Limitations imposed by cross - phase modulation in dense wavelength division multiplexing systems

Adolfo V. T. Cartaxo

Instituto de Telecomunicações, Pole of Lisboa,

Department of Electrical and Computers Engineering, Instituto Superior Técnico,

Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Tel.: +351-1-8418476; Fax: +351-1-8417164; email: adolfo.cartaxo@lx.it.pt

Motivation

Optical networks with capacity of Tbit/s per fiber

Multi-channel (WDM) with very large number of channels

Limited EDFA's bandwidth

Narrow channel separation

Dense WDM

(channel separation of 50, 100, 200 GHz)

Inter-channel nonlinear effects (FWM, SRS, XPM) affect system performance

XPM appears as one of the most detrimental effects over SMF and NZDSF

Cross - phase modulation (XPM)

<u>Power</u>

of one optical wave propagating in an optical fiber changes

the refractive index of the fiber which induces

<u>phase shifts</u>

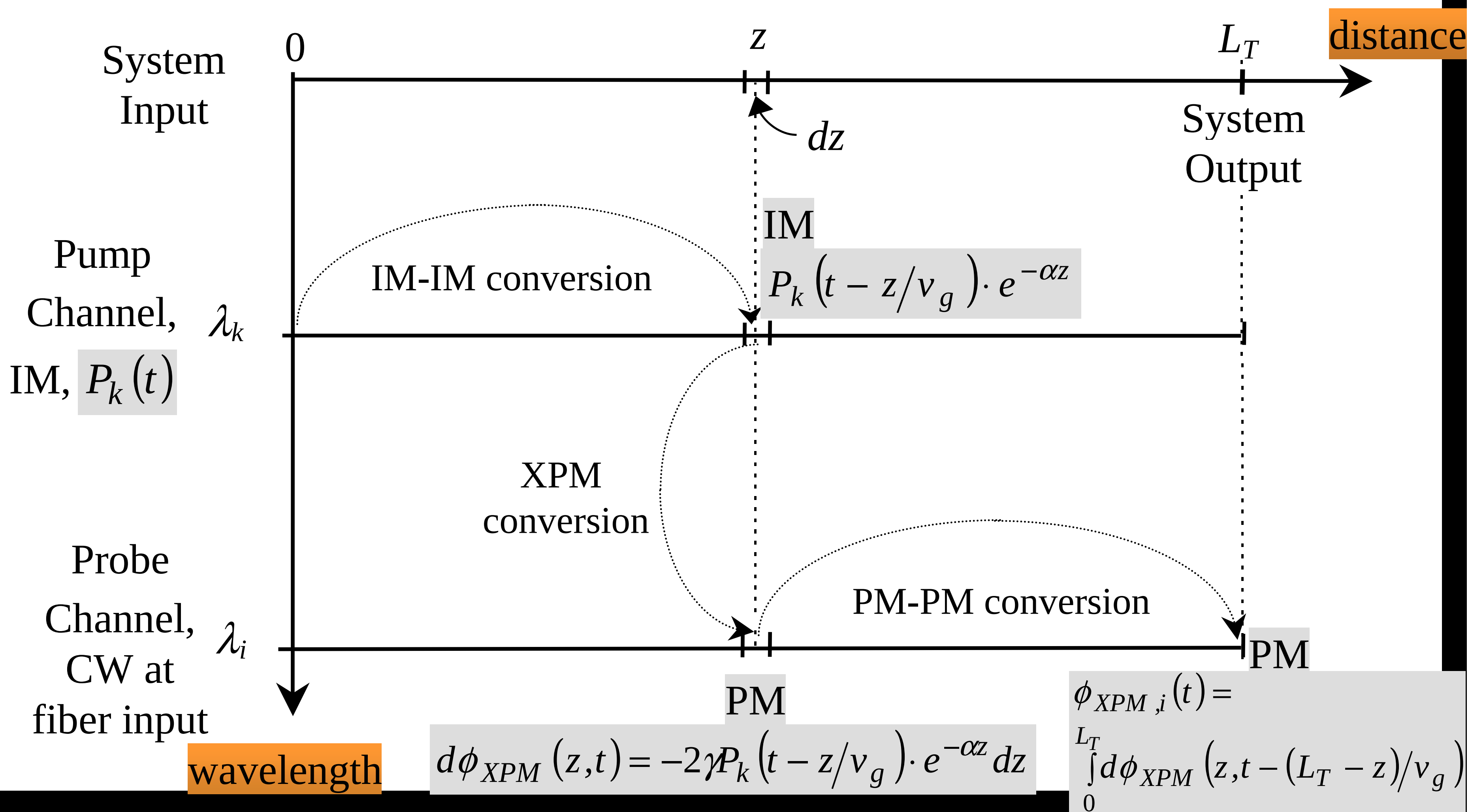
in *other* co-propagating waves of different wavelengths

Outline

XPM in optical fiber DWDM systems:

- How does it work?
- How does it limit the system performance?
- How can it be suppressed / reduced?

XPM-induced phase shift
- dispersionless fiber -



XPM-induced phase shift

- dispersionless fiber -

- One interfering channel

$$\phi_{XPM,i}(t) = -2\gamma P_k\left(t - L_T/v_{g,i}\right)\cdot L_{eff} \qquad L_{eff} = \left[1 - e^{-\alpha L_T}\right]/\alpha$$

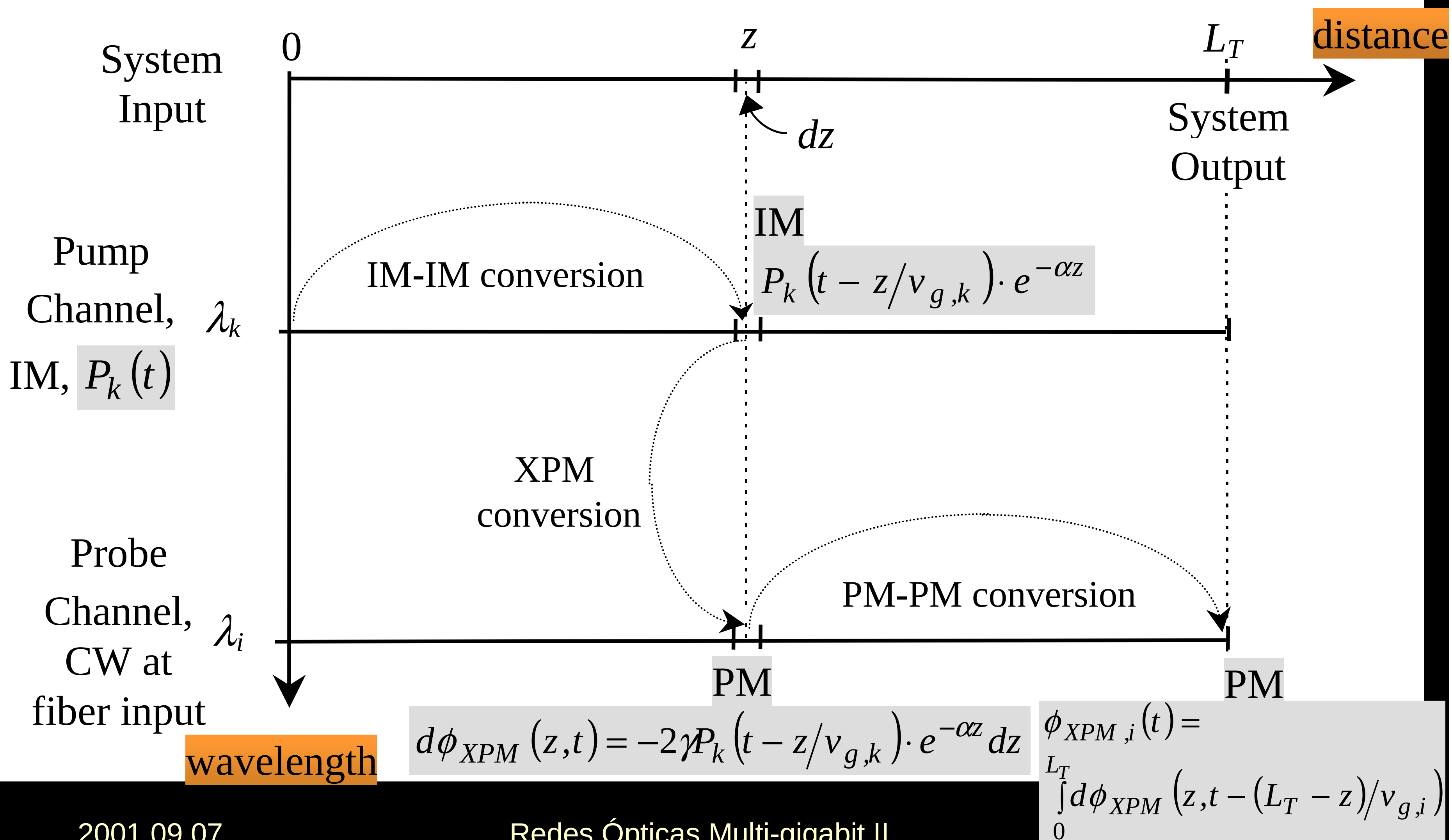
XPM-induced phase shift with same shape as power of interfering channel

- *M* interfering channels

$$\phi_{XPM,i}(t) = -2\gamma L_{eff}\sum_{k=1}^{M} P_k\left(t - L_T/v_{g,i}\right)$$

Synchronized interfering channels ⇒ XPM-induced phase shifts add synchronously

XPM-induced phase shift
- dispersive fiber -



XPM-induced phase shift

- dispersive fiber -

- One interfering channel

$$\phi_{XPM,i}(t) = -2\gamma \int_0^{L_T} P_k\left(t - L_T/v_{g,i} - d_{k,i}z\right)\cdot e^{-\alpha z}dz \qquad d_{k,i} = v_{g,k}^{-1} - v_{g,i}^{-1}$$

Walk-off parameter

(normalized delay propagation difference)

- *M* interfering channels

$$\phi_{XPM,i}(t) = -2\gamma \sum_{k=1}^{M} \int_0^{L_T} P_k\left(t - L_T/v_{g,i} - d_{k,i}z\right)\cdot e^{-\alpha z}dz$$

$$d_{k,i} = \int_{\lambda_i}^{\lambda_k} D(\lambda)d\lambda \approx D(\lambda_i)\cdot(\lambda_k - \lambda_i)$$

XPM-induced phase shift spread over time (shape different from the power of interfering channel)

XPM-induced phase shifts do not add synchronously

Reduction of XPM efficiency

XPM in IM-DD systems

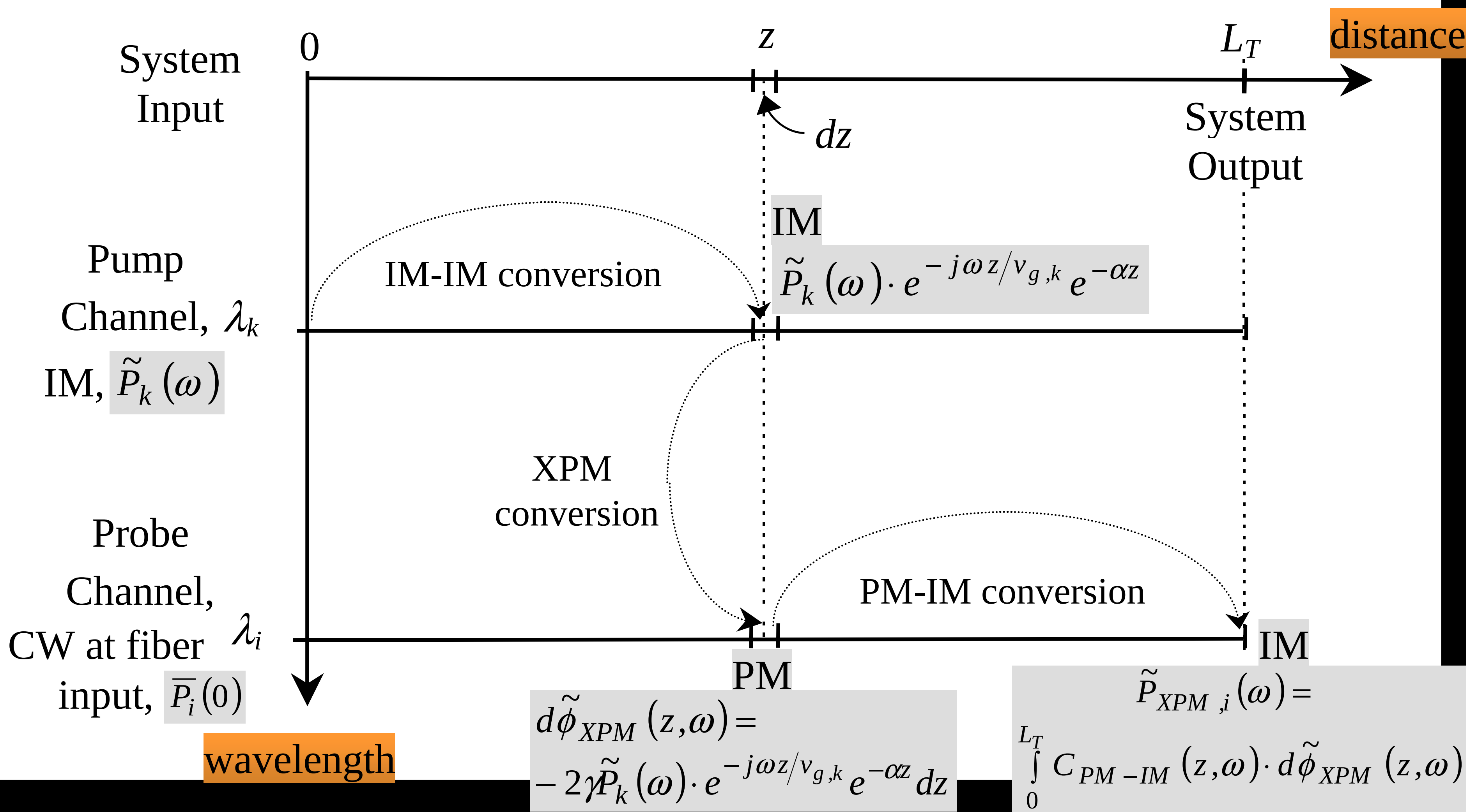
- Current receivers based on direct detection (DD) are insensitive to phase variations

but …

- Fiber dispersion converts pattern-dependent XPM-induced phase shifts to power fluctuations
  - XPM manifests in waveform distortion leading to eye diagram deformation

Phase shifts (frequency chirping) + GVD $\Rightarrow$ intensity fluctuations

Physical explanation of XPM effect in IM-DD systems



XPM-induced IM caused by group velocity dispersion

- One interfering channel

$$\tilde{P}_{XPM,i}(\omega) = \int_0^{L_T} \underbrace{\overline{P}_i(0)e^{-\alpha z}}_{\substack{\text{Average probe power}\\ \text{at co-ordinate } z}} \cdot \underbrace{e^{-j\omega(L_T - z)/v_{g,i}}}_{\substack{\text{Propagation delay}\\ \text{in probe channel}}} \cdot \underbrace{e^{-\alpha(L_T - z)}}_{\substack{\text{Fiber loss due}\\ \text{to propagation}\\ \text{in probe channel}}} \sin\left(\omega^2 \frac{D(\lambda_i)\lambda_i^2}{4\pi c}\right) \cdot d\tilde{\phi}_{XPM}(z,\omega)$$

Small signal PM–IM conversion

$$\tilde{P}_{XPM,i}(\omega) = -2\gamma \overline{P}_i(0)\tilde{P}_k(\omega)e^{-\alpha L_T} \cdot e^{-j\omega L_T/v_{g,i}} \int_0^{L_T} e^{-j\omega z d_{k,i}} e^{-\alpha z} \cdot \sin\left(\omega^2 \frac{D(\lambda_i)\lambda_i^2}{4\pi c}\right) dz$$

$$\tilde{P}_{XPM,i}(\omega) = H_{i,k}(\omega) \cdot \tilde{P}_k(\omega)$$

$$P_{XPM,i}(t) = F^{-1}\left[\tilde{P}_{XPM,i}(\omega)\right]$$

- *M* interfering channels

$$\tilde{P}_{XPM,i}(\omega) = \sum_{k=1}^{M} H_{i,k}(\omega) \cdot \tilde{P}_k(\omega)$$

Features of XPM-induced IM

- Depends on bit in probe channel
  - Vanishes for null power in probe channel
- Depends on average power, bit and pulse shape in interfering channel
  - Vanishes for constant power in interfering channel

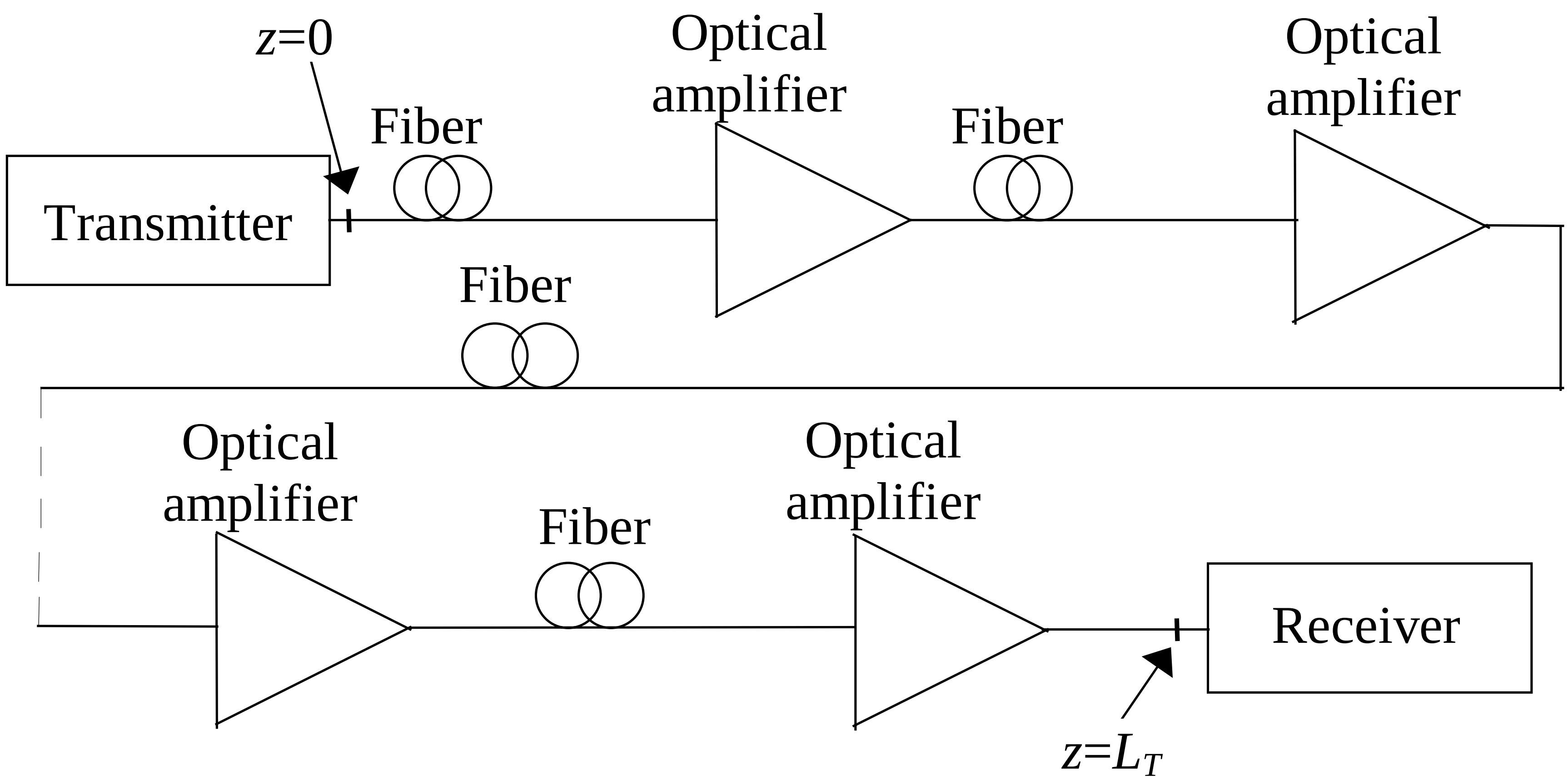
Signal dependence leads to stochastic XPM-induced intensity distortions

When an edge in the interfering channel overlaps with a signal pulse, XPM-induced chirp is introduced

➢ The main contribution to XPM effect comes from adjacent channels

➢ XPM effect is maximized when pulses in neighboring channels are time-aligned in the front part of the fiber

Multiple span fiber link



- Several configurations can be investigated through appropriate choice of optical amplifiers' gain and fiber segment properties.

Normalized XPM-induced IM index

- Normalized magnitude of IM response induced by XPM in the probe channel *i*

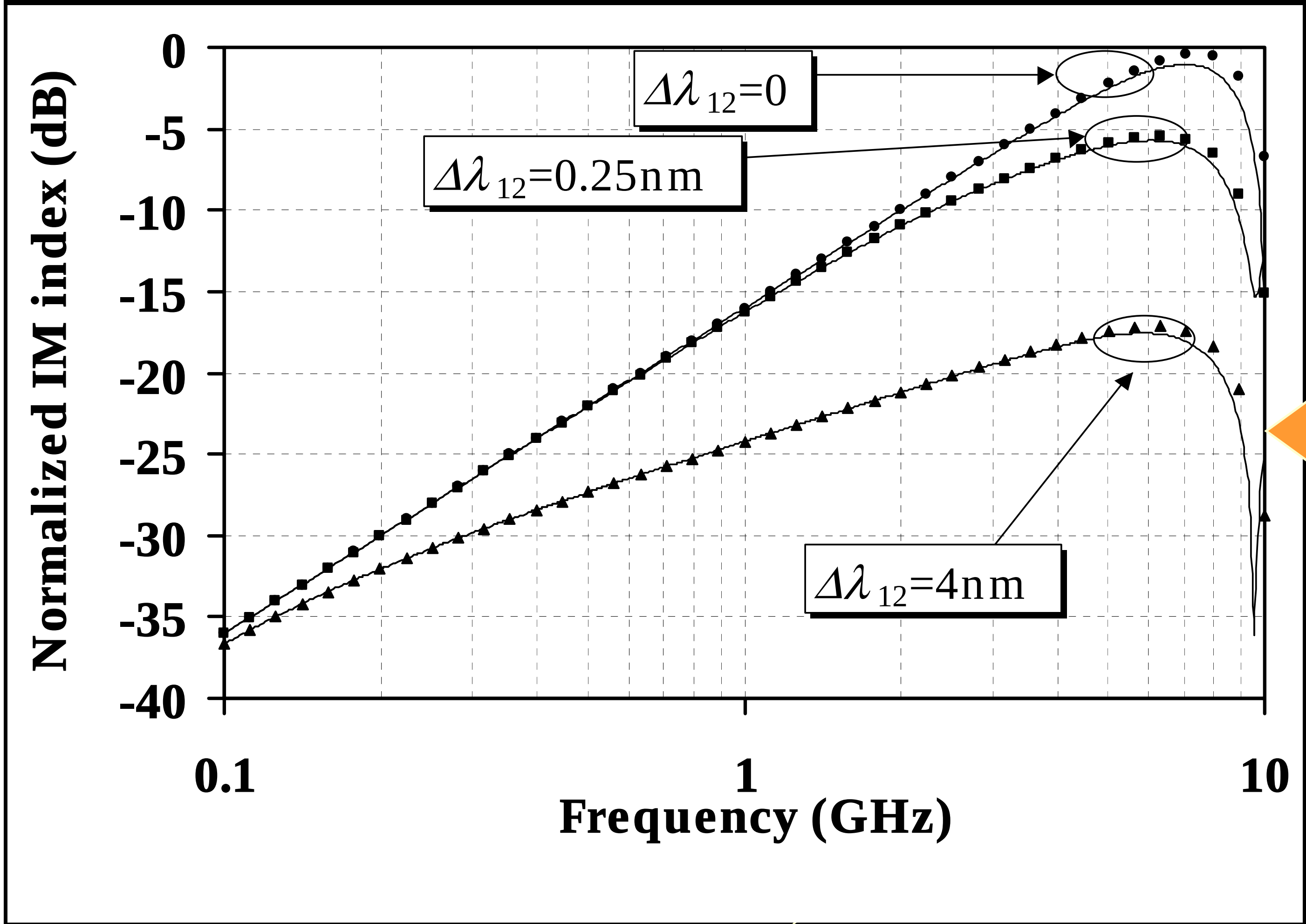
$$m_{IM,i}^{XPM} = \left| \tilde{P}_{XPM,i}(\omega) \Big/ \left(\tilde{P}_k(\omega) \cdot g_i^{net}(L_T) \right) \right|$$

➡ *net* power gain for the *i*-th channel from the transmitter up to the receiver

$$g_i^{net}(L_T) = \prod_{n=1}^{N} e^{-\alpha^{(n)} L^{(n)}} g_i^{(n)}$$

Normalized XPM-induced IM index

Single span of 80 km of SMF, 2 channels



$\Delta\lambda_{12}=\lambda_1-\lambda_2$

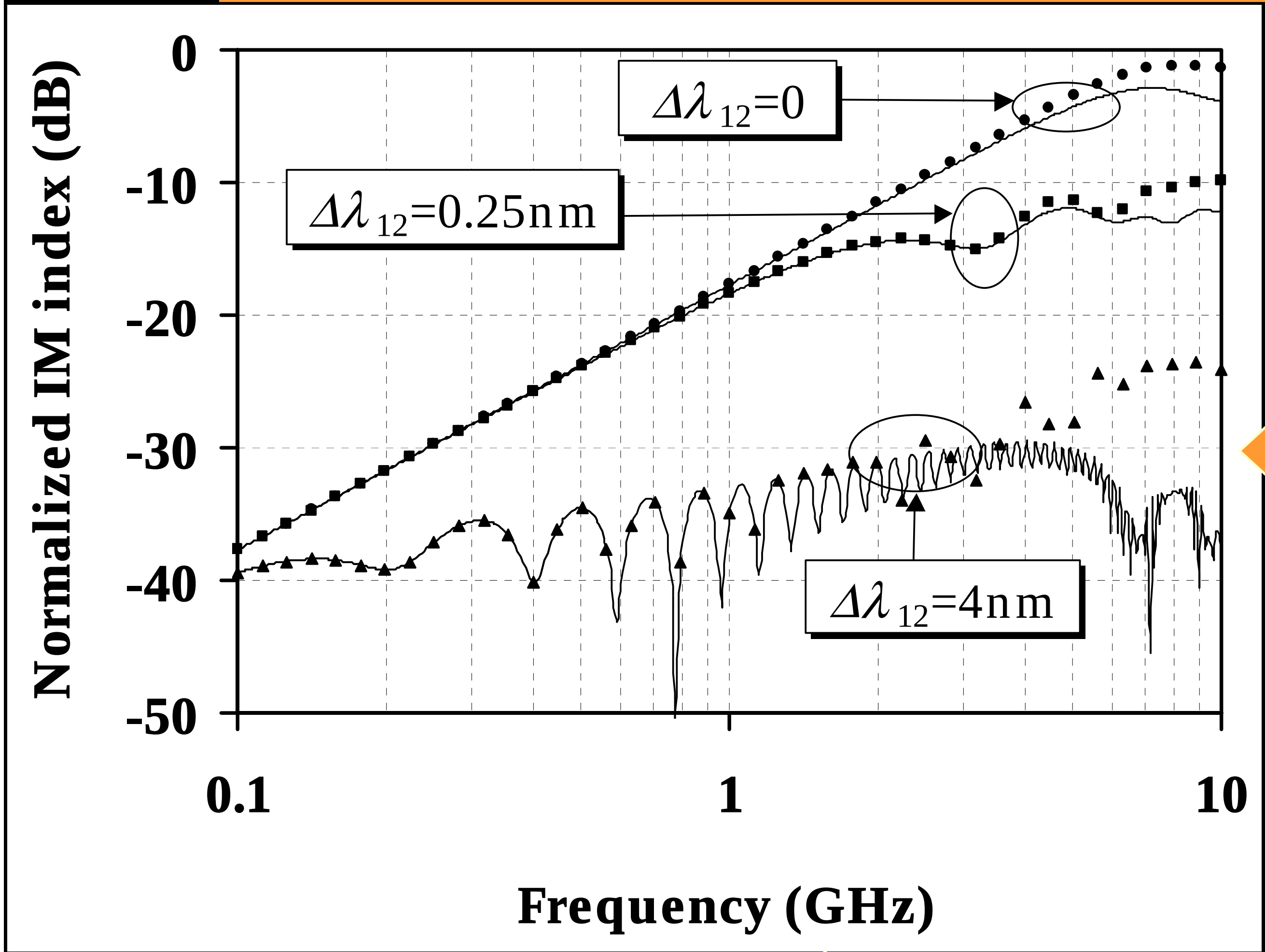
Average power / channel at fiber input = 10 dBm

Simple high-pass characteristic

PM-IM conversion caused by GVD

Normalized XPM-induced IM index

Four spans of 80 km of SMF dispersion compensated (after each SMF span) by DCF, 2 channels

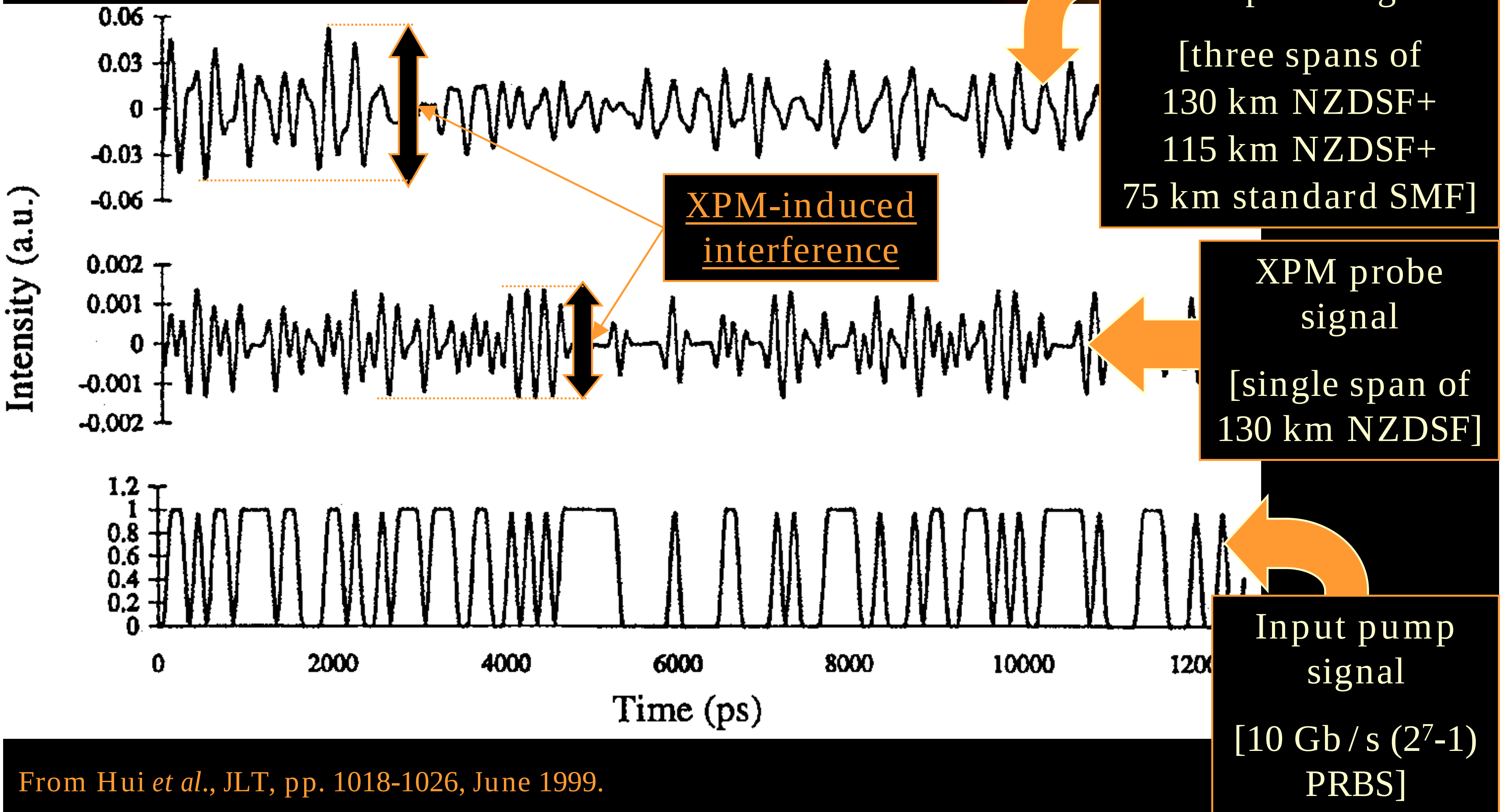


Average power / channel at fiber input = 7 dBm

Characteristic with various dips (notches) whose location depends on channel separation and span length

XPM time domain waveforms

2 channels, 0.8 nm of channel separation



From Hui *et al.*, JLT, pp. 1018-1026, June 1999.

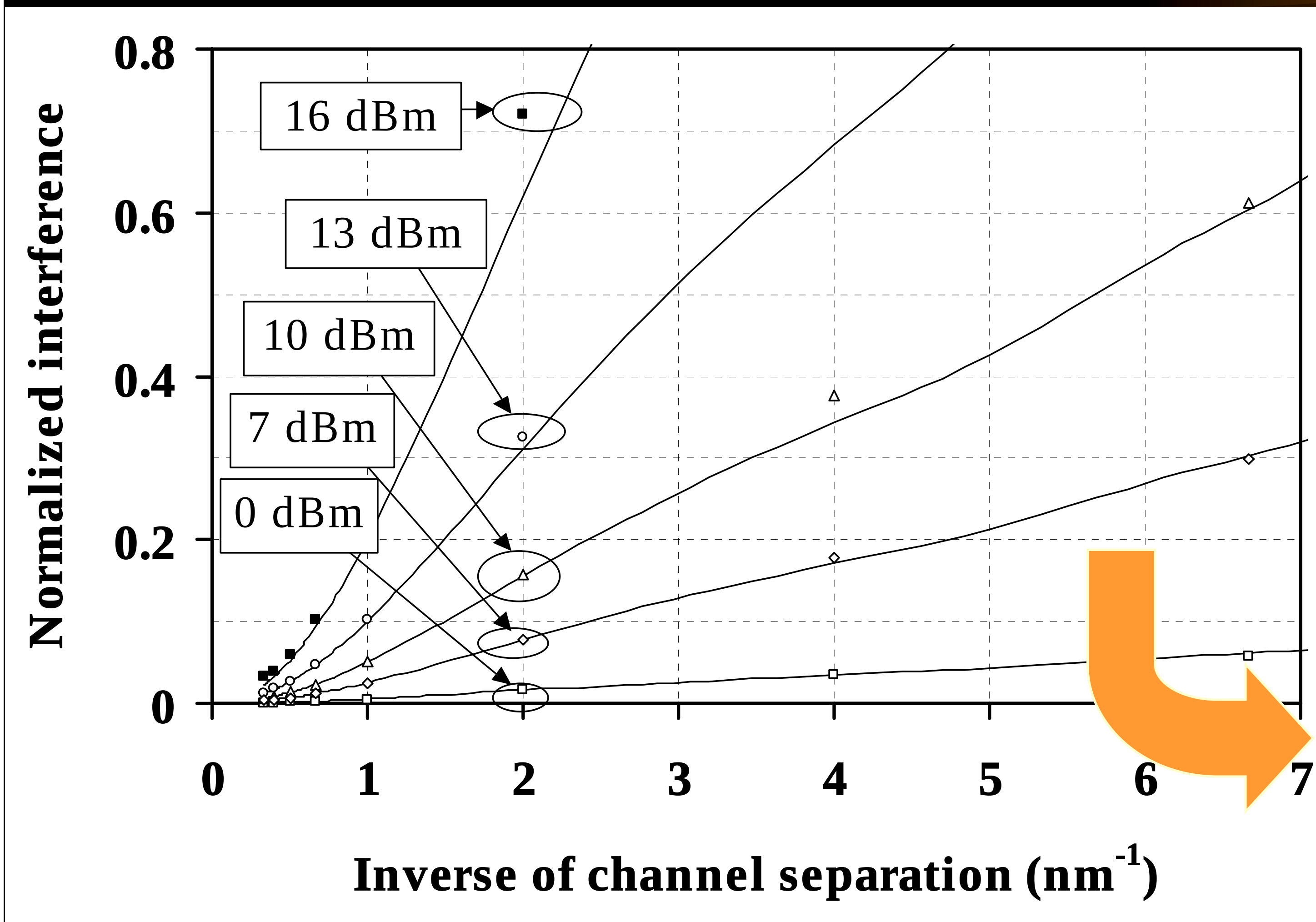
Measure for the extent of the XPM-induced signal distortion

Normalized interference induced by XPM

ratio of the
difference between maximum and minimum value of the
intensity of the probe channel and
the average value of the intensity in the probe channel

Normalized interference induced by XPM

Single span of 80 km of SMF, 3 channels

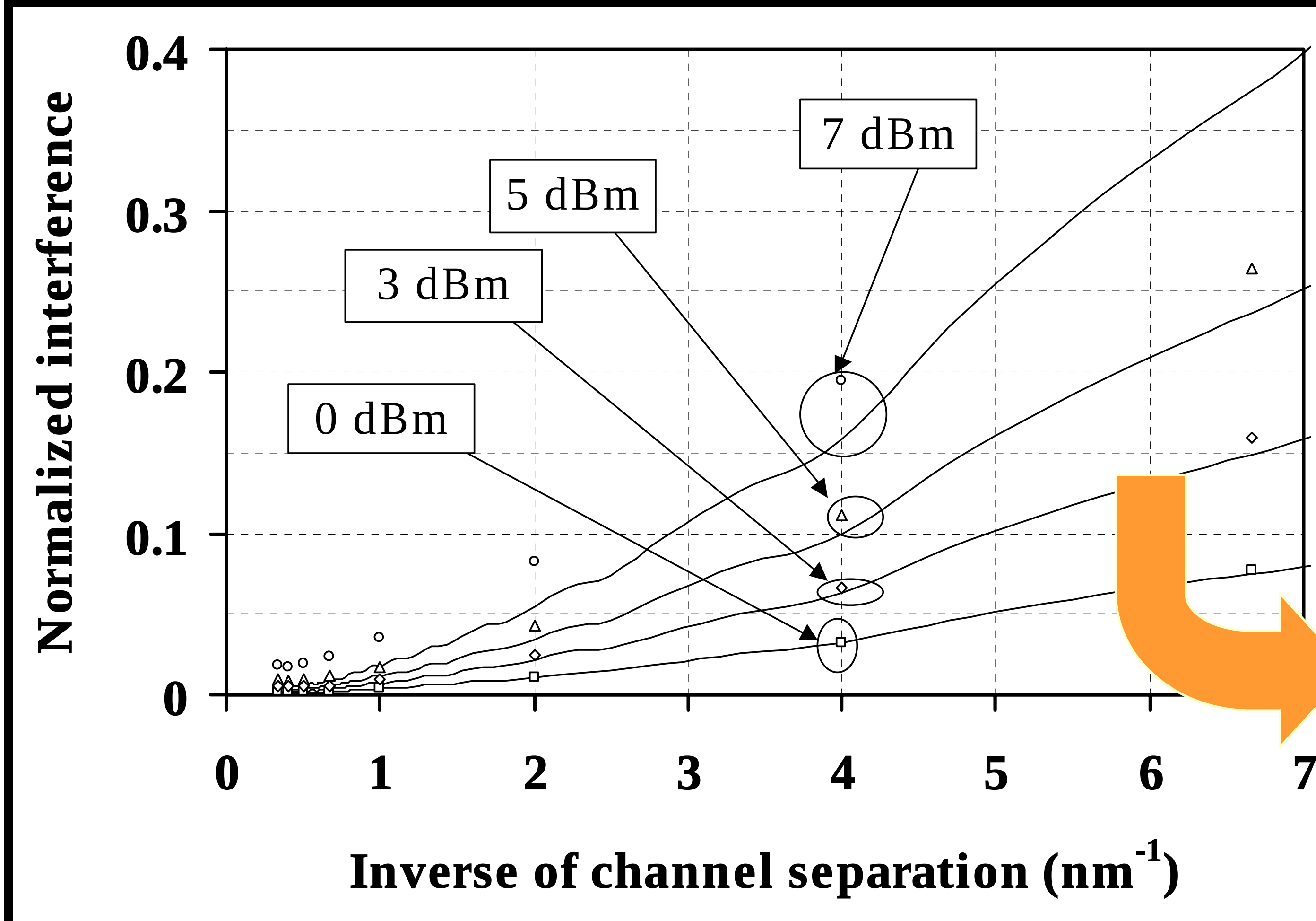


Pump channel externally (chirpless) modulated with a 2^7 bit sequence at 5 Gb/s

XPM interference increases linearly with interfering signal power and inversely with channel separation

Normalized interference induced by XPM

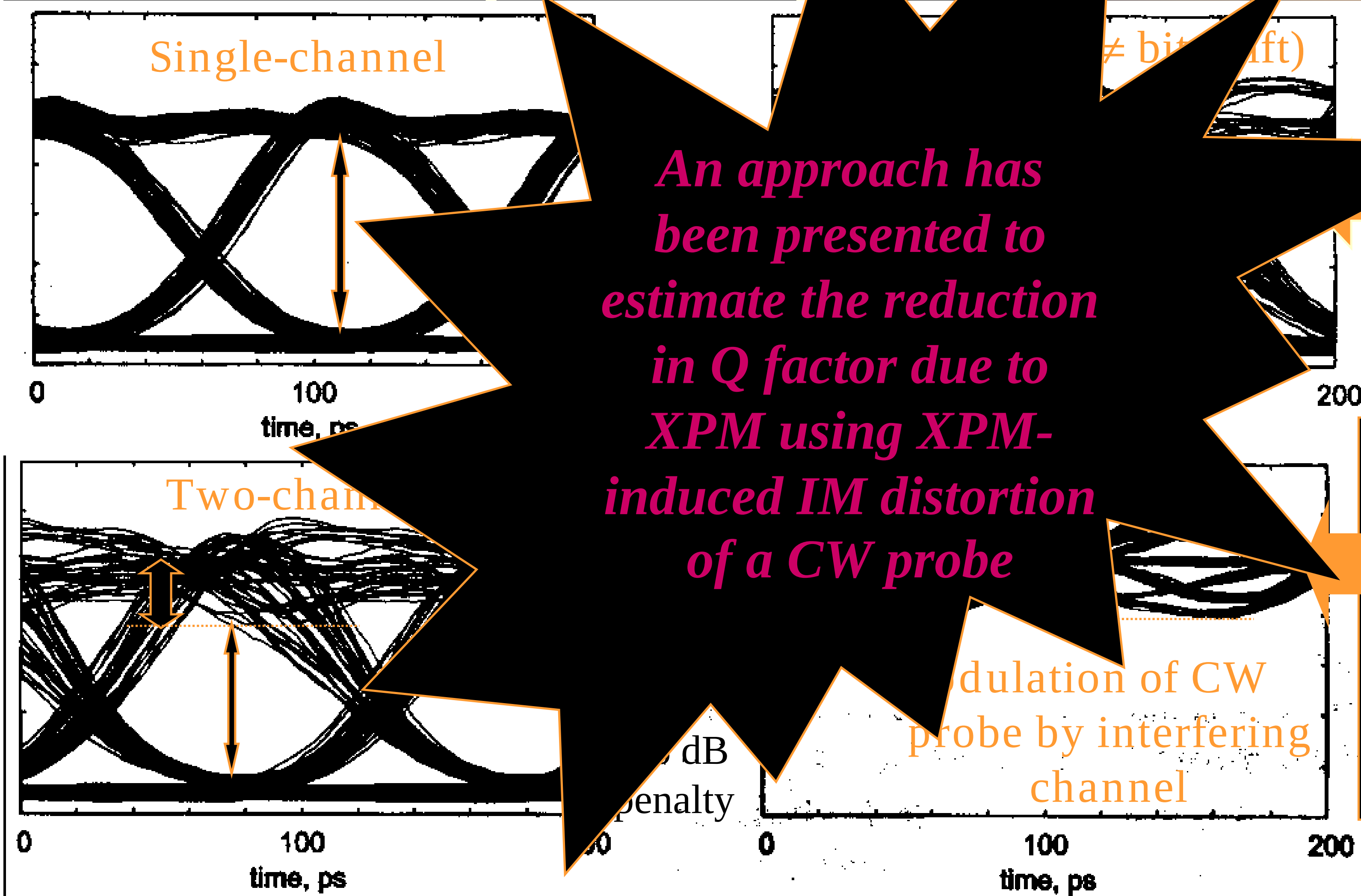
Four spans of 80 km of SMF dispersion compensated (after each SMF span) by DCF, 2 channels



Pump channel externally (chirpless) modulated with a 2^7 bit sequence at 5 Gb/s

XPM interference increases linearly with interfering signal power and inversely with channel separation

Estimating the XPM-induced system penalty from CW probe results



An approach has been presented to estimate the reduction in Q factor due to XPM using XPM-induced IM distortion of a CW probe

80 km of NZDSF, 10 Gb/s, 10 dBm, $\Delta\lambda$=0.8nm

Change of bit alignment: look at perturbed CW trace at different times

From Eiselt *et al.*, IEEE PTL, pp. 748-750, June 1999.

Timing jitter induced by XPM

Frequency chirping (due to XPM-induce phase t) + propagation through dispersive fiber (slightly different v it > puls timing jitter

Ass

Worst-case timing jitter:
jitter caused by the first interfering edge at the fiber input

collision:
n interfering pulse has part way through the signal

The nonlinear interaction respo occurs only in the first v

$L_{eff} \approx L_{wo} = \varepsilon T / (D$

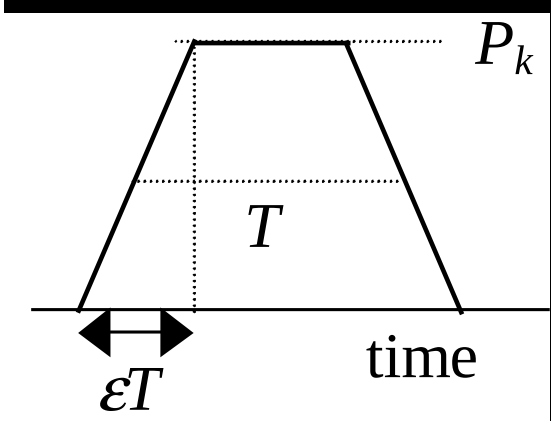
It can be the main impairment for high bit rates approaching 40 Gbit/s

Frequency chirping:

$\approx -2\gamma P_k / (2\pi \varepsilon T) \cdot L_{wo}$

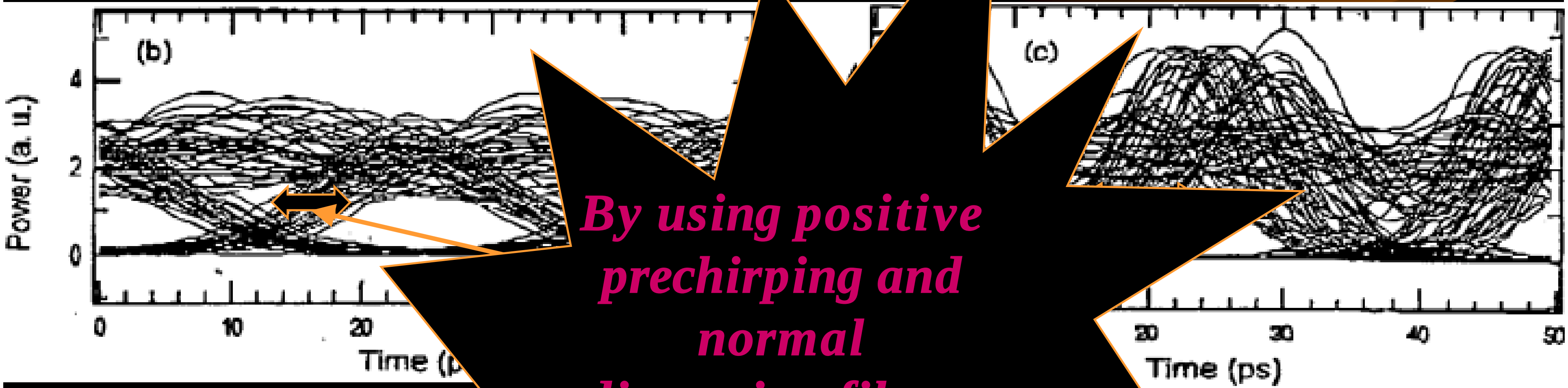
Timing jitter:

$|\delta t|$ $L \cdot$ $_{XPM}$ $= DL \cdot \delta f_{XPM} \cdot \lambda^2 / c = 2\gamma P_k L / (2\pi \Delta f)$



Jitter value:
- independent of dispersion parameter
- independent of bit rate

Timing jitter induced by XPM



α_c = 0.7, *D*=-2ps/nm/km

2ps/nm/km, D_{tot}=70ps/nm

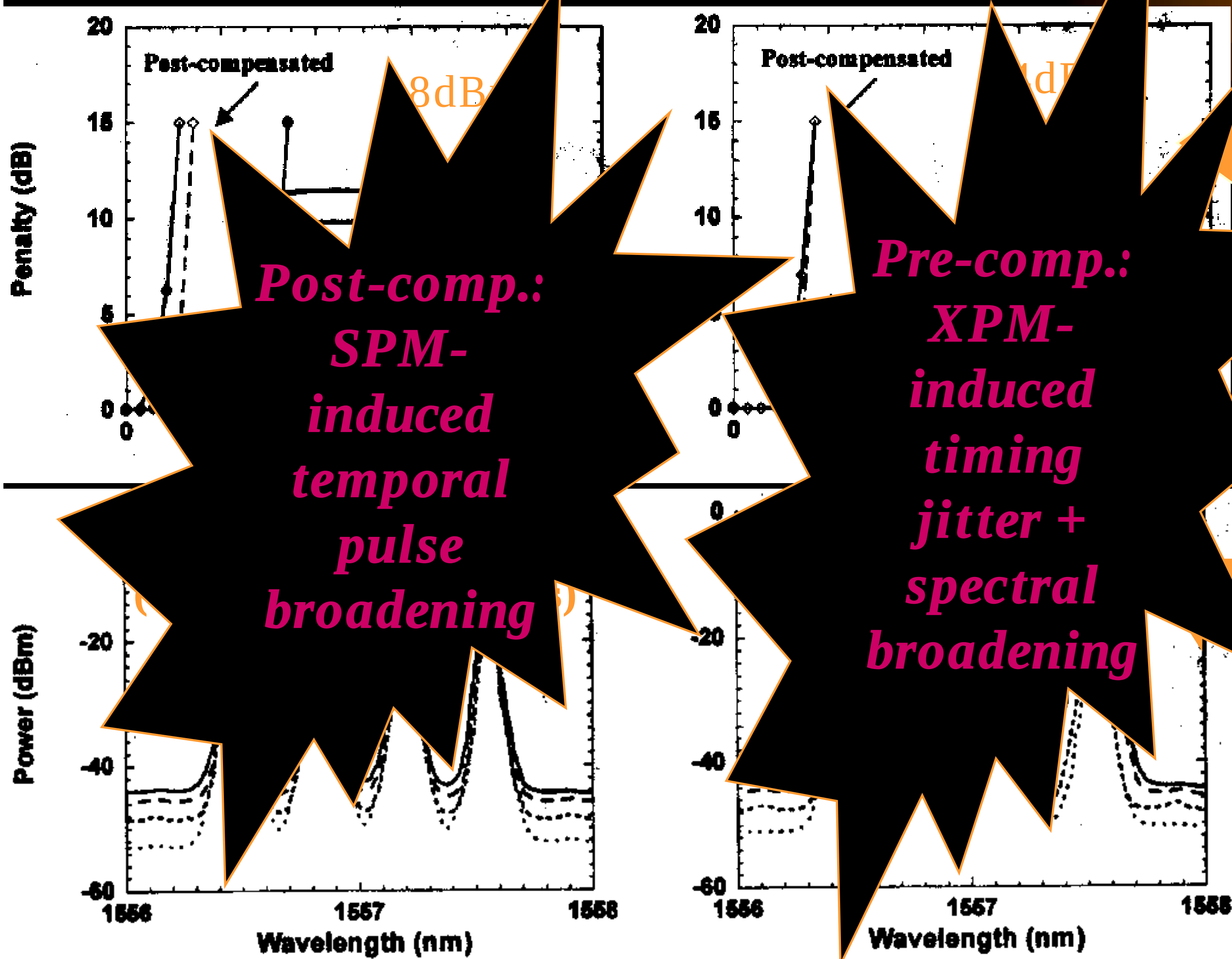
By using positive prechirping and normal dispersion fibers, the system performance is improved

4 NRZ channels at 40 Gbit/
200 GHz of channel sepa
km exactly post-DC, to
the receiving termi

2^7–1 PRBS is shifted by a quarter
eriod from the sequence of the
neighboring channel

From Sano *et al.*, JLT, pp. 1519-1527, Nov. 2000.

Spectral broadening induced by XPM



Post-comp.: SPM-induced temporal pulse broadening

Pre-comp.: XPM-induced timing jitter + spectral broadening

Four channel, 10 Gb/s, spans of 40 km of SMF compensated exactly by DCF

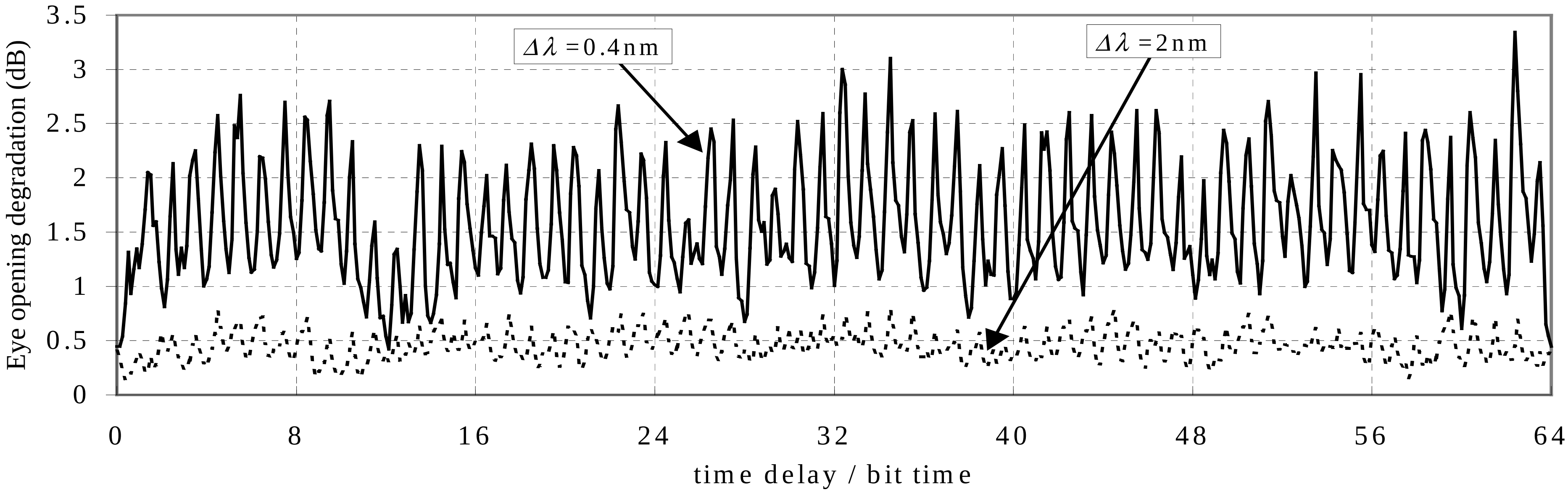
Spectral broadening leads to coherent crosstalk between spectral components of neighboring channels in DWDM system

This effect is enhanced in NZDSF

From Mikhailov *et al.*, IEEE PTL, pp. 994-996, Aug. 1999.

XPM dependence on relative delay between channels

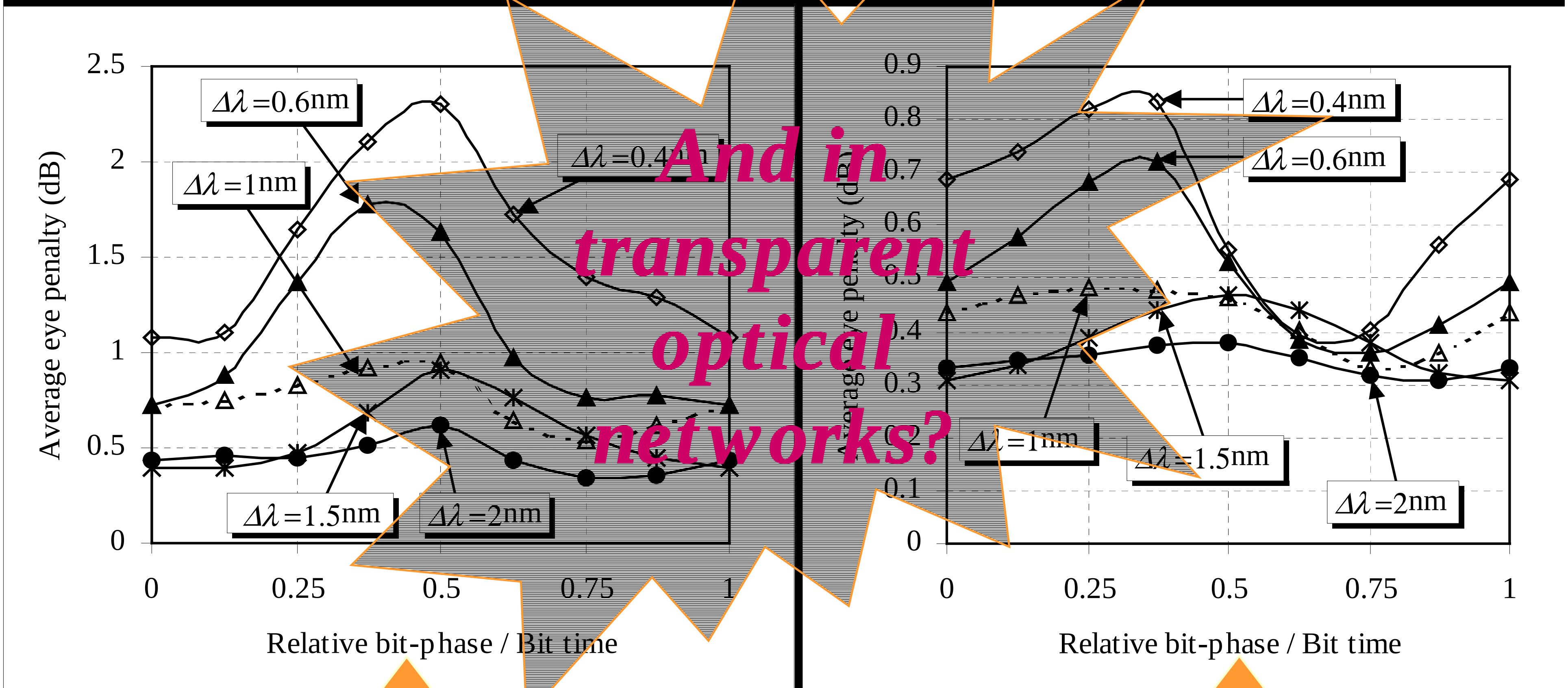
System length = 360km of SMF, amplifier span = 120km, peak power = 30mW, two-channel at 2.5 Gb/s



8 time delays per bit are examined and sequences of N_b=64 bits are used in the simulation ⇒ 512 simulations corresponding to 512 different time delays are performed for each set of system parameters.

XPM dependence on relative bit-phase between channels (point-to-point links)

System length = 360km of SMF, amplifier span = 120km, 2 channels at 2.5 Gb/s

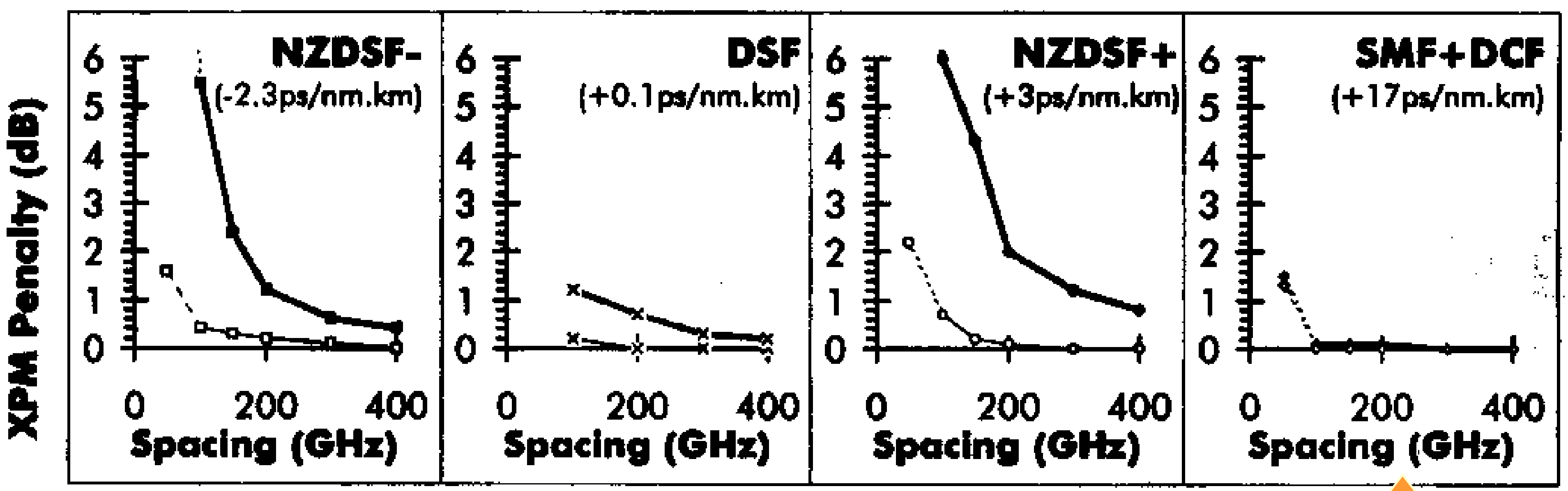


Peak power = 30mW

Peak power = 10mW

XPM dependence on type of fiber infrastructure

Two identical 100 km long fiber spans, 10 Gb/s



- Thick lines: worst case
- Thin lines: best case
- Worst and best cases obtained as the relative signal-pump polarization and delay are adjusted

Residual dispersion of –320 ps/nm

From Bigo *et al.*, IEEE PTL, pp. 605-607, May 1999.

Suppression of XPM

- By using source polarisation optimization
- By controlling appropriately the prechirping at transmitter
- By controlling the relative time delays of adjacent channels at the transmitter

only applicable to point-to-point links

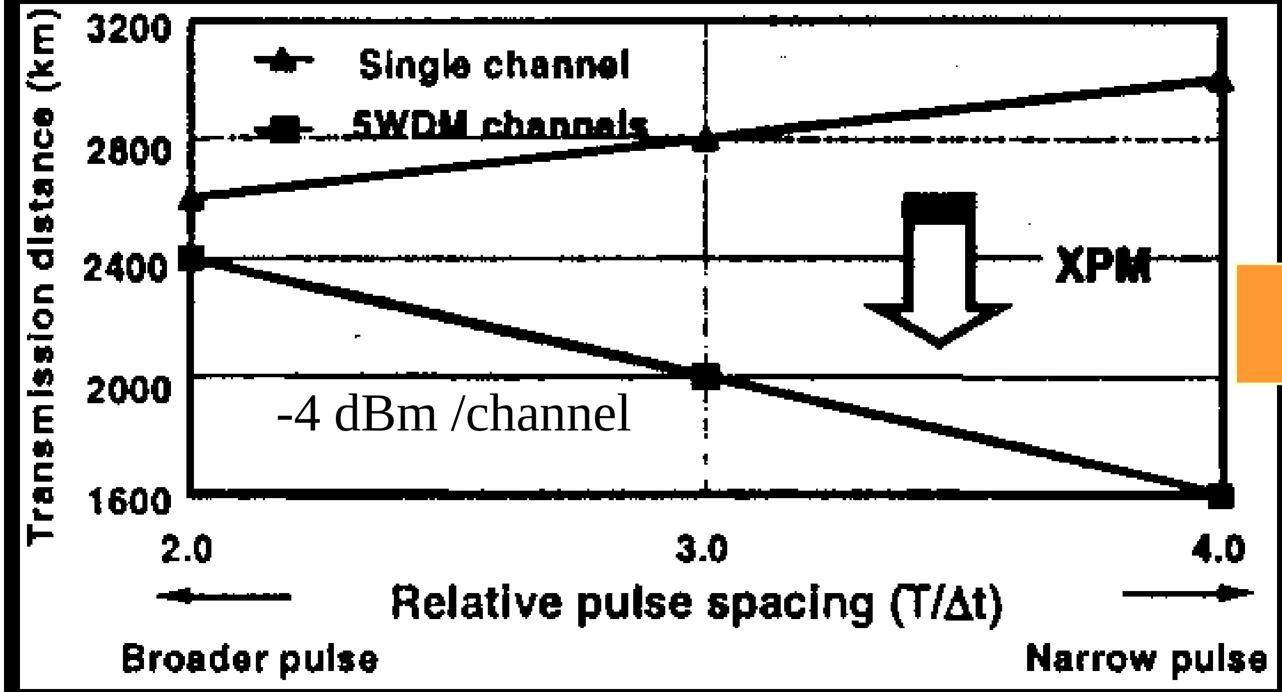
- By appropriate compensation of the fiber dispersion (does not remove the XPM-induced chirp!!!)

Inconsistent with full GVD compensation at each span (which requires also in-line dispersion slope compensation) …

but causes realignment of the relative time delay between channels

Suppression of XPM by pulse-width optimisation

20 Gbit/s/ch, 5 channels, channel spacing of 0.4 nm,
20 km SMF + 20 km RDF per span



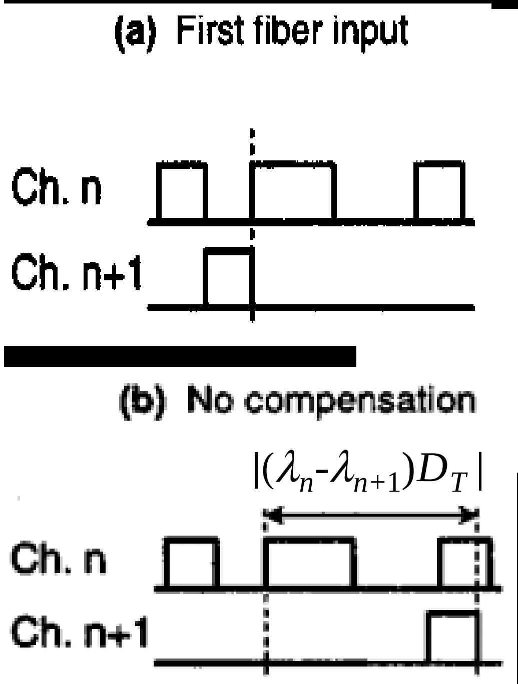
Single-channel:
decrease of pulse width

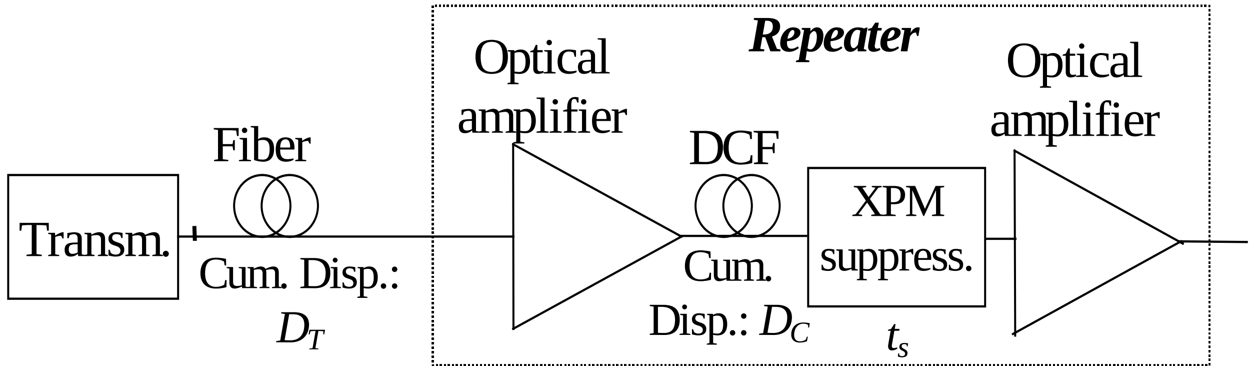
Multi-channel:
increase of pulse width

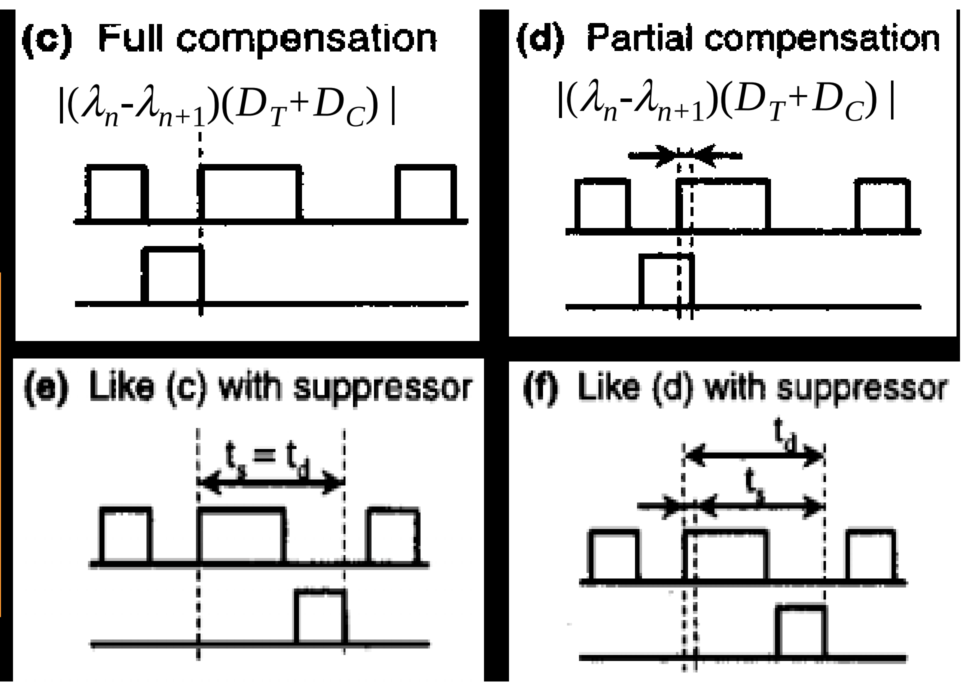
To suppress XPM in DWDM systems, wider pulses are desirable because of their less peak power (duty-cycle of 50% is suitable)

From Gupta *et al.*, OFC’2000, paper TuJ7.

Suppression of XPM by controlling the timing delays at each span





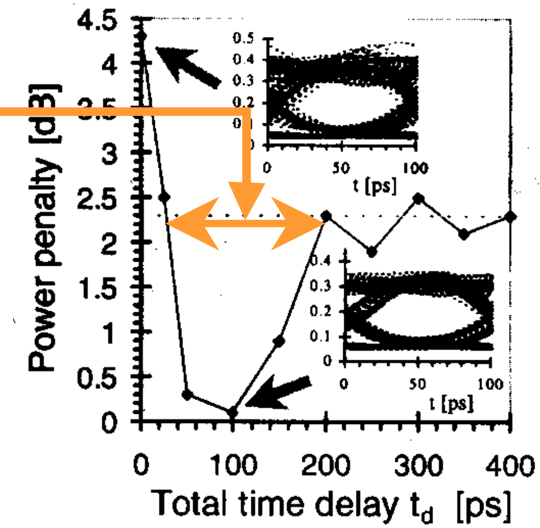


Key idea: to force the destructive addition between the contributions of the different spans to the overall XPM-induced IM by introducing adequate time delays between adjacent channels at the repeaters

From Bellotti *et al.*, IEEE PTL, pp. 726-728, June 2000.

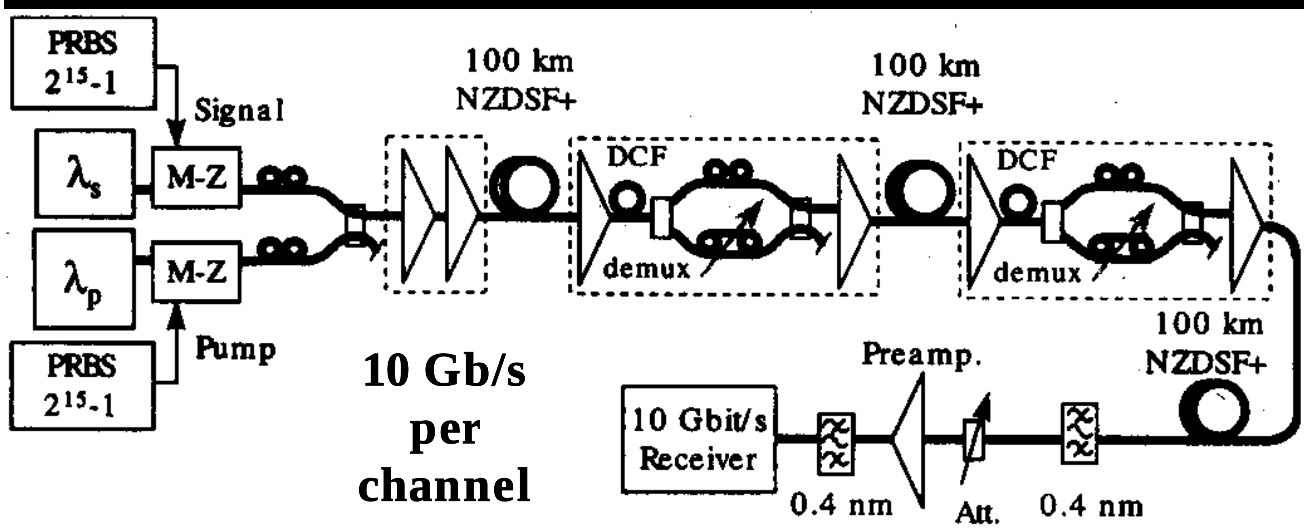
Suppression of XPM by controlling the timing delays …(cont.)

The delays need not to be set with very high precision: relaxed design of XPM suppressor



The XPM suppressor can be based on

- Integratable delay lines between demux/mux stages
- Series of narrow-band fiber Bragg gratings written at specific locations



From Bellotti *et al.*, IEEE PTL, pp. 726-728, June 2000.

- Avoid the need of management of GVD and dispersion slope to suppress the XPM effect
- Suppress the BER floor due to XPM

Conclusions

- The main features of XPM have been identified and discussed.
- The ways, by which XPM limits the IM/DD DWDM system performance, have been highlighted.
- Several strategies for suppressing or reducing the degradation caused by XPM in DWDM systems have been presented and their main advantages and drawbacks have been discussed.
- XPM can be the most detrimental effect in DWDM systems over SMF and NZDSF at both low and high bit rates.

Thank you

for

your attention !!!