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TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

ULTRA DISTANCE TRANSMISSION OF THE (VERY NEAR) FUTURE: SOLITONS IN AN ALL OPTICAL SYSTEM

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ULTRALONG DISTANCE TRANSMISSION OF THE (VERY NEAR) FUTURE:

SOLITONS IN AN ALL OPTICAL SYSTEM

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OUTLINE

- Repeatered versus the all-optical approach

- The Non-Linear Schrodinger Equation
  - a) Dispersion
  - b) Self-phase modulation
  - c) Solitons, the eigenmodes of transmission
  - d) What happens if the pulses aren't solitons

- Amplification
  - a) Amplifier systems: lumped vs distributed
  - b) The stimulated Raman effect
  - c) Er amplifiers
  - d) Spontaneous emission and error rates
  - e) Noise penalties
  - f) The right way to make bit error rate measurements

- Experimental demonstration of soliton transmission
  - a) The experiment
  - b) Achievement of 6000 km
  - c) Study of pulse pair interactions

- Dispersion shifted fiber and system design
  - a) Advantages of low dispersion
  - b) Polarization dispersion
  - c) Effects of varying dispersion

- Wavelength Division Multiplexing with Solitons
  - a) Transparency of solitons
  - b) Effects of perturbations
  - c) Potential for WDM

- Phase Noise
  - a) Why amplitude shift keying (ASK) is superior to phase shift (PSK) or frequency shift keying (FSK) in ultralong distance systems.

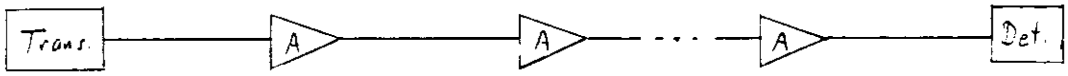
REPEATERS VS THE ALL-OPTICAL APPROACH

Repeatered System:

Repeaters are:

1) Severely bit-rate limiting
2) Not truly compatible with Wavelength Division Multiplexing
3) Unidirectional
4) Costly!

All-Optical System:



Advantages:

1) High single-channel bit rates
2) Relatively easy to use WDM
3) Potentially bidirectional
4) Relatively inexpensive

The viewgraphs in this section concern:

THE FUNDAMENTAL PROPAGATION EQUATION FOR SINGLE MODE FIBERS

EFFECTS OF FIBER NONLINEARITY AND SOLITONS

THE NONLINEAR SCHRODINGER EQN:

$$-i\frac{\partial u}{\partial z} = \underset{\substack{\uparrow\\ \text{ordinary}\\ \text{dispersion}}}{\frac{1}{2}\frac{\partial^2 u}{\partial t^2}} + \underset{\substack{\uparrow\\ \text{based on}\\ n = n_0 + n_2 I}}{|u|^2 u} - i\Gamma u$$

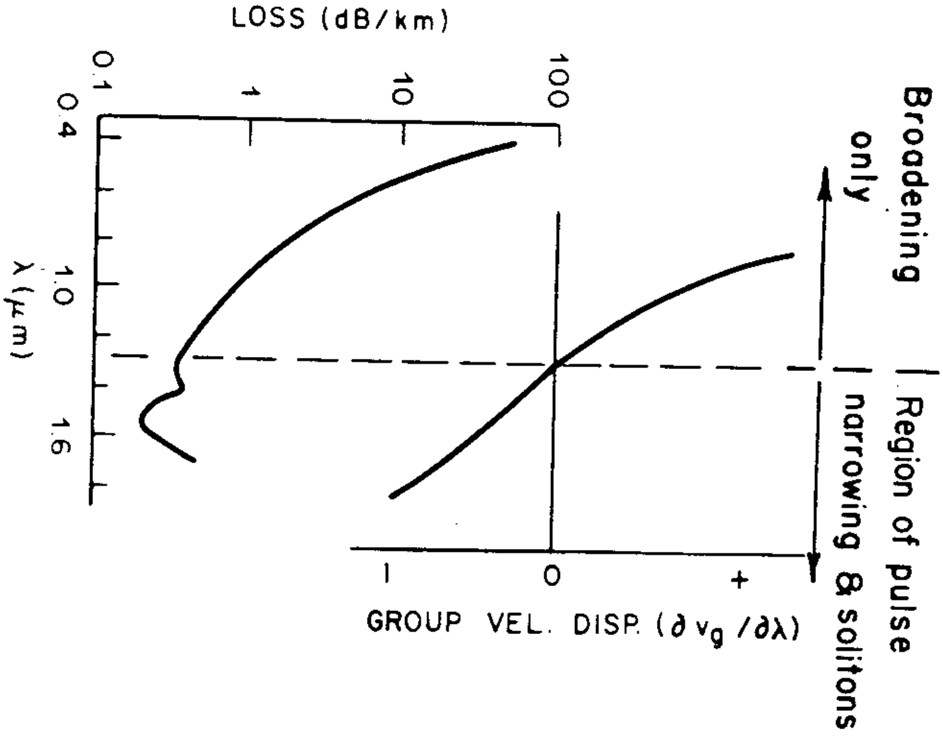
SOLITON:

$$u(z,t) = \operatorname{sech}(t)e^{iz/2}$$

SOLITON UNITS:

Length	Time	Power
$\frac{2}{\pi}z_0 = 0.322\frac{2\pi c}{\lambda^2}\frac{\tau^2}{D}$	$\frac{\tau}{1.76}$	$P_1 = \frac{A_{eff}}{4n_2}\frac{\lambda}{z_0} \propto \frac{D}{\tau^2}$

(For τ=50 ps, D= 16 ps/nm/km, and λ= 1.58 μm, z_0~ 60 km.)



PULSE NARROWING

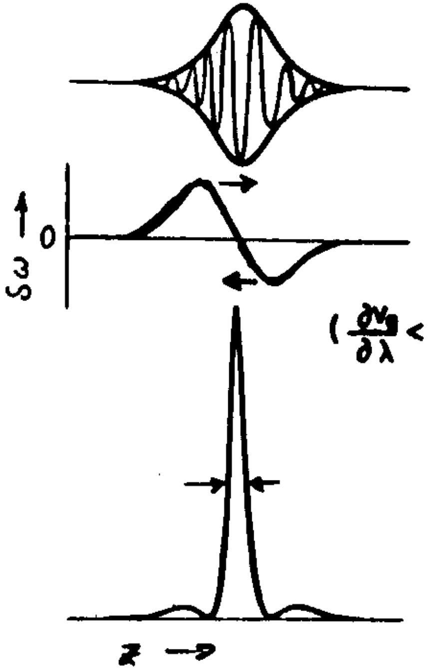
The index is nonlinear:

$$\boxed{n = n_0 + n_2 I}$$

(for quartz glass, $n_2 = 3.2 \times 10^{-16}\ cm^2/W$)

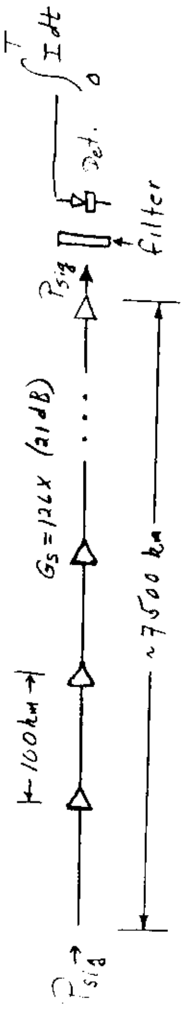
Self Phase Modulation:

$$\boxed{\Delta\Phi = \frac{2\Pi}{\lambda} L n_2 I} \qquad \delta\omega = \frac{\partial\phi}{\partial t}$$



$\left(\frac{\partial v_g}{\partial\lambda} < 0 \Rightarrow \frac{\partial v_g}{\partial\omega} > 0\right)$

The System:



Assumptions:

Fiber: 0.21 dB/km, $A_{eff} = 50 \mu m^2$

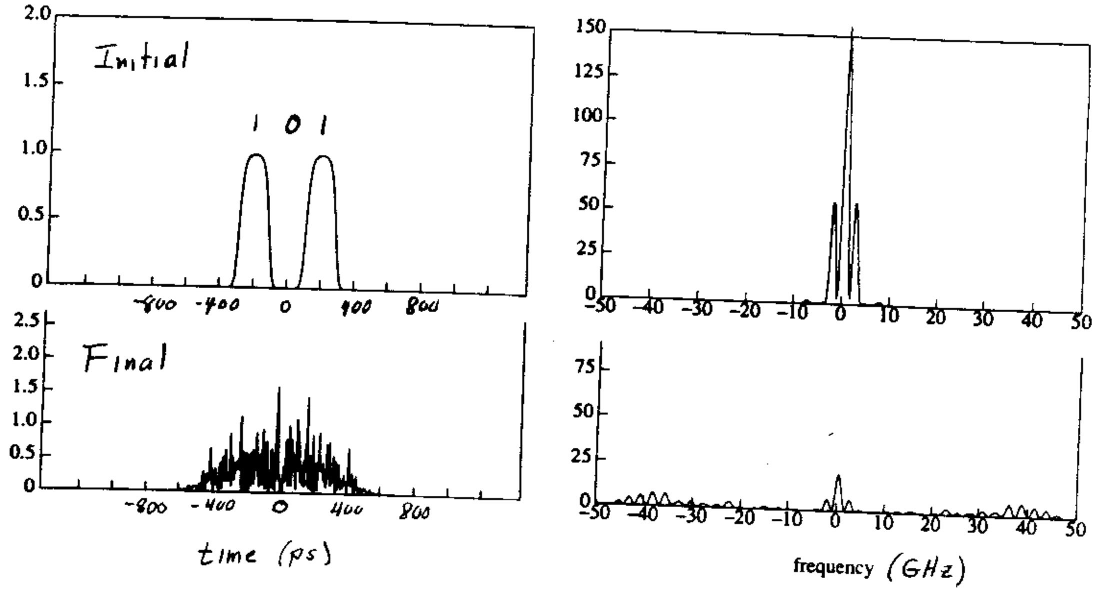
$\delta D = \pm 0.5$ ps/nm/km at random every 20 km

Bit rate (GHz)	$\delta\nu_{filter}$ (GHz)	P_{spont}, into 1/T (μW)	P_{sig}^*, (mW)
5	24	~20	≥3
2.5	12	~10	≥1.5

* Minimum P_{sig}, averaged over the bit period T, required at the detector for Bit Error Rate $\leq 10^{-11}$

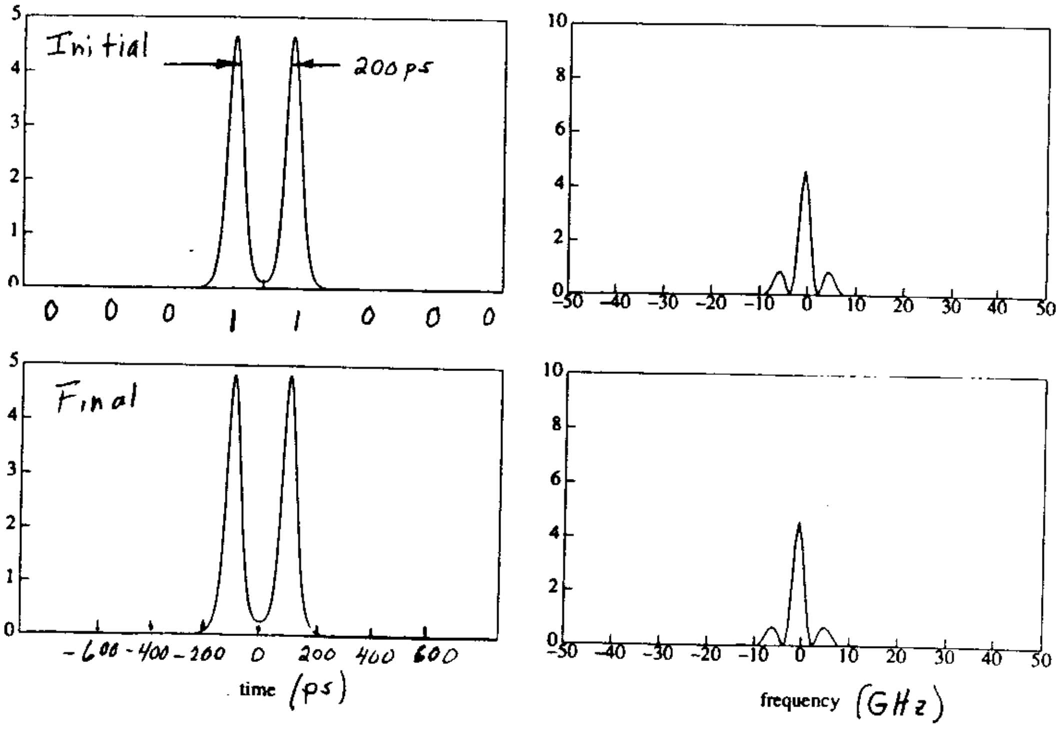
5 GBit/s Trans. over 7500 km – 1 lumped amp./100 km

NRZ @ $\bar{D} = 0$; $\delta D = \pm 0.5$ ps/nm/km



5 GBit/s Trans. over 7500 km: 1 lumped amp./100 km

Solitons @ $\bar{D} = 0.5$ ps/nm/km ; $\delta D = \pm 0.5$ ps/nm/km



AL REVIEW A VOLUME 17, NUMBER 4 APRIL 1978

Self-phase-modulation in silica optical fibers

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Bell Telephone Laboratories, Holmdel, New Jersey 07733

(Received 10 October 1977)

$$\Delta \phi = n_2 I \, 2\pi \, \frac{z}{\lambda} \qquad \left(n_2 = 3.2 \times 10^{-16} \, cm^2/w \right)$$

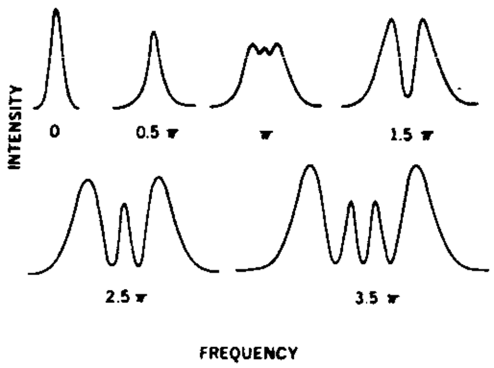
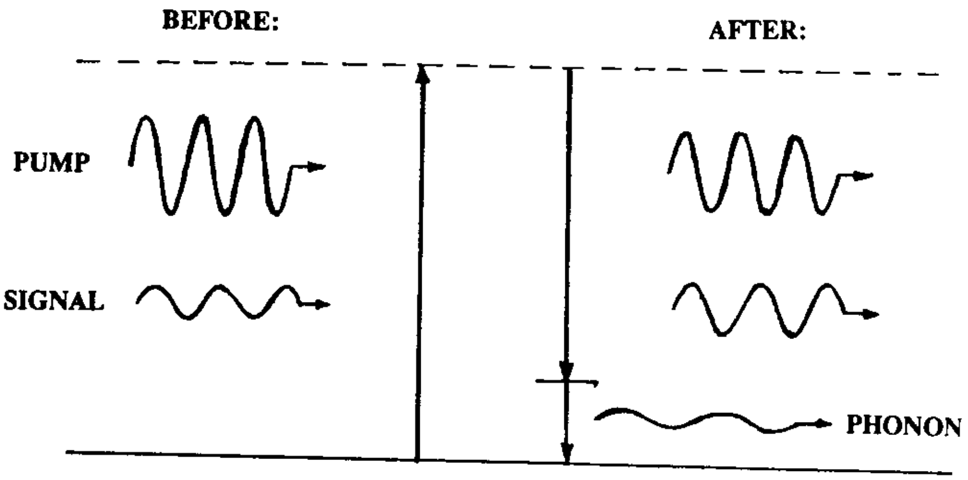


FIG. 3. Calculated frequency spectra for a Gaussian pulse. Spectra are labeled by maximum phase shift at the peak of the pulse.

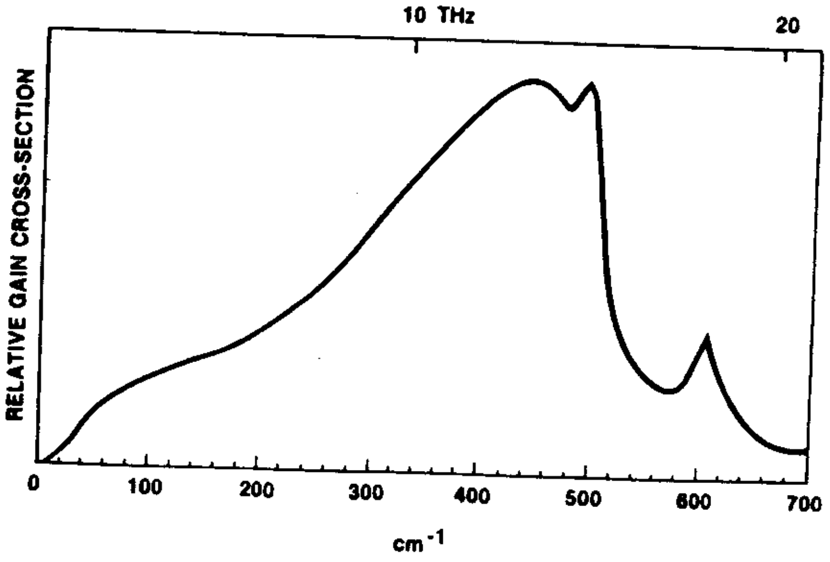
The viewgraphs in this section concern:

OPTICAL AMPLIFICATION AND NOISE

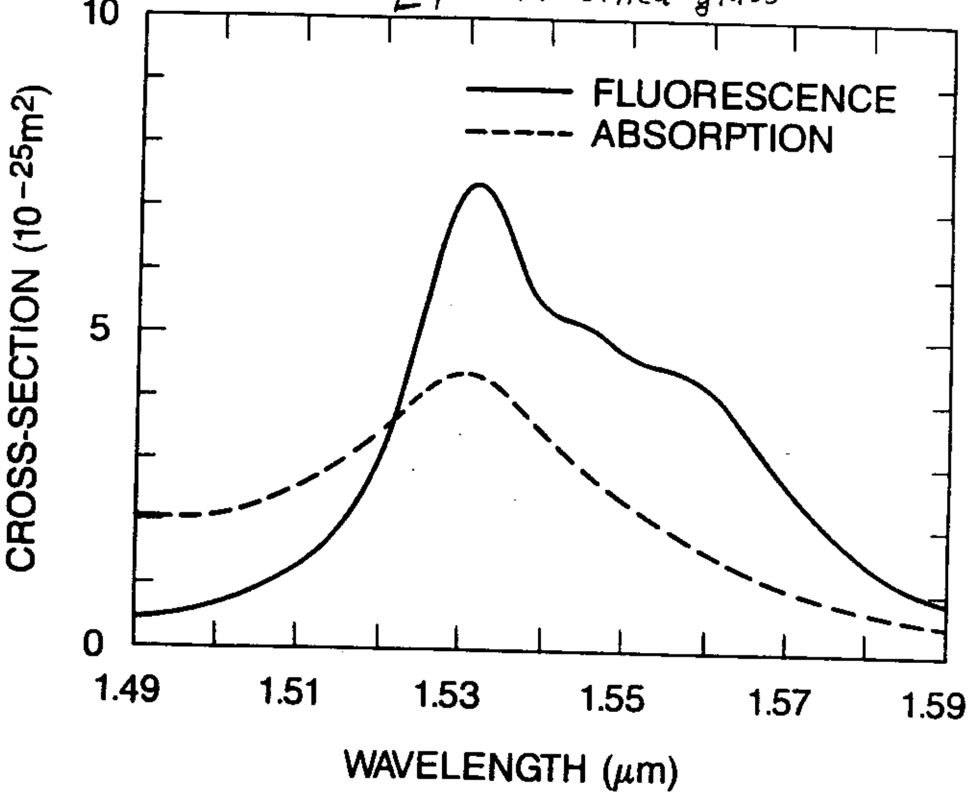
STIMULATED RAMAN EFFECT

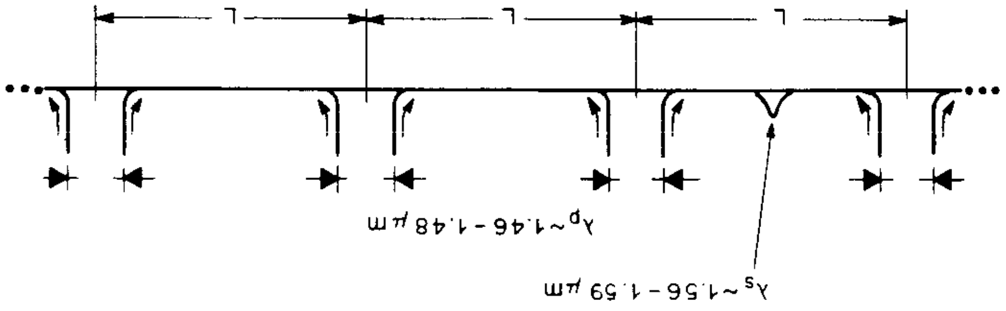


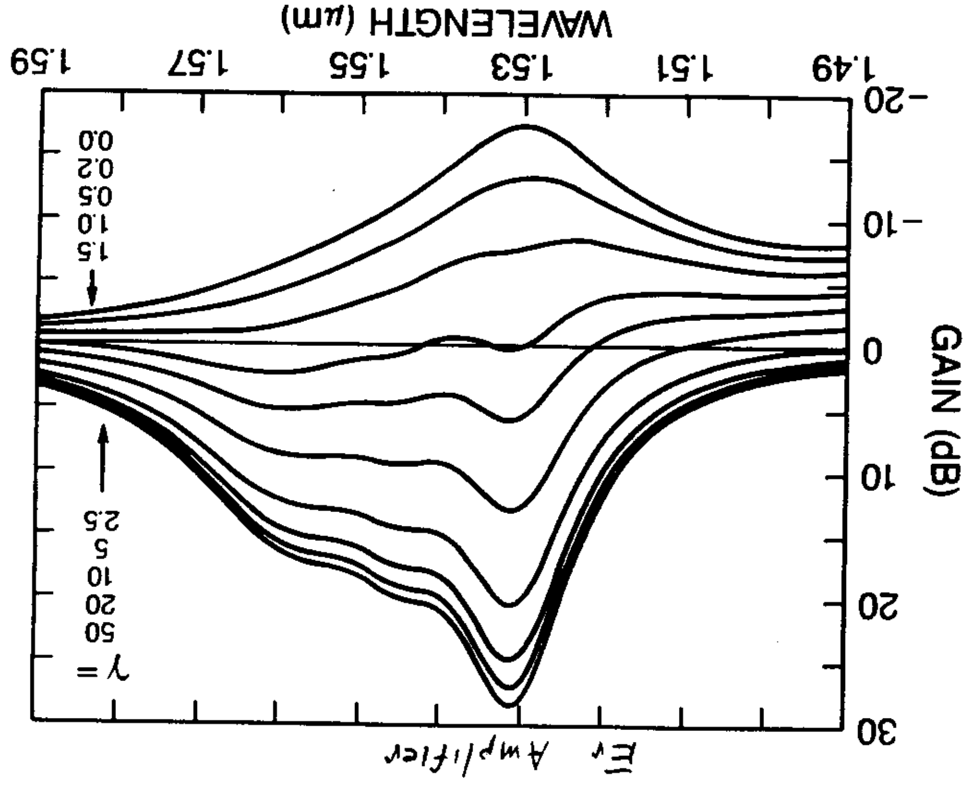
RAMAN GAIN vs PUMP-SIGNAL FREQUENCY SEPARATION



Er^{3+} in silica glass







Er – Raman Distributed Amplifier

Assumptions:

$\lambda_p = 1.47\,\mu m \Rightarrow$ no significant pumping into emission band

$\sigma_a = 1.5 \times 10^{-21}\,cm^2$

$\lambda_s = 1.56\,\mu m$

$\sigma_e = 4.2 \times 10^{-21}\,cm^2$; $\sigma_a = 1.5 \times 10^{-21}\,cm^2$; $\tau = 14\,ms$

$A_{eff} = 0.5 \times 10^{-6}\,cm^2$

Target pump power (into each end of 80km length):

$P_p \sim 50\,mW$ (~25 mW/diode for polarization mult. diodes)

Basic scheme: Choose n such that gain coeff. from largely inverted Er yields $\alpha_g \sim \alpha_{loss} = 0.048/km$ (.21 dB/km)

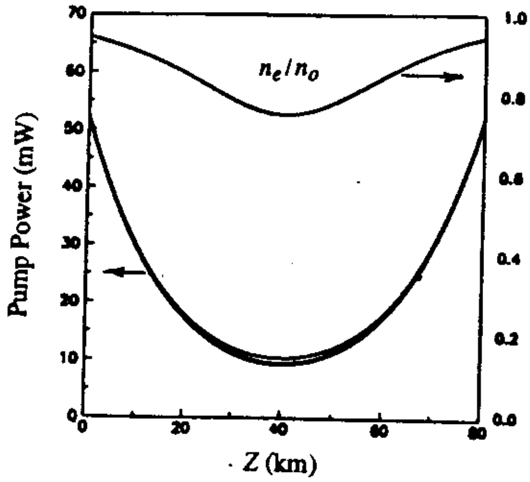
Reduce n where Raman is significant

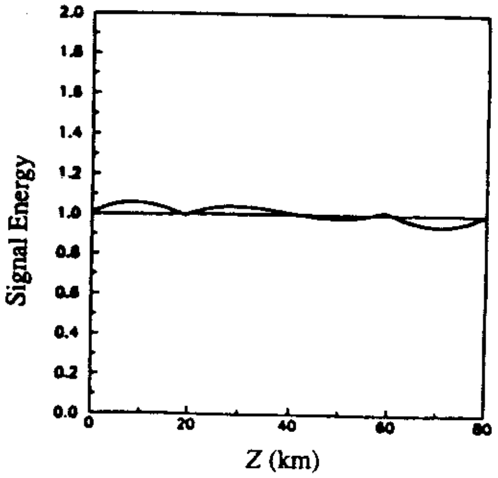
Total gain is about 75% from Er + 25% from Raman

ERBIUM-RAMAN DISTRIBUTED AMPLIFIER

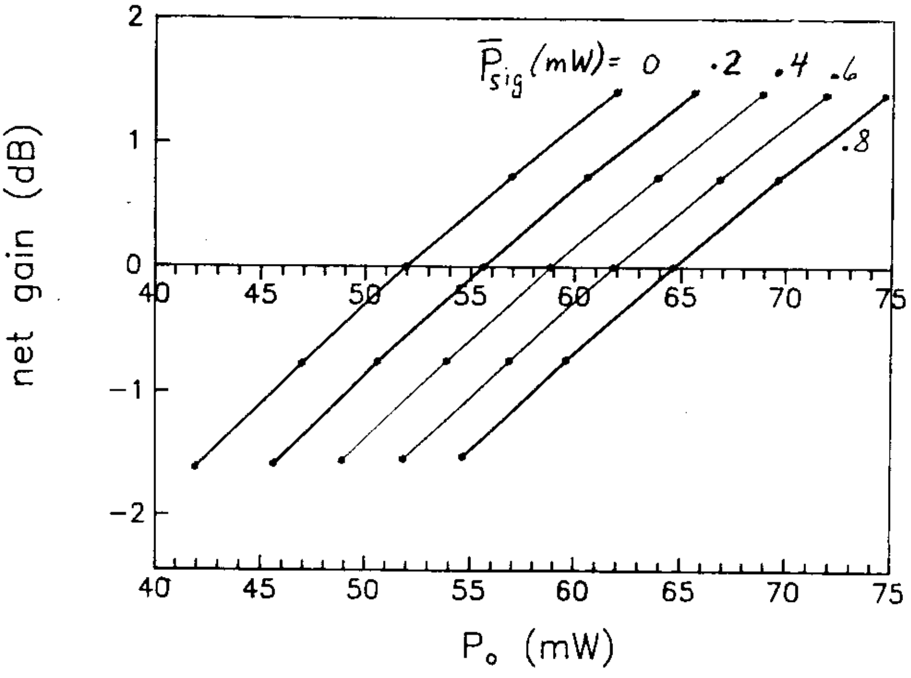
Er conc. = $0.8\times10^{14}/\text{cm}^3$ (0-20 & 60-80 km); $1.4\times10^{14}/\text{cm}^3$ (20-60 km).

Assumes A_{eff} = 50 μm^2; λ_p = 1.48 μm; λ_s = 1.55 μm.

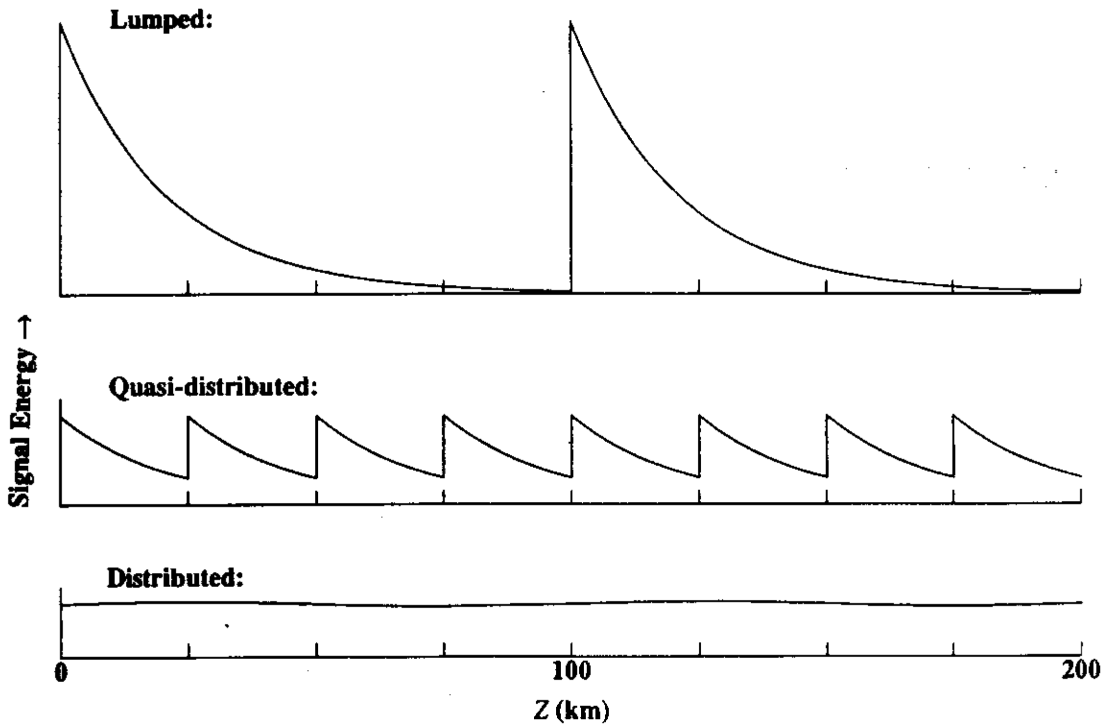




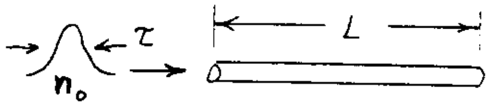
ERBIUM-RAMAN DISTRIBUTED AMPLIFIER



AMPLIFIER SYSTEMS



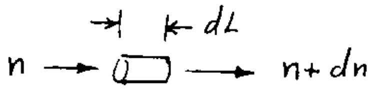
Spontaneous Emission in Optical Amplifiers



$$G = e^{\alpha L}$$

Radiation modes: Choose mode to have same properties (shape, bandwidth, etc) as the pulse itself. Thus, the pulse interacts with just one mode.

Consider an element dL of amp:



$$dn = d(n+1) = (n+1)\,\alpha\, dL$$

Integrating, one obtains:

$$(n+1)_{out} = (n_0+1)\, e^{\alpha L} = (n_0+1)\, G$$

$$\boxed{n_{out} = n_0 G + (G-1)}$$

Temporarily setting $n_0 = 0$, we find that $\bar{n}_{spont} = (G-1)$

(Note: for Er, must mult. $(G-1)$ by $\frac{N_{ex}}{2N_{ex} - N_0}$)

$$P_{spont.} = h\nu (G-1) \frac{1}{\tau} \frac{\delta\nu}{1/\tau} = h\nu \delta\nu (G-1)$$

$n_{spont} = n$ has Boltzmann statistics:

Thus, for $n >> 1$

$$P(n) = \frac{1}{\bar{n}} e^{-\left(\frac{n}{\bar{n}}\right)} \qquad (\bar{n} = G-1)$$

Chain of m amplifiers of gain G_s, each preceeded by loss G_s^{-1}:

$$\bar{n}_{out} = m(G_s - 1)$$

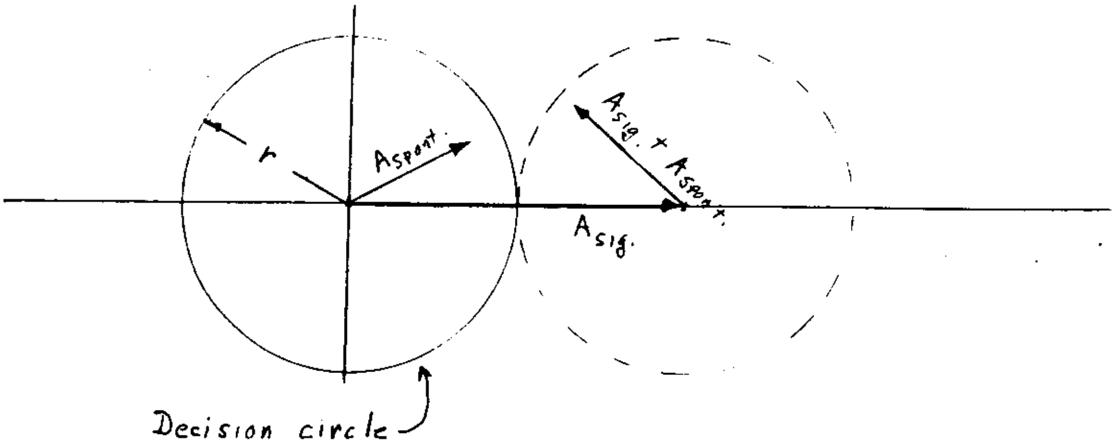
let $\alpha_{loss} z = \ln G = m \ln G_s$

$$\bar{n}_{out} = m\left(G^{\frac{1}{m}} - 1\right) = m\left(e^{\left(\frac{1}{m}\ln G\right)} - 1\right)$$

Distributed gain $\rightarrow \lim_{m \to \infty} = \ln G$

$$\frac{\bar{n}_{lumped}}{\bar{n}_{dist.}} = \frac{m(G_s - 1)}{\ln G} = \frac{G_s - 1}{\ln G_s}$$

Determination of Error Rate:



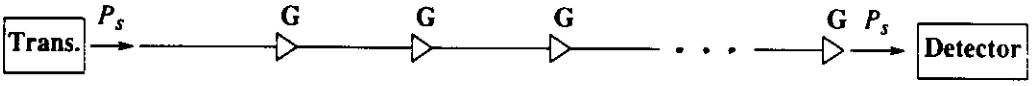
Get min. combined error for $r \cong \frac{1}{2} |A_{sig}|$

$\therefore$, decision level should be at $n_d = \frac{n_{sig}}{4}$

Can show that for error rate $\leq 10^{-m}$,

$$\frac{n_{sig}}{\bar{n}_{spont}} \geqslant 4m \ln 10 = 9.2m$$

AMPLIFIER GAIN PENALTIES



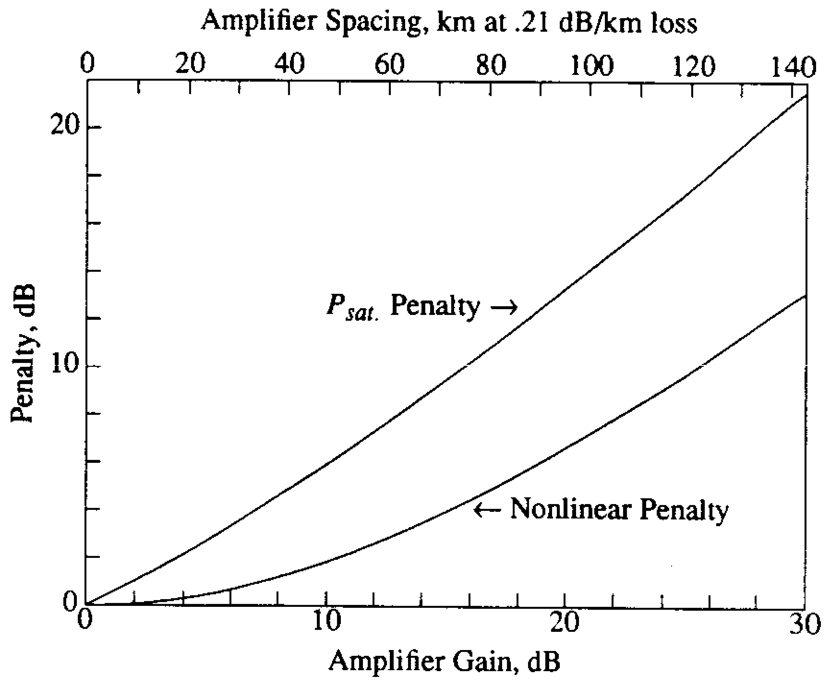
$P_{sat.}$ **Penalty:**

$$\frac{(P_s)_{lump}}{(P_s)_{dist.}} = \frac{ASE_{lump}}{ASE_{dist.}} = \frac{G-1}{lnG}$$

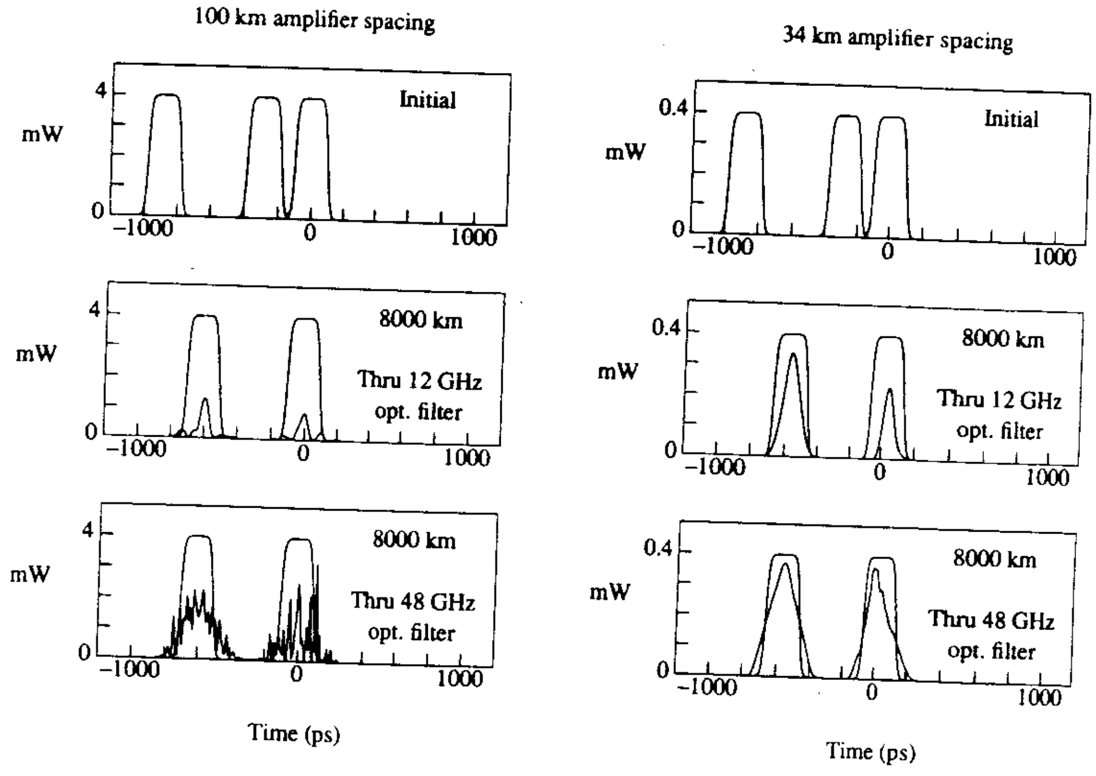
Nonlinear Penalty:

$$\frac{(\overline{P}_s)_{lump}}{(\overline{P}_s)_{dist.}} = \frac{G-1}{lnG} \times \frac{1-G^{-1}}{lnG} = \frac{(G-1)^2}{G(lnG)^2}$$

POWER PENALTIES VS AMPLIFIER GAIN



5 GBit/s WDM with NRZ at λ_0 and $\lambda_0 - \delta\lambda$
$\delta\lambda$ = 1 nm; δD = ±0.5 ps at random every 20 km; D'= 0.07ps/km/nm^2; A_{eff} = 50 μm^2.

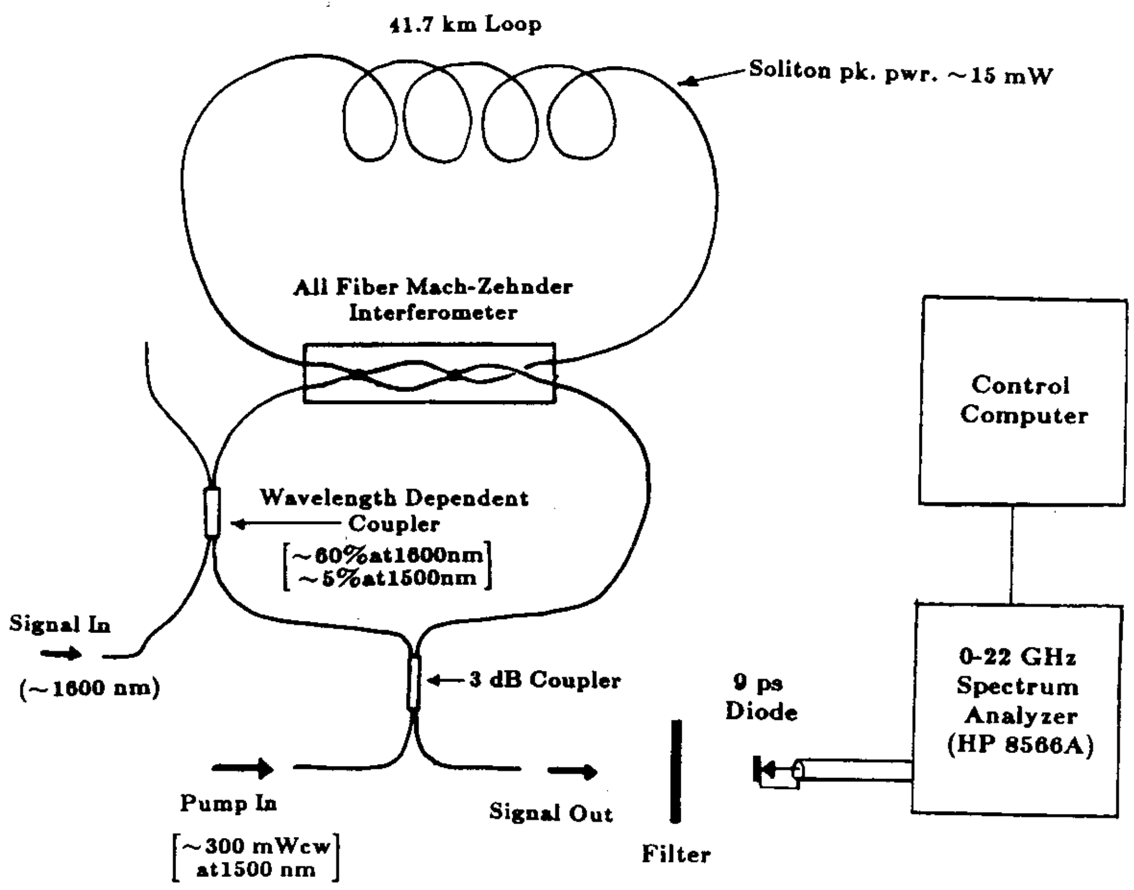


BENEFITS OF
DISTRIBUTED OR QUASI-DISTRIBUTED AMPLIFICATION:

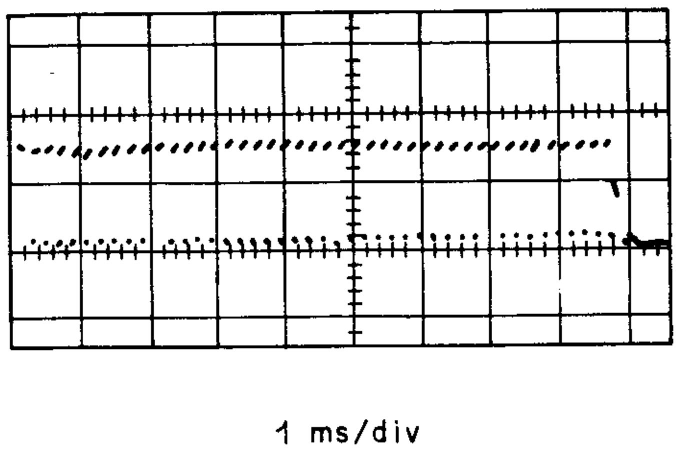
- Provides significant reduction in nonlinear effects and in $P_{sat.}$ for *any* transmission mode.
- These advantages are *required* for trans-oceanic distances.
- The transmission can be *bidirectional.*
- Makes many channel WDM possible with solitons.

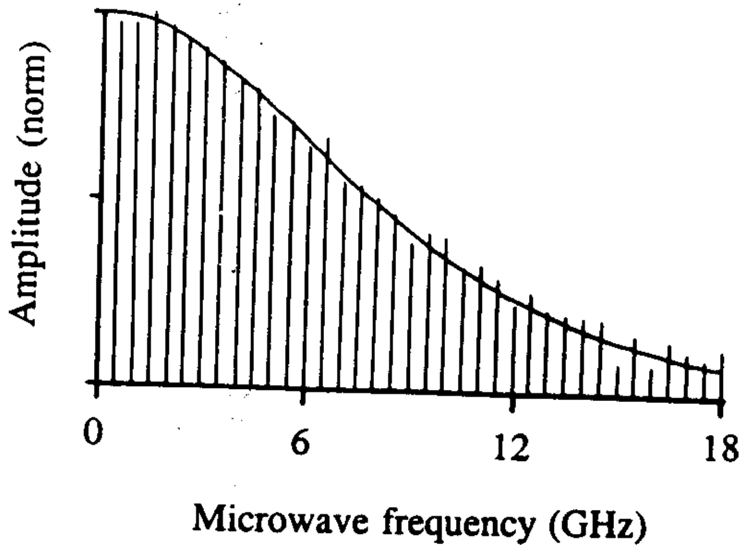
The viewgraphs in this section concern:

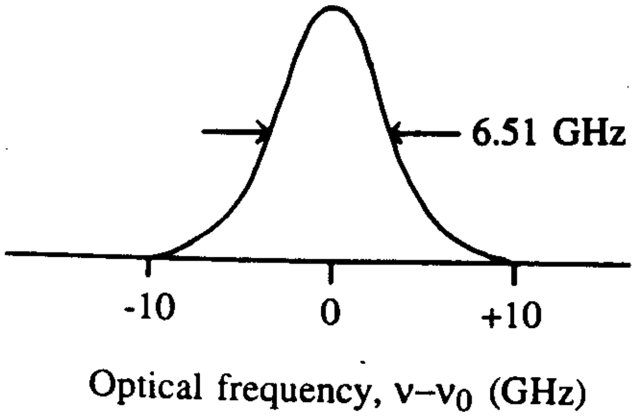
EXPERIMENTAL DEMONSTRATION
OF ULTRA LONG DISTANCE SOLITON TRANSMISSION



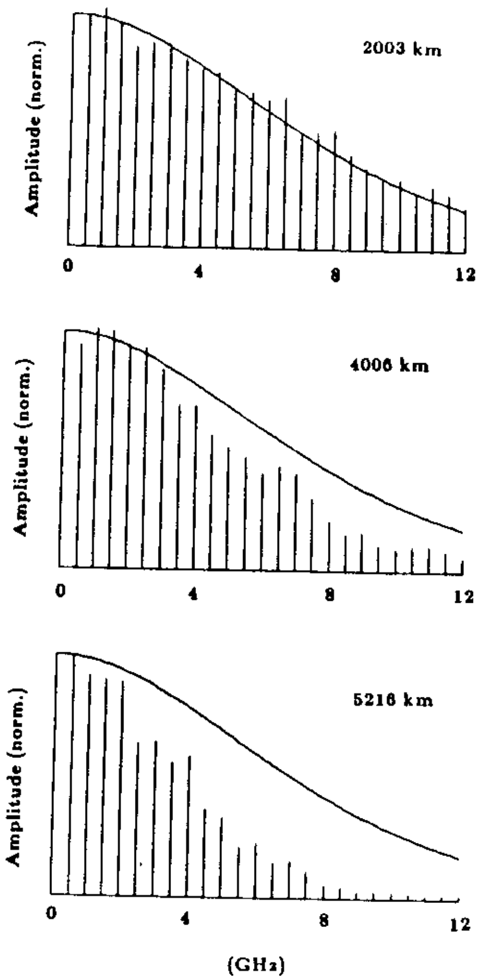
PULSE TRAIN STRENGTH vs ROUND TRIPS





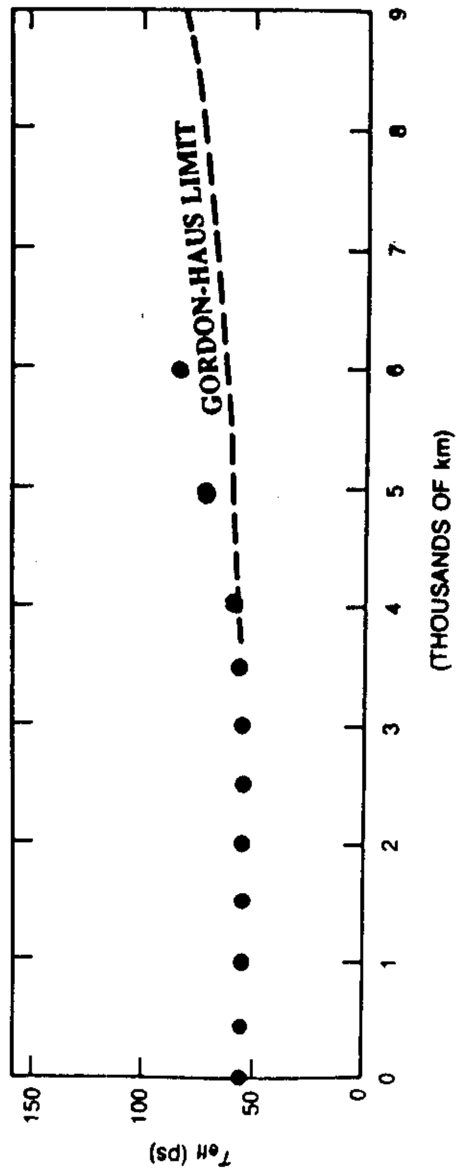


SPECTRA OF 55 ps PULSES



Soliton Propagation Experiment of
L. F. Mollenauer and K. Smith
AT&T Bell Laboratories
Holmdel, NJ
Results of July, 1988

EFFECTIVE PULSE WIDTH vs DISTANCE



THE GORDON-HAUS EFFECT: VARIANCE IN PULSE ARRIVAL TIMES FROM AMPLIFIED SPONTANEOUS EMISSION

Amplified spontaneous emission perturbs the soliton velocities such that at the end of a system of length L, there is a Gaussian distribution in arrival times with the following variance:

$$\frac{\langle(\delta t)^2\rangle}{\tau^2} = \frac{1.763}{9}\, hn_2\, \beta F(G)\, \frac{\alpha_{loss}}{A_{eff}}\, D\, \frac{L^3}{\tau^3}$$

where β is the amplifier spontaneous emission factor, and $F(G) = \frac{1}{G}\left[\frac{G-1}{lnG}\right]^2$. For α_{loss} in km^{-1}, D in ps/nm/km, L in km, and τ in ps, the above becomes:

$$\frac{\langle(\delta t)^2\rangle}{\tau^2} = 4.1376\times10^{-6}\, \beta F(G)\, \frac{\alpha_{loss}}{A_{eff}}\, D\, \frac{L^3}{\tau^3}$$

Example: Let L=9000 km, τ=50 ps, D=1 ps/nm/km, A_{eff}=35 μm^2, $\beta F \approx 1$, and α_{loss}=0.0484/km (0.21 dB/km).
Then from the above, one obtains:

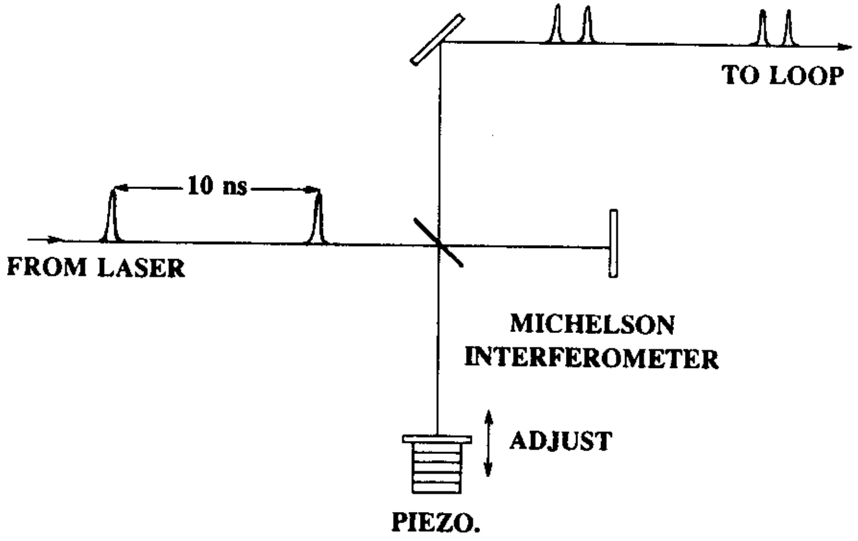
$$\sigma = \langle(\delta t)\rangle^{1/2} = 9.14 \text{ ps}$$

As long as 7σ is less than half the bit period, the error rate from timing jitter will be negligibly small.

The viewgraphs in this section concern:

EXPERIMENTAL STUDY OF SOLITON PAIR INTERACTIONS

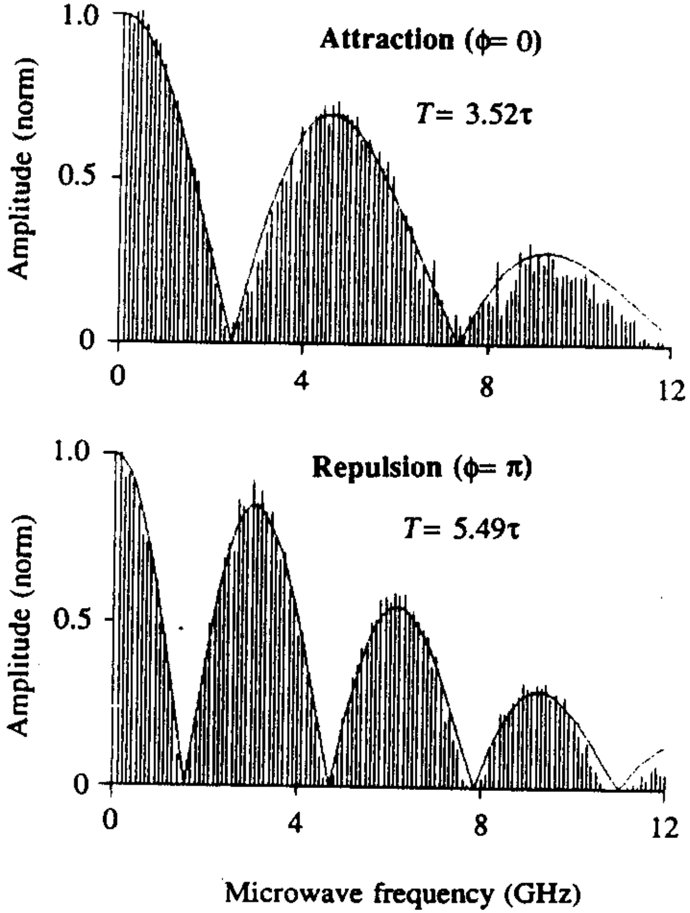
GENERATION OF PULSE PAIRS



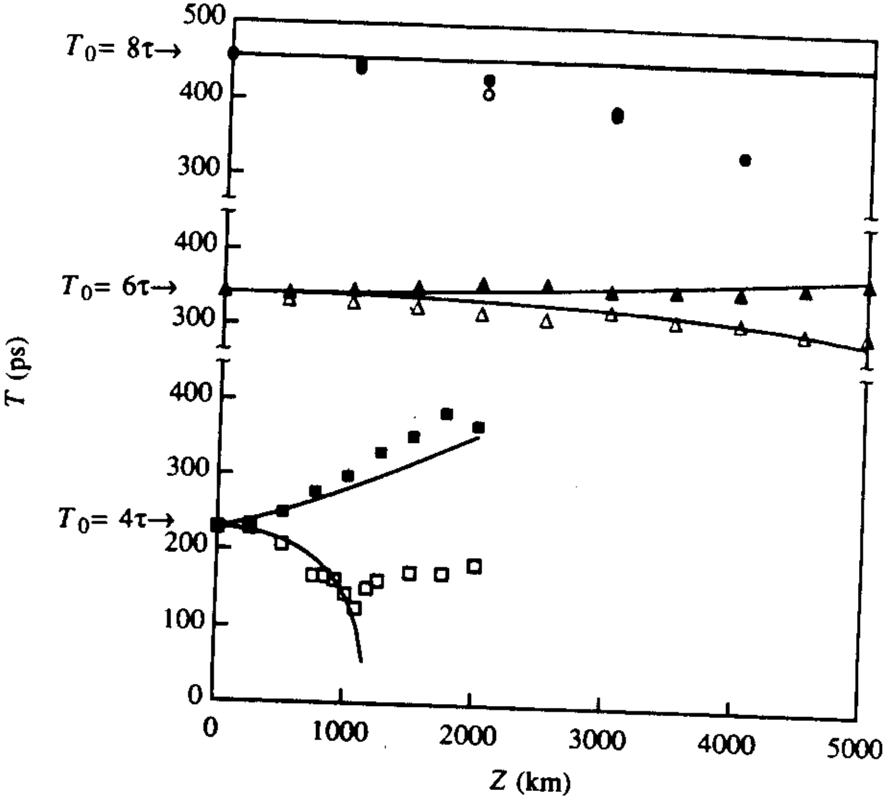
PULSE PAIR SPECTRA

Z=1752 km

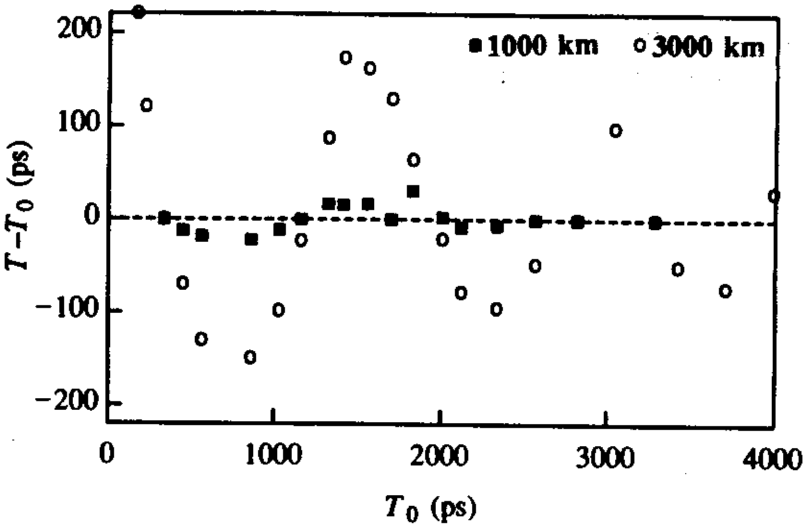
T_0= 4.66τ



PULSE PAIR INERACTION VS Z

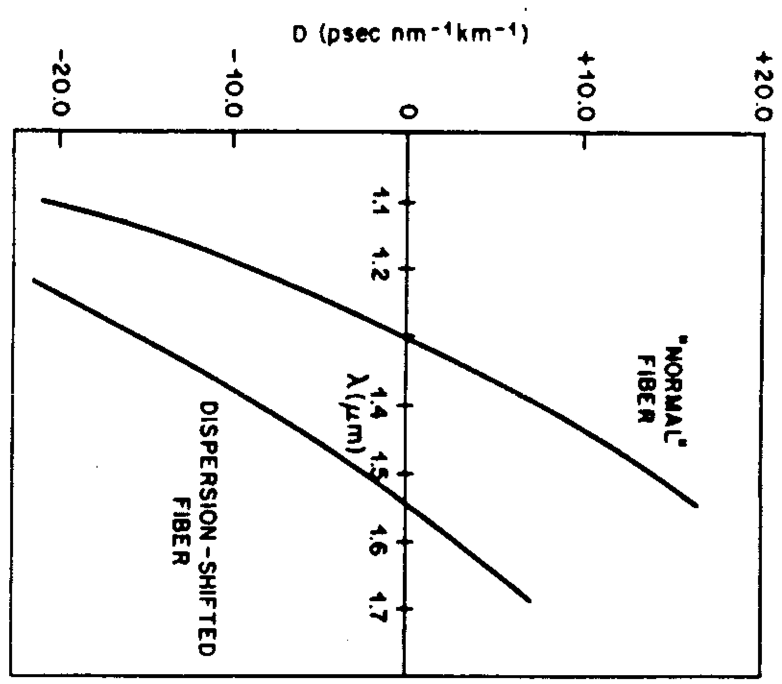


LONG RANGE PAIR INTERACTION



The viewgraphs in this section concern:

ADVANTAGES OF USING DISPERSION SHIFTED FIBER IN SOLITON TRANSMISSION



DISPERSION SHIFTED FIBER AND SOLITONS

Advantages of small D:

- P_{sol} is smaller ($P_{sol} \propto D$).
  => Smaller unwanted nonlinear effects:
  - a) Can space solitons closer together (4-5τ vs 8-10τ).
  - b) Reduced soliton-soliton scattering in WDM.
  - c) Reduced loading on the optical amplifiers.
- Gordon-Haus effect is reduced.
  (Rate-length product scales like $D^{-1/3}$).

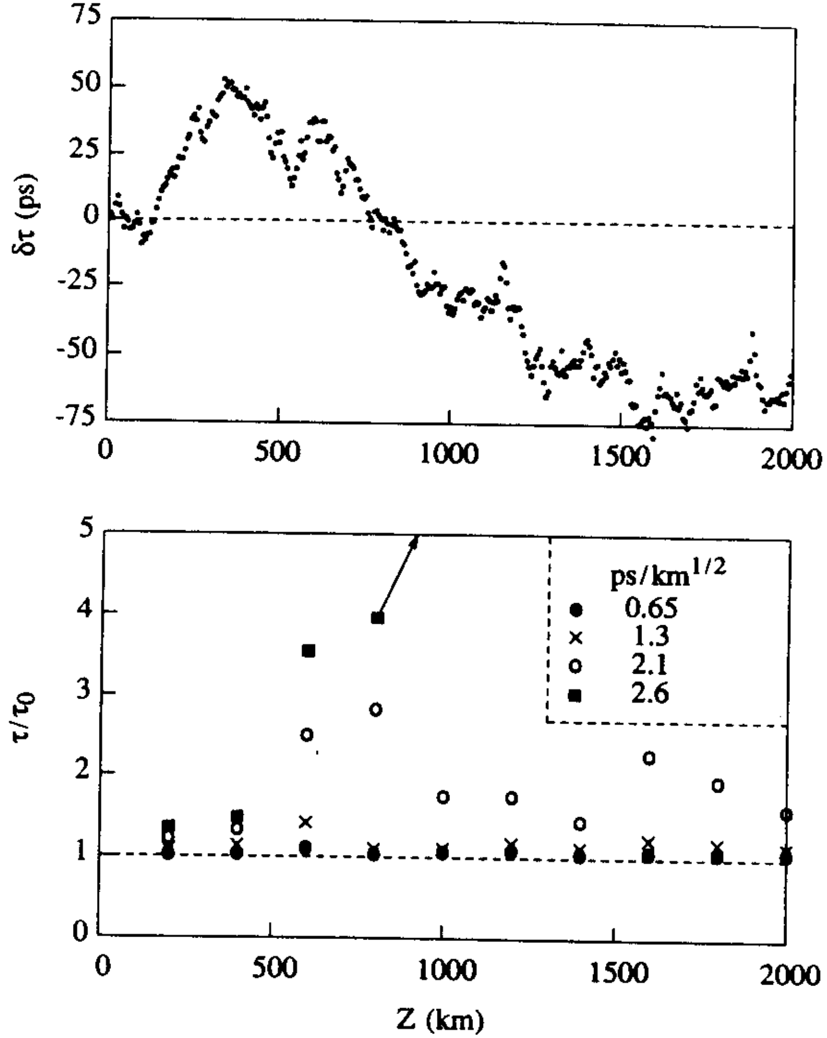
WHAT SETS THE LIMIT TO SMALL D?

- Must have $P_{sol} > 100P_{spont}$ for $< 10^{-9}$ error rate.
- To defeat polarization dispersion, must have

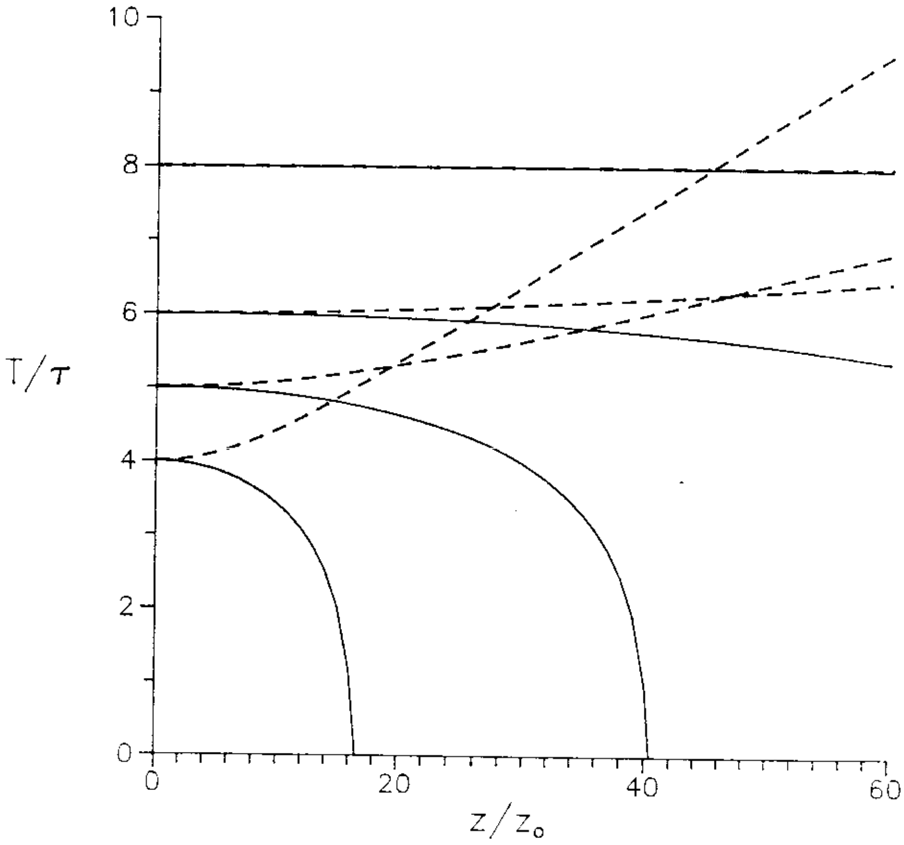
$$\underset{\underset{\text{ps/nm/km}}{\nwarrow}}{0.3D^{1/2}} \geq \underset{\underset{\text{ps/km}^{1/2}}{\uparrow}}{\Delta\beta/h^{1/2}}$$

- Variation in D along length of fiber?

EFFECT OF POLARIZATION DISPERSION ON SOLITONS: COMPUTER SIMULATION

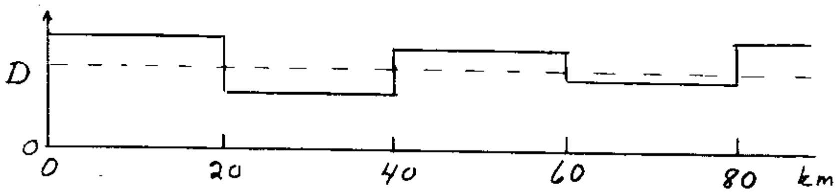


PULSE PAIR INTERACTION VS. Z



EFFECT OF FLUCTUATING *D* ON SOLITONS

In D.S. fiber, typical draw-to-draw variance in *D*
is ≥0.5 ps/nm/km, and typical draw length = 20 km:



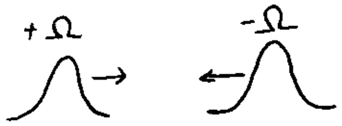
Simulated effect on 50 ps solitons in 7500 km:

$\bar{D}$(ps/nm/km)	δD(ps/nm/km)	$\delta\tau/\tau_0$	Disp. wave rad.	z_0(km)
2	random ±.5	~10%	$<10^{-3.4}$	450
1	random ±.5	~18%	$<10^{-3}$	900
0.5	random ±.5	~29%	$<10^{-2.5}$	1800
0.5	regular ±.5	0	none	1800

The viewgraphs in this section concern:

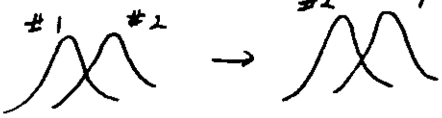
WAVELENGTH DIVISION MULTIPLEXING WITH SOLITONS

Soliton - Soliton Collisions



Eqn. of motion of soliton: $t/t_c = \Omega\, z/z_c$

Length of collision:



$$\delta t = \tau = 1.763\ t_c$$

$$L_{coll.} = 1.763\ z_c/\Omega$$

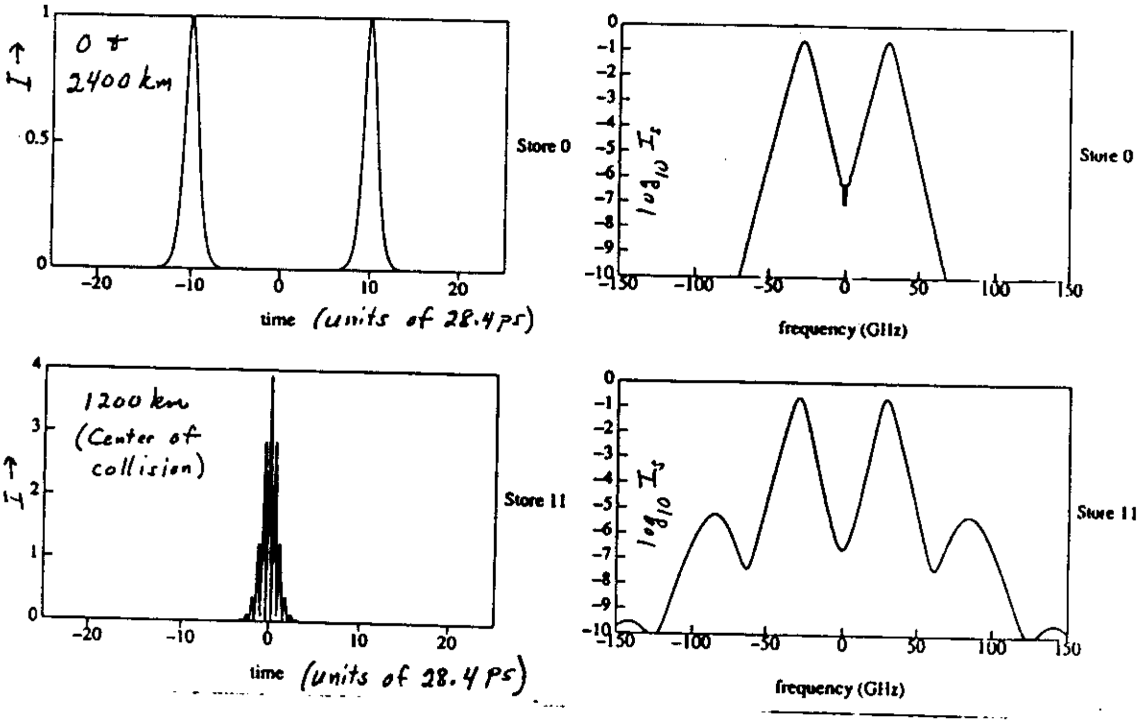
Ω is also a freq, ie, Ω = radians$/t_c$

$$\text{so}\quad f = \frac{\Omega}{2\pi\, t_c}$$

Ex: for $\tau = 50ps$, $t_c = 28.4\,ps$ + $f = 5.6\,\Omega$ GHz

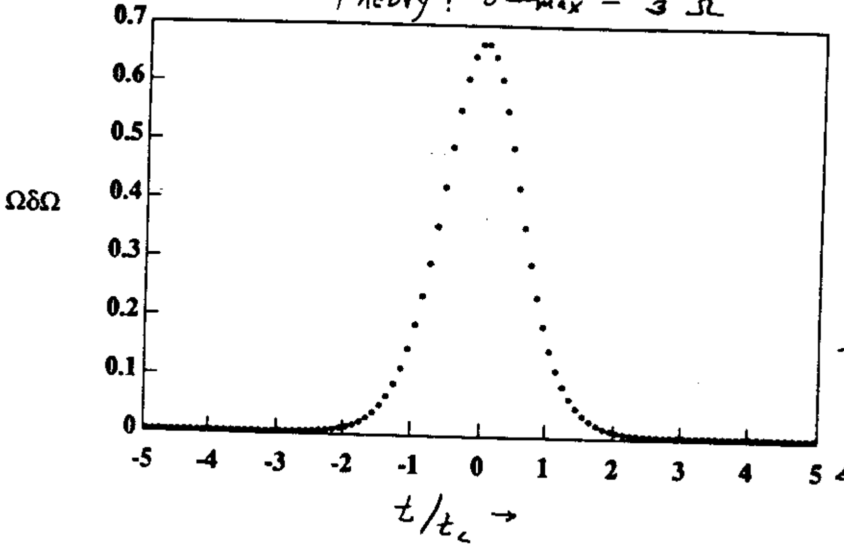
Collision between 50 ps solitons in lossless fiber

$D = 1\,ps/nm/km$; $\Omega = \pm 5$ $(\delta f = \pm 27.5\,GHz)$



VELOCITY CHANGE DURING COLLISION OF SOLITONS

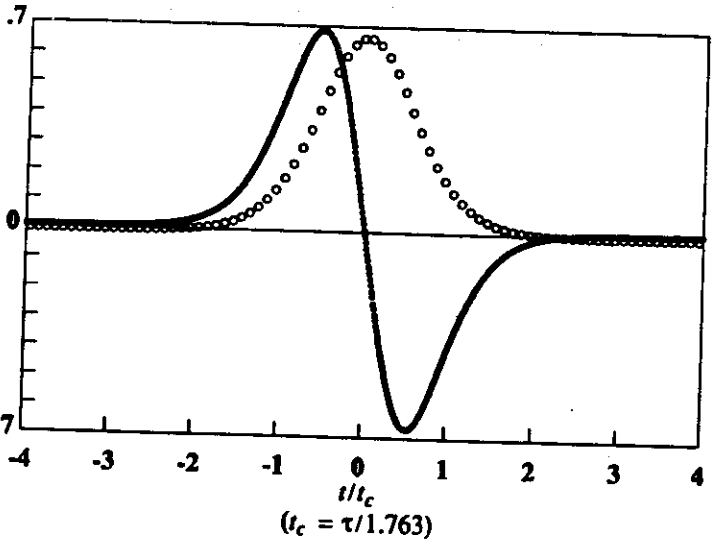
Theory : $\delta\Omega_{max} = \frac{2}{3}\frac{1}{\Omega}$



To get distance scale, mult. by $\leftarrow z_c/\Omega$

$$\delta t = t_c \ln(1 + \Omega^{-2})$$

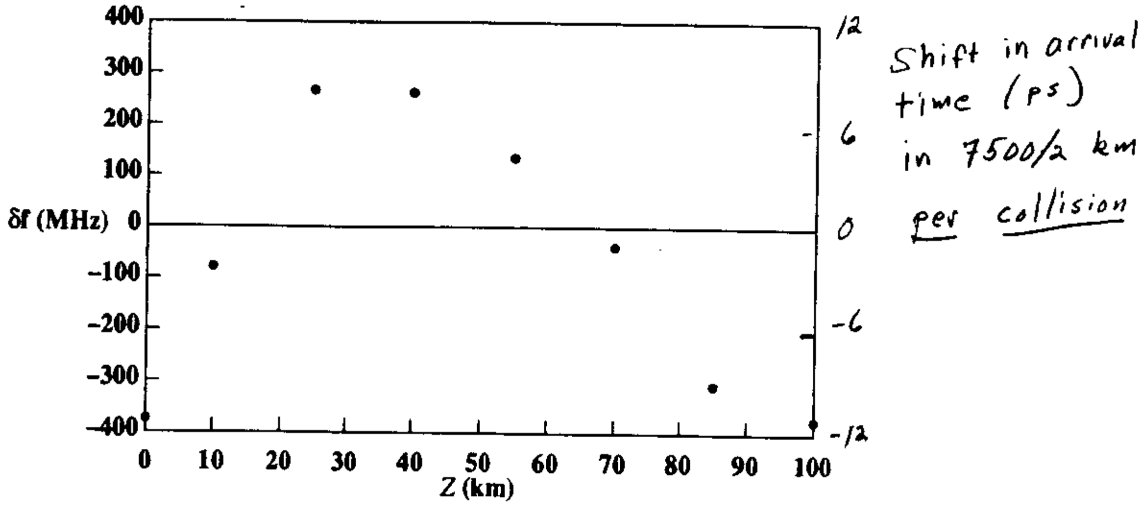
VELOCITY & ACCEL. DURING COLLISION OF SOLITONS



VELOCITY CHANGE DURING COLLISION OF 50 ps SOLITONS
VS POINT IN AMPLIFICATION PERIOD
LUMPED AMPS at 0, 100, 200, ... km.

Velocity determined by average of frequency spectrum.

0.21 dB/km: *D* = 1 ps/nm/km; δλ = 1.9 nm (2Ω = 41.69)

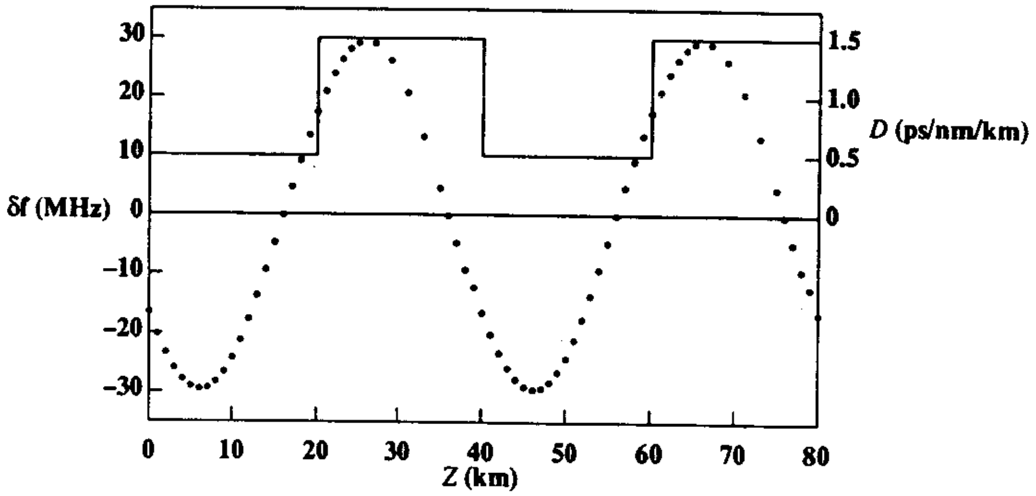


VELOCITY CHANGE DURING COLLISION OF 50 ps SOLITONS VS POINT IN AMPLIFICATION PERIOD

LUMPED AMPS at 0,20,40, ... km.
δD = ±0.5ps/km/nm REGULARLY EVERY 20 km.

Velocity determined by average of frequency spectrum.

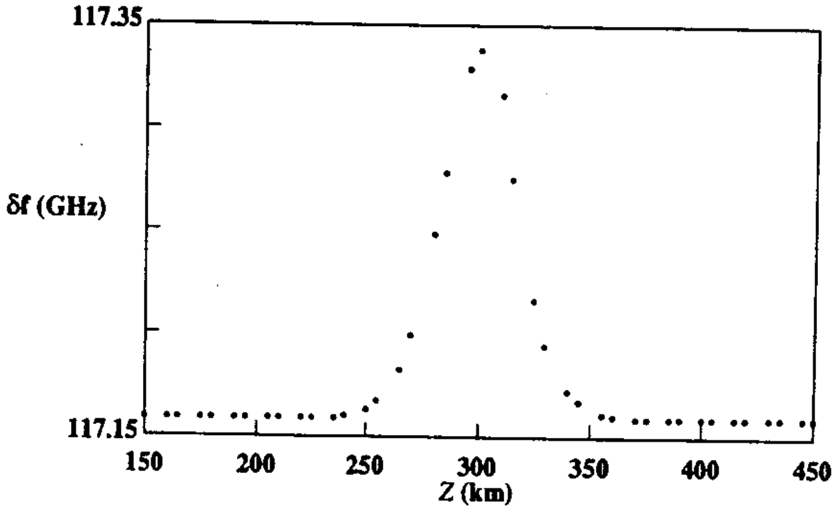
0.21 dB/km: D = 1 ps/nm/km; $\delta\lambda$ = 1.8 nm (2Ω = 40)



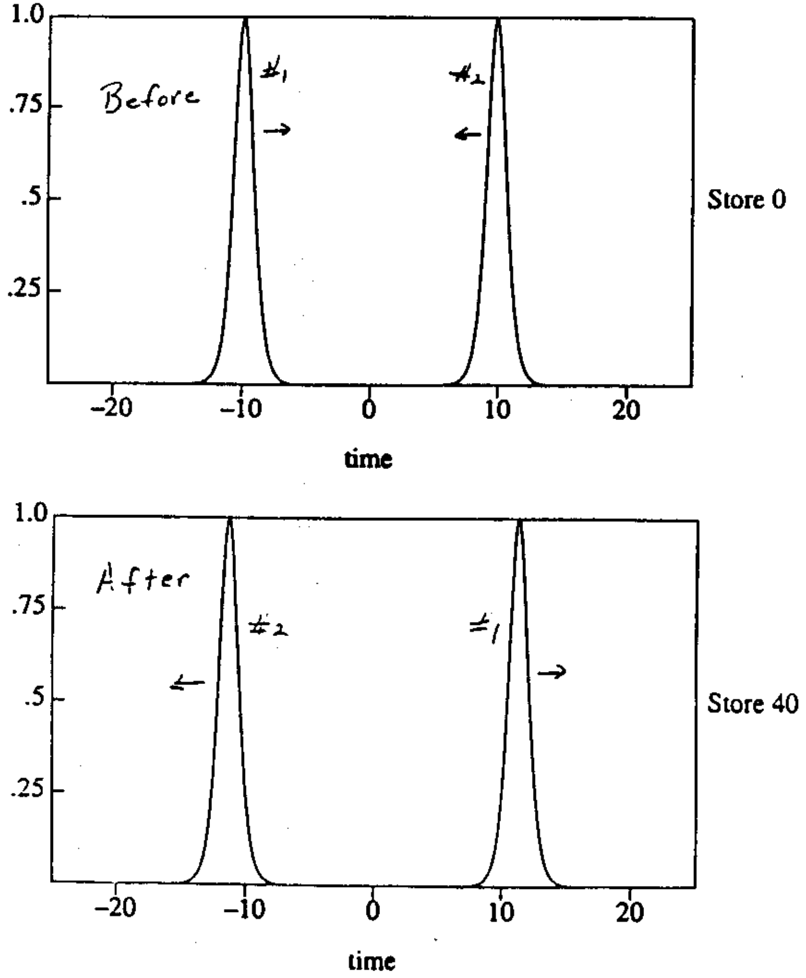
VELOCITY CHANGE DURING COLLISION OF 50 ps SOLITONS AT 0 and 10 km POINTS IN 1 LUMPED AMP/20 km PERIOD.

Velocity determined by average of frequency spectrum.

0.21 dB/km: D = 1 ps/nm/km; $\delta\lambda$ = 1 nm (Ω = 20.88)



50 ps solitons before and after collision
in "quasi-distributed" amp. (1 amp/20km)
$D = 1 ps/nm/km$; $\delta\lambda = 2 nm$ $(\Omega = 20.8)$

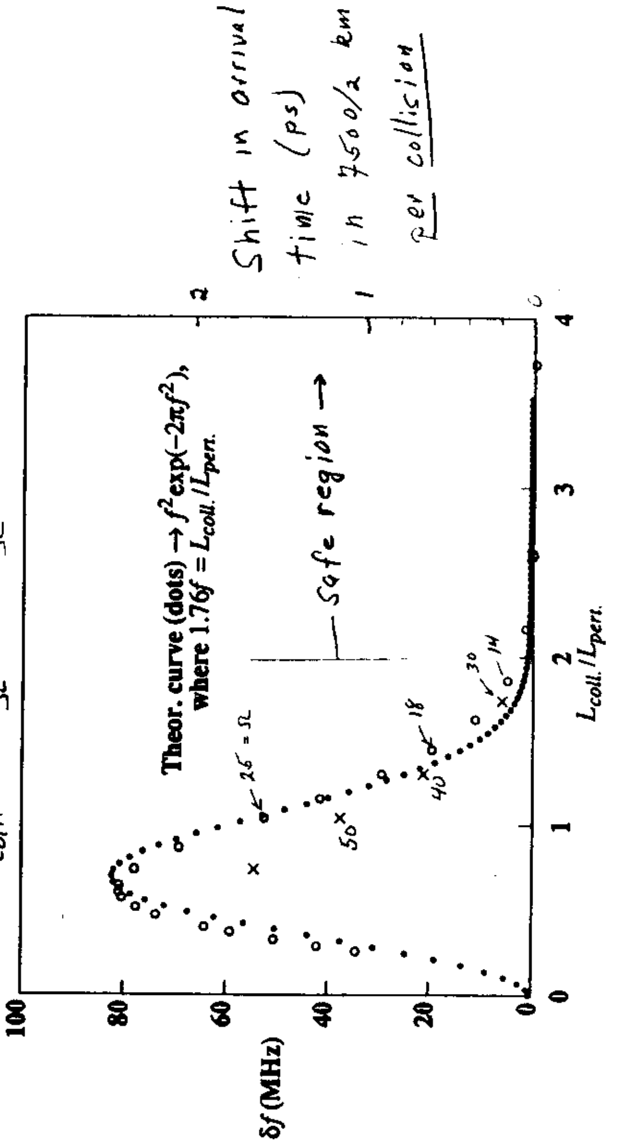


VELOCITY CHANGE DURING COLLISION OF 50 ps SOLITONS VS $L_{coll.}/L_{pert.}$

LUMPED AMPS at 0,20,40, ... km.
$\delta D = \pm 0.5$ps/km/nm REGULARLY EVERY 10 or 20 km.
(Period L_d = 20 (x's) or 40 (circles) km)

0.21 dB/km: D = 1 ps/nm/km

$$L_{coll.} = \frac{1.76\, z_c}{\Omega} = \frac{1042}{\Omega} (km)$$



δt from soliton - soliton collisions:

$\tau = 50\,ps$; 5 GBits/s

$\bar{D}$ (ps/nm/km)	Ω_{min}	δt/coll (ps)	Max # coll. between channels sep. by 2Ω	Mean displacement (ps)
1	6	0.78	21.6	8.4
1	3	3.0	10.8	16
0.5	3	3.0	5.4	8.1

Based on: $\delta t = \frac{\tau}{1.76} \ln\left(1 + \Omega^{-2}\right) \cong \frac{\tau}{1.76} \frac{1}{\Omega^2}$

$$\text{Max \# coll} = \frac{7500\,km}{z_c}\, 2\Omega\, \frac{\tau}{1.76}\, \frac{1}{(200\,ps)}$$

$(z_c = 592\,km$ for $\bar{D} = 1\,ps/nm/km$ + $\tau = 50\,ps)$

WDM WITH 50 PS SOLITONS

5 GBits/s per channel
$\delta D \le \pm 0.5$ ps/nm/km with 40 km period.
Lumped Amps. every 20 km.

$\bar{D}$ (ps/nm/km)	Ω_{min}*	$\overline{\Delta t}_{total}$ (ps)	Gordon-Haus with $P = 10^{-10}$, $\lvert \delta t \rvert \ge$ (ps)	Ω_{max}*	No. of channels	Total bidirectional capacity (GBits/s)	$\Delta\lambda_{total}$ (nm)
1.0	6	8.4	37	12	3	30	1.09
1.0	3	16.0	37	12	5	50	1.09
0.5	3	8.1	26	24	9	90	2.18

*(For 50 ps solitons, $\Omega = 1 \rightarrow \delta f = 5.6$ GHz.)

The viewgraphs in this section concern:

THE EFFECTS OF ASE ON PHASE SHIFT KEYING

NOISE SPECTRUM
$\beta(G-1)h\nu B$

$\frac{1}{2}\beta(G-1)h\nu$ energy/d.o.f.

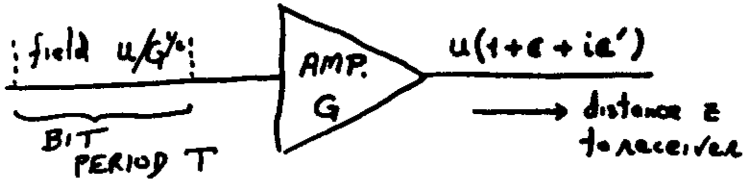
---

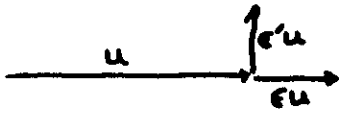
fiber $\phi_{NL} = k_2\overline{P}L$

$k_2 \cong 2.6$ radian/watt/km.

50 μwatt × 8000 km. = 1 radian

NOISE EFFECTS ON PHASE





$$\langle\epsilon^2\rangle = \frac{1}{2}\underset{\wedge}{\overset{\beta}{\,}}(G-1)\hbar\omega/E$$

$E \equiv$ BIT ENERGY

AT AMPLIFIER	AT RECEIVER
$\delta\varphi = \epsilon'$	$\delta\varphi = \epsilon'$
$\delta E = 2\epsilon E$	$\delta\varphi = 2\epsilon\,\varphi_{NL}(z/L)$

AT RECEIVER

$$\langle\Delta\varphi^2\rangle = N\left[\langle\epsilon^2\rangle + \frac{4}{3}\langle\epsilon^2\rangle\varphi_{NL}^2\right]$$

$$\nearrow \underset{\sim}{\propto} E^{-1} \qquad \uparrow \underset{\sim}{\propto} E$$

$$\langle\Delta\varphi^2\rangle_{min} \underset{\sim}{\propto} L^2/T \quad \left[at\ \phi_{NL} = \sqrt{3}/2\right]$$

8000 km
5 G Bit

$$\langle\Delta\varphi^2\rangle_{min} \cong .006\,\beta F(G)$$

$[F = 4.6$ at 20 db gain$]$

NTT expt
OFC PD2 1990

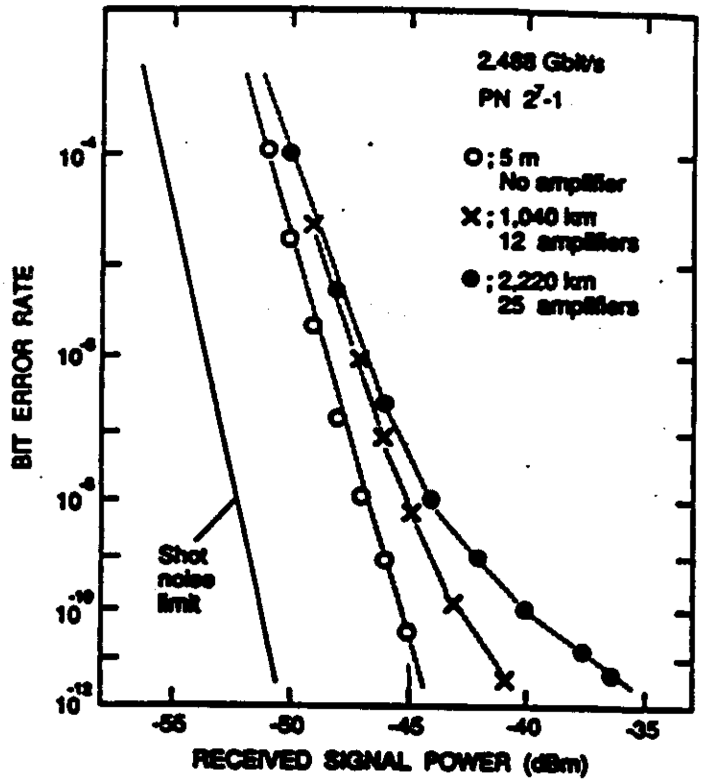
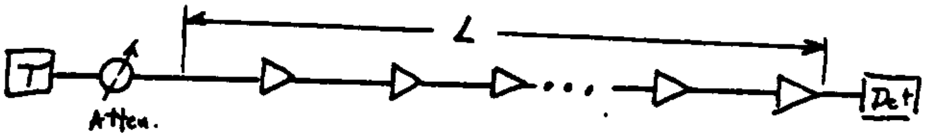
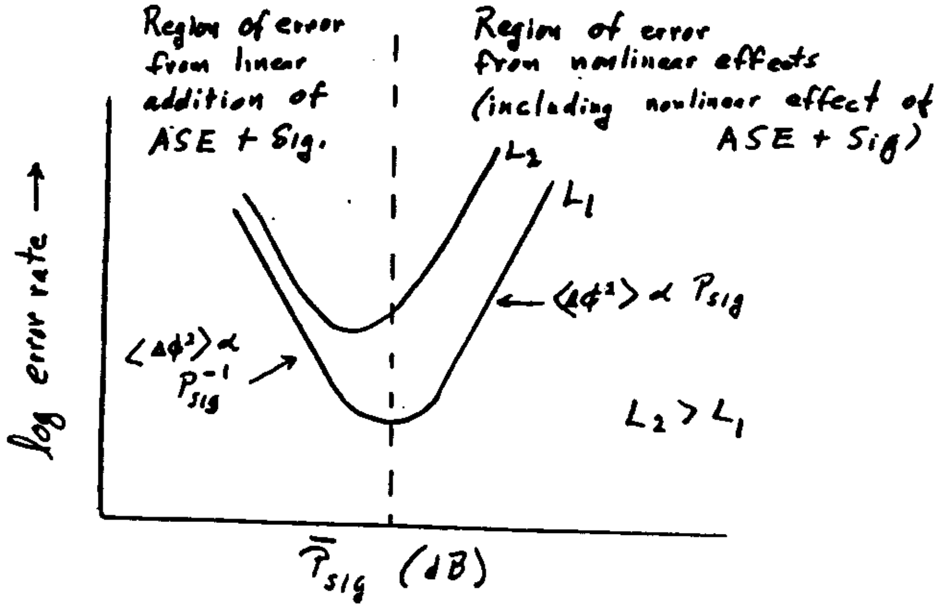


Fig.2. Bit-error-rate performance for 2.488-Gbit/s 2^7-1 pseudo-random bit sequence.

Bit Error Rate Measurement

The better way for a system with amplifiers:





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[1] L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental Observation of Picosecond Pulse Narrowing and Solitons in Optical Fibers," Phys. Rev. Lett. **45**, 1095 (1980)

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[3] J. P. Gordon, "Interaction forces among solitons in optical fibers," Opt. Lett. **8**, 596 (1983)

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[5] L. F. Mollenauer and K. Smith, "Demonstration of soliton transmission over more than 4000 km in fiber with loss periodically compensated by Raman gain," Opt. Lett. **13**, 675 (1988)

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[8] K. Smith and L. F. Mollenauer, "Experimental observation of soliton interaction over long fiber paths: discovery of a long-range interaction," Opt. Lett. **14**, 1284 (1989)