Impact of nonlinear optical crosstalk on 10GEPON architecture

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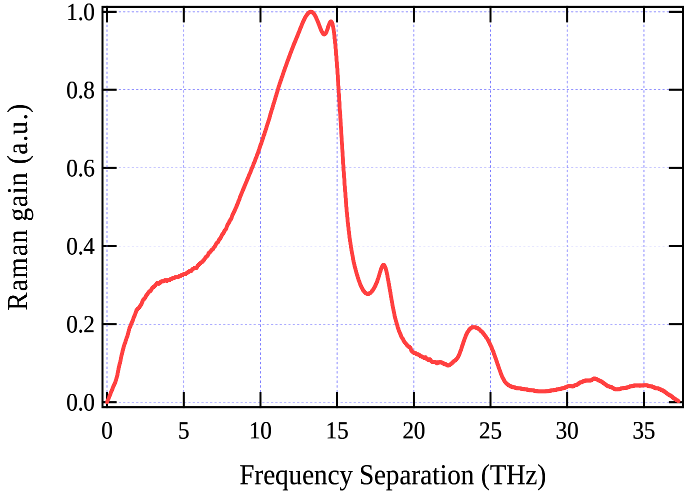
Background information

Downstream signals in CATV and PON systems:

- CATV: 1550nm
- GPON: 1490nm
- 10G data channel: ???
- Crosstalk due to Stimulated Raman Scattering (SRS) between CATV and GPON signals is well understood.
- Theoretical model is used to study the implication of nonlinear optical interaction between CATV and 10G data signals.

Nonlinear optical effects in single mode fibers

- Stimulated Raman scattering (SRS): Optical power transfers from shorter wavelength to longer wavelength through photon-phonon interaction in optical fibers.



Raman gain spectrum

$$\frac{\partial P_1}{\partial z} + \frac{1}{v_1}\frac{\partial P_1}{\partial t} = -\frac{\lambda_2}{\lambda_1}\frac{g_R(\lambda_1)}{A_{eff}} P_1 P_2 - \alpha(\lambda_1) P_1$$

$$\frac{\partial P_2}{\partial z} + \frac{1}{v_2}\frac{\partial P_2}{\partial t} = \frac{g_R(\lambda_1)}{A_{eff}} P_1 P_2 - \alpha(\lambda_2) P_2$$

$$(\text{assumption}: \lambda_1 < \lambda_2)$$

- Cross phase modulation (XPM): Optical power in pump channel induces phase change for signal channel → frequency modulation of signal → amplitude modulation of signal due to fiber dispersion. Effect arises due to nonlinear index of fiber and is proportional to the pump strength ($n=n_0+n_2I$).

Mathematical formulae (ref [1])

$$CrossTalk = \frac{\text{Relative signal RF power}}{\text{Relative pump RF power}} = \frac{\left\langle \delta P_{sig}{}^{2} \right\rangle / \left\langle P_{sig}{}^{2} \right\rangle}{\left\langle \delta P_{pump}{}^{2} \right\rangle / \left\langle P_{pump}{}^{2} \right\rangle}$$

$$CrossTalk(SRS) = (\frac{\rho g_R P_{pump}}{A_{eff}})^2 \frac{1 + e^{-2\alpha L} - 2e^{-\alpha L}\cos(\Omega d_{12} L)}{\alpha^2 + (\Omega d_{12})^2}$$

$$CrossTalk(XPM)$$

$$= (\frac{4\pi n_2 \beta \Omega^2 P_{pump}\rho}{\lambda A_{eff}})^2 \cdot \frac{1 + e^{-2\alpha L} - 2e^{-\alpha L}(1 - \alpha L)\cos(d_{12}\Omega L) - 2L[\alpha + d_{12}\Omega e^{-\alpha L}\sin(d_{12}\Omega L)] + [\alpha^2 + (d_{12}\Omega)^2]L^2}{[\alpha^2 + (d_{12}\Omega)^2]^2}$$

ρ : polarization overlap factor (1 for parallel alignment, 0 for perpendicular alignment)

$g_R / Aeff$: Raman gain

d_{12} : group velocity difference $(1/v_{signal} - 1/v_{pump} = \int D(\lambda) d\lambda)$

α : fiber attenuation

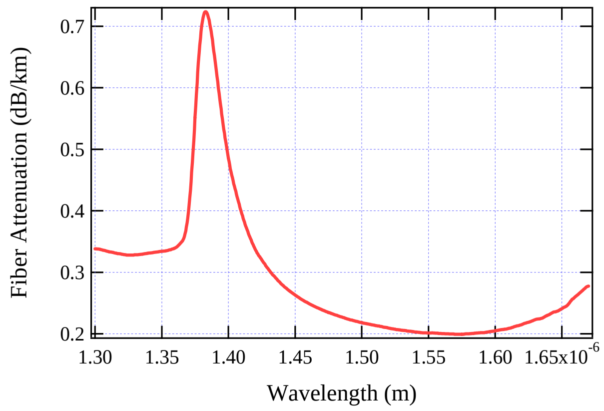
L : fiber length

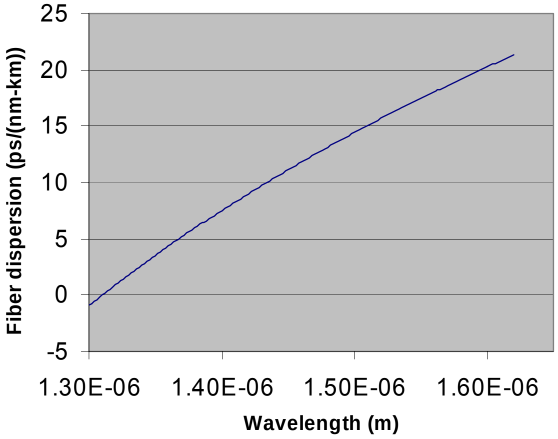
Ω : angular frequency

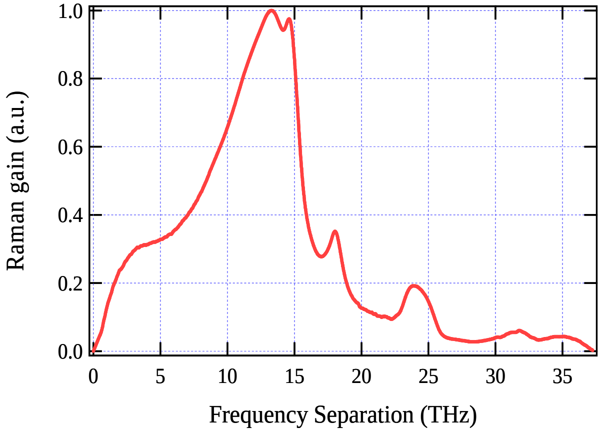
n_2 : fiber nonlinear index

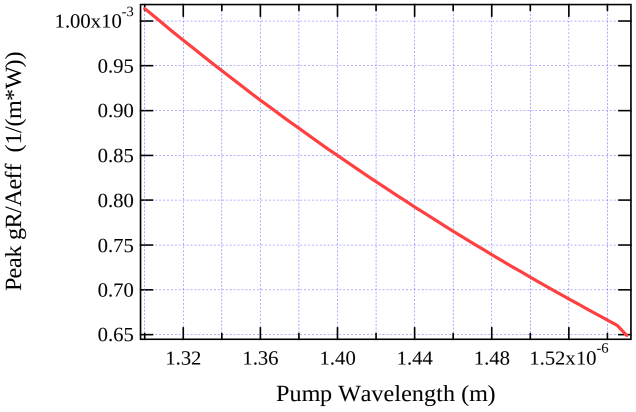
$\beta = \frac{-\lambda_{signal}{}^{2}}{2\pi c} D$, D = fiber dispersion

Fiber parameters used in calculation


Fiber Attenuation


Fiber Dispersion

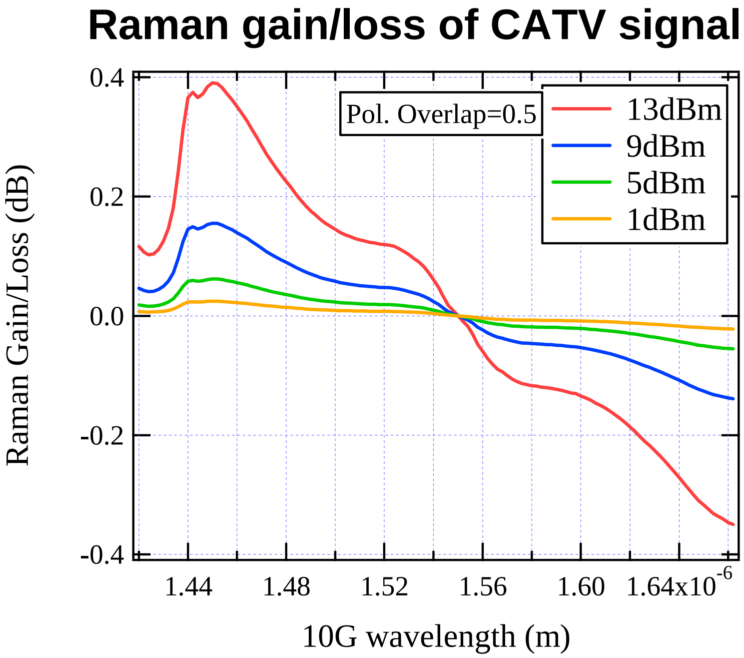

Raman gain spectrum

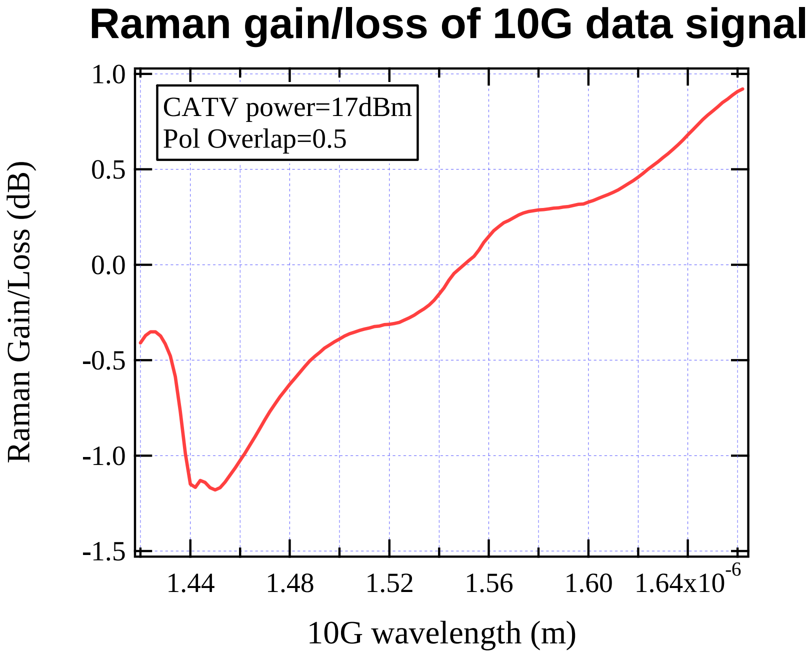

Raman gain peak vs. pump wavelength
(parallel polarization between pump and signal)

Fiber nonlinear index = 2.6e-20 (m^2/W), Fiber effective area = 80 μm^2

DC Raman gain/loss

In addition to AC noise transfer, the signal strength also experiences DC gain/loss due to SRS (Gain in dB ~ (gR/Aeff)*Leff*P0)


Raman gain/loss of CATV signal

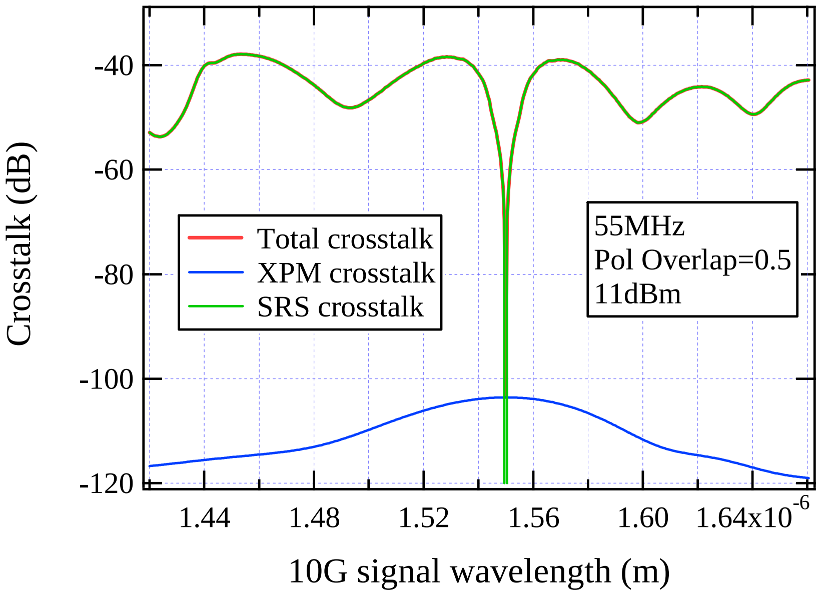

Raman gain/loss of 10G data signal

Assumptions: CATV wavelength=1550nm, Power=17dBm, Polarization overlap = 0.5, fiber length=20km

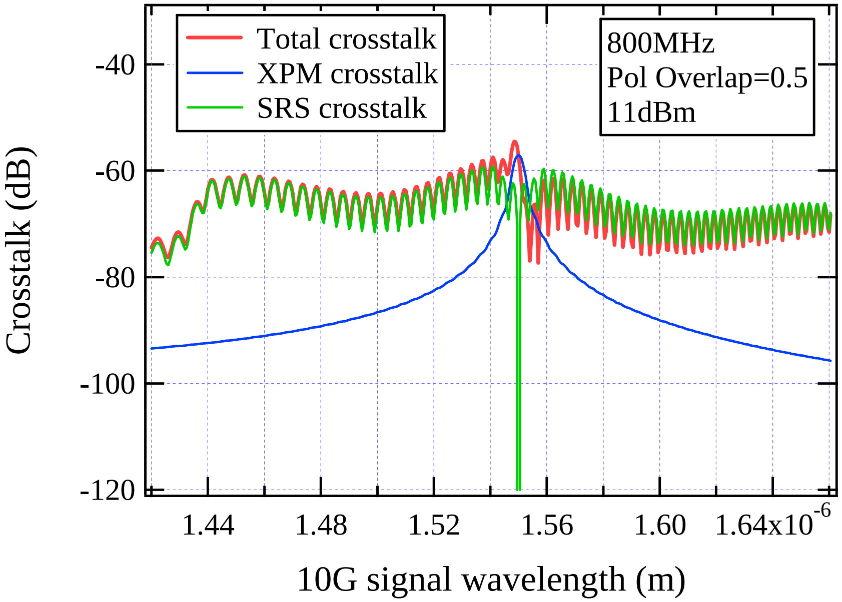
Crosstalk from 10G digital signal to analog CATV signal

Assumptions: CATV wavelength=1550nm, Polarization overlap = 0.5, Fiber length = 20km, 10G launch power = 11dBm

Crosstalk at 55MHz



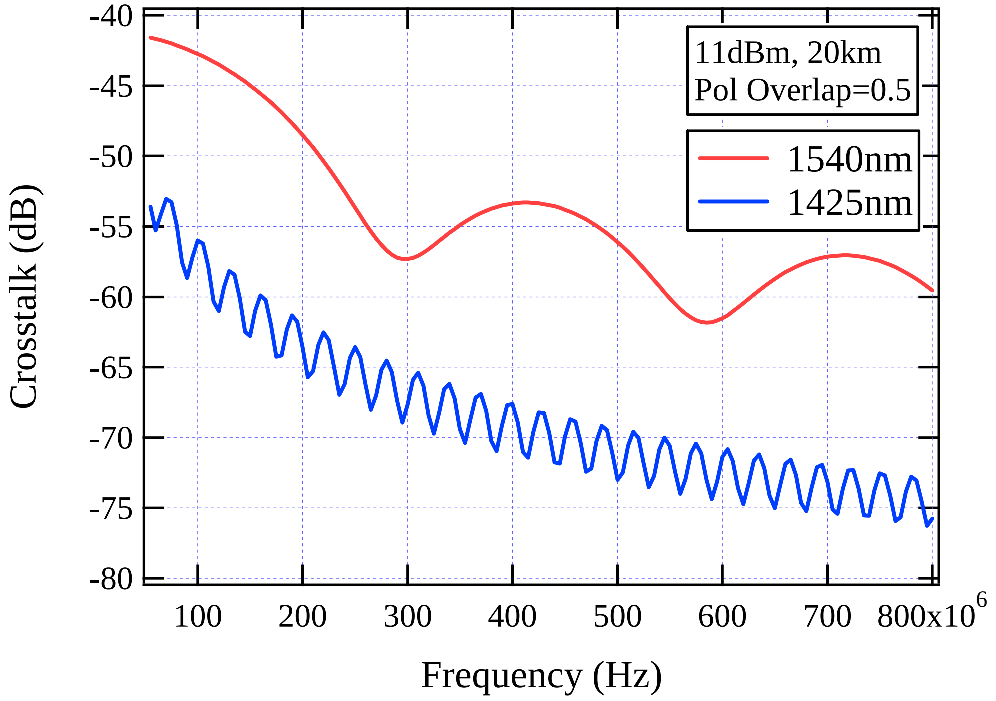
Crosstalk at 800MHz



- At low frequency (55MHz), SRS crosstalk dominates.
- At high frequency (800MHz), both SRS and XPM contribute to crosstalk.
- There is more crosstalk for the low frequency case.

Frequency dependence of crosstalk

Assumptions: CATV wavelength=1550nm, Polarization overlap = 0.5, Fiber length = 20km, 10G launch power = 11dBm



General trend: crosstalk decreases with frequency

Impact of CATV signal on 10G signal

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \qquad BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}})$$

$$\sigma_i^2 = I_{th}^2 B_e + 2eI_i B_e + I_i^2 N_{xt}$$

$$N_{xt} = \sum (\frac{m_{CATV}^2}{2} \cdot CrossTalk)$$

I_1, I_0 : "1" and "0" level signal current

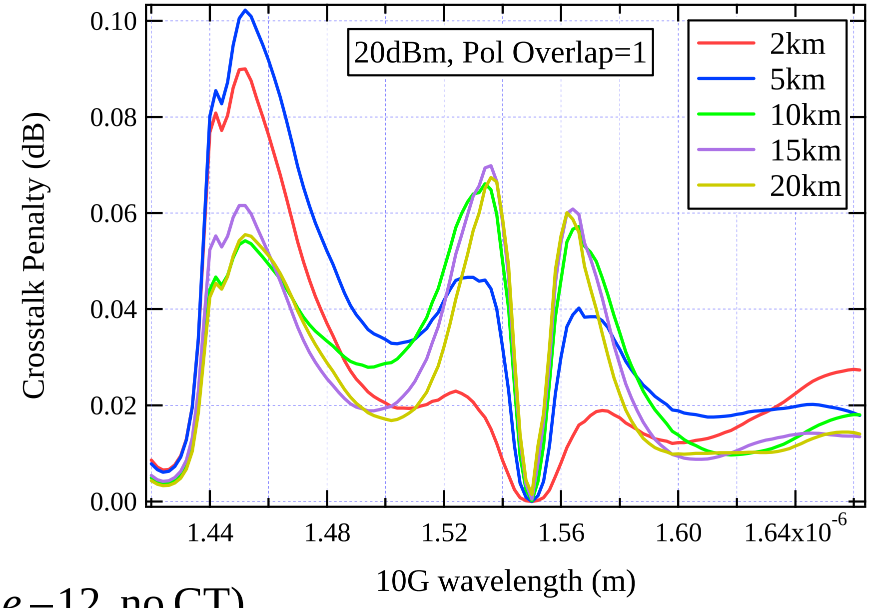
σ_1, σ_0 : "1" and "0" level noise

I_{th} : Thermal noise

B_e : Receiver electrical bandwidth

Penalty = $P_{rx}(BER = 1e-12$, with CT) - $P_{rx}(BER = 1e-12$, no CT)

Calculated sensitivity penalty due to crosstalk (at BER=1e-12)



Assumptions:

1) 10G receiver baseline sensitivity = -18dBm at ER=8.2dB
2) CATV wavelength = 1550nm, launch power = 20dBm, 110 channels from 55MHz to 800MHz
3) Polarization overlap =1 (parallel alignment, worst case scenario)

Conclusion: 10G data signal is essentially unaffected by crosstalk from CATV signal

System implication of crosstalk

$$\text{Carrier to Noise Ratio} = \frac{\frac{1}{2} m_{CATV}{}^2 I^2}{B_e[I_{th}{}^2 + 2eI + (RIN + RIN_{xt})I^2]}$$

m_{CATV} = CATV signal modulation index = 0.035

$\mathrm{B_e}$ = CATV channel bandwidth = 4.2MHz

RIN = source relative intensity noise

$\mathrm{RIN_{xt}}$ = relative intensity noise induced by crosstalk

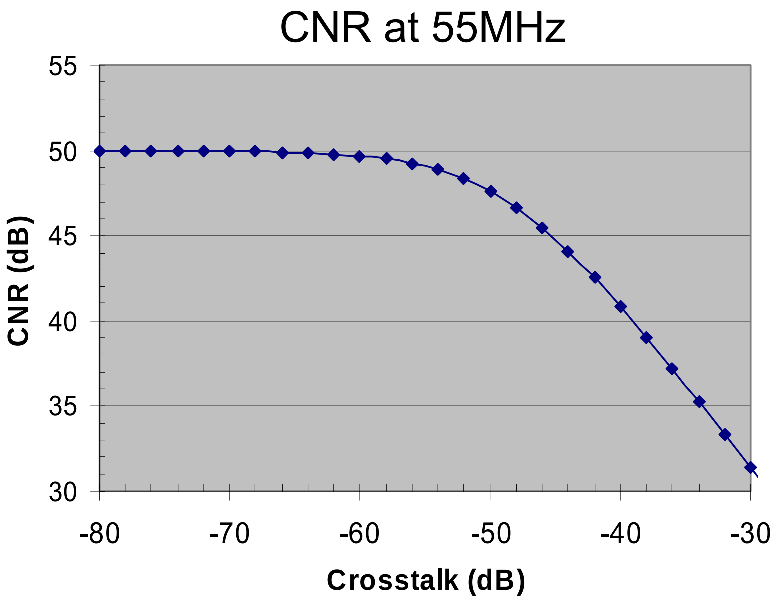
$\mathrm{I_{th}}$ = receiver thermal noise = $8\,pA/\sqrt{Hz}$

I = DC signal current

$$RIN_{xt} = \frac{2}{R_b} \cdot \left(\frac{ER-1}{ER+1}\right)^2 \cdot \left(\frac{\sin(\pi f/R_b)}{(\pi f/R_b)}\right)^2 \cdot CrossTalk$$

R_b = Bit rate of digital signal = 10.3Gbps

ER = extinction ratio of digital signal = 8.2dB



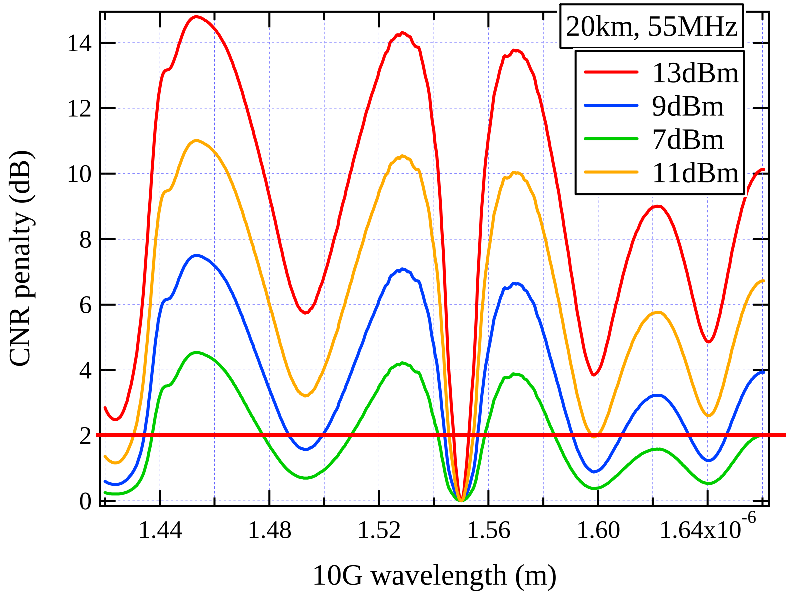
CNR penalty < 2dB requires Crosstalk < -51dB

RIN expression valid for NRZ data with long PRBS-like pattern (e.g. 2^31-1).

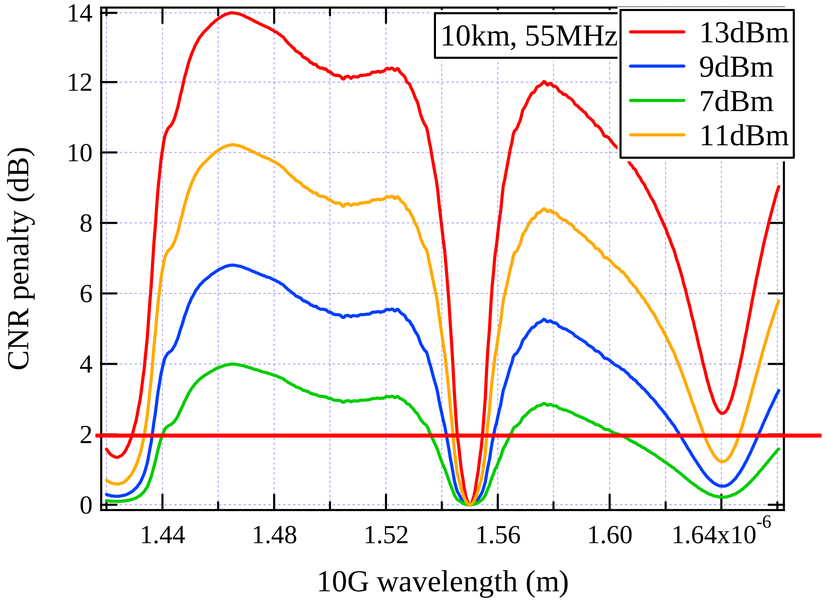
Crosstalk penalty on CATV signal

Assumptions: CATV wavelength=1550nm, Polarization overlap = 0.5, CATV channel=55MHz

20km



10km

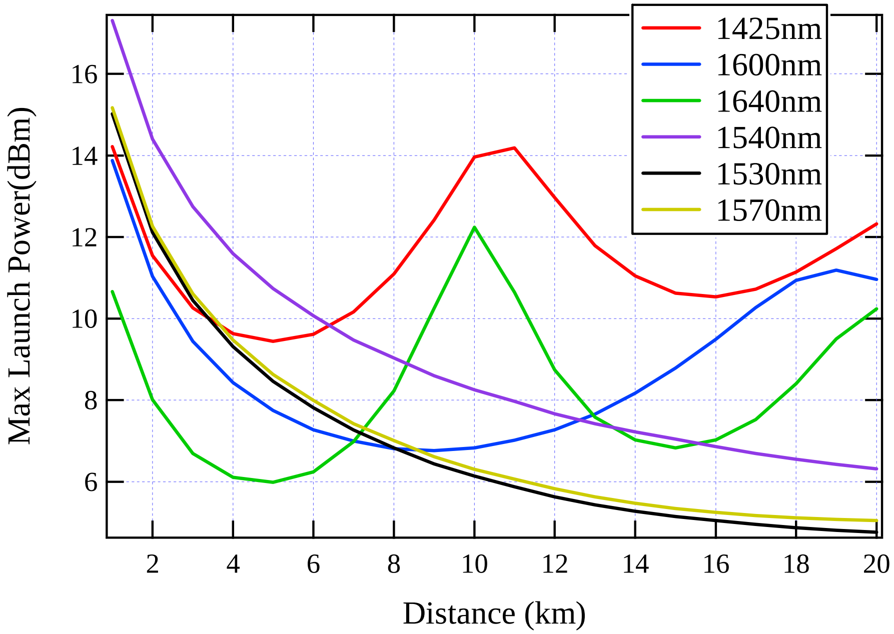


To minimize crosstalk penalty, the optimal wavelength choices for 10G signal are:

1) 1425nm
2) CATV wavelength +/- 10nm
3) 1600nm
4) 1640nm

Power limitations on 10G launch power

Maximum 10G launch power for 2dB CNR penalty at 55MHz



10G wavelength (nm)	Max Power for 0~20km (dBm)
1425	9.44
1600	6.76
1540	6.31
1640	5.98
1570	5.04
1530	4.76

Downstream Tx/Rx choices

Assumptions:

- **PIN sensitivity = -16dBm, PIN+FEC sensitivity = -19dBm**
- **APD sensitivity = -25dBm, APD+FEC sensitivity = -28dBm**
- **Link budget =31dB (29dB channel loss + 2dB dispersion penalty)**

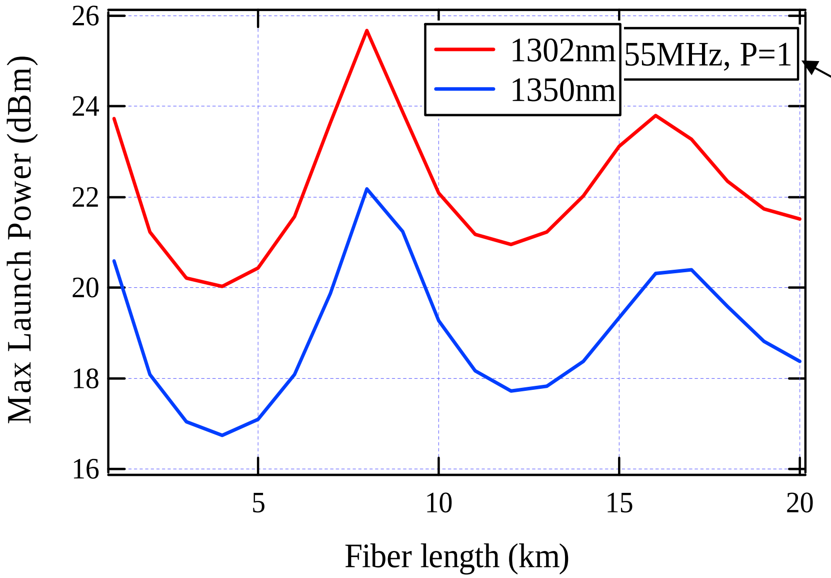
	1425nm	1600nm	1540nm	1640nm	1570nm	1530nm
Tx SRS limit (dBm)	9.44	6.76	6.31	5.98	5.04	4.76
Link budget (dB)	31	31	31	31	31	31
Proposed Tx power (dBm)	3	3	3	3	3	3
Proposed Tx Type	EML	EML	EML	EML	EML	EML
Proposed Rx Type	APD+FEC	APD+FEC	APD+FEC	APD+FEC	APD+FEC	APD+FEC

Only APD can be used at ONU due to Tx launch power limitation

Elimination of SRS crosstalk

- APD based solutions are more expensive for end users than PIN based solutions.
- To be able to use PIN, high launch power is needed and SRS crosstalk needs to be eliminated.
- To reduce SRS: reduce Raman gain and increase group velocity walk-off, both can be achieved by large wavelength separation (>200nm)

Maximum launch power for 2dB CNR penalty



Parallel polarization alignment (absolute worst case)

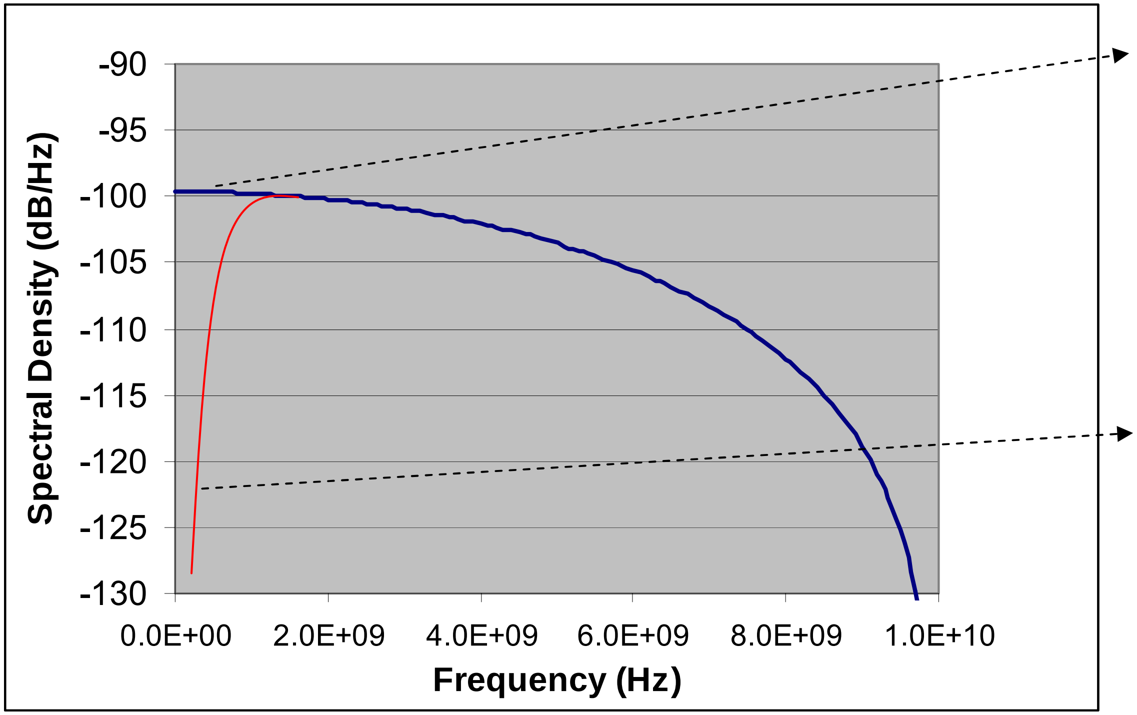
Tx/Rx for 1300nm downstream

Assuming 10G source wavelength =1350nm

	0~20km
Tx SRS limit (dBm)	16.74
Link budget (dB)	31
Proposed Tx power (dBm)	12
Proposed Tx Type	DFB + LiNbO3 MZ
Proposed Rx Type	PIN+FEC

Other potential Tx types include: EML+SOA, DML+SOA, DFB + InP MZ modulator, or high power DML. But these options currently do not provide the required output power.

10G NRZ data spectrum



Long PRBS pattern (e.g., 2^31-1)

8B/10B data ??

Question: Will data encoding impact crosstalk?

Answer: It will likely depend on the encoding scheme.

- For 8B/10B encoding, the lowest frequency content of a 10G NRZ signal could be as high as 1GHz, which is higher than any CATV frequency → No crosstalk
- For 64B/66B encoding, the lowest frequency content of a 10G NRZ signal is ≤80MHz, which is very close to the lowest CATV frequency → Crosstalk remains

10GEPON configurations

Configuration 1

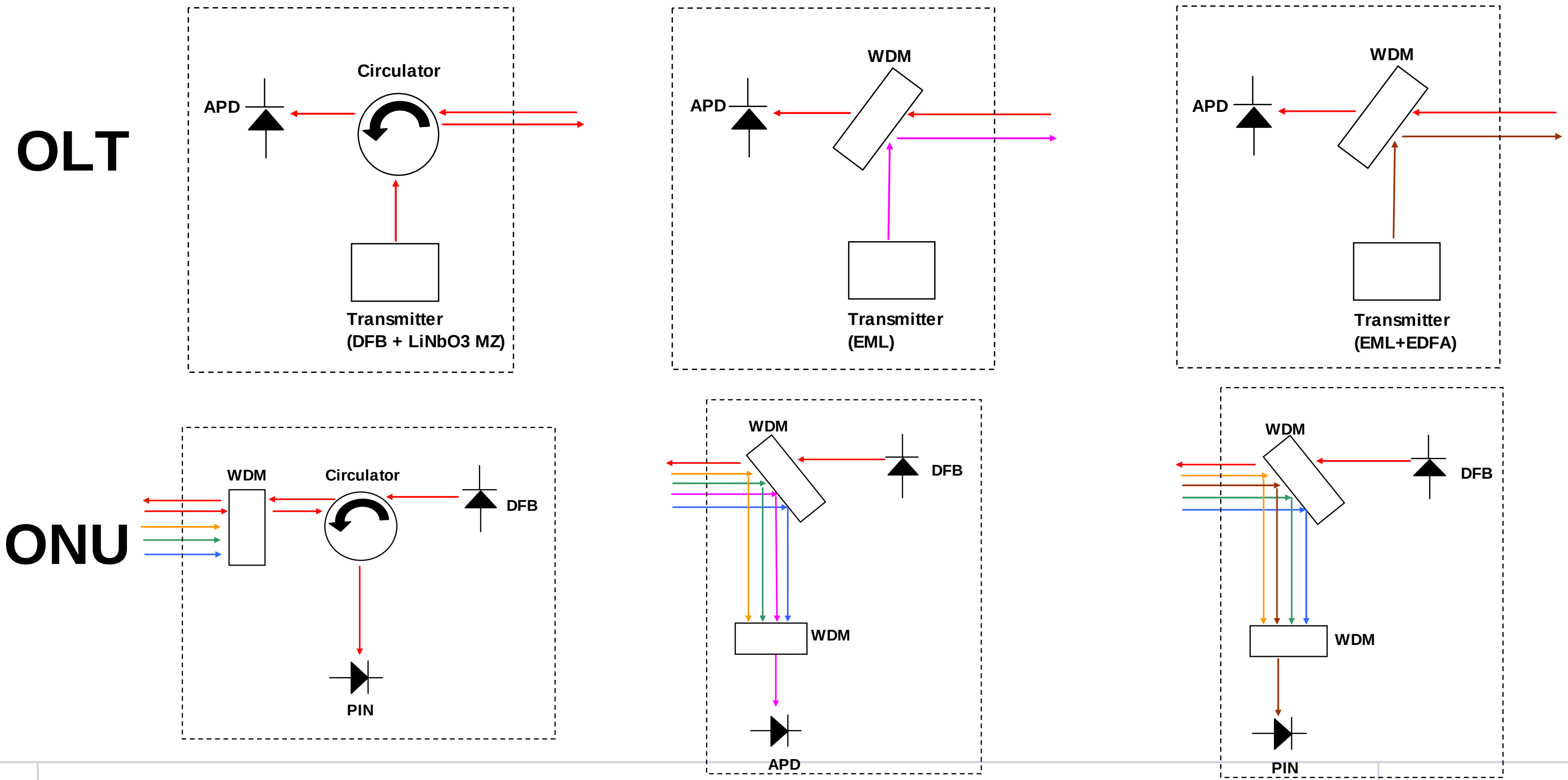
- → 1310nm, 10G up and down
- → 1490nm, 1G down
- → 1550nm, Video
- → 1640nm, OTDR

Configuration 2

- → 1310nm, 10G up
- → 1490nm, 1G down
- → 1550nm, Video
- → 1600nm, 10G down
- → 1640nm, OTDR

Configuration 3

- → 1310nm, 10G up
- → 1490nm, 1G down
- → 1530nm, 10G down
- → 1550nm, Video
- → 1640nm, OTDR



Cost analysis

Configuration 1: 1310nm downstream, DFB (CW) + LiNbO3 MZ at OLT, PIN at ONU
Configuration 2: 1600nm downstream, EML at OLT, APD at ONU
Configuration 3: 1530nm downstream, EML+EDFA at OLT, PIN at ONU

Component	Relative Cost
EML	6.3
APD	5
PIN	1
Circulator	2
High power DFB (1310nm)	12.5
10G LiNbO3 Modulator	11.3
WDM	0.6
EDFA	25
1310nm 10G DFB	2

Cost per subscriber

	Config 1	Config 2	Config 3
1x16	7.55	8.99	6.55
1x32	6.59	8.62	5.40
1x64	6.11	8.44	4.83

- Configuration 3 offers the lowest cost, but it requires 8B/10B encoding to avoid SRS crosstalk.
- Configuration 1 or 2 are free of SRS risk. **Configuration 1 is the preferred solution due to lower cost.**

Conclusion

- **Nonlinear optical crosstalk (mainly SRS) can have significant impact on low frequency amplitude modulated CATV signal quality when co-propagating with 10G digital signal.**

- **10G digital signal quality is relatively immune to crosstalk from CATV signal**

- **For 10G signal with long pattern lengths, all downstream wavelengths from 1420~1660nm require APD at ONU. 1310nm band allows for the use of PIN at ONU.**

- **Certain data encoding scheme (e.g., 8B/10B) for 10G digital signal may reduce (or eliminate) crosstalk.**

- **Given the risk of SRS crosstalk and cost considerations, the preferred downstream solution is to use the 1310nm band for 10G data channel, with CW DFB and LiNbO3 modulator at OLT and PIN at ONU (Configuration 1 below).**

Configuration	Tx wavelength (nm)	Tx type	Tx power (dBm)	Rx type	Note	Cost per user (1:32)
1	1310	DFB + LiNbO3 MZ	12	PIN+FEC	No SRS risk	1.2
2	1600	EML	3	APD+FEC	No SRS risk	1.6
3	1530	EML+EDFA	12	PIN+FEC	SRS problem, needs 8B/10B encoding	1

References

[1] M.R. Phillips and D. M. Ott, “Crosstalk Due to Optical Fiber Nonlinearities in WDM CATV Lightwave Systems”, Journal of Lightwave Technology, Vol. 17, No. 10, pp. 1782~1792 (October 1999).

[2] H. Kim, K. H. Han and Y. C. Chung, “Performance Limitation of Hybrid WDM Systems Due to Stimulated Raman Scattering”, IEEE Photonics Technology Letters, Vol. 13, No. 10, pp. 1118~1120 (October 2001)

[3] C.R.S. Fludger, V. Handerek and R. J. Mears, “Pump to signal RIN transfer in Raman fibre amplifiers”, Electronics Letters, Vol. 37, No. 1, (January 2001)

[4] M. Aviles, K. Litvin, J. Wang, B. Colella, F.J. Effenberger and F. Tian, “Raman crosstalk in video overlay passive optical networks”, OFC 2004, paper FE7.