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Conference on Ultrafast Transmission Systems in Optical Fibres

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Long Distance All Optical ASK transmission Near Zero Dispersion (λ_o)

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Long distance All Optical ASK transmission Near Zero Dispersion (λ_o)

Why does it work so well when we understand so little?

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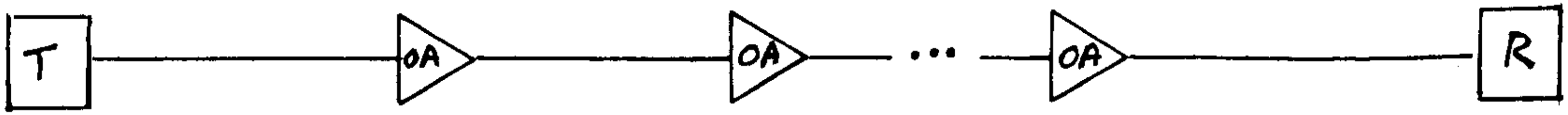


In a long distance all optical transmission system like the one above we have in effect a very long "lossless" weakly nonlinear fiber.

- Expect signal degradation due to: Amplifier ASE noise
  Dispersion
  Four Wave Mixing (FWM), Self Phase Modulation (SPM)
  Polarization Mode Dispersion (PMD) (Birefringence)
  Polarization Dependent Loss (PDL)
  Polarization Dependent Gain (PDG)

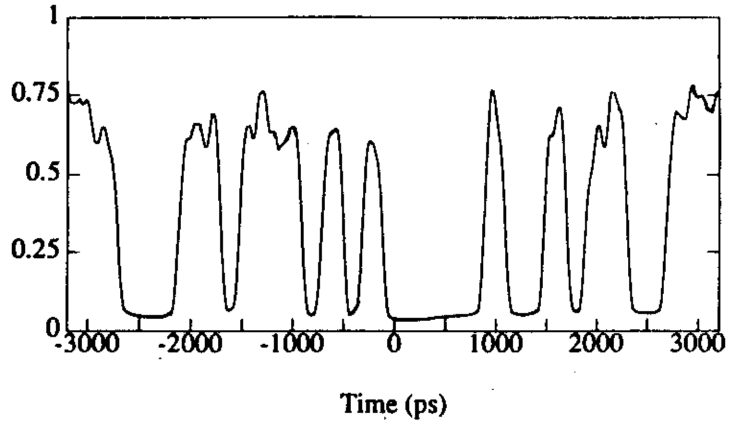
- For The NRZ waveform there is no analytic solution of the NLS.
- Our approach is to model individual phenomena analytically and
to make comprehensive numerical models which include all phenomena.

Performance Evaluation

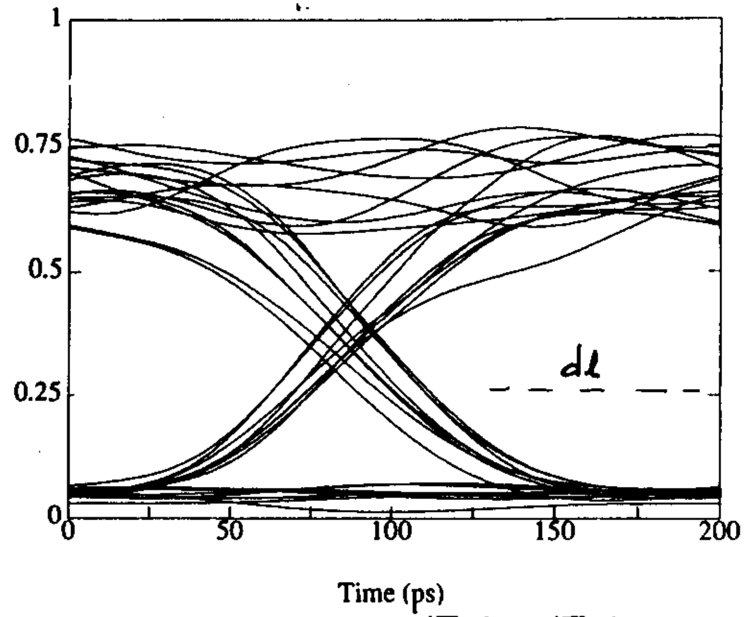
• For soliton systems if we know the distribution of pulse energies and arrival times we can calculate the bit error rate (BER). These distributions can be calculated analytically and measured. Hence there is a direct connection between theory and experiment for most soliton systems.

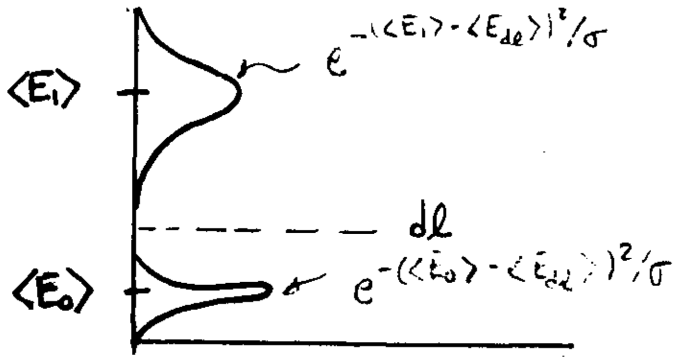
• For NRZ systems the only measurement of system performance is Q. For linear systems with noise Q works well and can be calculated. For nonlinear systems with dispersive effects Q cannot be calculated. Further it is not clear that the measured Q is truly indicative of true system performance.

Q



$\Longrightarrow$





$$Q_{linear} = \frac{\langle E_1\rangle - \langle E_0\rangle}{\sigma_1 + \sigma_0}$$

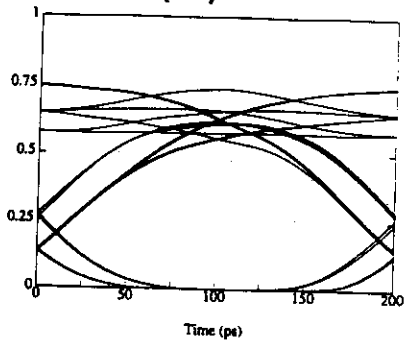
$$Q^{2dB} = 20\log_{10}(Q_{linear})$$

$$BER(Q_{linear}) = \frac{1}{\sqrt{2\pi}\,Q}\,e^{-\frac{1}{2}Q^2{}_{linear}}$$

$Q_{linear} = 6 \quad Q^2 = 15.5\text{dB} \Rightarrow 10^{-9}\text{BER}$ $\qquad$ $Q_{linear} = 7 \quad Q^2 = 16.9\text{dB} \Rightarrow 10^{-12}\text{BER}$

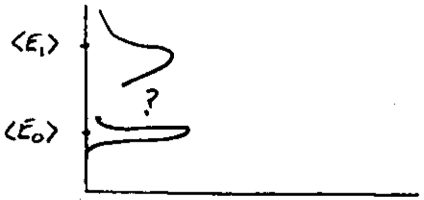
Problems With Q

Intersymbol Interference (ISI)



In the nonlinear systems we are considering all bits are not treated equally. The final shape of a bit will depend on what its nearest neighbor bits are. The electronics following the transmission line can produce greater than nn bit ISI.

The Gaussian Approximation.



When measuring Q or calculating it from simulations we assume the distributions of the 1s and 0s are Gaussian. We do not know for sure, we have only measured 6 σ or 7 σ out. The coupled effects of PMD, PDL and PDG may change this.

ASE Noise

For a **linear** system with ASE noise using the above definition of Q and the proper expressions for the noise distributions we write and expression for Q:

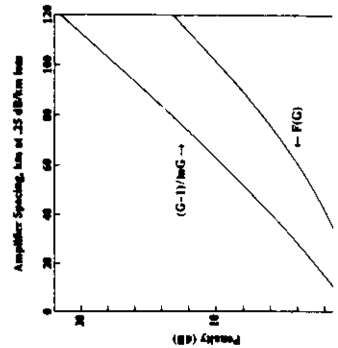
$$Q_{linear} = SNR\frac{\sqrt{B_o/B_e}}{\sqrt{2\,SNR+1}+1}$$

Where: $SNR = \dfrac{E_{bit}}{E_{equipartition}}$ $\qquad E_{equipartition} = N_{amps}\, n_{sp}(G-1)h\nu$

B_0 is optical width of the receiver $\qquad B_e$ is the electrical width of the receiver

Penalty for Discrete Amplifiers:

$$\tilde{F}(G) = \frac{(G-1)}{\ln(G)}$$



Improvements

• Decrease n_{sp}	980 nm pumped amplifiers can have n_{sp}=1.1
• Increase SNR by increasing P_{signal}	Increases effects of SPM
• Decrease G (i. e. distance between amplifiers)	PDG, and PDL penalties increase

Self Phase Modulation

$$n = n_o + n_2 I$$

- For an amplitude modulated signal this gives rise to intensity dependent phase shift. Which gives rise to spectral spreading of the signal.

- For D=0

$$U(z,t) = U(0,t)\, e^{i|u(0,t)|^2 z}$$

$\Rightarrow$ SPM causes spectral spreading, but if one can recover the whole spectrum at the receiver the temporal shape of the signal will remain unchanged.

- Amount of spectral spreading will depend on $|U(t)|^2$

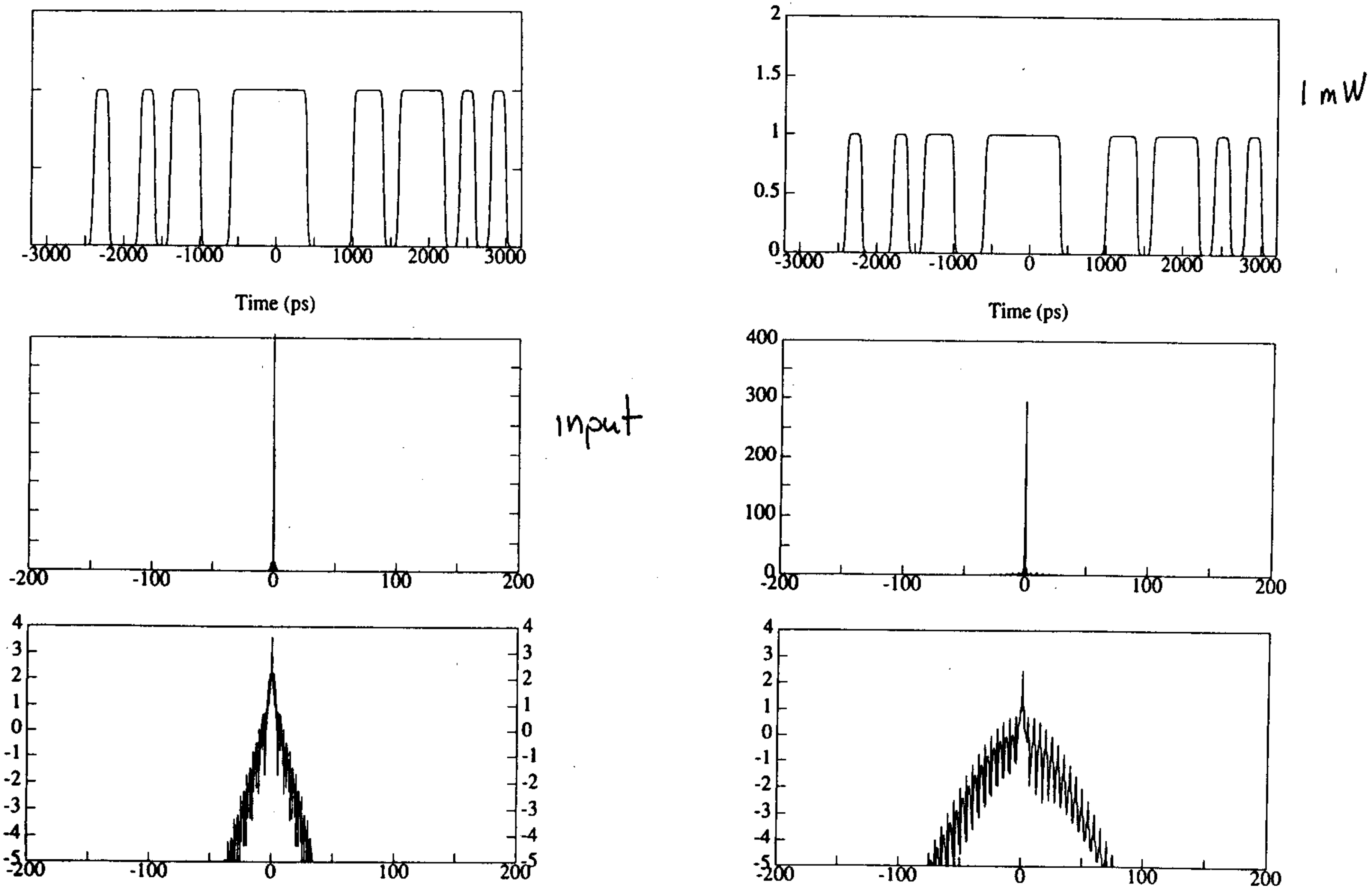
$$\delta\omega(t) \propto \frac{\partial |U(0,t)|^2}{\partial T}$$

- The addition of ASE in the presence of n_2 noise will accelerate the spectral spreading. This is due to four wave mixing (FWM) between signal and noise.

- n_2 and ASE will perform as well as a linear system if the whole spectrum is recovered at the receiver. If the receiver is too narrow the signal will be significantly degraded.

Effects of SPM on an NRZ Waveform at D=0

L_{amp} = 45km   Z = 9000 km



Effects of SPM on an NRZ Waveform at D=0

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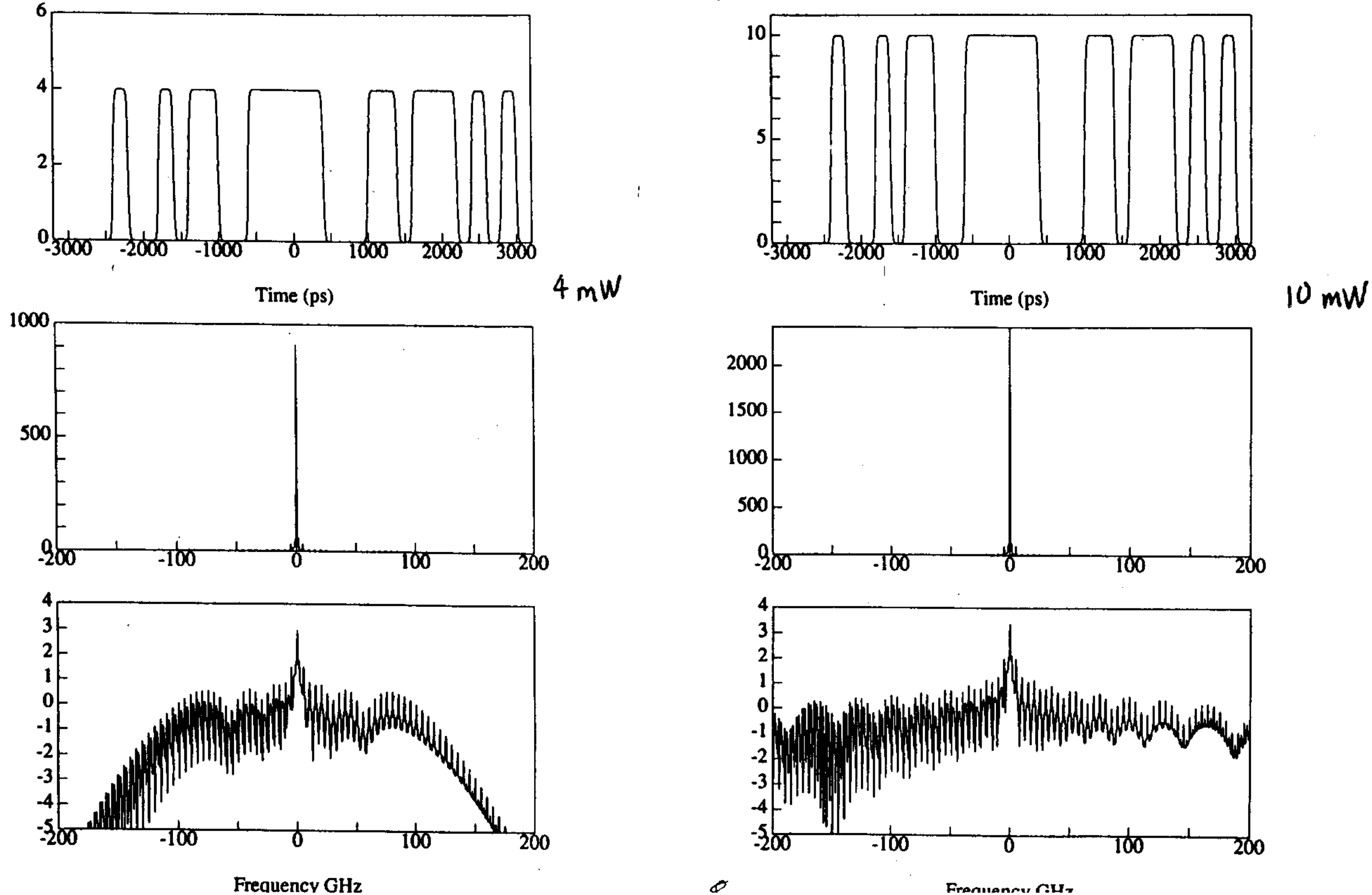
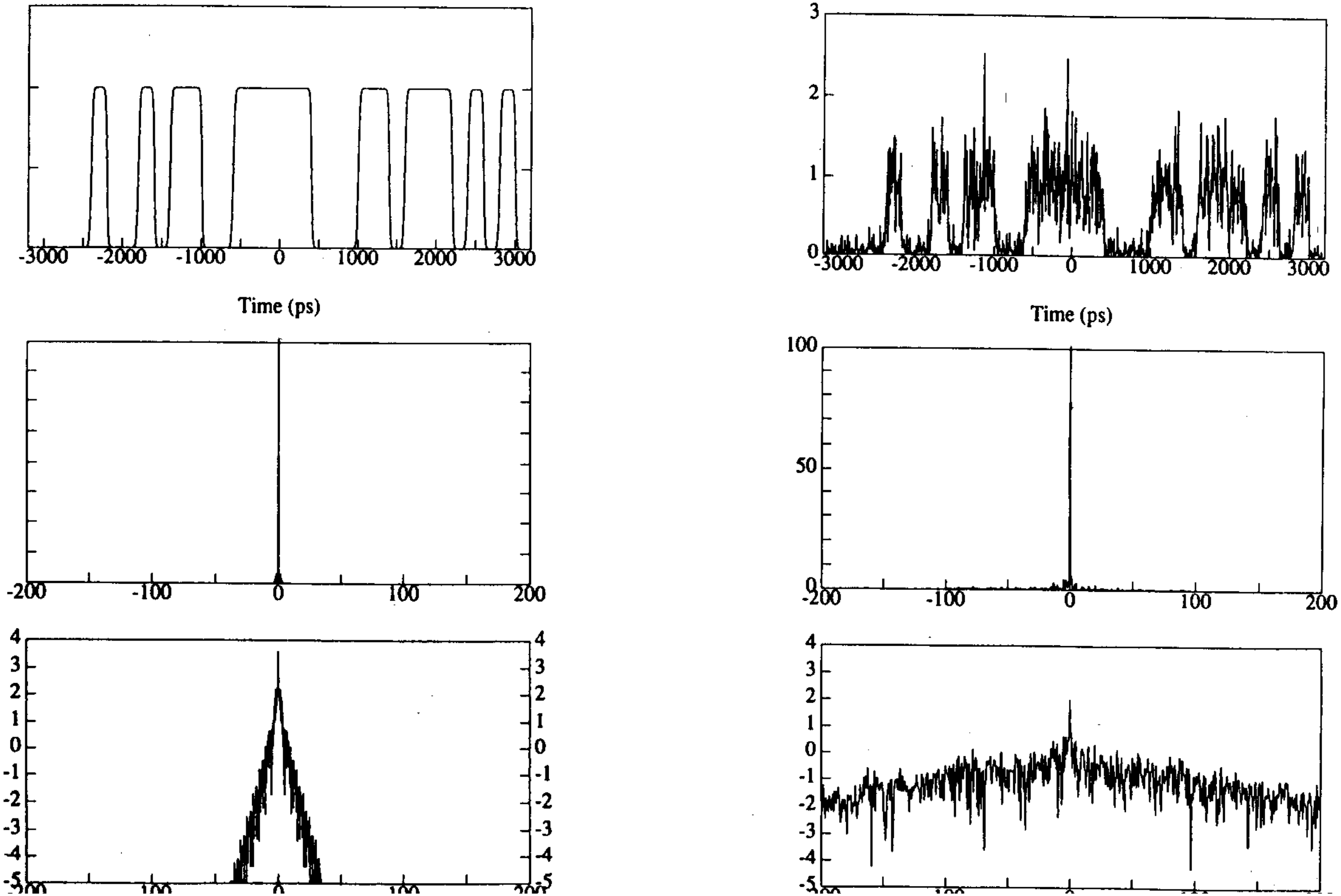


Effects of SPM and ASE noise on an NRZ Waveform at D=0

L_{amp} = 45km Z = 9000 km n_{sp} = 1.5



Effects of SPM and ASE noise on an NRZ Waveform at D=0

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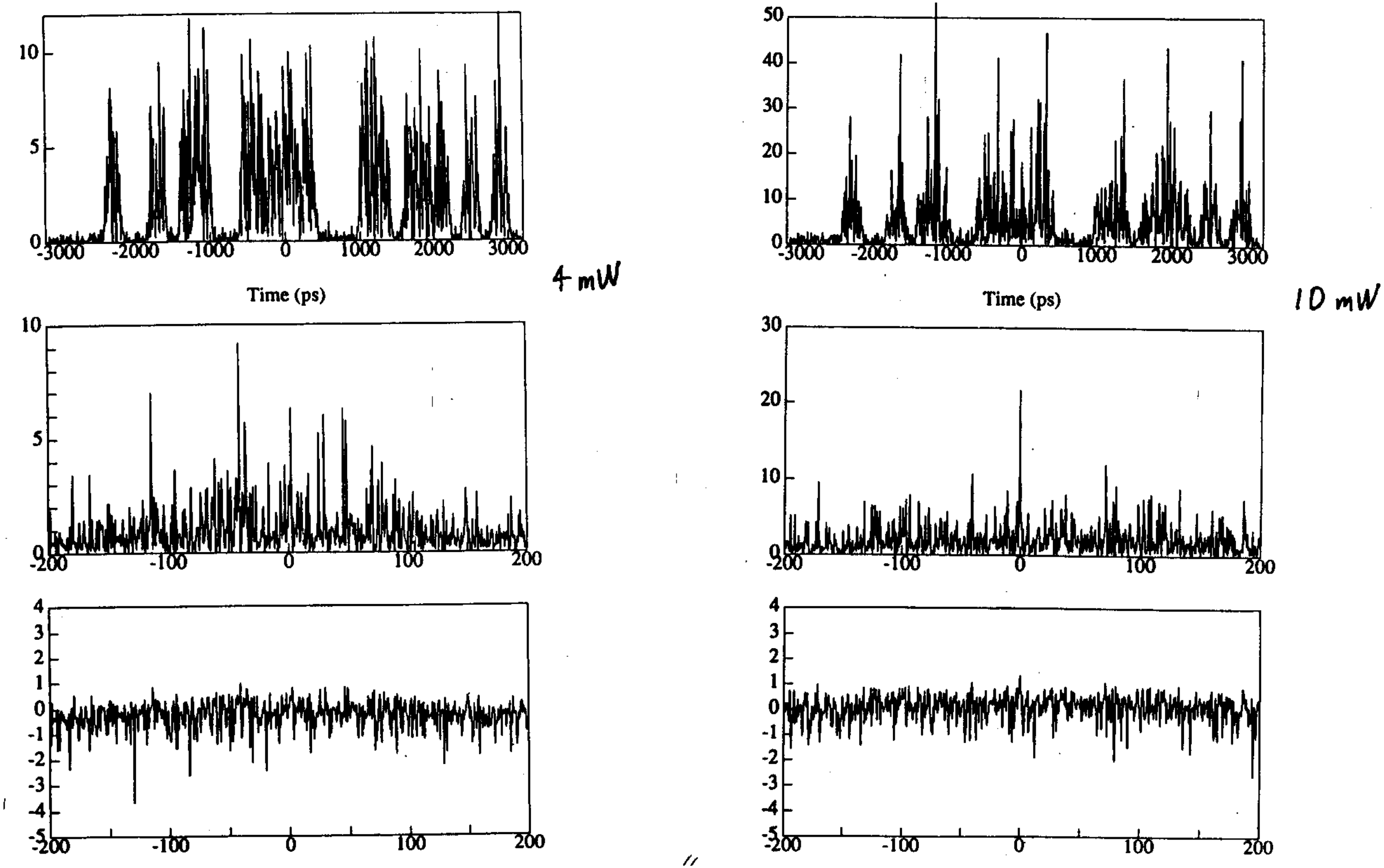
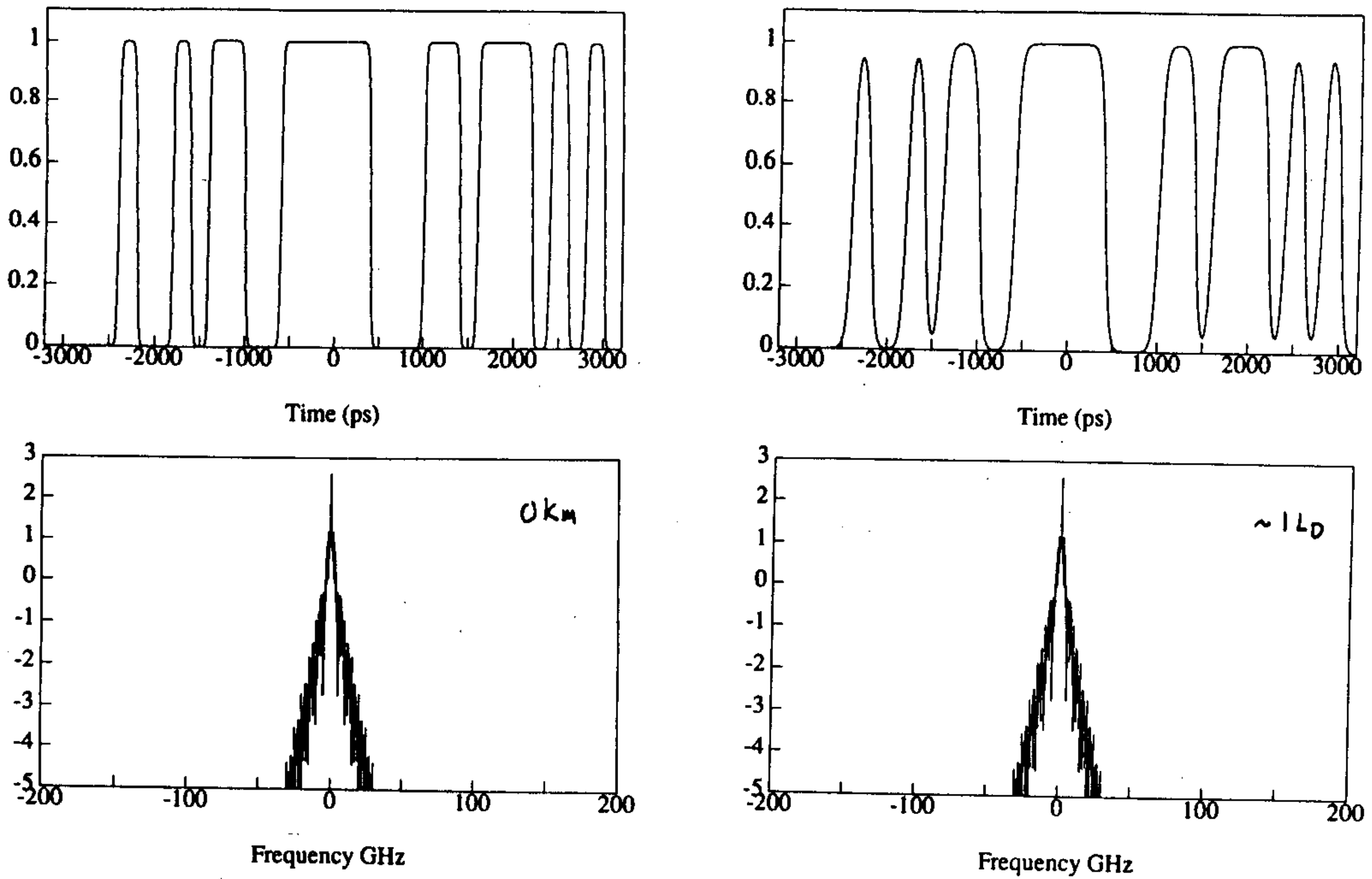


Chromatic Dispersion

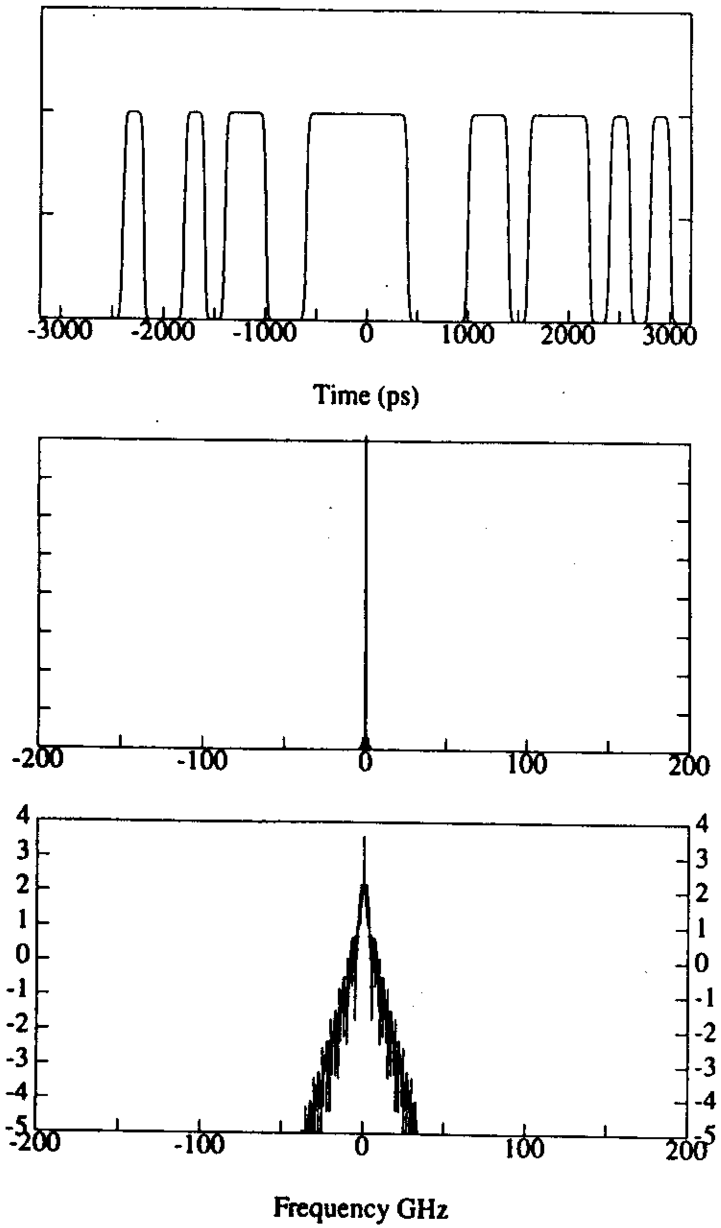


- Dispersion alone causes temporal broadening but no spectral broadening
- Rate of temporal spreading increases with bit rate.

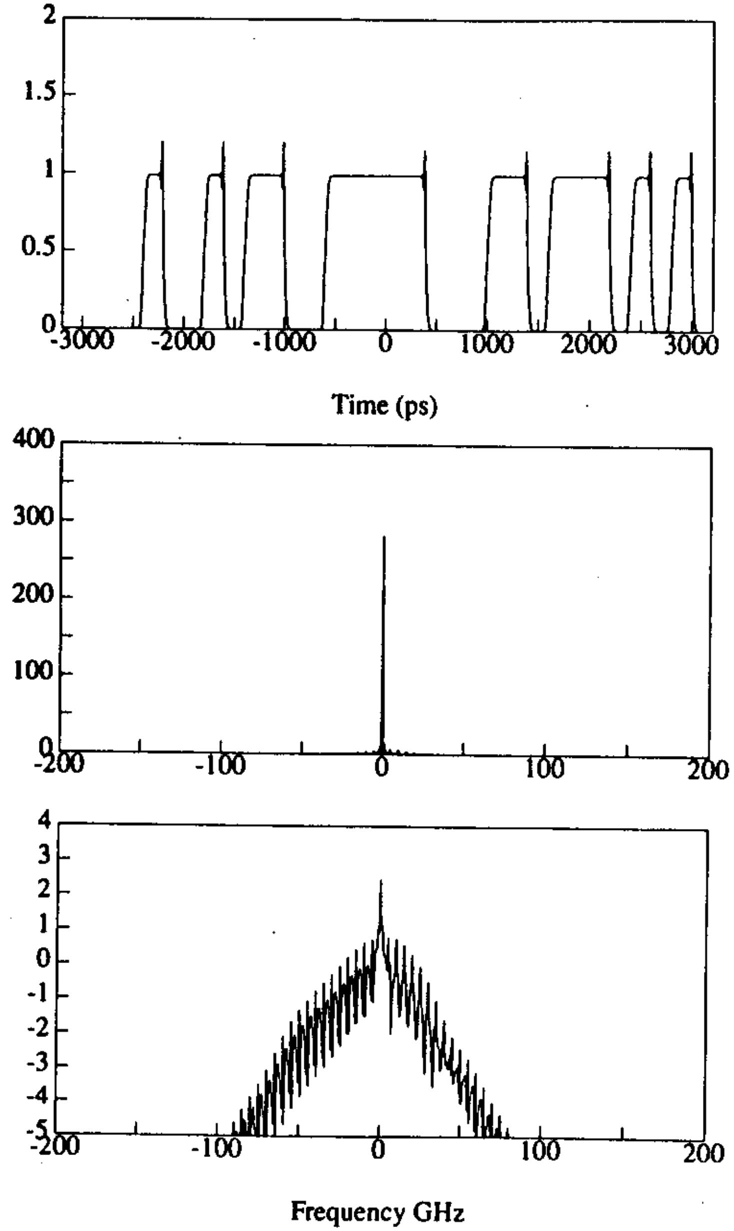
$$L_D = \frac{\tau^2}{|D\lambda^2|}$$

Effect of Third Order Dispersion D′ at D=0

+ n_2

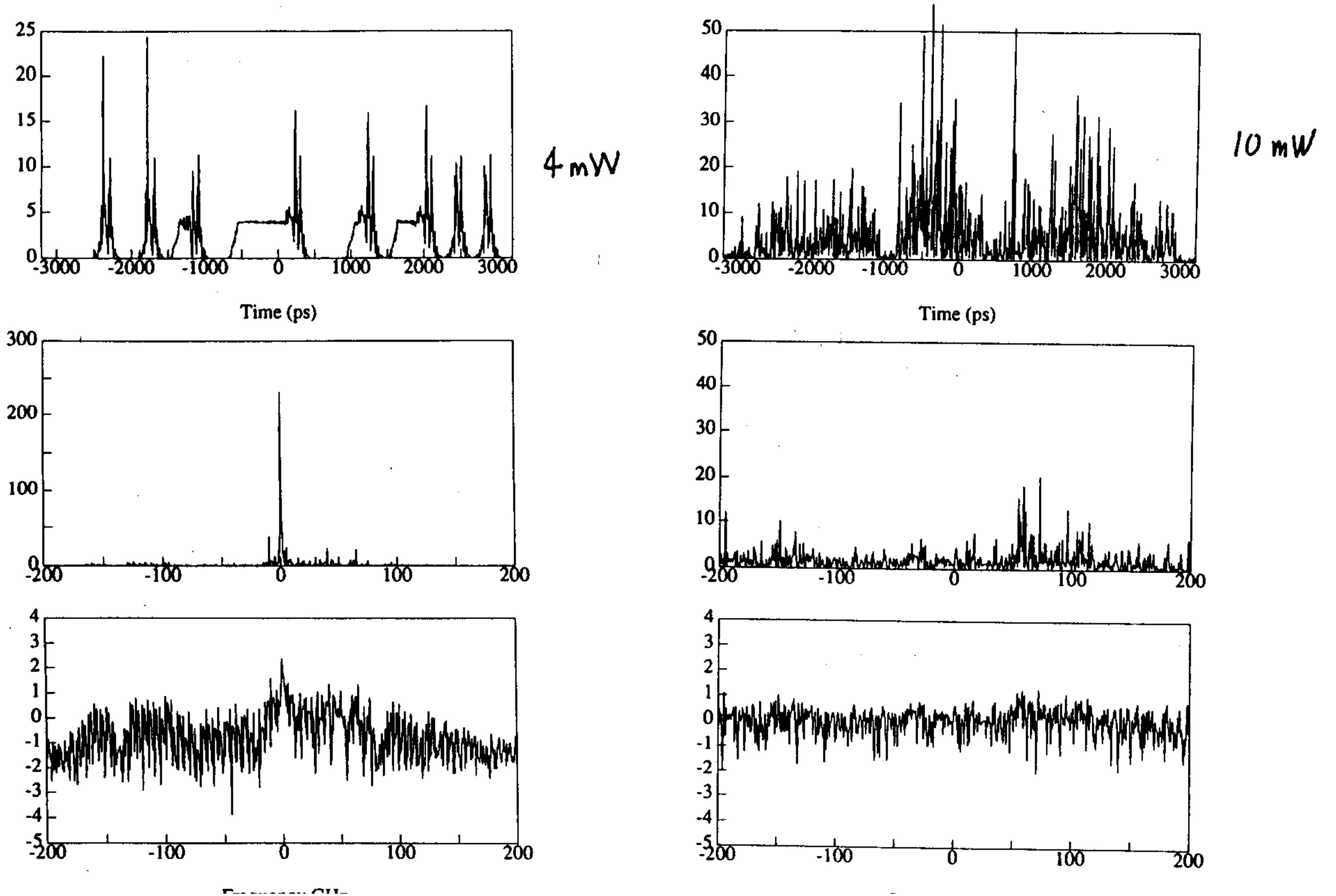


0 km
input

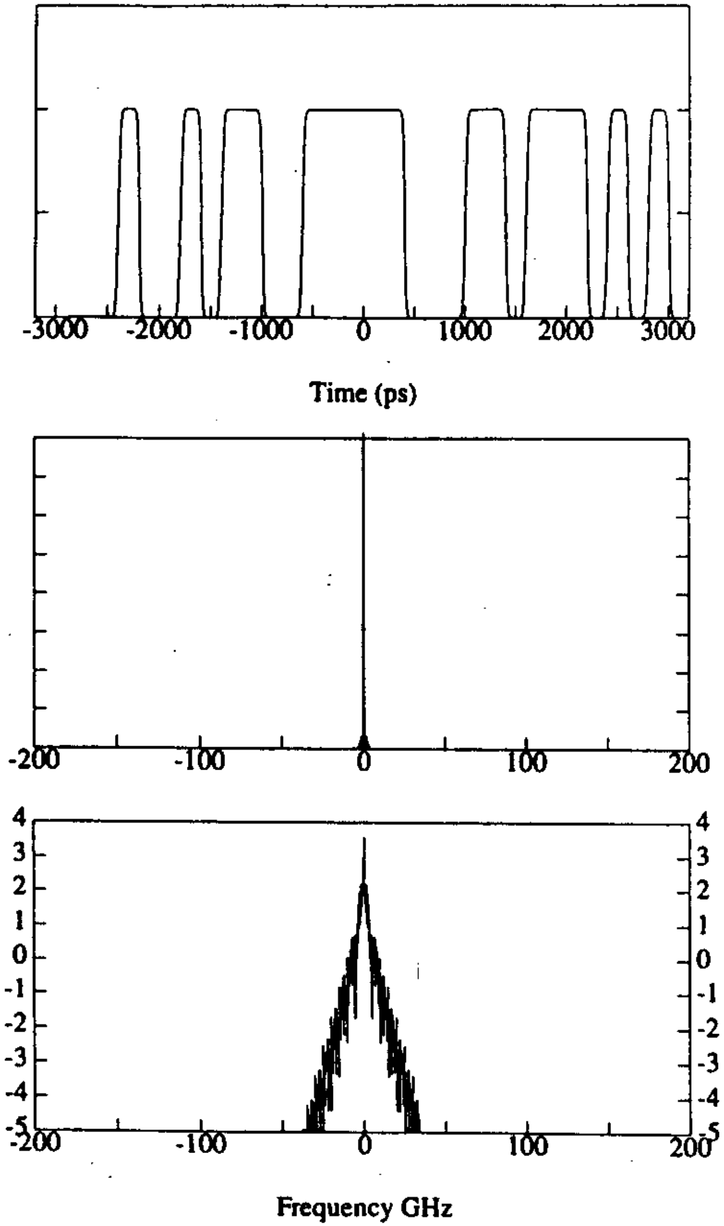


1 mW

Effect of Third Order Dispersion D′ at D=0



Dispersion and SPM



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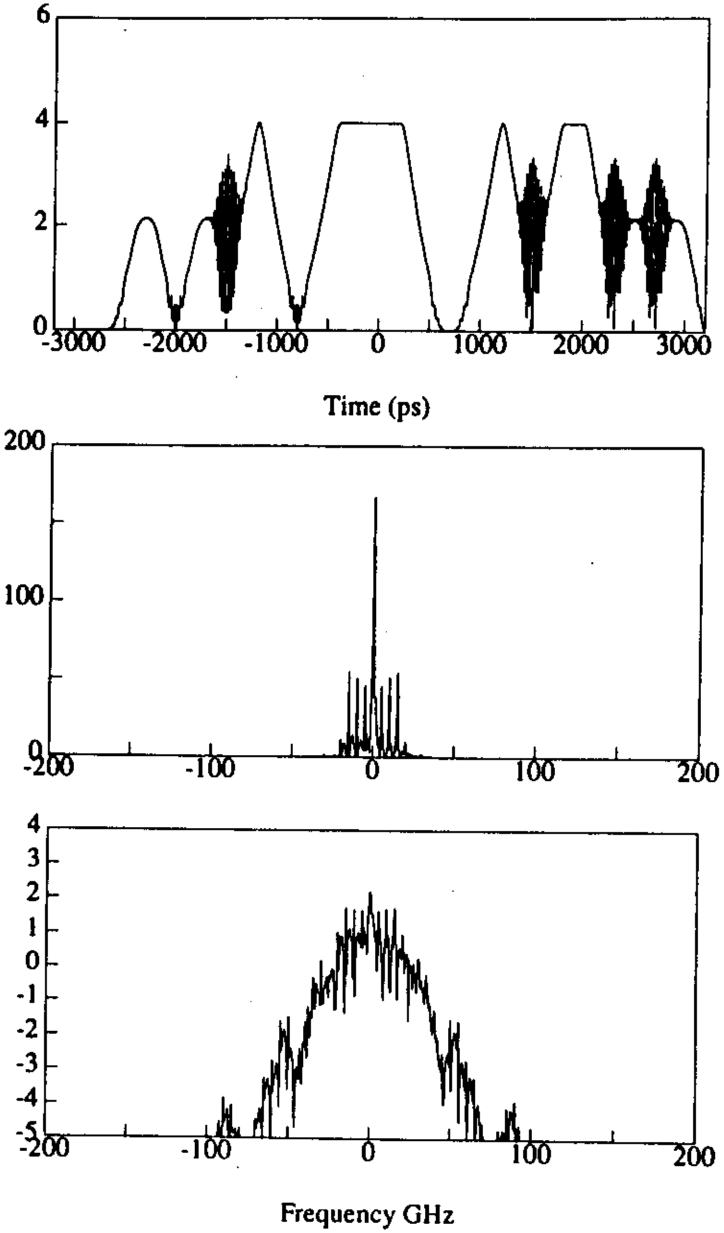
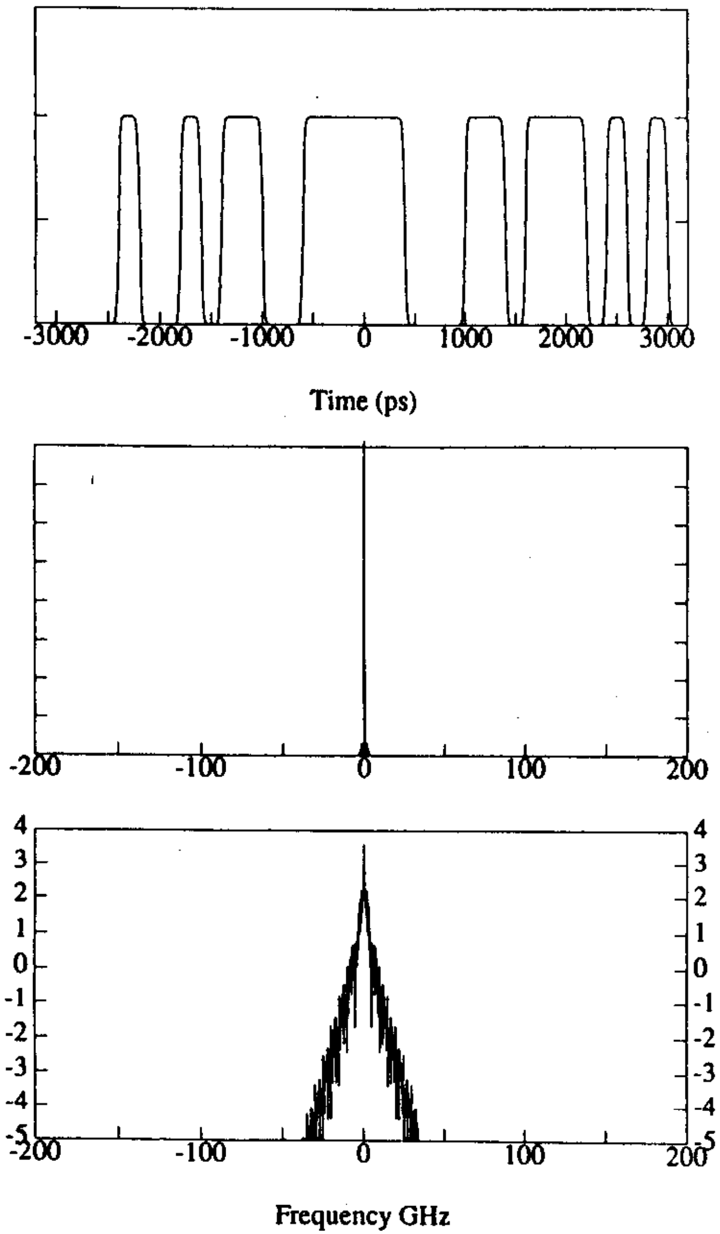


9000 Km
D = -.1
4 mW

- Adding some dispersion degrades the pulse shape. In the normal regime (D<0) the spectral spreading is suppressed

Dispersion and SPM



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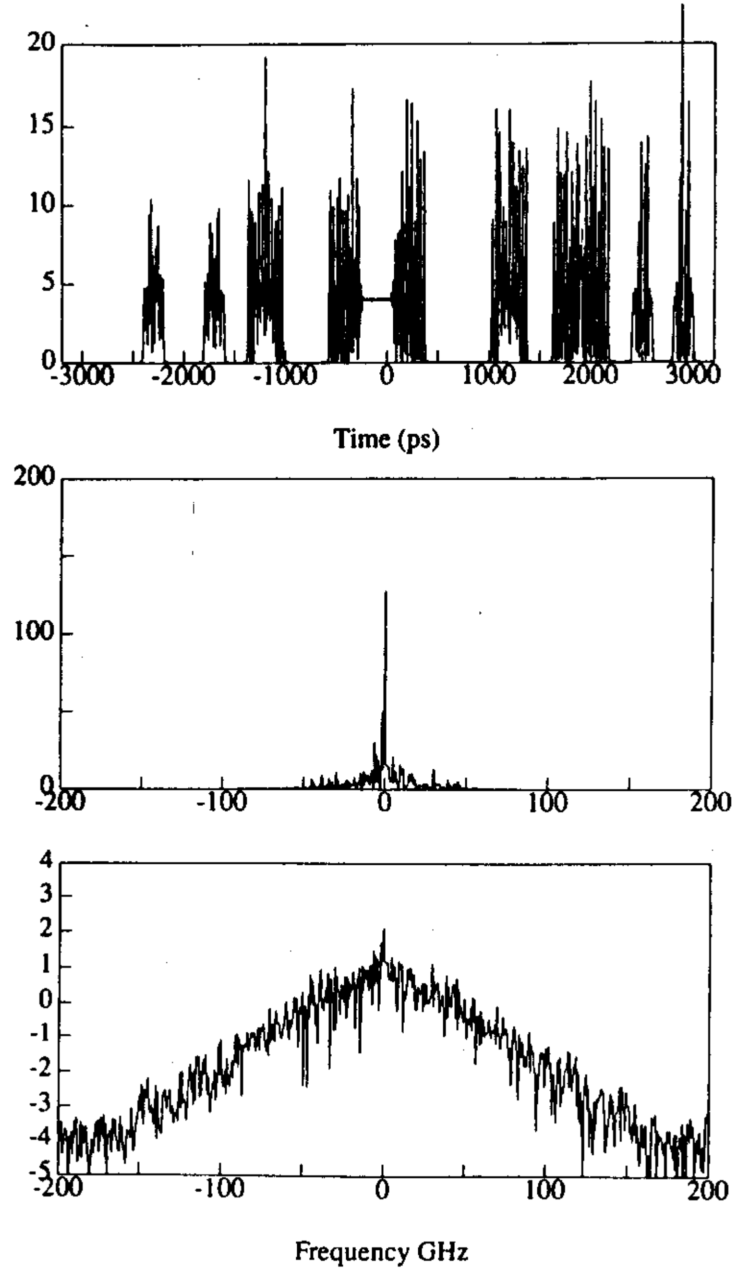


9000 km
D = +.1
4 mW

- Adding some dispersion degrades the pulse shape. In the normal regime ($D<0$) the

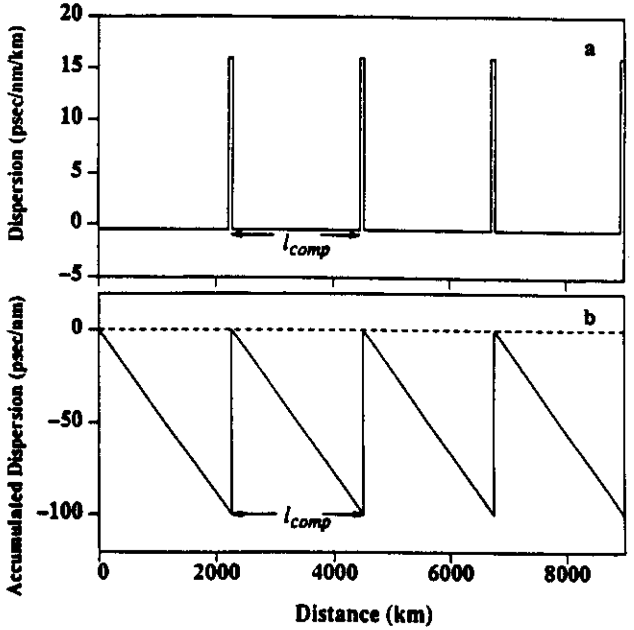
Using Dispersion to Manage Spectral Spreading

The basic idea is to make the phase matching of the signal and noise poor. While keeping that of the signal with itself relatively good.

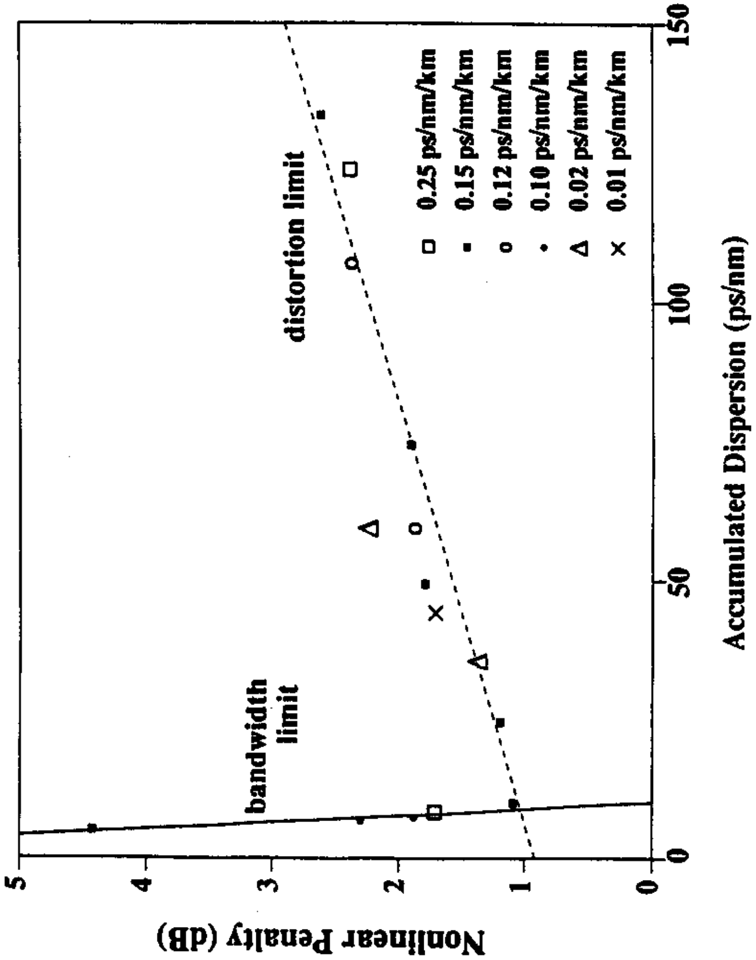
$$\Delta k = \frac{2\pi\lambda^2 D \Delta f^2}{c}$$

Over a single span l we want:

$$\Delta k l = \begin{cases} > 1 & \text{S–N interactions (spectral broadening)} \\ \ll 1 & \text{S–S interactions (pulse distortion)} \end{cases}$$



Simulation Results for Dsipersion compensation



Using Dispersion to Manage Spectral Spreading

Some Refinements

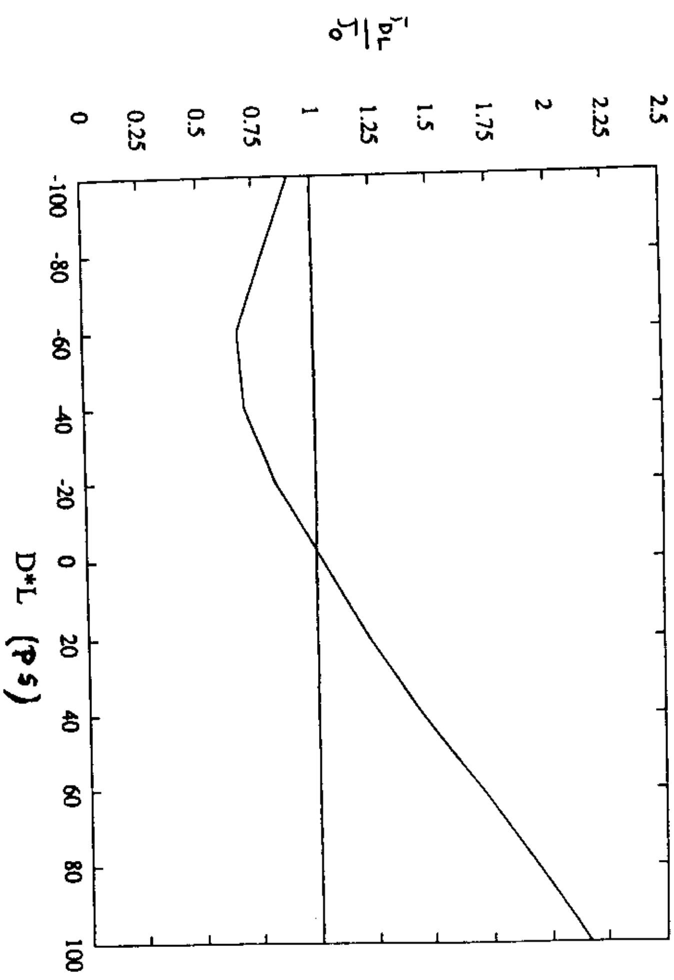
- Having $\overline{D} = 0$ is not the "best" one can do (though it is quite good)

- The problem is that $\overline{D} = 0$ is optimum for a linear system, however, in real systems the signal spectrum still spreads. The effects of dispersion are bandwidth dependent. To get optimum performance one should correct for this.

- For a fiber with a loss coefficient of 0.05 1/km it's effective length is 20 km. Hence for a span of length L_{amp} the portion of it after the first 20 km can be considered "linear". $\Rightarrow$ Compensate exactly for $N_{amps}(L_{amp} - 20)$ km of fiber exactly.

- The other $N_{amps}\times 20$km should be under compensated. (See following results of D. Marcuse)

Simulation Results for $\overline{D} \neq 0$



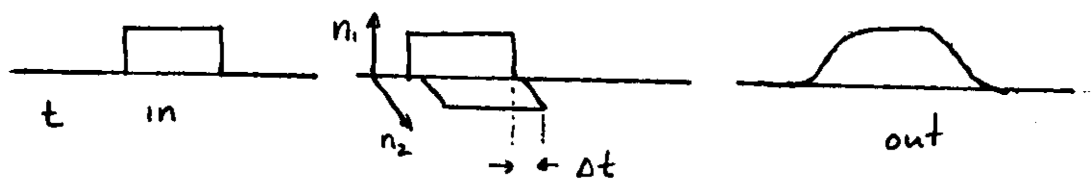
from D. Marcuse

Polarization Issues

• Fiber:	Polarization Mode Dispersion (PMD) from varying birefringence.
• Passive Components:	Polarization Dependent Loss (PDL) and birefringence.
• Amplifier:	Polarization Dependent Gain from polarization hole burning.

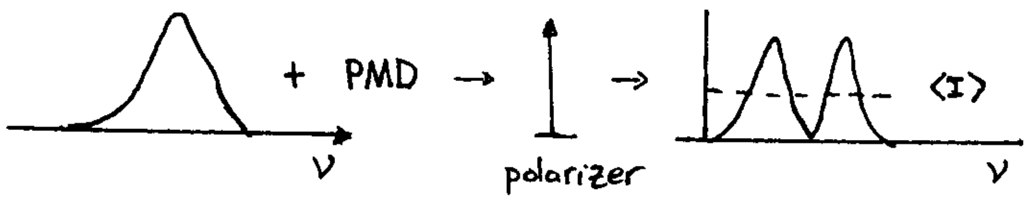
Polarization Mode Dispersion

- Temporal picture:



$\langle \Delta t \rangle = |\vec{\Omega}| = \mathrm{PMD}(\mathrm{ps}/\sqrt{\mathrm{km}}) \times \sqrt{L}$

- Frequency space picture:

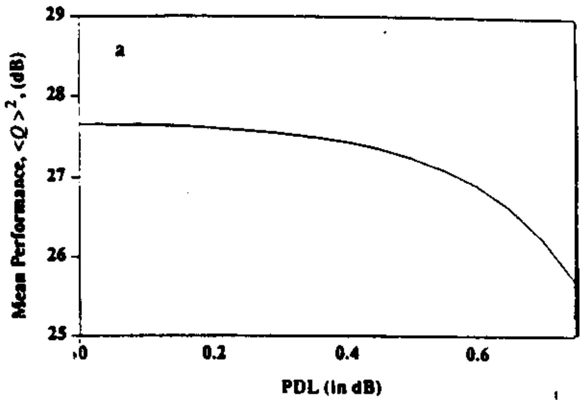


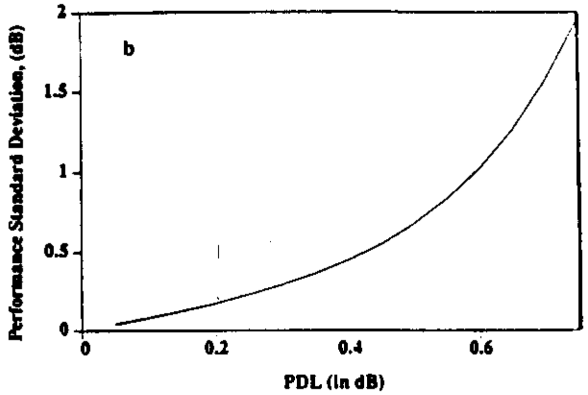
PMD: $\dfrac{d\vec{s}}{d\omega} = \vec{\Omega} \times \vec{S}$

$\langle N_c \rangle = \dfrac{\langle \Delta t \rangle \Delta\omega}{0.824\,\pi}$

- Limit PMD such that $\langle \Delta t \rangle \ll$ Bit Period
- for typical 9000 km system $\langle N_c \rangle \sim 1$ $\Rightarrow$ signal about 80% - 90% polarized at end.

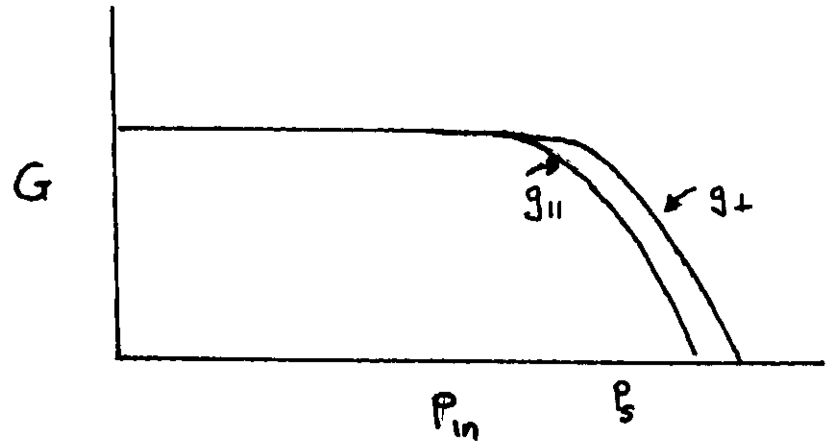
Polarization Dependent Loss





• With amplifiers running in compression the combined effect of PMD and PDL is to cause wider fluctuations in the system Q. Because the output power of the amplifiers is constant the average Q will remain the same (until the PDL becomes large).

Polarization Dependent Gain



• For an amplifier in compression and a polarized strong signal present the small signal gain in the orthogonal polarization state is greater than the small signal gain in the state parallel to the strong signal.

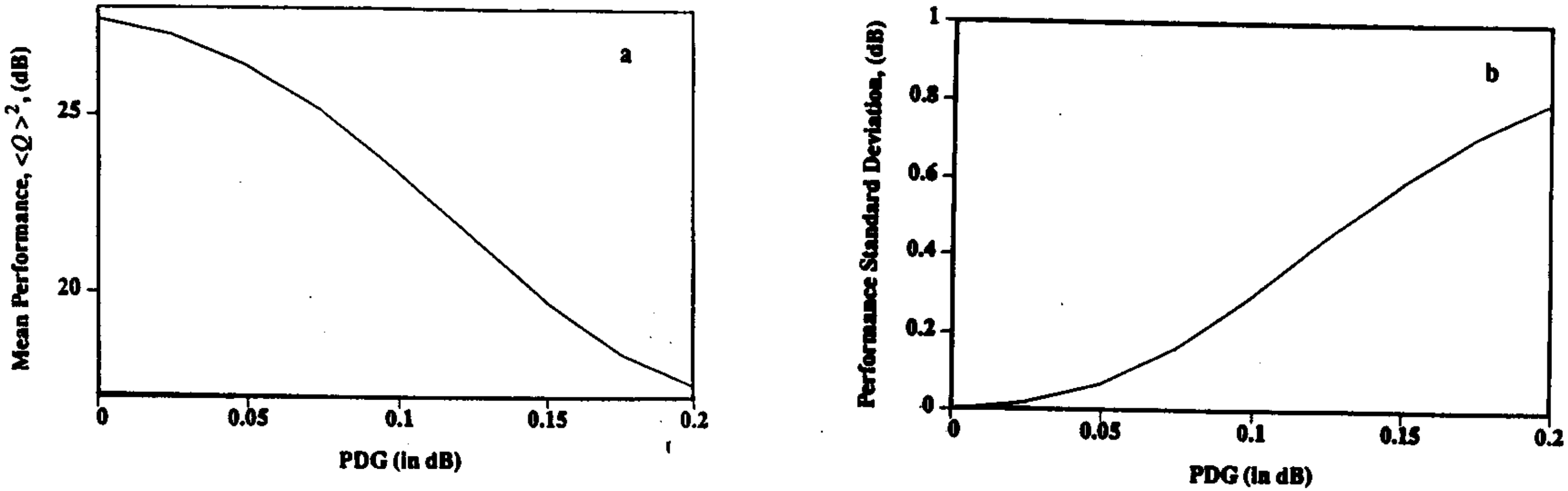
$$\delta = \left[10^{\frac{PDG}{10}}\right]\frac{(1-\varepsilon)}{(1+\varepsilon)} \times DOP$$

Where: $\delta = g_{\perp} - g_{\parallel}$ ε is the ellipticity of the strong signal. DOP is degree of polarization of the strong signal. PDG is the **maximum** gain differential in dB: typically $0.05\ \text{dB} \leq PDG \leq 0.15\ \text{dB}$.

• **Impairment:** Growth of noise orthogonal to signal results in lower S/N (remember the amplifiers are set to run constant power out).

• **Impairment:** Pulse shape distortion. As signal depolarizes some parts of the

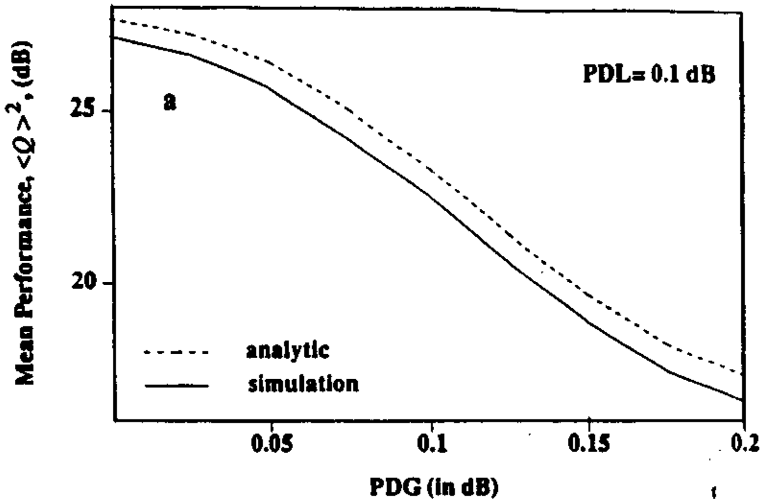
PDG

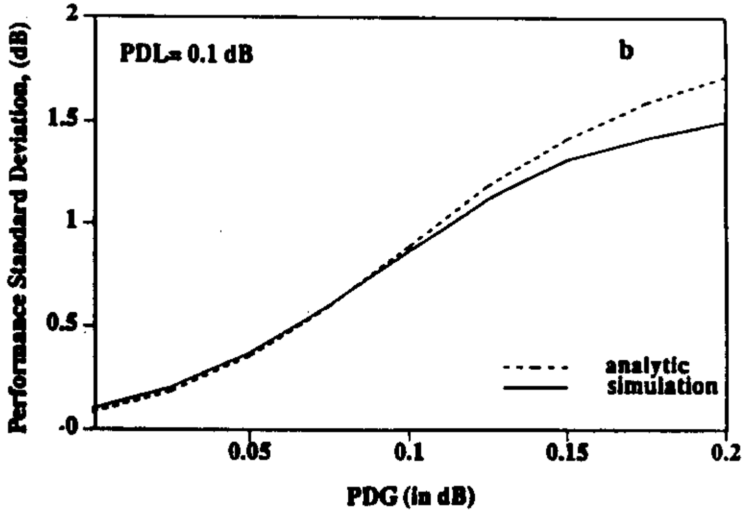


Z= 9000 km L_{amp} = 33 km G_{amp} = 10 n_{sp} = 2.0 P_{Launch} = 4 mW B_o = 4nm B_e = 3.5GHz

PDG+PDL

PDL = 0.1 dB / amplifier





Z= 9000 km L_{amp} = 33 km G_{amp} = 10 n_{sp} = 2.0 P_{Launch} = 4 mW B_o = 4nm B_e = 3.5GHz

The Combined Effects of PMD PDL and PDG

$$Q = \frac{P_{signal}\sqrt{B_o/B_e}}{\sqrt{4P_{signal}N_{\parallel} + 2(N_{\parallel}^2 + N_{\perp}^2)} + \sqrt{2(N_{\parallel}^2 + N_{\perp}^2)}}$$

Where: P_{signal} is the launch power of the signal
B_o is the optical bandwidth B_e is the electrical bandwidth.
$N_{\parallel}$ is the noise in the polarization mode of the signal $= N_{amp} n_{sp} (G - 1) h\nu\Delta\nu$
$N_{\perp}$ is a complex function of the PMD PDL and PDG

Caveat: This expression **does not** include Q degratation due to pulse shape distortion.

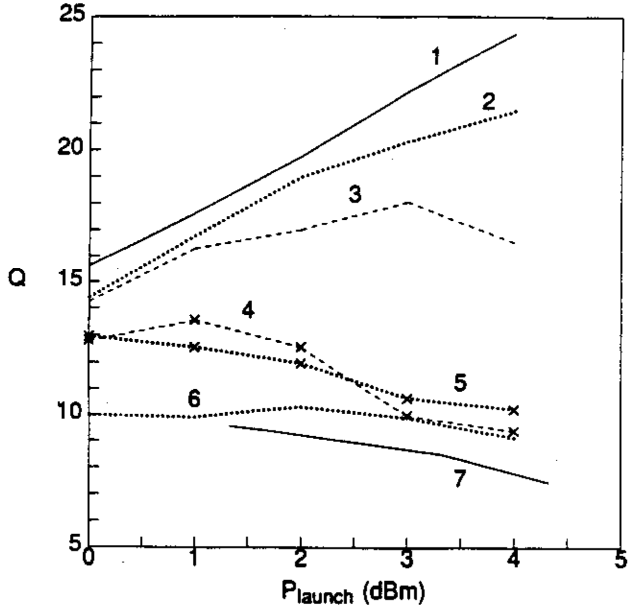
Numerical Modeling of NRZ Transmission.

• We have shown analytic expressions for the effects of many specific impairments. As stated before there is no comprehensive analytic theory that can account for the combined effects of all the effects described. Hence we must use numerical simulations to evaluate the combined effect.

• Split step Fourier transform methods for solving the nonlinear Schrodinger equation (NLSE) are time consuming but have yielded much understanding about NRZ transmission.

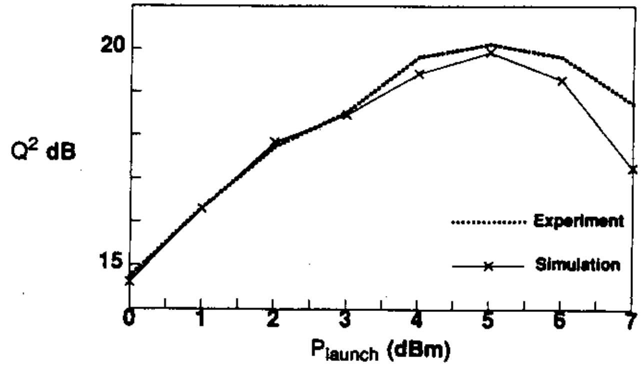
• We have developed models that do quite well at matching existing experiments.

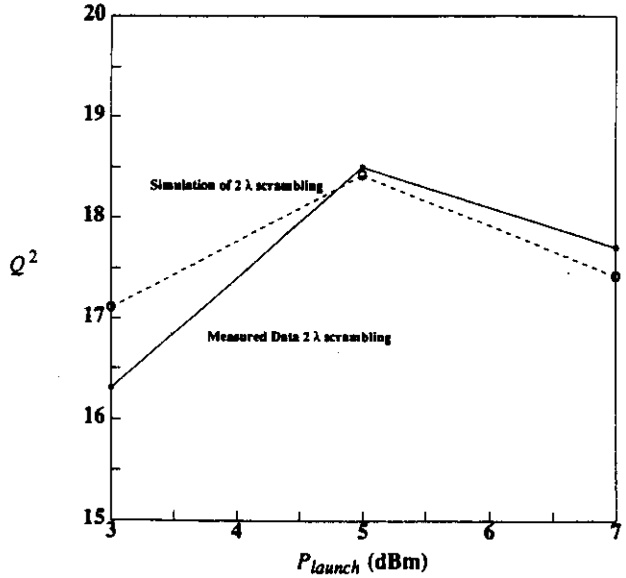
Simulation of 6000 km Straight Line Experiment



1. Linear
2. Ideal dispersion map, nonlinearity
3. Ideal dispersion map, nonlinearity, D´
4. Real dispersion map, nonlinearity
5. Real dispersion map, nonlinearity, D´
6. Real dispersion map, nonlinearity, D´, PMD, PDL, PDG
7. Measured data

Simulation of the Loop Experiments of Neal Bergano and Carl Davidson





Simulation of the Loop Experiments
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Neal Bergano and Carl Davidson