All O band Uneven Spacing Wavelength Plan for 100G EPON

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Background

- The FWM and other nonlinear issues with the all O band wavelength plan A (johnson_3ca_1a_0916.pdf) were discussed in “dai_3ca_1.1116.pdf” and “dai_3ca_2a.1116.pdf”
- This contribution further explores solutions to mitigate FWM and other nonlinear problems in zero dispersion region and proposed a new all O band wavelength plan

Outline

- Considerations for 100G EPON DWDM Wavelength plans
- Rules for DWDM wavelength plan in O band
- Mitigate FWM with uneven channel plan
- O band upstream and downstream uneven channel spacing 400GHz WDM wavelength plan
- Mixed 800 GHz even spacing and 400 GHz uneven spacing WDM wavelength plan

Considerations for 100G EPON DWDM Wavelength Plans (1)

- Performance
  - Wavelength plans should allow PR30 power budget, possibly PR40 power budget
    - This could be challenging in the near zero dispersion O band
    - Limiting transmission power to mitigate FWM may not be an option
  - Uniformity of the dispersions across all channels
- Coexistence
  - Should allow wavelength coexistence with 10G EPON
    - Mixed TDM and WDM coexistence is difficult and may impact scheduling performance

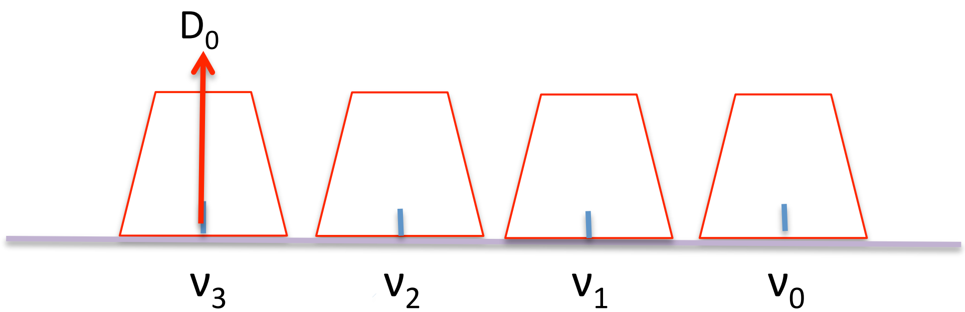
Considerations for 100G EPON DWDM Wavelength Plans (2)

- Cost
  - Should not only focus on component cost, but need to consider system cost
- Scalability
  - The 100G EPON system should be scalable to higher splitting ratios, or longer distances in the future
  - Therefore the wavelength plan should allow scaling to higher transmission power
- Convergence
  - Convergence with NG-PON2 with DWDM spectra could avoid wavelength fragmentations (but may not be at the top of the list)

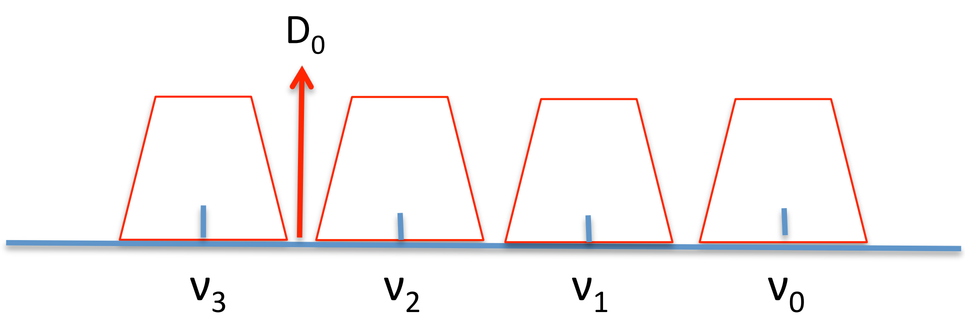
Rules for DWDM Wavelength Plan in O Band

- **Phase matched FWM could creates strong nonlinear optical penalties in a DWDM system including**
  - **Optical noises at the source wave**
  - **In band FWM products**
  - **Possible FWM induced SBS**
- **In a DWDM system, the center wavelength of any channel should not be in the zero dispersion region of a fiber.**
- **The zero dispersion of a fiber should not be placed in the middle of adjacent DWDM channels**

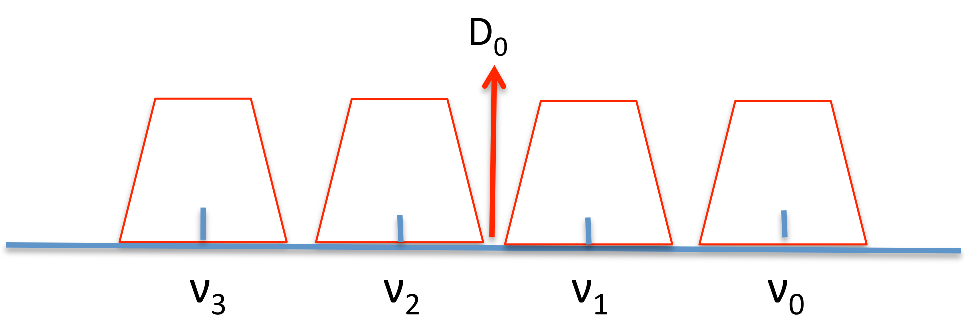
Scenarios to Avoid



- Zero dispersion is at the center of a channel
- Could happen in "plan A"



- Zero dispersion is at the middle of 2 adjacent channels
- Could happen in "plan A"



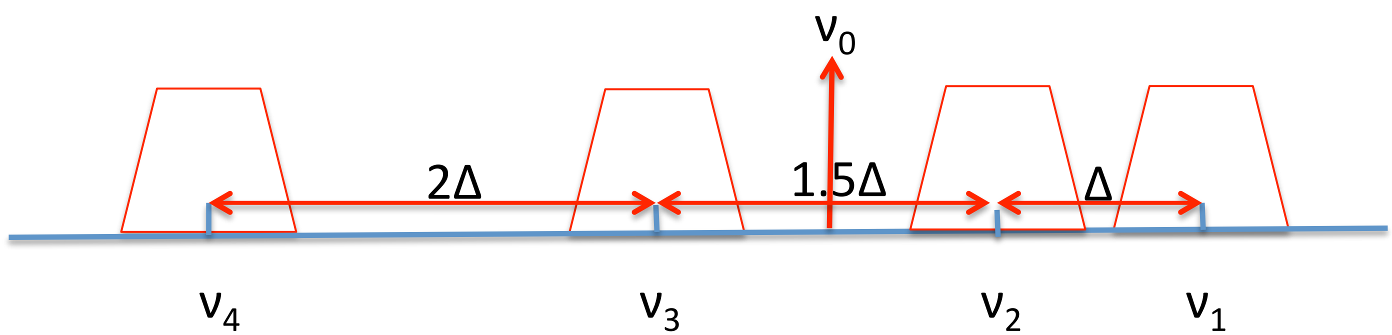
- Zero dispersion point is symmetric to all channels
- Could not happen in "plan A"
- Worse case

Uneven spacing wavelength plan

- Uneven spacing channel plans are well known as means to mitigate FWM in a DWDM system
- Uneven spacing channel plans are used in analog optical transmission even in C band
- However, for a DWDM system with many channels, it is difficult to design an uneven channel plan that excludes all in band FWM products (16 channel DWDM system has 1920 FWM products!)
- Uneven channel plan could use more spectra resources (although this may not true for all cases)

However, It is feasible to design a uneven spacing wavelength plan for a 4-channel DWDM

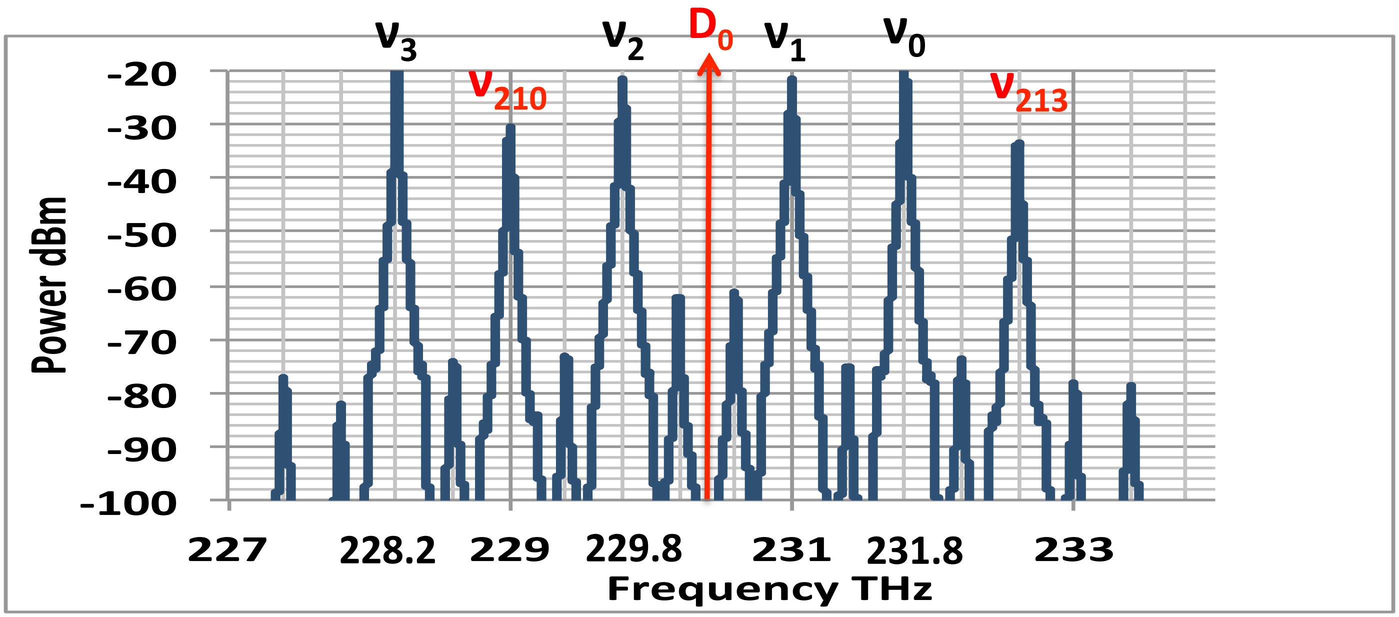
An Uneven Spacing 4 Channels Plan



- Minimum channel space is Δ
- $\nu_2 = \nu_0 + 0.75\Delta$; $\nu_3 = \nu_0 - 0.75\Delta$;
- $\nu_1 = \nu_0 + 1.75\Delta$; $\nu_4 = \nu_0 - 2.75\Delta$;

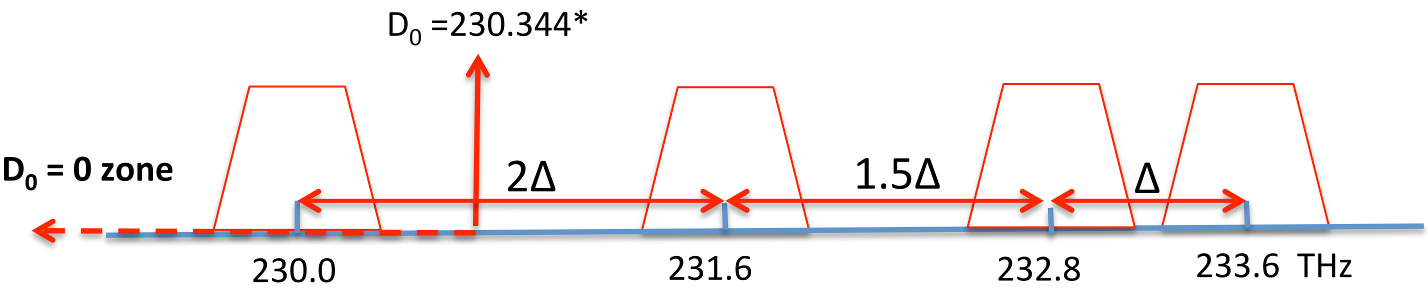
In this 4-channel uneven spacing wavelength plan all FWM products are out of band

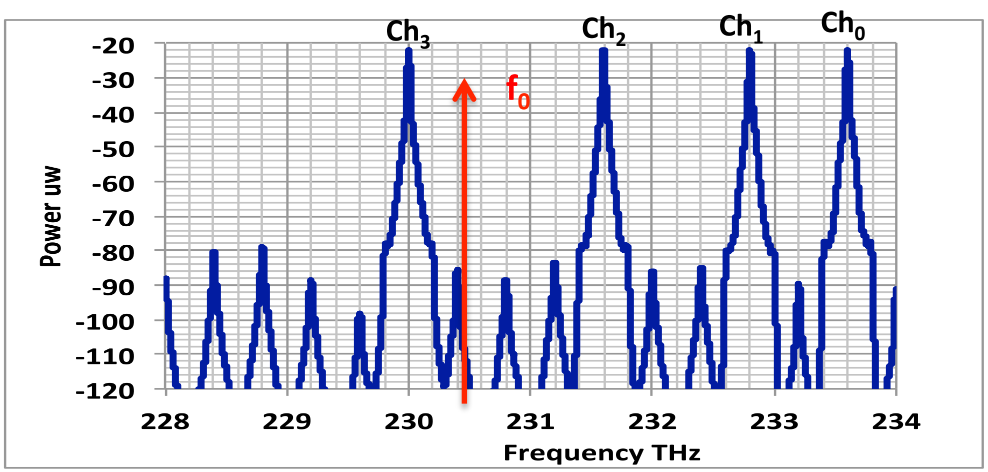
An Example of Uneven Spacing 4 Channel Plan

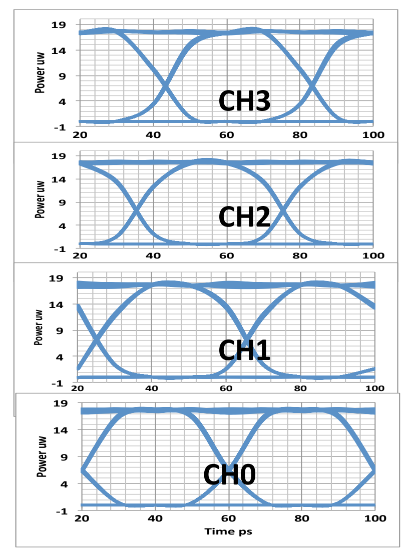


In this example of the worse case scenario of 4 channels 800 GHz uneven spacing DWDM with symmetric zero dispersion location, FWM mixing products ν_{210} and ν_{213} are strong but are out of band. If it were even channel spacing they would be in band under channel 3 and channel 0 respectively.

Performance of 800 GHz Uneven Spacing Wavelength Plan Example

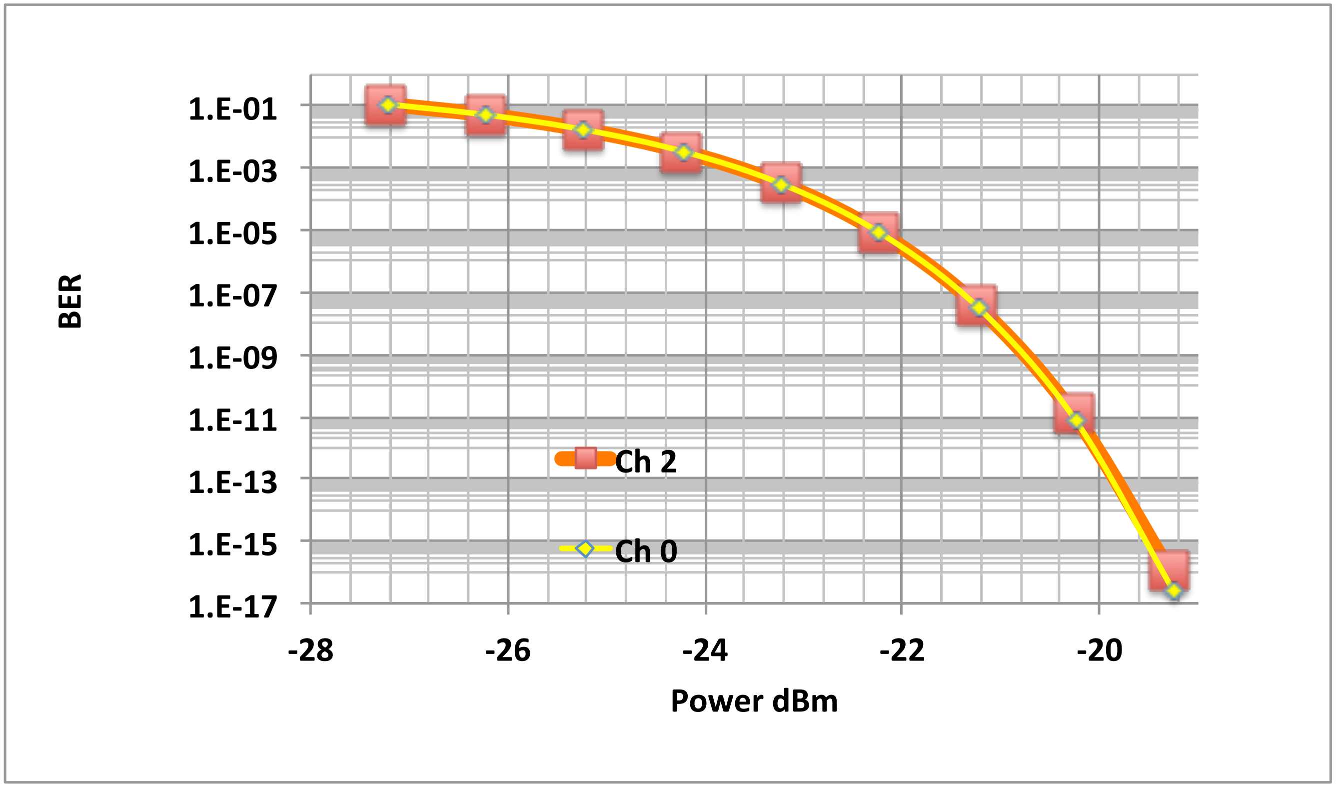






* Corning SMF-28 CPC6: Zero Dispersion Wavelength (λo): 1301.5 nm≤ λo ≤ 1321.5 nm

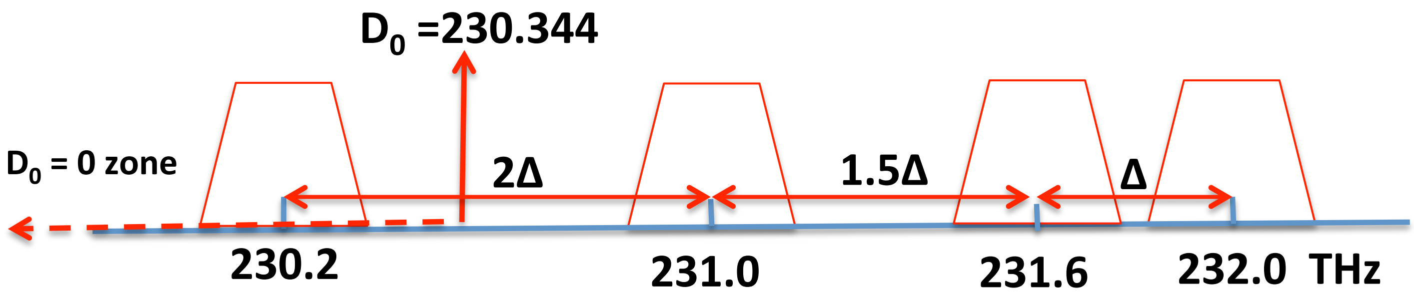
Performance of 800 GHz Uneven Spacing Wavelength Plan Example

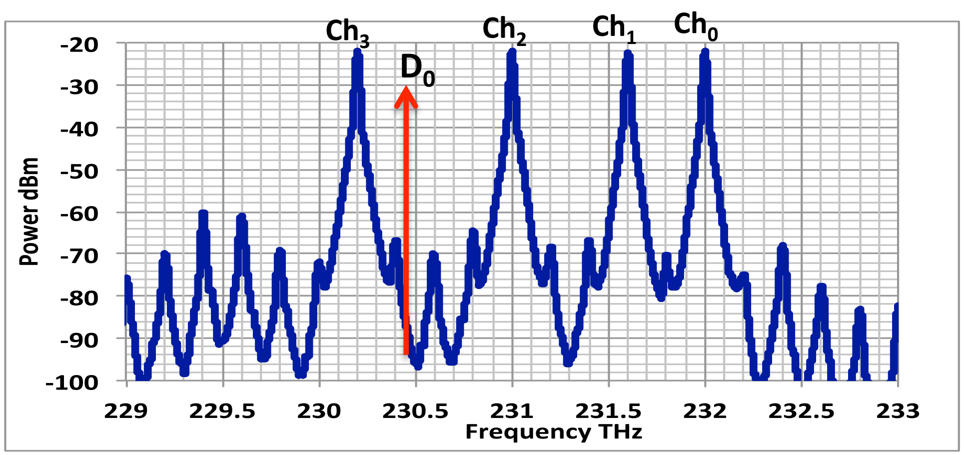


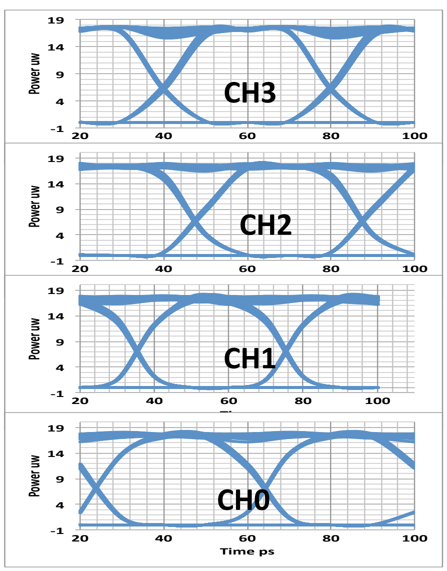
- No FWM penalties were observed
- Compared with 800 GHz even spacing, it uses 1.5Δ more spectra

400 GHz Uneven Spacing Wavelength Plan Example

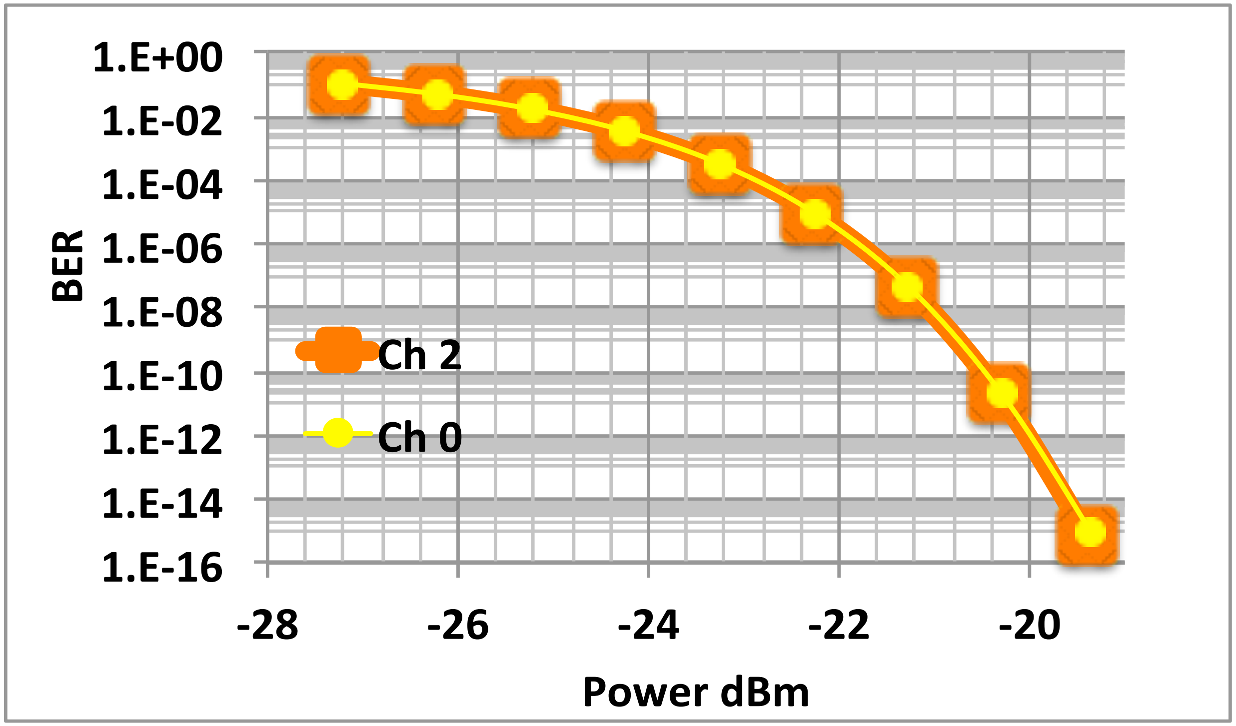
The same method can be used to construct a 400 GHz plan





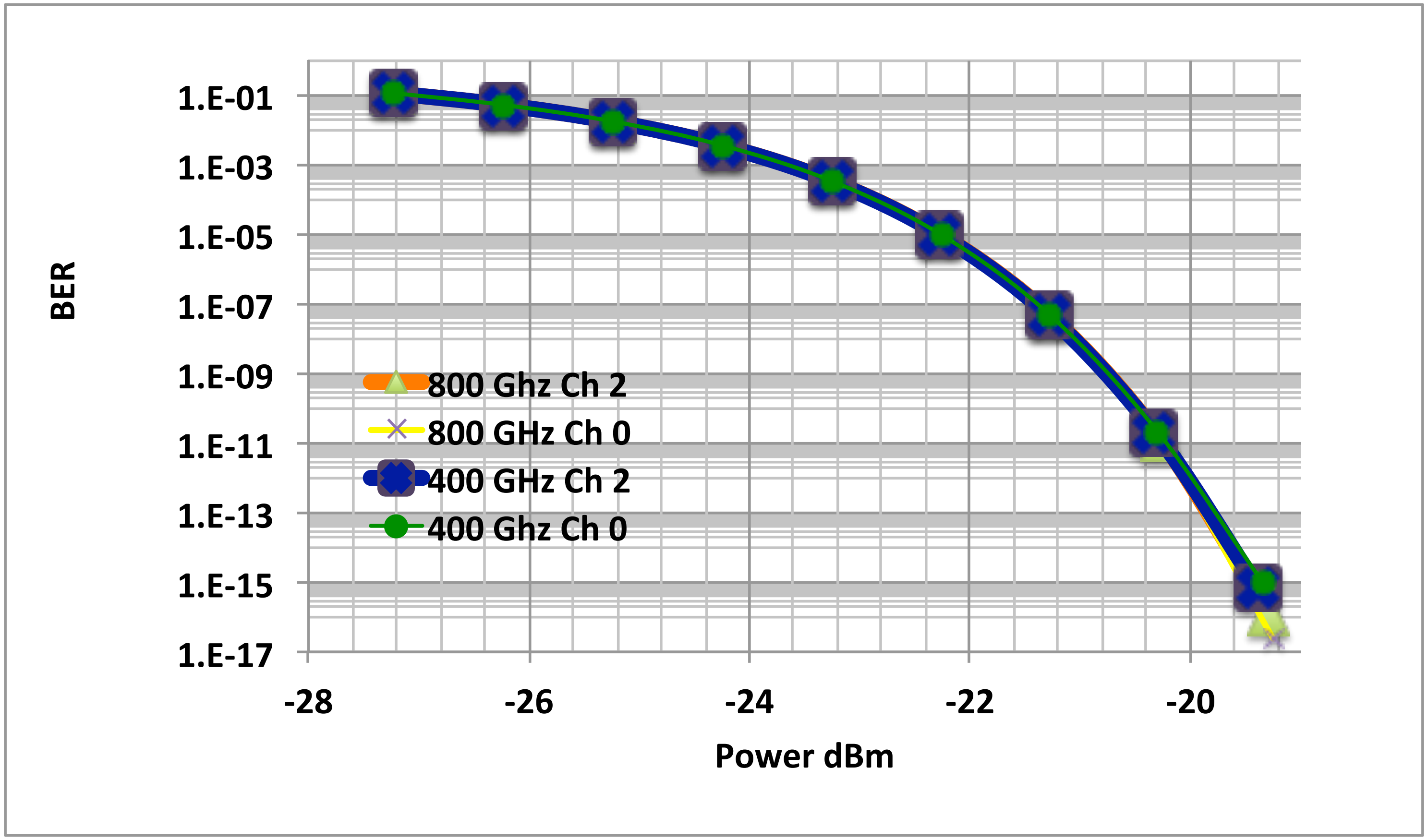


Performance of the 400 GHz Spacing Uneven Channel Wavelength Plan Example



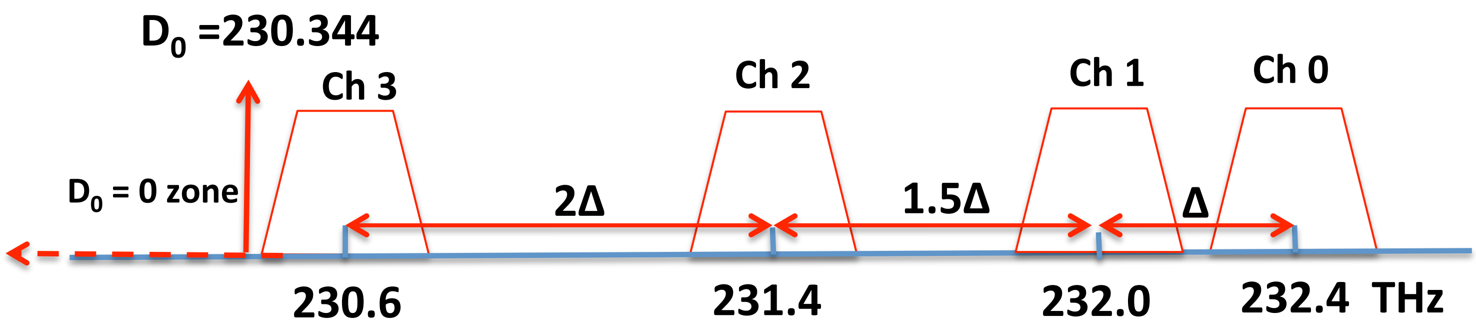
- No FWM penalties were observed
- It uses less spectra than the 800 GHz even spacing plan, but has similar tolerance on FWM

Comparison



The BRE and power penalty performance of 400 GHz and 800 GHz uneven spacing channel plans and are almost indentical

Proposed 400 GHz Upstream Uneven Spacing Wavelength Plan (option I)



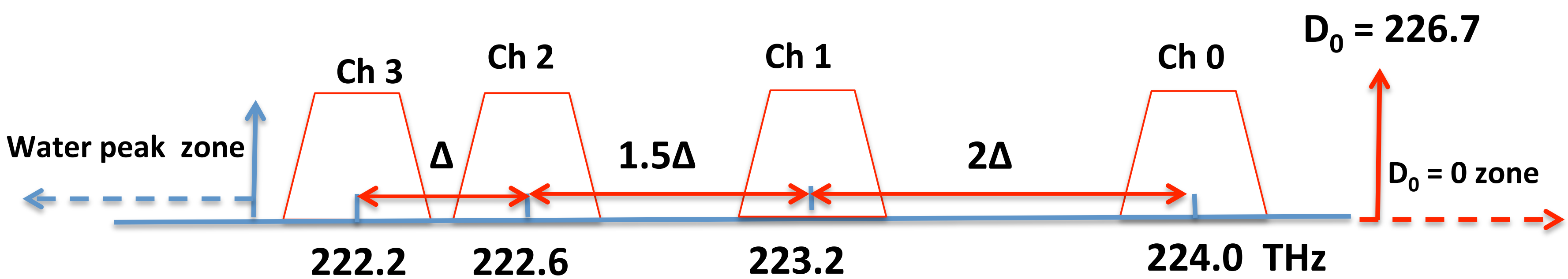
Upstream center frequency/wavelength

US Ch 3	230.600 THz	1300.054 nm
US Ch 2	231.400 THz	1295.559 nm
US Ch 1	232.000 THz	1292.209 nm
US Ch 0	232.400 THz	1289.985 nm

- Uneven channel spacing 2 : 1.5 : 1
- 400 GHz DWDM filter with pass band = 0.8 nm
- Ch 3 center frequency is outside of the phase matched FWM gain (maximum laser detune + 20GHz)
- No possible phase matched FWM products
- FWM is further mitigated by uneven channel spacing

Proposed Downstream Wavelength Plan (option I)

The same uneven channel scheme applies to downstream as well

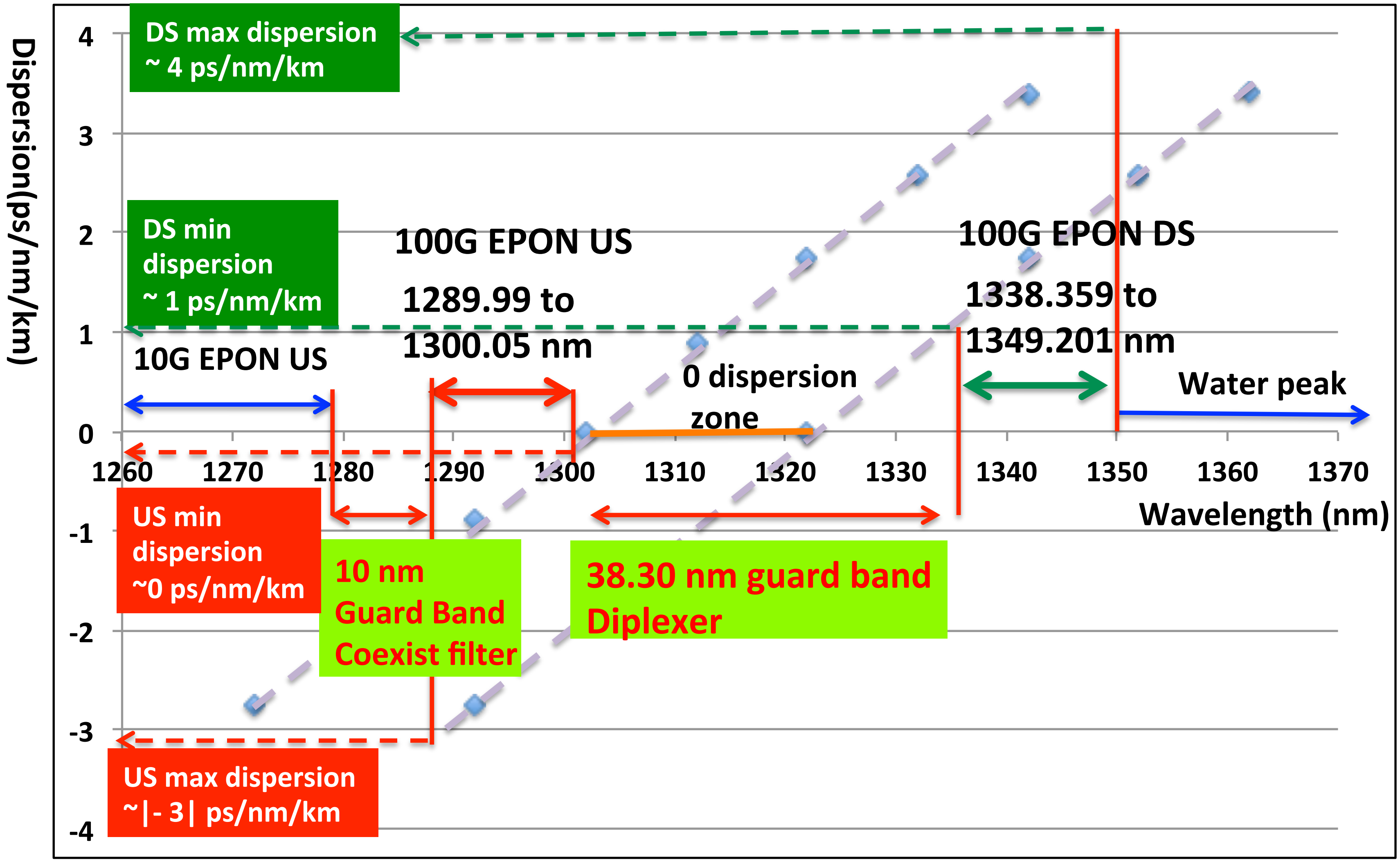


Downstream center frequency/wavelength

DS Ch 3	222.200 THz	1349.201 nm
DS Ch 2	222.600 THz	1346.777 nm
DS Ch 1	223.200 THz	1343.156 nm
DS Ch 0	224.000 THz	1338.359 nm

- Uneven channel spacing 2 : 1.5 : 1
- 400 GHz DWDM filter with pass band = 0.8 nm
- Ch 0 and Ch 1 spaced 800 GHz.
- 2.7 THz away from zero dispersion, and FWM is further mitigated by uneven channel spacing
- Entirely outside of “water peak”, more uniform attenuations

Dispersions Range and Guard Band for Wavelength Plan Option I



Wavelength Plan Option I Summary

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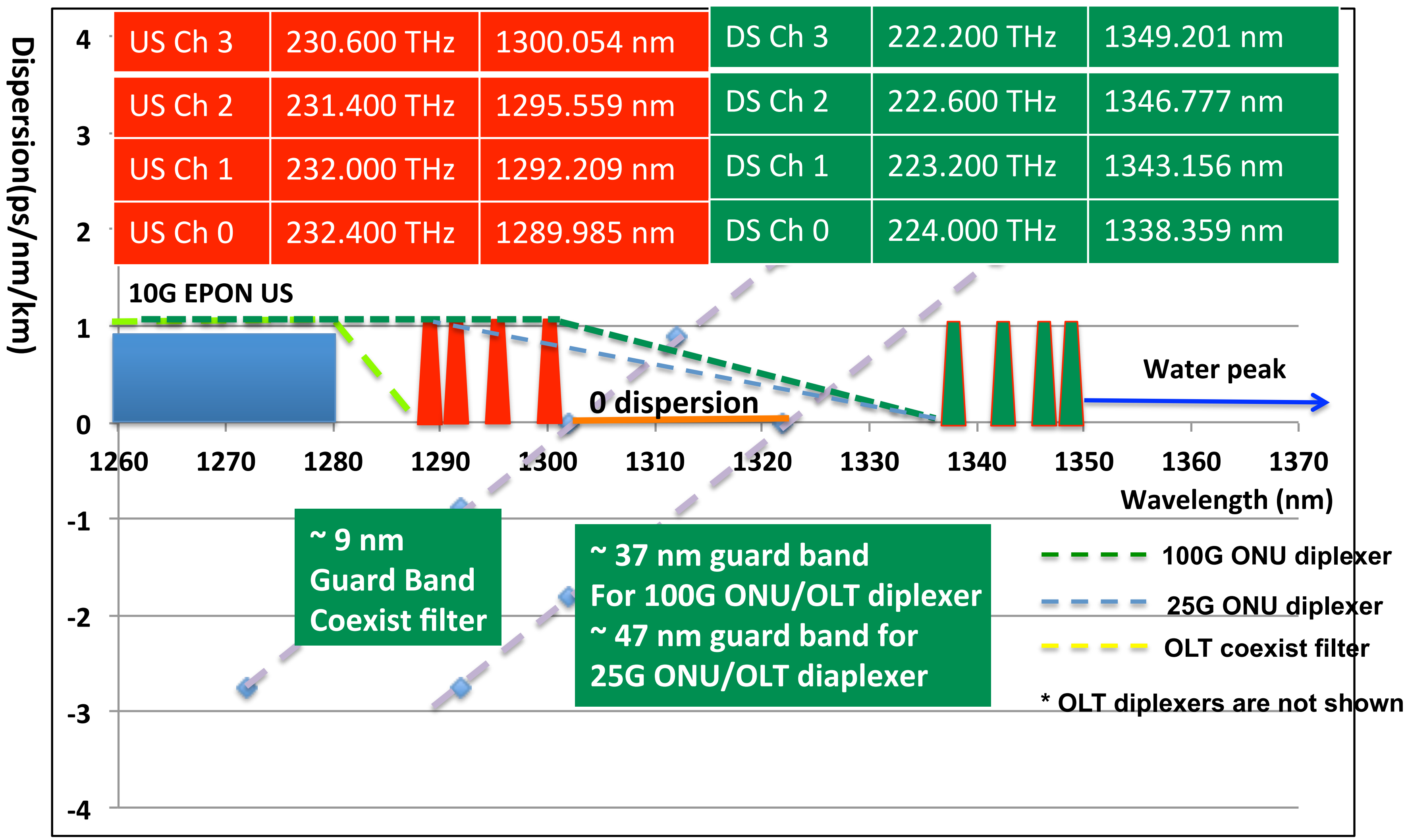
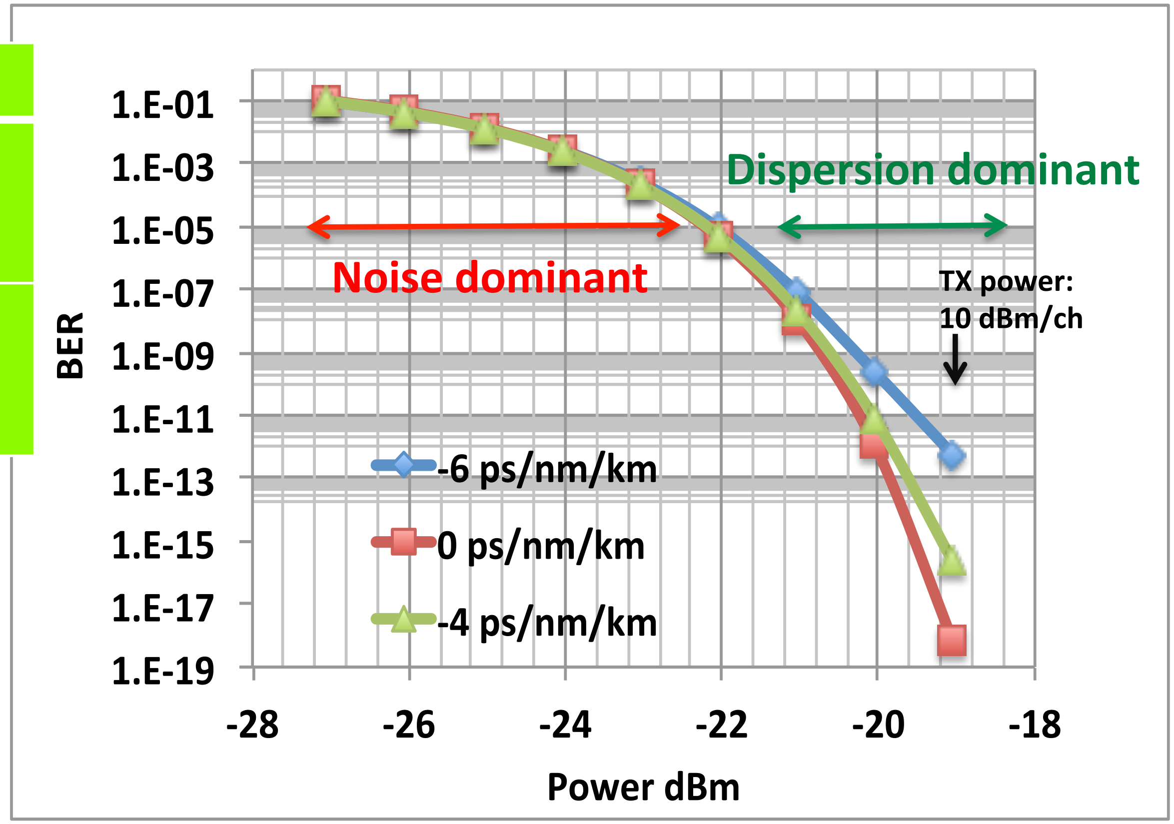


Performance of Dispersive Channels* in Option I

	US	DS
Maximum Dispersion	|-3| ps/nm/km	4 ps/nm/km
Minimum Dispersion	0 ps/nm/kn	1 ps/nm/km

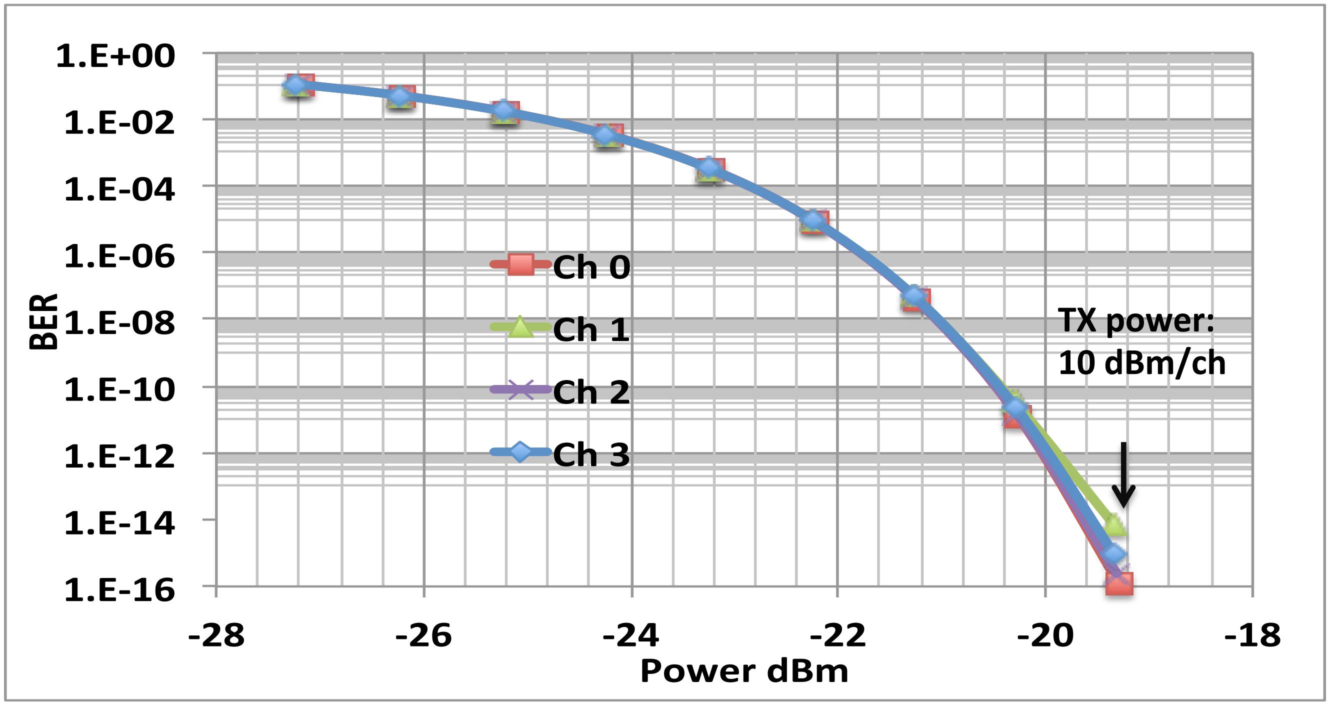
* 20 km SMF fiber, 25 Gbps rate

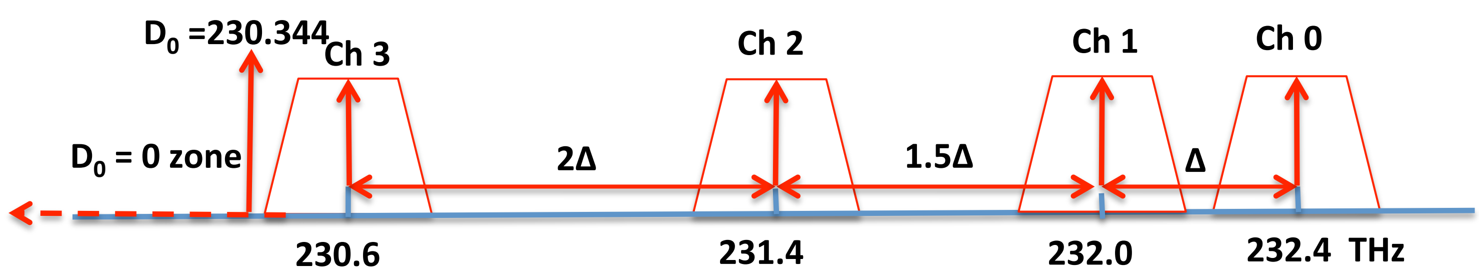


- When power is low, noise is the dominant factor for BER
- At higher powers, dispersion becomes the dominant factor for BER

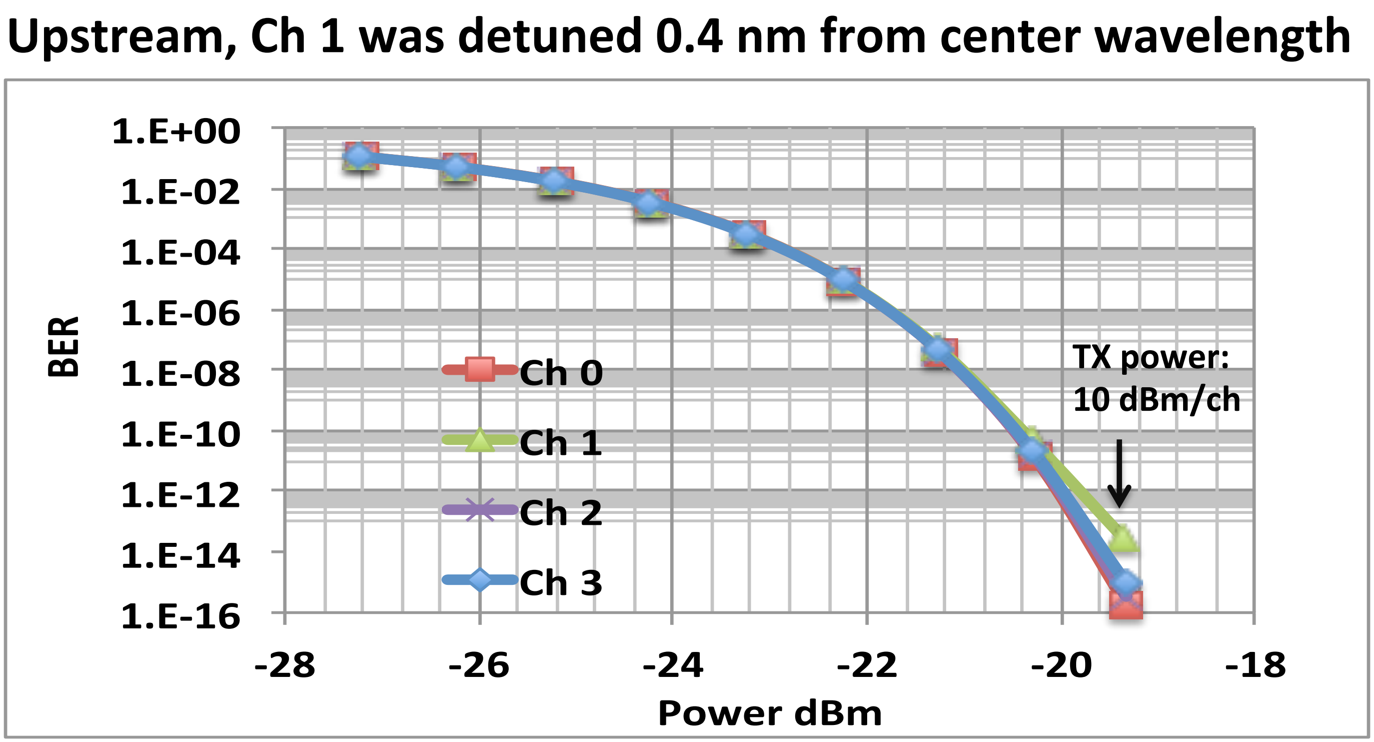
US Performance of Wavelength Plan Option I

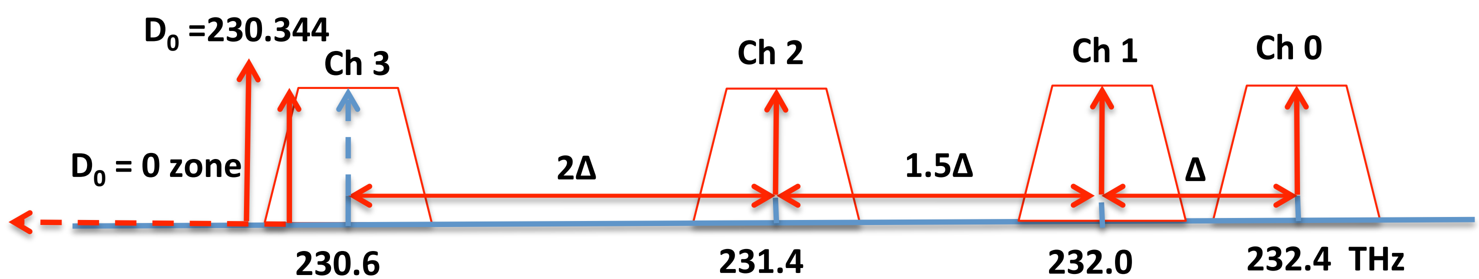
Upstream, all channels are at center frequencies





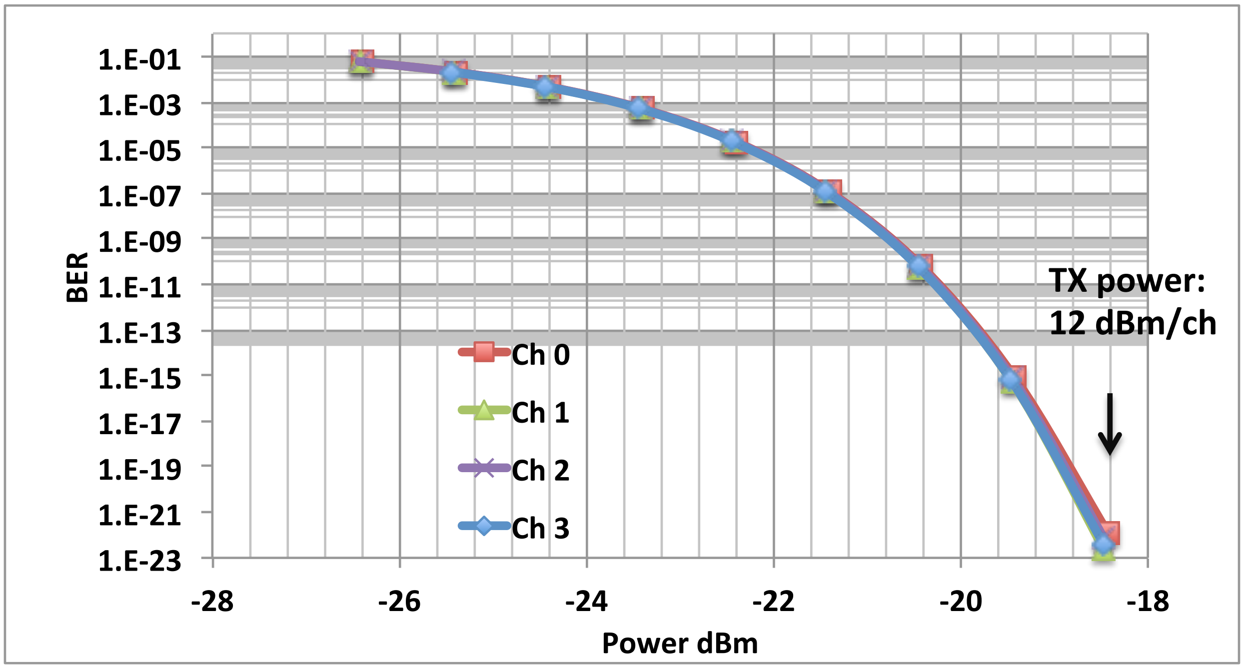
US Performance of Wavelength Plan Option I with Laser Detune

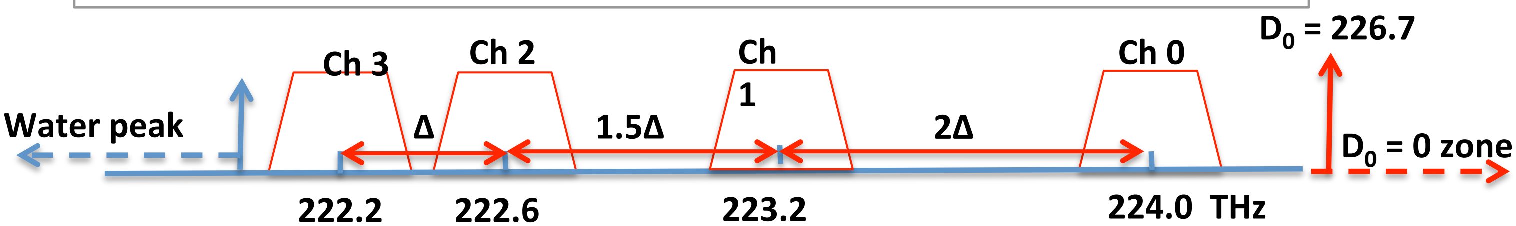




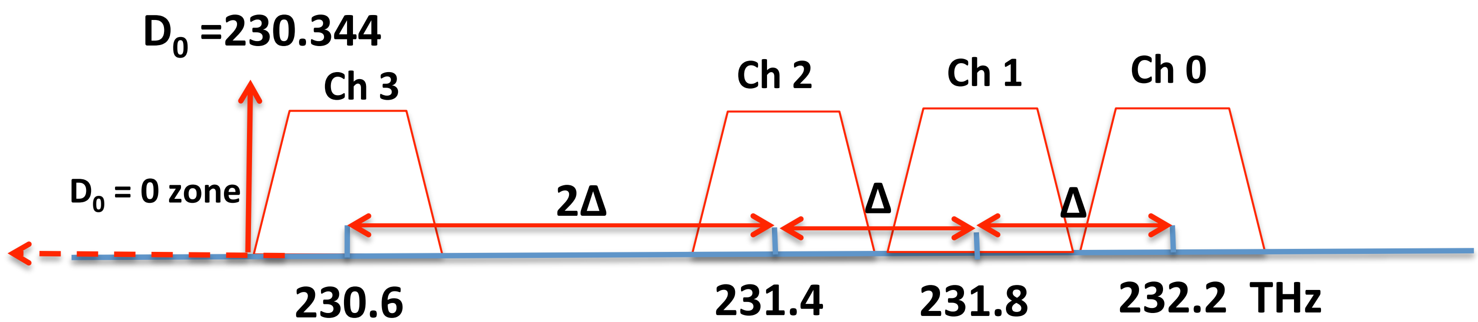
DS Performance of Wavelength Plan (option I)

Downstream, all channels are at center frequencies, maximum channel power = 12dBm





Proposed 400 GHz Upstream Uneven Spacing Wavelength Plan (option II)



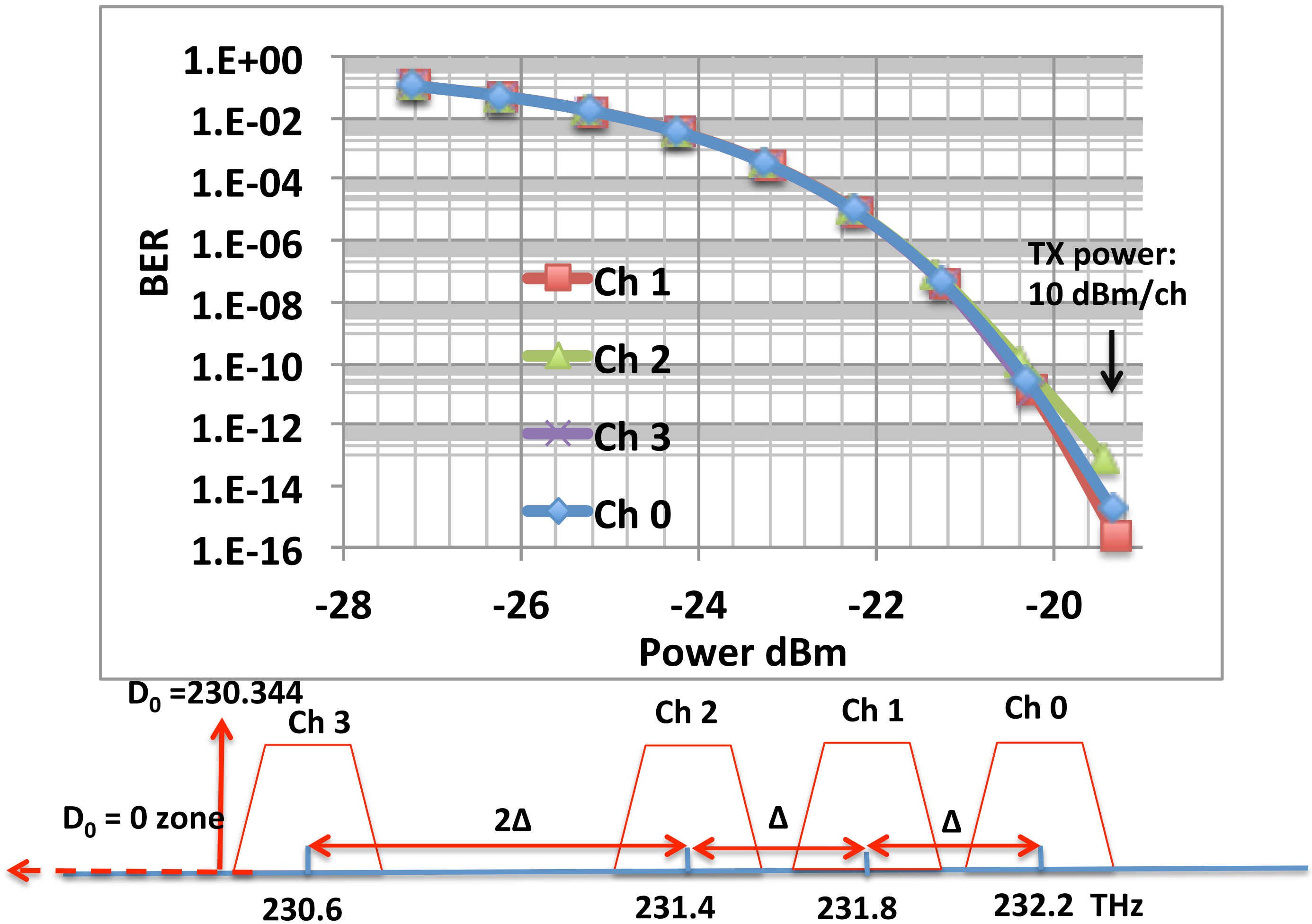
Upstream center frequency/wavelength

US Ch 3	230.600 THz	1300.054 nm
US Ch 2	231.400 THz	1295.559 nm
US Ch 1	231.800 THz	1293.324 nm
US Ch 0	232.200 THz	1291.096 nm

- Uneven channel spacing 2 : 1 : 1
- 400 GHz DWDM filter, pass band = 0.8 nm
- Ch 3 center frequency is out side of the phase matched FWM gain (laser maximum detune + 20GHz)
- No possible phase matched FWM products
- FWM is further mitigated by uneven channel spacing

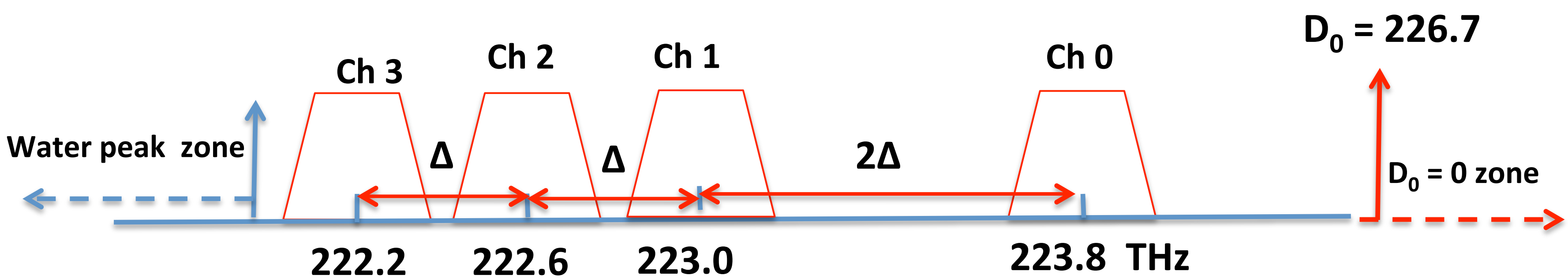
US Performance of Wavelength Plan Option II

Upstream, all channels are at center frequencies



Proposed Downstream Wavelength Plan Option II

The same uneven channel scheme applies to downstream as well

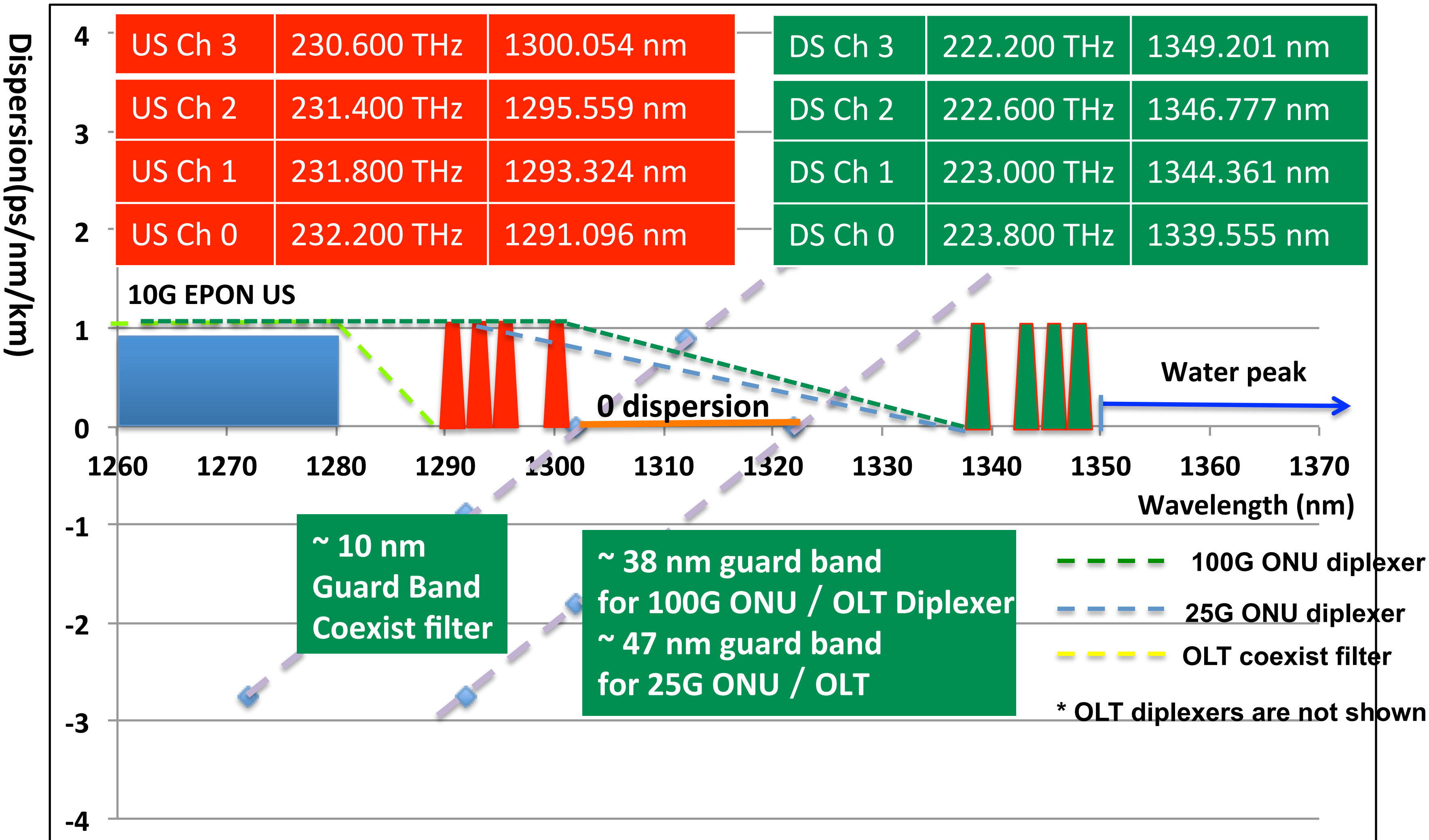


Downstream center frequency/wavelength

DS Ch 3	222.200 THz	1349.201 nm
DS Ch 2	222.600 THz	1346.777 nm
DS Ch 1	223.000 THz	1344.361 nm
DS Ch 0	223.800 THz	1339.555 nm

- Uneven channel spacing 2 : 1 : 1
- 400 GHz DWDM filter, pas band =0.8 nm
- Ch 0 and Ch 1 spaced 800 GHz.
- Zero dispersion is 2.9THz away from Ch 0, and FWM is further mitigated by uneven channel spacing
- Entirely outside of "water peak", more uniform attenuations

Wavelength Plan Option II Summary



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DS Ch 0	223.800 THz	1339.555 nm

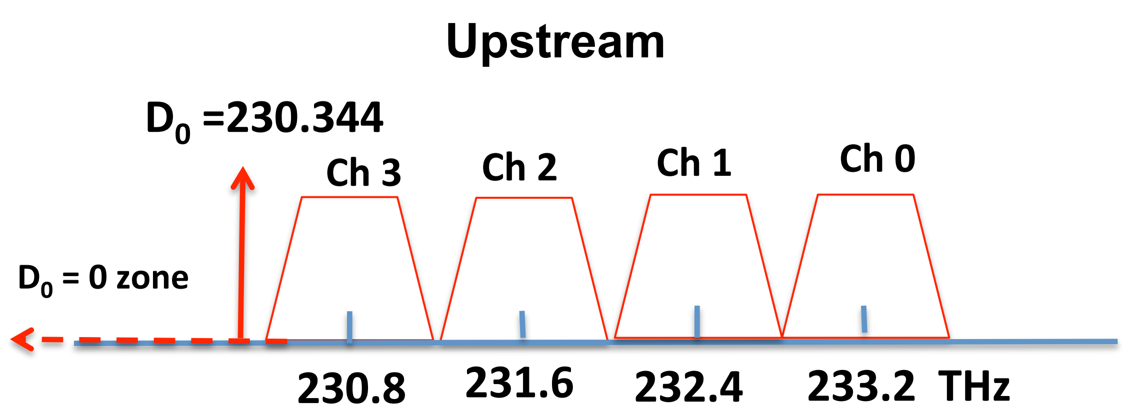
Comparison of Option I and Option II

- FWM mitigation: The primary FWM products in option I are all out of band. Therefore option I has better performance in FWM mitigation
- However, this benefit is only important when the zero dispersion is symmetrical to all channels. In 4-channel case, zero dispersion would be in the middle of channel 2 and channel 3. The proposed channel plan prevents this happen.
- Therefore, the performance of option I and option II are almost identical
- The benefit of option II is mainly on the DWDM filter. The DWDM filter for option II can be viewed as a 5-channel 400 GHz DWDM filter that skips one channel.

Is 800 GHz Channel Spacing Still Possible in O Band?

- The cost difference between cooled 800 GHz and 400 GHz DWDM grid lasers may not be big.
- To avoid phase matching DFWM, the channel 3 must be outside the zero dispersion frequency (maximum laser detune range + 20 GHz)
- As the result, the guard band of coexist filter for 800 GHz will be much less
- Therefore, the answer is "may be, but at cost of coexist filter".

Proposed 800 GHz Wavelength Plan Option III

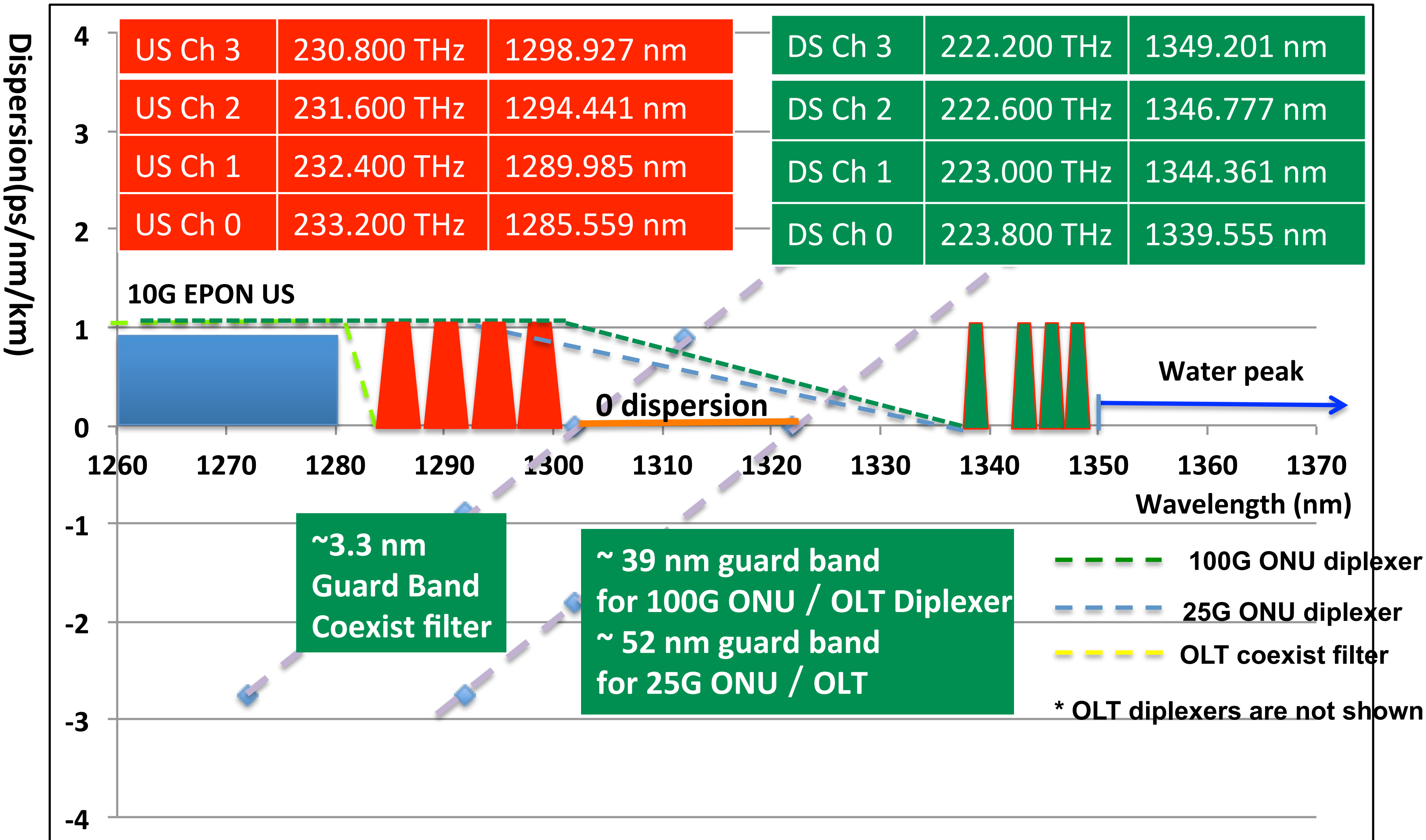


Upstream center frequency/wavelength

US Ch 3	230.800 THz	1298.927 nm
US Ch 2	231.600 THz	1294.441 nm
US Ch 1	232.400 THz	1289.985 nm
US Ch 0	233.200 THz	1285.559 nm

- Even channel spacing
- 800 GHz DWDM filter
- Ch 3 center frequency is outside of the phase matched FWM gain (maximum laser detune + 20GHz)
- No possible phase matched FWM products
- Downstream use option II downstream plan

Wavelength Plan Option II Summary



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DS Ch 2	222.600 THz	1346.777 nm
DS Ch 1	223.000 THz	1344.361 nm
DS Ch 0	223.800 THz	1339.555 nm

Performance of the Proposed all O Band Wavelength Plans

- Maximum upstream transmission power: > 10 dBm per channel without apparent FWM penalties, exceeding PR 30 and PR 40
- Maximum downstream transmission power: ≥ 12 dBm per channel without apparent FWM penalties, meet PR 40
- Dispersion uniformity for US channels: 0 to|-3.5| ps/nm/km
- Dispersion uniformity among DS channels: 1 to 4 ps/nm/km
- Guard band for WDM coexistence filter is about ~ 9 nm for option I, ~ 10 nm for option II and ~ 3.3 nm for Option II
- Guard band reserved for 100G diplexer are about ~ 37 nm for option I, and ~38 nm for option II and ~39 nm for option III

400GHz and 800 GHz Comparison

- The costs between commonly used DWDM grids filters are largely depending on volumes
- The cost between 400 GHz and 800 GHz DWDM filters may not be a big difference
- The 400 GHz spacing channel plan has more uniformity in loss and dispersion than that of the 800 GHz spacing channel plan
- 800 GHz spacing laser may has lower cost than 400 GHz spacing laser. However, since temperature controlled lasers are needed for both 400G and 800G grid, the cost difference may not be big.

Conclusions

- All O band wavelength plan has advantages over split band solutions, mainly in avoiding dispersion compensations
- The proposed all O band wavelength plans meet or exceeds PR 30/PR 40 maximum power requirements without hit apparent FWM and other nonlinear penalties
- All options support WDM coexistence with 10G EPON.
- Since cooled lasers are needed for both 400 GHz and 800 GHz grid DWDM, cost may not be a big differentiation. Therefore, option II is a more balanced solution.
- The guard band for coexist filter may be a problem for option III, other wise option III is also a valid choice

Thanks

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