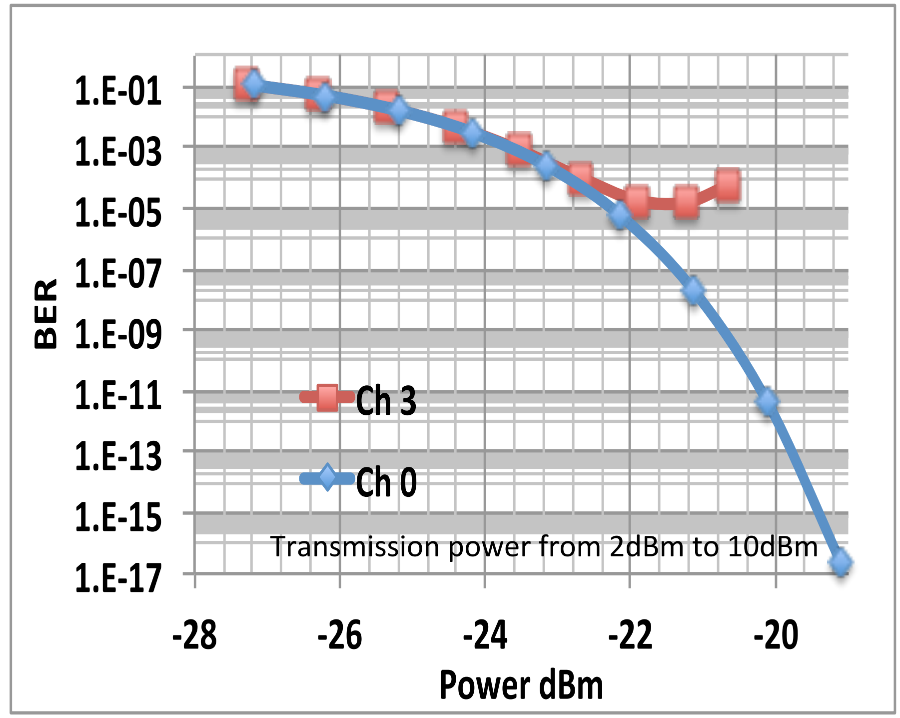


800 GHz spacing even channels ("plan A")

What is the origin of the noises observed in channel 3?

Impacts of FWM in Zero Dispersion Regions



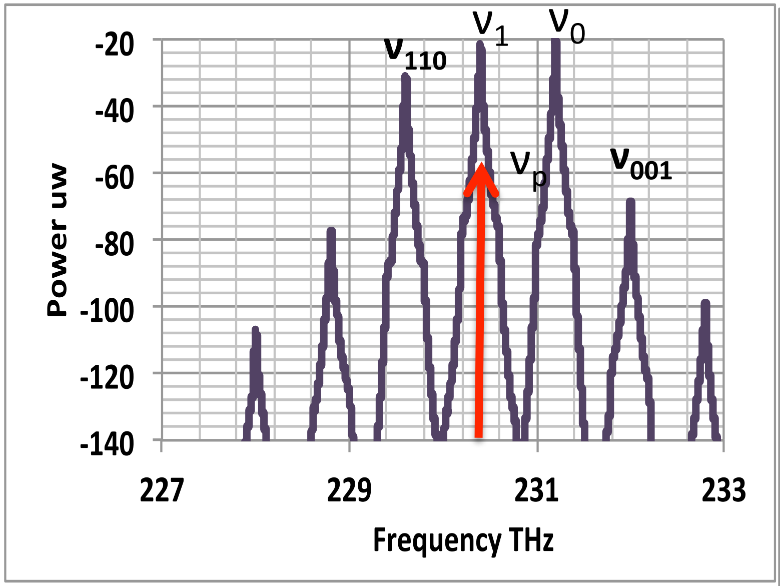


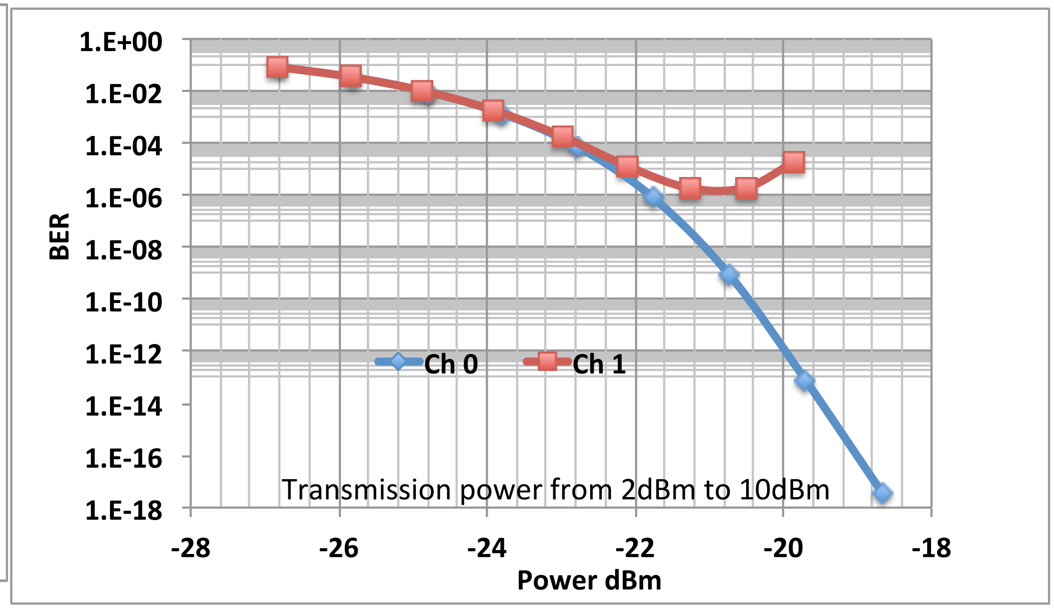
Zero dispersion wavelength is at the center of channel 3

- **Significant FWM penalty is observed for channel 3**
- **The non phase matched FWM product ν_{210} does not seem strong enough to cause such a big penalty**

A Simple Case First: Degenerated FWM in a 2-channel System

DFWM in a 2-channel system with zero dispersion at center of ch 1

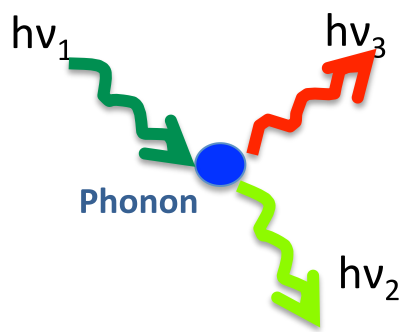




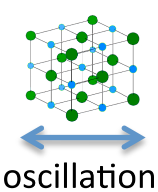
Let's first looking into a simple case. In a 2-channel system, there is no primary FWM product that falls under channel 1, so why there still is significant FWM penalty observed?

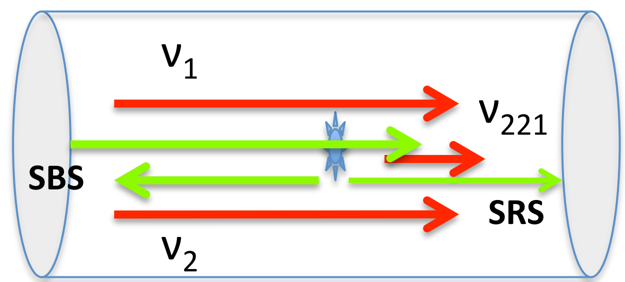
The Origin of FWM

- **In Quantum theory, FWM is treated as annihilation of photons in two or three wavelengths and creates photons at a new wavelength.**
- **Photons interact with crystal lattices in a silicon fiber via acoustics phonon exchange that creates oscillations which causes a local reflection index change**
- **Local fluctuations of the reflection index in silicon fiber are also the mechanism for other nonlinear phenomenon such as Simulated Brillouin Scatting (SBS) and Simulated Raman Scatting (SRS).**



$h\nu_1 + h\nu_2 = h\nu_3$





Photon-phonon interaction (acoust-optic)

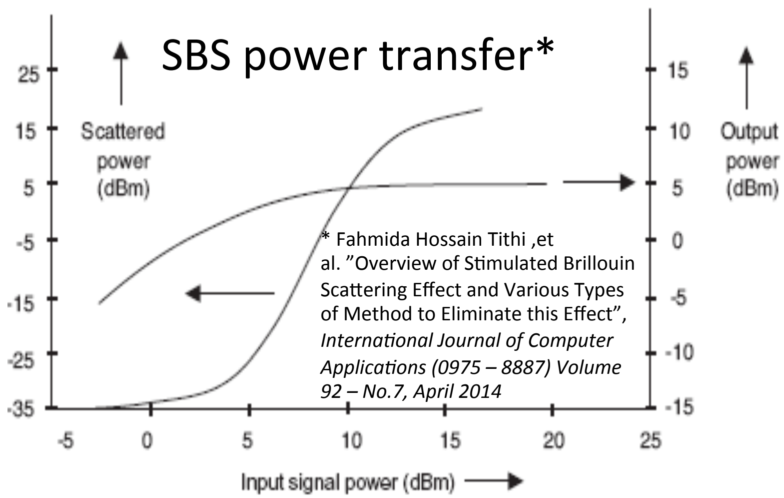
$h = 6.626 \times 10^{-34}$ J •s is Plank's constant

Local fluctuations of reflection index caused by FWM could induce SBS under the right condition* (further study).

* SBS has narrow gain region ~ 40MHz but has ~ 1THz bandwidth with low threshold ≤ 1.4 mw

Sources of DFWM penalty at zero dispersion

- FWM products that fall under the signal channels (this seems not to be the major contributor for a 4 channel wide spacing plan such as “plan A”).
- **Noises generated at the source wavelength due to the photon interactions (this may be significant if zero dispersion is at the center of the source when a strong wavelength conversion took place)**

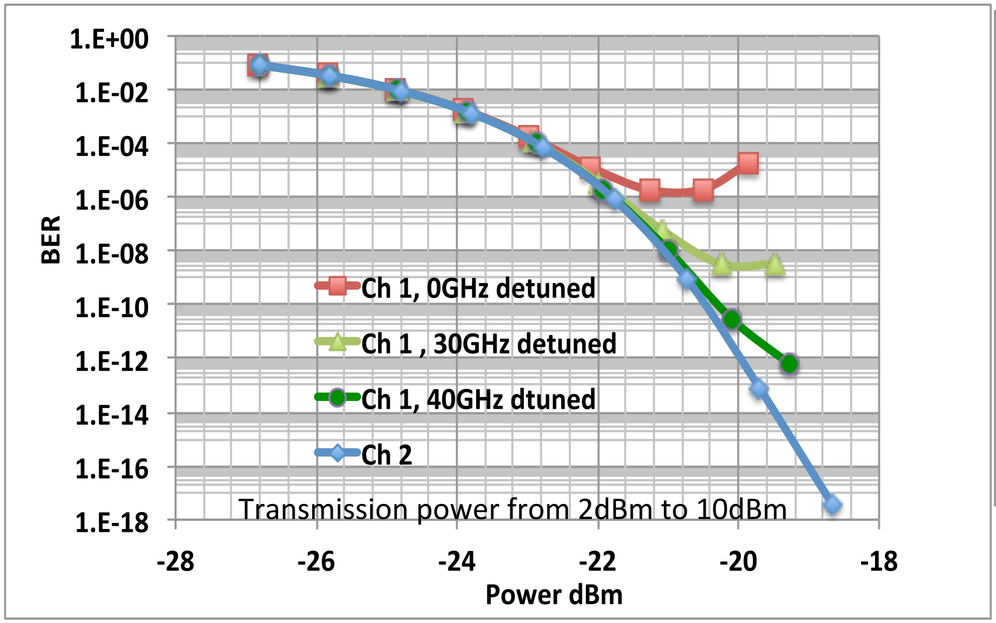


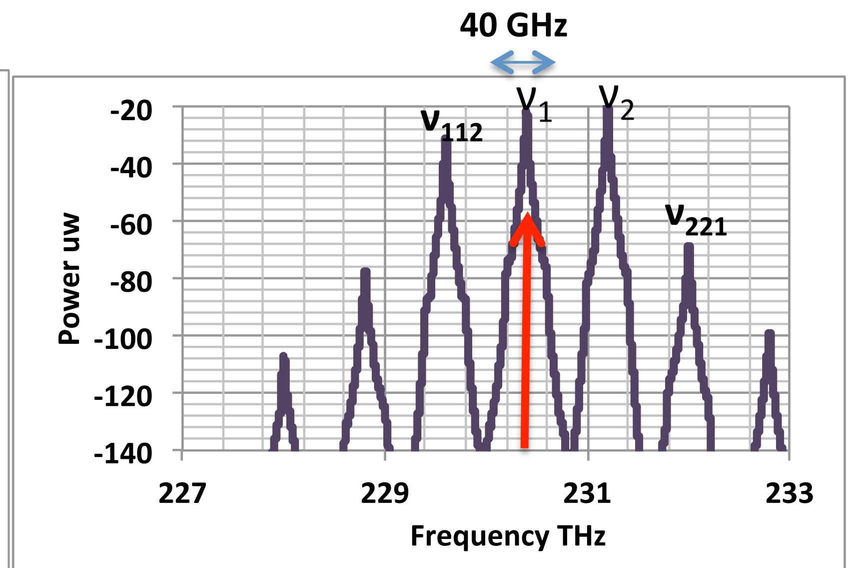
* Fahmida Hossain Tithi ,et al. ”Overview of Stimulated Brillouin Scattering Effect and Various Types of Method to Eliminate this Effect”, *International Journal of Computer Applications (0975 – 8887) Volume 92 – No.7, April 2014*

- **Possible SBS induced by the reflection index fluctuations caused by DFWM**

Zero dispersion at center of a DWDM channel should be avoided

Laser wavelength detuning



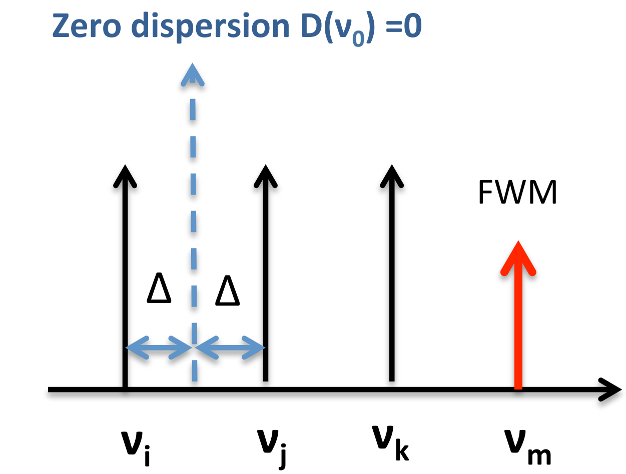


Laser in the source wavelength is detuned from 0 - 40GHz (+/-20GHz)

- At 800GHz channel spacing 20km distance, the FWM gain bandwidth is about 40GHz, consistent with the theoretical model
- In practice, the laser drift/detuning could cause variations of channel characteristic, i.e. FWM and other nonlinear effects "randomly" on/off

Non degenerated FWM in Zero Dispersion Regions

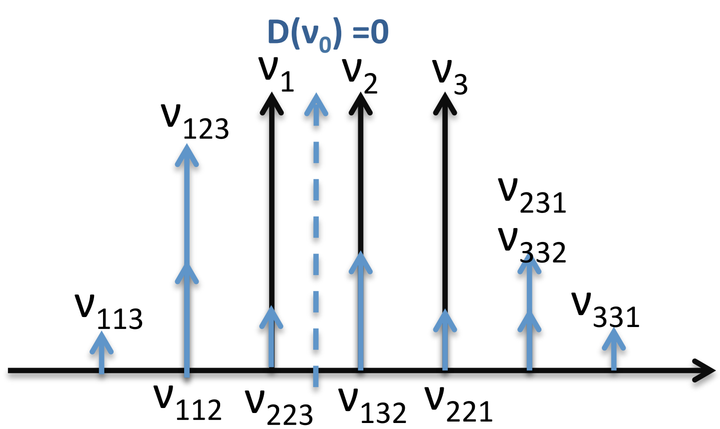
Non degenerated FWM phase matching condition

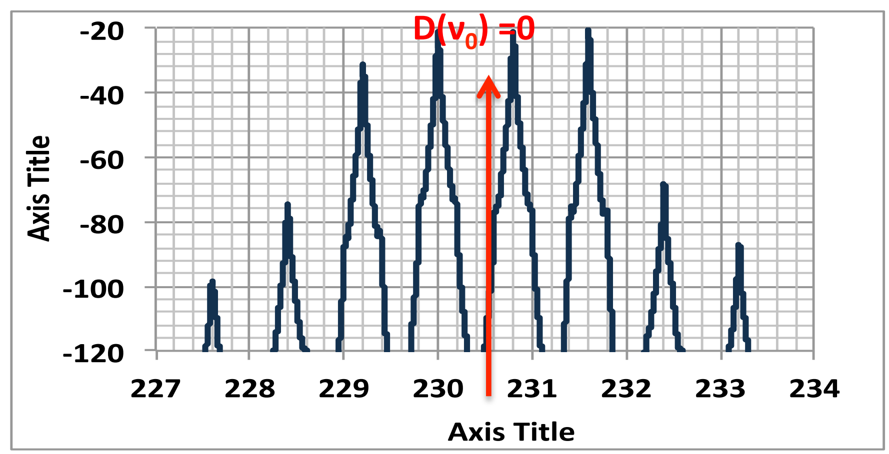


$\beta_m = \beta_i + \beta_j - \beta_k$; Since $D(\nu_0) = 0$, we have

$$\Delta\beta = \frac{2\pi\lambda^2}{c}\,\Delta\nu_{ik}\,\Delta\nu_{jk}\left(\frac{\lambda^2}{2c}(\nu_i-\nu_0)+(\nu_k-\nu_0)\frac{dD}{d\lambda}\right)$$

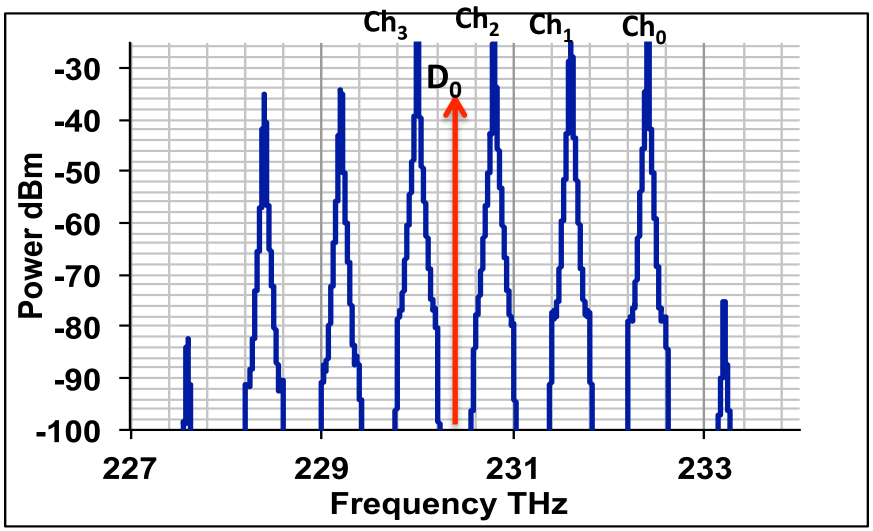
When ν_0 is at the center of 2 adjacent channels, $\Delta\beta=0$. Phase matched non degenerated FWM is created.



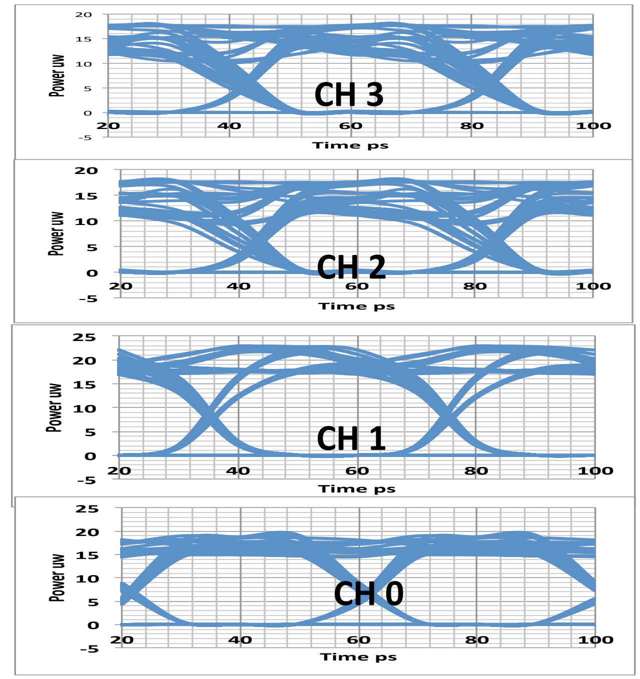


A 3-channel system

Zero dispersion is at the middle of 2 channels

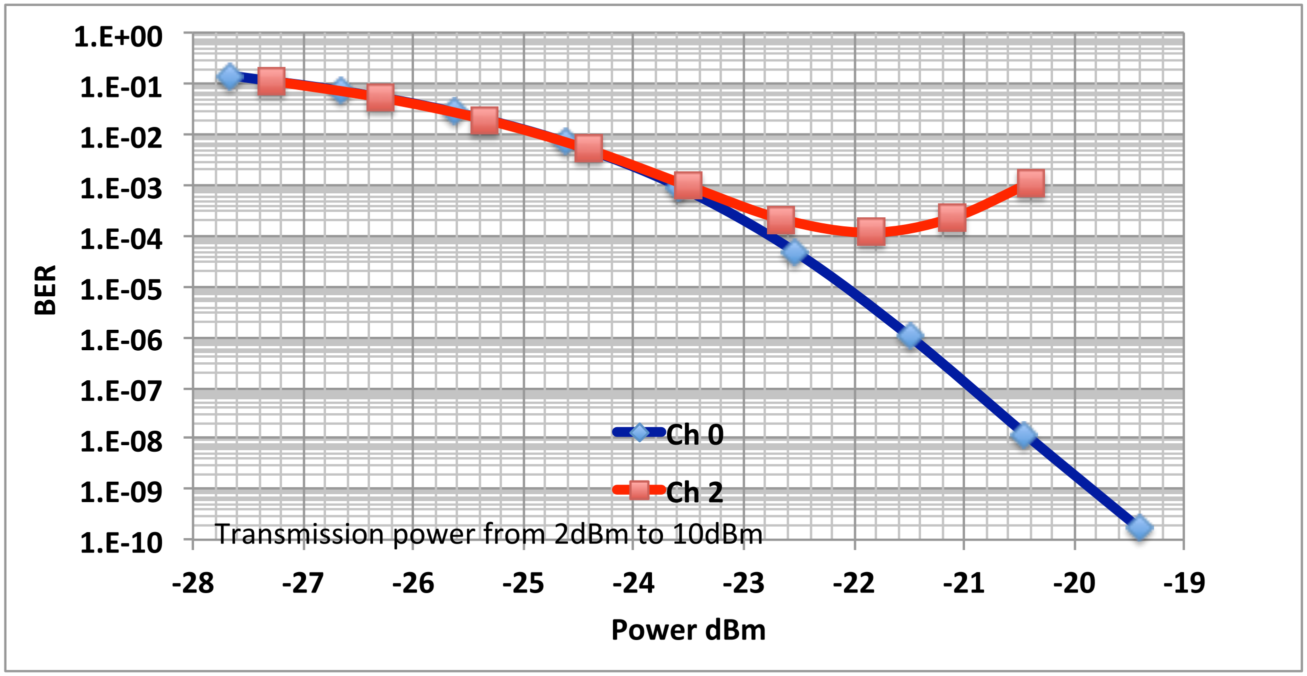


All O band "plan A"



- Zero dispersion could at the middle of Ch 3 and Ch 2
- Ch 3 and Ch2 show significant noise

Non degenerated FWM in Zero Dispersion Regions



Zero dispersion is at the middle of Ch 3 and Ch2

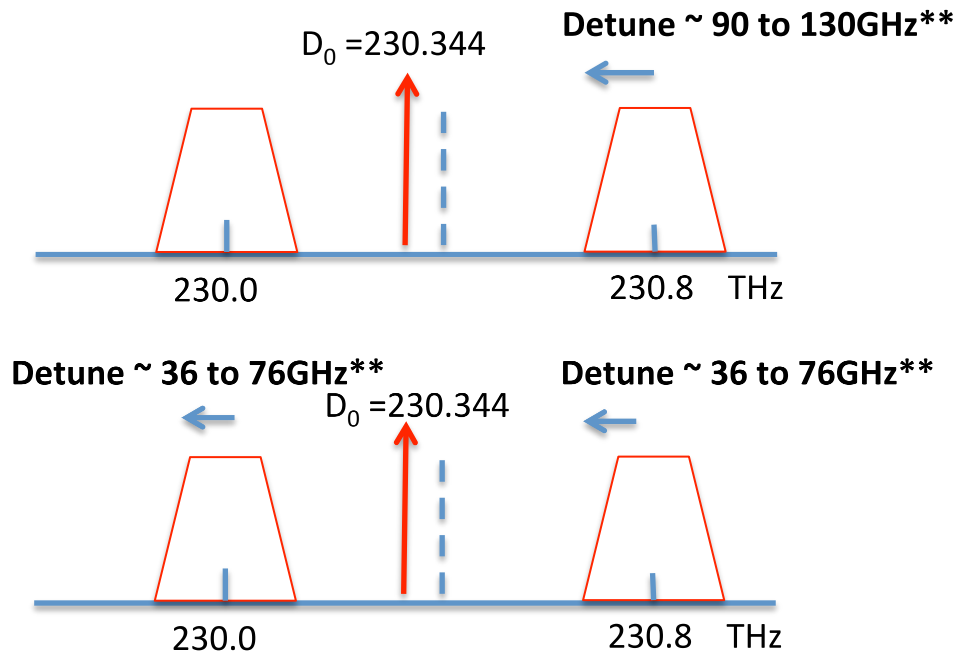
- **Simulation results show significant BER and power penalties when zero dispersion is at the middle of 2 WDM channels**
- **Origins of the penalties may be similar to the DFWM case, ie.,**
  - **FWM products fall under the signals**
  - **Noises generated at source wave when exact phase matching condition met**
  - **Possible SBS induced by FWM**

All O band "plan A"

In the all O band wavelength plan A, zero dispersion could be located at the middle of upstream Ch 3 and Ch 2*

Plan A

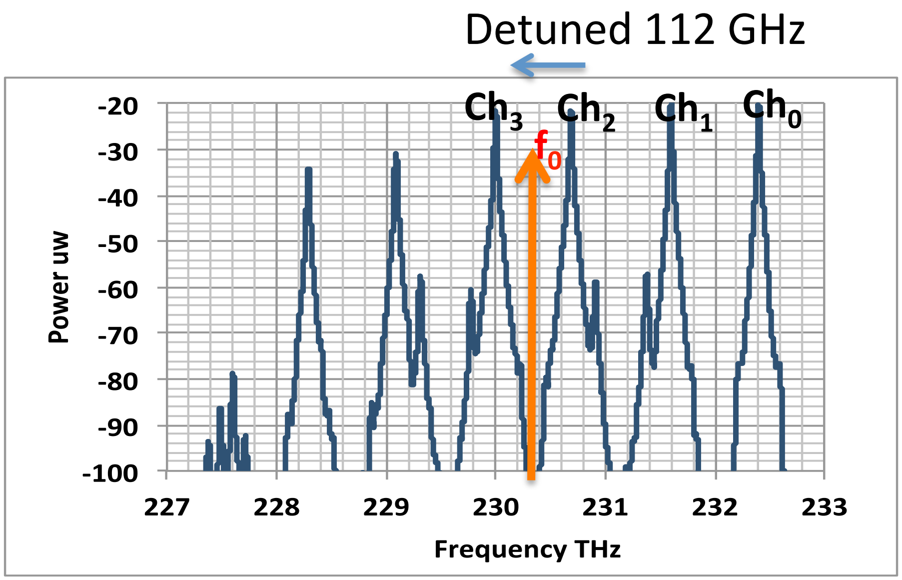
	Center Freq (THz)	Center WL (nm)
US0	232.400	1289.985
US1	231.600	1294.441
US2	230.800	1298.927
US3	230.000	1303.445
DS0	224.600	1334.784
DS1	223.000	1344.361
DS2	222.200	1349.201
DS3	221.400	1354.076

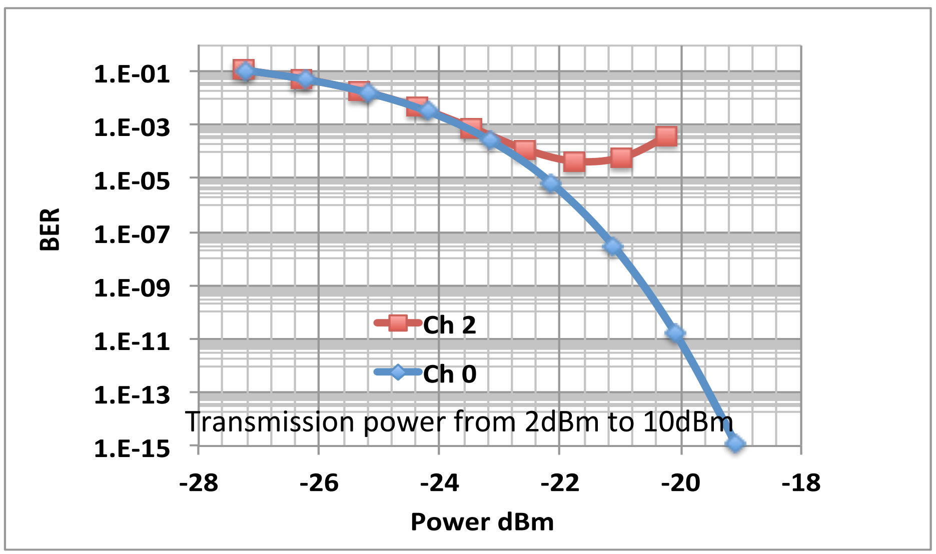


* Corning SMF-28 CPC6: Zero Dispersion Wavelength (λo): 1301.5 nm≤ λo ≤ 1321.5 nm

** FWM detune range +/- 20 GHz was considered (800 GHz channel spacing, 20 km)

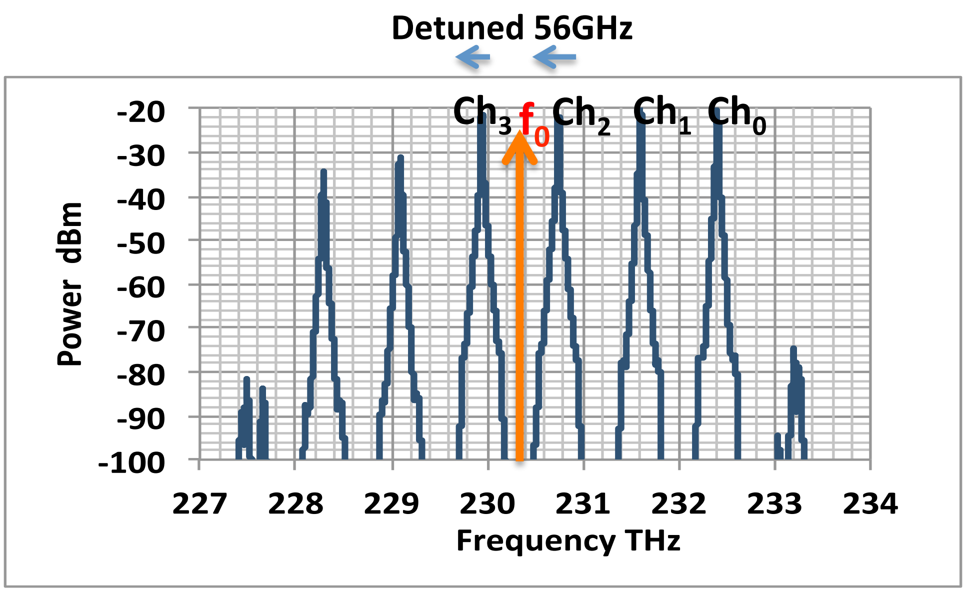
FWM in all O band "plan A" (1)

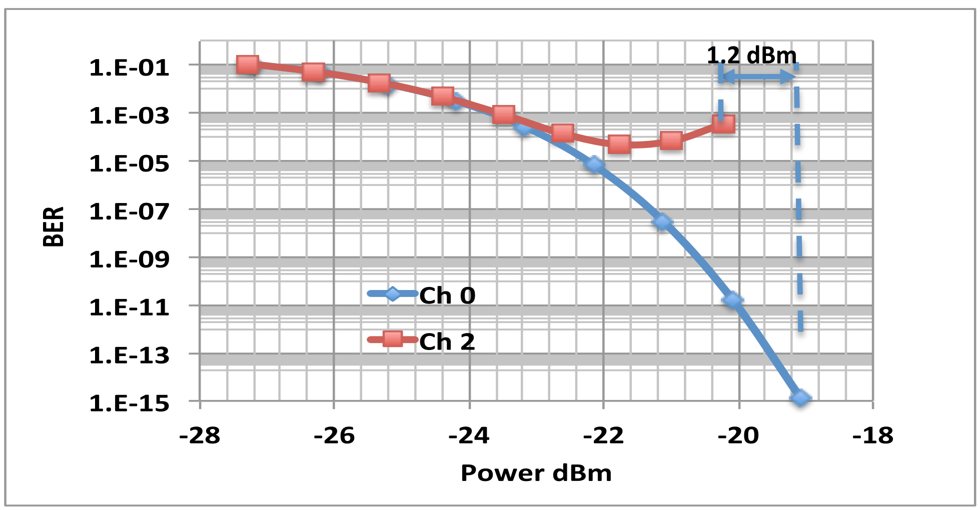




- If Ch 2 center frequency shifts to the left 90 GHz to 130 GHz, the zero dispersion point 230.344 THz fall into the middle of Ch 2 and Ch 3
- Phase matching FWM happens.
- Both Ch 2 and Ch 3 show significant BER and power penalties.

FWM in all O band "plan A" (2)





- If the center frequencies of Ch 2 and Ch 3 shift to the left 36 GHz to 76 GHz, the zero dispersion point 230.344 THz fall into phase matching FWM gain regions
- Both Ch 2 and Ch 3 show significant BER and power penalties.

Discussions (1)

- Precautions should be taken if DWDM channels are placed near zero dispersion regions
- In the FWM phase matching gain region the optical noise in the source wave becomes significantly noticeable
- The origin of the strong noise could be related to SBS induced by FWM due to the changing of the reflection index and the low threshold of SBS
- If some DWDM channels are near or in zero dispersion region, the center wavelength of any channel SHOULD NOT be in the zero dispersion point, especially when high optical transmission powers are used

Discussions (2)

- The zero dispersion point in a SMF SHOULD NOT be in the middle between any adjacent DWDM channels, especially when high optical transmission powers are used
- The all O band "plan A" the zero dispersion could be at in the center of channel 3 or in the middle of ch 3 and ch 2
- The laser drift/detuning could create phased matched strong FWM
- The phase matched FWM could induce other nonlinear penalties such as SBS, that needs further study
- The laser drift/detuning could cause variations of channel characteristics and could affect the stability of the system
- Uneven wavelength plan may be a solution

Conclusions

- **Phase matched FWM could create strong optical noises in the source wave**
- **In a DWDM system, the center wavelength of any channel should not be in the zero dispersion region of a fiber.**
- **In a DWDM system, the zero dispersion point of fiber should not be placed in the middle of adjacent channels.**
- **In the all O band "plan A" the zero dispersion could be in the center of channel 3 or in the middle of channel 2 and channel 3, and therefore will suffer from FWM when channel powers are high**
- **Uneven channel plan may be a solution. A all O band uneven channel wavelength plan will be discussed in a separated contribution(dai_3ca_3a_1116)**

Thanks

Eugene.dai@cox.com