INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

H4.SMR/540-24

Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

Why Solitons are the Right Choice

S. G. Evangelides Jr.
AT&T Bell Laboratories
Holmdel, N.J. USA

ULTRA LONG DISTANCE HIGH BIT RATE OPTICAL COMMUNICATION SYSTEMS

or

WHY SOLITONS ARE THE RIGHT CHOICE

Stephen G. Evangelides Jr.

Linn F. Mollenauer

Mike J. Neubelt

AT&T Bell Laboratories
Crawford's Corner Rd.
Holmdel, N. J.
07733

OUTLINE

I Background; Relevant Optical Fiber Properties

1. Dispersion
2. Loss
3. Nonlinear index n_2
4. Birefirngence

II Impact of Fiber Properties On System Design

A Compensating for Fiber Properties.

1. Dispersion: Solitons or Transmission at λ_o ?
2. Loss compensation: Regenerators or Optical Amplifiers?
a A quick look at Erbium doped fiber amplifiers (EDFAs)
3. Nonlinear Index: ASK vs. PSK and FSK

B Summary of Design Considerations. Choice of best candidate systems.

III Solitons (with frequent comparisons to NRZ)

A What is a Soliton
1 The Nonlinear Schrodinger Equation.

B Ultra Long Distance, High Bit Rate, All Optical Soliton Transmission system.
1. Resistance of solitons to perturbations
2. Effects of Amplifier ASE (the Gordon Haus effect)
3. System performance: Amplifier spacings and Error rates

C Comparison with NRZ

IV Experiments

A The Loop

B Transmission results
1 200 Mhz
2 1.25 GHz
3 2.4 GHz

C Soliton-Soliton interactions
1 Theory
2 Experiments

V Wavelength Division Multiplexing

A Theory and Results of Computer Simulations
B Experimental Results (by Andrikson and Olsson)

VI Conclusions

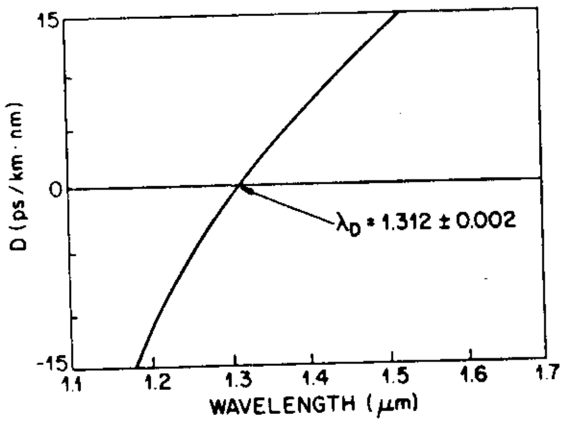
Ultimate System Capacity

DISPERSION

(Group Velocity Dispersion)

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n(\lambda)}{d\lambda^2}$$

$$L_D = 0.322 \cdot \frac{\pi^2 c}{\lambda^2}\frac{\tau^2}{D}$$



D < 0 Normal dispersion regime. Higher frequency (blue shifted, $\nu > \nu_0$) frequency components of a pulse travel slower than the low frequency ($\nu < \nu_0$) components.

D > 0 Anomalous dispersion regime. High frequency components of a pulse travel faster than the low frequency components.

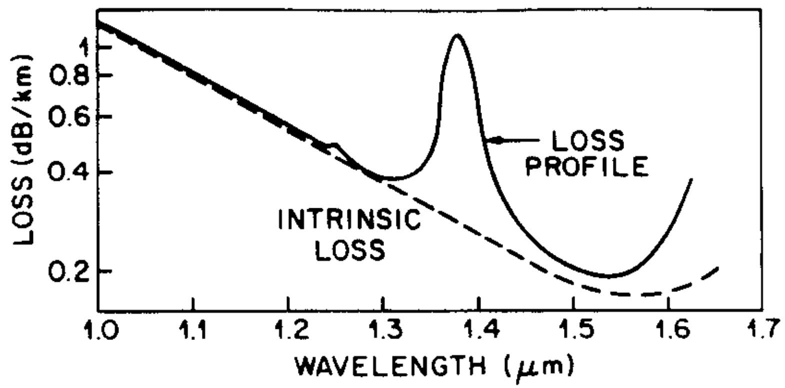
OPTICAL LOSS

$$I(z) = I_0 e^{-\alpha \cdot z}$$

$$\alpha_{Intrinsic} \propto \frac{1}{\lambda^4}$$

(Rayleigh scattering from density fluctuations in fiber)

Typical for good fiber α= 0.20 db/km



NONLINEAR INDEX

$$n = n_0 + n_2(I)$$

$$n_2 = 3.2\times10^{-16}\, cm^2/W$$

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

Where $k_2 = \dfrac{2\pi n_2}{\lambda_0 A_{eff}}$ is the Kerr coefficient.

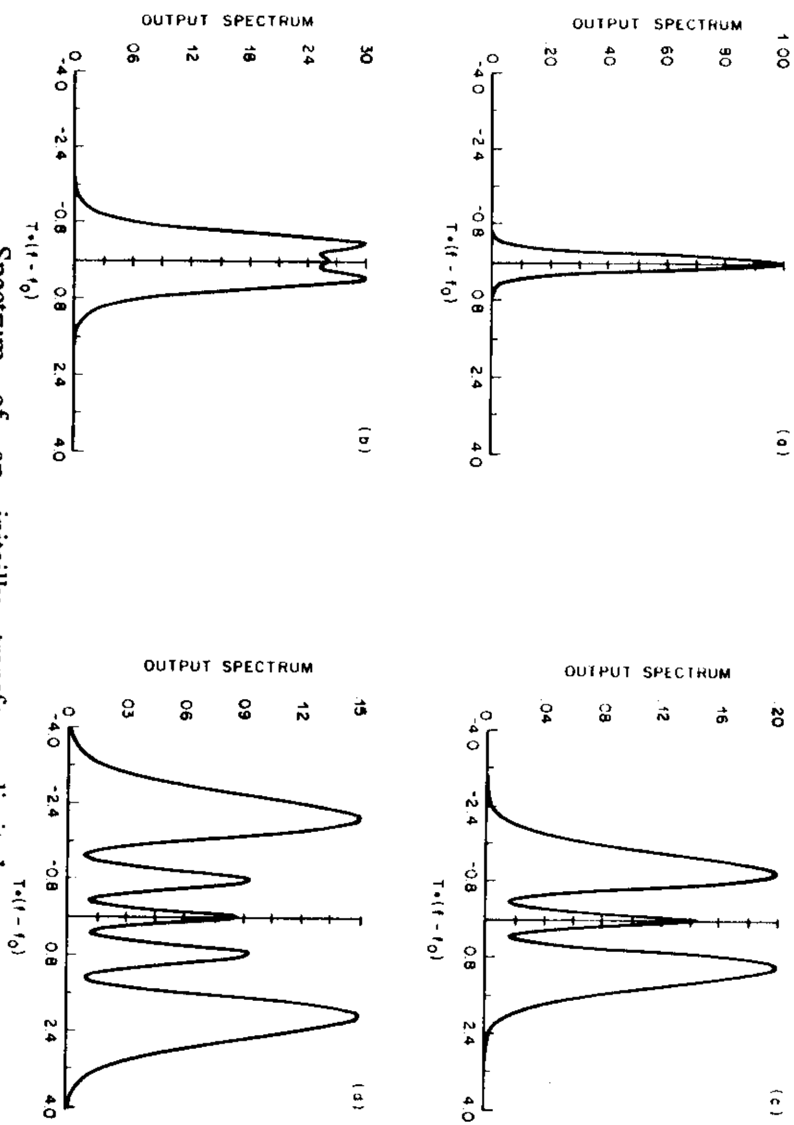
L is the length of the fiber, and P is the optical power.

(typical value $k_2 = 3.7$ radians/W/km)

$$\frac{\partial I}{\partial t} \rightarrow \frac{\partial \phi_{NL}}{\partial t} = \partial\omega$$

(Self Phase Modulation)

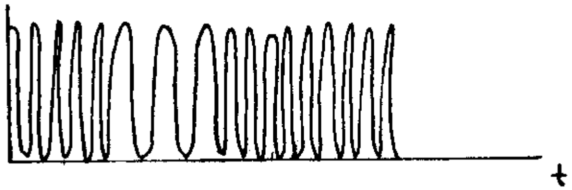
An Example



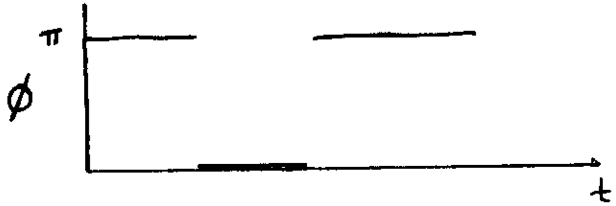
Spectrum of an initailly transform limited Gaussian pulse (a). Spectra of the same pulse with nonlinear phase shifts, $\Delta\phi$, of π (b) 2.5π (c) and 4.5π (d)

Signaling Formats

FSK (Frequency Shift Keyed)



PSK (Phase Shift Keyed)



ASK (Amplitude Shift Keyed)

NRZ (Non Return to Zero)

RZ (Return to Zero)

Compensating for Dispersion

Dispersion Shifted Fiber. Decrease the fiber core size, the waveguide contribution to the dispersion will shift the zero dispersion wavelength. In this way the zero dispersion wavelength can be made to coincide with the wavelength of minimum loss. (1.5 μm). This is a fiber optimized for NRZ, PSK and FSK signaling systems.

Solitons The soltion has an intensity envelope that produces a SPM that exactly cancels the dispersion. The pulse envelope does not change with time. Allows signal to be at 1.5 μm regardless of D.

Compensating Fiber Loss

1. Electronic Regenerators (present technology)

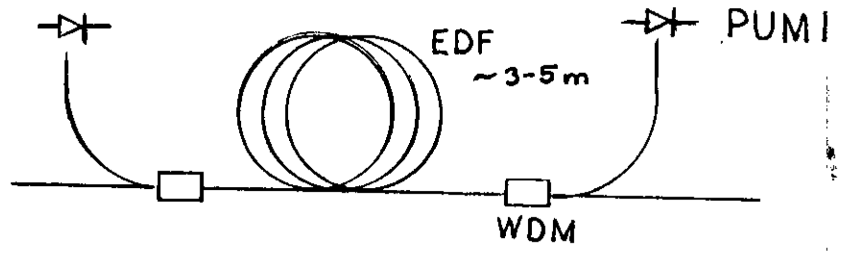
- Complex
- Expensive (cost increases *rapidly* with bit rate.)
- Not upgradable (bit rate is fixed)
- Not easily compatible with WDM
- Unidirectional

2. Optical Amplifiers

- **Semiconductor Amplifiers**
  - Overly sensative to high frequency noise
  - Large excess noise factor
  - Large insertion losses (due to mode mismatching)
  - Gain is polarization dependent
- **Erbium Doped Fiber Amplifiers (Technology of choice for future)**

ERBIUM DOPED FIBER AMPLIFIERS

- Low noise $\beta \simeq 1.2 - 1.5$
- Gain independent of signal polarization
- Can be pumped by semiconductor diode lasers at 1480 nm and 980 nm
- Can be spliced right into the signal fiber spans.
- Long lived upper level lifetime ~ 100 μ sec
- Efficient: gain coefficients of ~ 6db/mW
- Powerful: P_{sat}^{out} of 2.5 dbm at 25 db gain
- Simple and inexpensive!



Effects of Fiber Nonlinear Index

PSK and FSK transmission formats, in an all optical system, experience too much SPM to be useful at high rates for distances more than 2000 km.

ASK formats are the only method that will work for distances of 2000 km or more in an all optical system. NRZ systems are limited to very low power at λ_0. Solitons work the best, since they compensate SPM with dispersion, they are unaffected by the fiber nonlinearity.

Birefringence

NRZ signals become thoroughly depolarized, and on average, will experience some extra broadening.

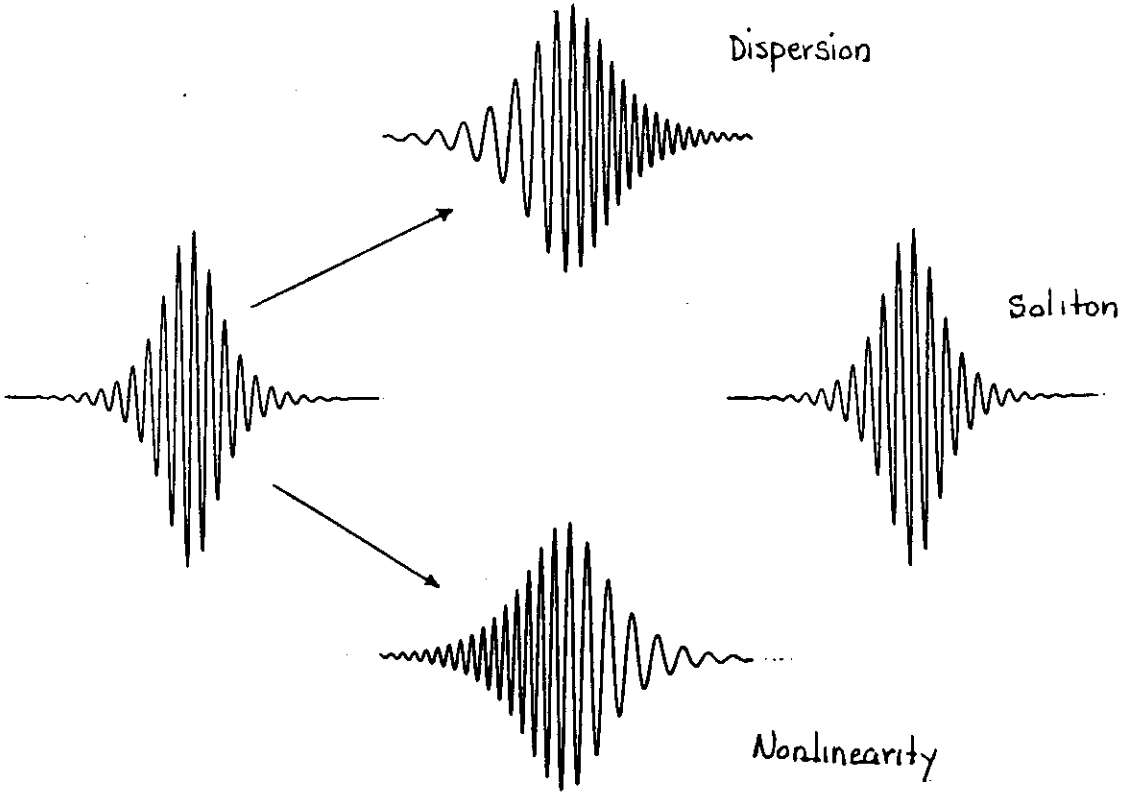
Solitons in birefringent fiber are self trapped so long as $\Delta\beta h^{1/2} \leq 0.3\ D^{1/2}$. If this obtains the soliton will remain in a well defined polarization state and resist the effects of birefringence.

Optimum Design Features for an Ultra Long Distance, High Bit Rate Optical Transmission System

- Use ASK format. (Solitons work best!)
- Use Erbium Doped Fiber Amplifiers
- Use Dispersion shifted fiber, at or near λ_0
- Use fiber with low polarization dispersion $\leq .3\ \mathrm{ps}/km^{1/2}$

What is an Optical Soliton

The exact balance of chromatic dispersion and the self phase modulation due to the small nonlinear index of the glass.



Begin With The Wave Equation

$$\frac{\partial^2 E}{\partial^2 z} = \frac{1}{c^2}\frac{\partial^2 (n^2 E)}{\partial t^2}$$

Consider only the nonlinear index (no dispersion)

$$n = n_o + |E^2| n_2$$

Make the Slowly Varying Envelope Approximation:

$$E = \phi(z,t)\, e^{i(\omega_o t - \beta_o z)}$$

Where $\beta_o = \frac{\omega_o n_o}{c}$

Neglecting second derivatives of ϕ and terms with n_2^2 we g the following propagation equation for the envelope in nonlinear medium.

$$\frac{\partial \phi}{\partial z} + \dot{\beta}_o \frac{\partial \phi}{\partial t} = -i\frac{n_2}{n_o}|\phi|^2 \phi$$

Consider a purely dispersive medium.

The propigation constant is approximated by:

$$\beta=\beta_o+\dot{\beta}_o(\omega-\omega_o)+\frac{1}{2}\ddot{\beta}_o(\omega-\omega_o)^2$$

And the pulse envelope is given by:

$$E=\int_{-\infty}^{\infty} A(\omega)e^{i(\omega t-\beta z)}\,d\omega$$

Again, make the Slowly Varying Envelope Approximation:

$$E=\phi(z,t)e^{i(\omega_o t-\beta_o z)}$$

Substituting into the wave equation we get:

$$\frac{\partial\phi}{\partial z}+\dot{\beta}_o\frac{\partial\phi}{\partial t}=\frac{i}{2}\ddot{\beta}_o\frac{\partial^2\phi}{\partial t^2}$$

Note that the left hand side of each of these equations is the same.

$$\frac{\partial\phi}{\partial z}+\dot{\beta}_o\frac{\partial\phi}{\partial t}=-i\frac{n_2}{n_o}|\phi|^2\phi$$

$$\frac{\partial\phi}{\partial z}+\dot{\beta}_o\frac{\partial\phi}{\partial t}=\frac{i}{2}\ddot{\beta}_o\frac{\partial^2\phi}{\partial t^2}$$

Since the nonlinearity and the dispersion in a typical optical fiber are small the two effects can be considered addative. This gives the proper propagation equation for light in an optical fiber.

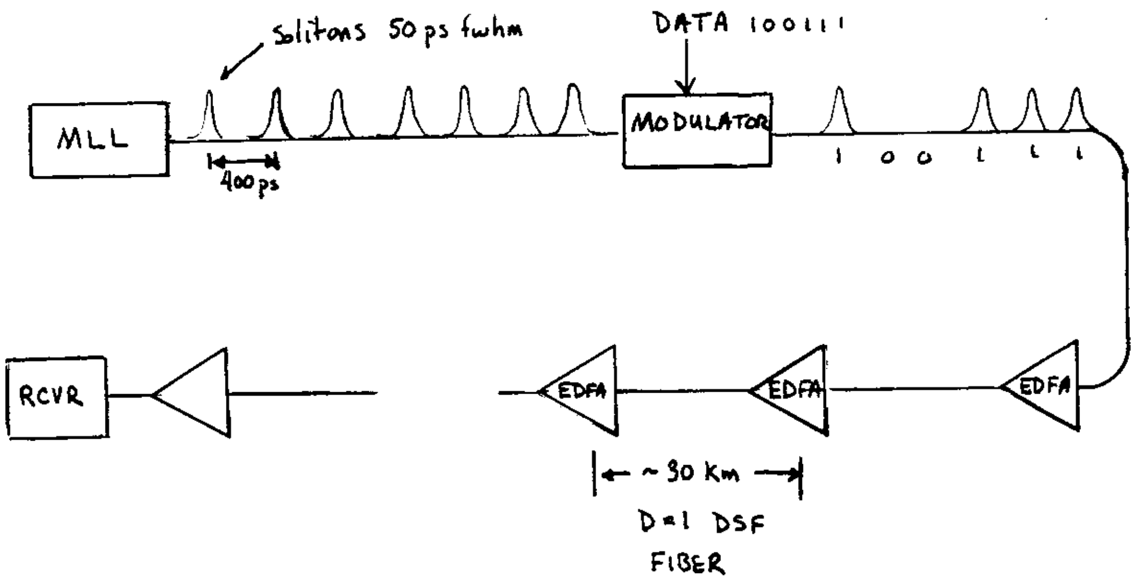
$$\frac{\partial\phi}{\partial z}+\dot{\beta}_o\frac{\partial\phi}{\partial t}=\frac{i}{2}\ddot{\beta}_o\frac{\partial^2\phi}{\partial t^2}-i\frac{n_2}{n_o}\beta_o|\phi|^2\phi$$

If we change to units of retarded time and appropriate distance units we rewrite the above equation in a more familiar form:

$$\frac{\partial u}{\partial z'}=\frac{i}{2}\frac{\ddot{\beta}_o}{|\ddot{\beta}_o|}\frac{\partial^2 u}{\partial t'^2}-i|u|^2u$$

where $t'=\frac{1}{\tau}(t-\dot{\beta}_o z)$ and $z'=\frac{|\ddot{\beta}_o|}{\tau^2}z$

Long Distance Soliton Transmission System



THE NONLINEAR SCHRODINGER EQN:

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

SOLITON:

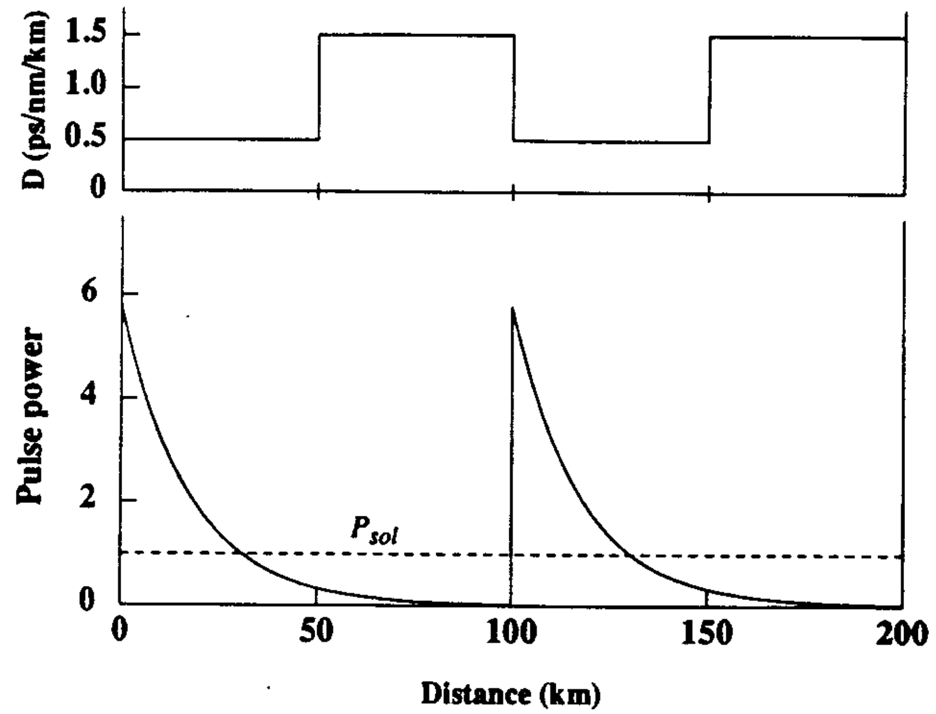
$$u(z,t) = \mathrm{sech}(t)e^{iz/2}$$

SOLITON UNITS:

Length	Time	Power
$\frac{2}{\pi}z_0 = 0.322\frac{2\pi c}{\lambda^2}\frac{\tau^2}{D}$	$\frac{\tau}{1.763}$	$P_{sol} = \frac{A_{eff}}{4n_2}\frac{\lambda}{z_0} \propto \frac{D}{\tau^2}$

(For τ=50 ps, D= 1 ps/nm/km, and λ= 1550 nm, z_0~1000 km.)

SEGMENT OF MODEL SYSTEM FOR TEST OF SOLITON PROPAGATION THROUGH CHAIN OF LUMPED AMPS AND D.S. FIBER



Note: L = 100 km is several times greater than would be chosen for low accumulated ASE noise.
Thus, the test is an especially rigorous one.

LONG DISTANCE SOLITON PROPAGATION USING LUMPED AMPLIFIERS AND DISPERSION-SHIFTED FIBER

Let L be the "amplification period" (span between amplifiers).

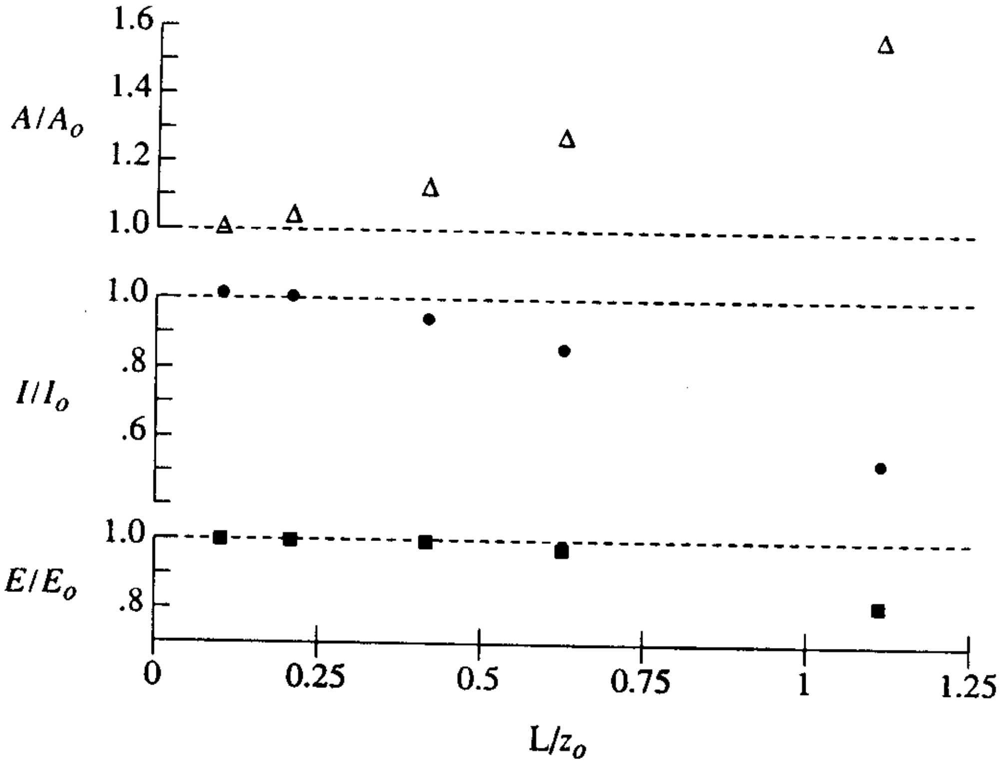
For $L \ll z_0$, essentially nothing happens to the pulse shape and width over one period L.

The nonlinear effect over each L is determined by the corresponding path-average power.

Thus, if the path-average power is equal to the usual soliton power over each period, one has a perfectly well behaved soliton.

In like manner, by keeping the path-average D constant from one period to the next, solitons can also tolerate considerable variation in D over distances $\ll z_0$.

Effects of Periodic Perturbations on Long Distance Soliton Transmission

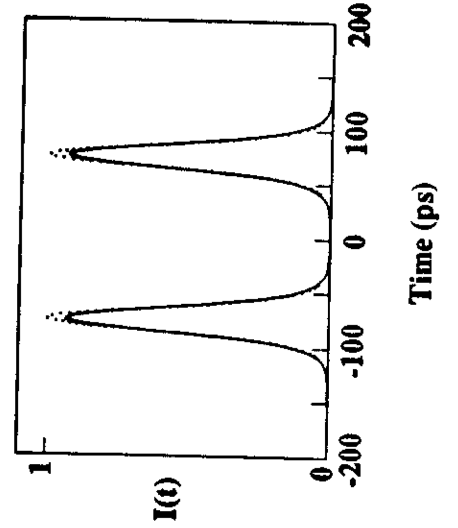


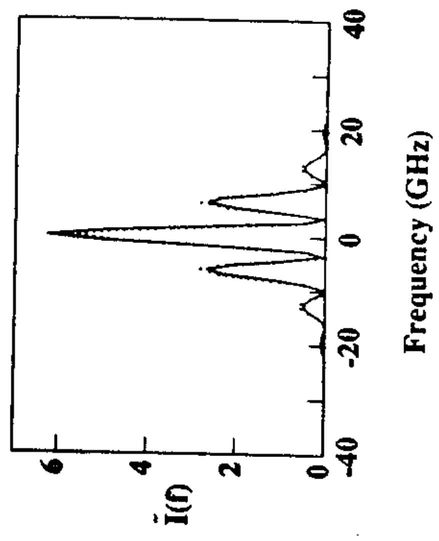
L is the length of one period of the perturbation.

NUMERICALLY SIMULATED SOLITON TRANSMISSION OVER 9000 KM THROUGH CHAIN OF LUMPED AMPS AND D.S. FIBER AT 1550 nm

$\tau = 25$ ps and $\bar{D} = 1$ ps/nm/km => $z_0 = 250$ km; L = 100 km
(D steps back and forth every 50 km between 0.5 and 1.5 ps/nm/km.)

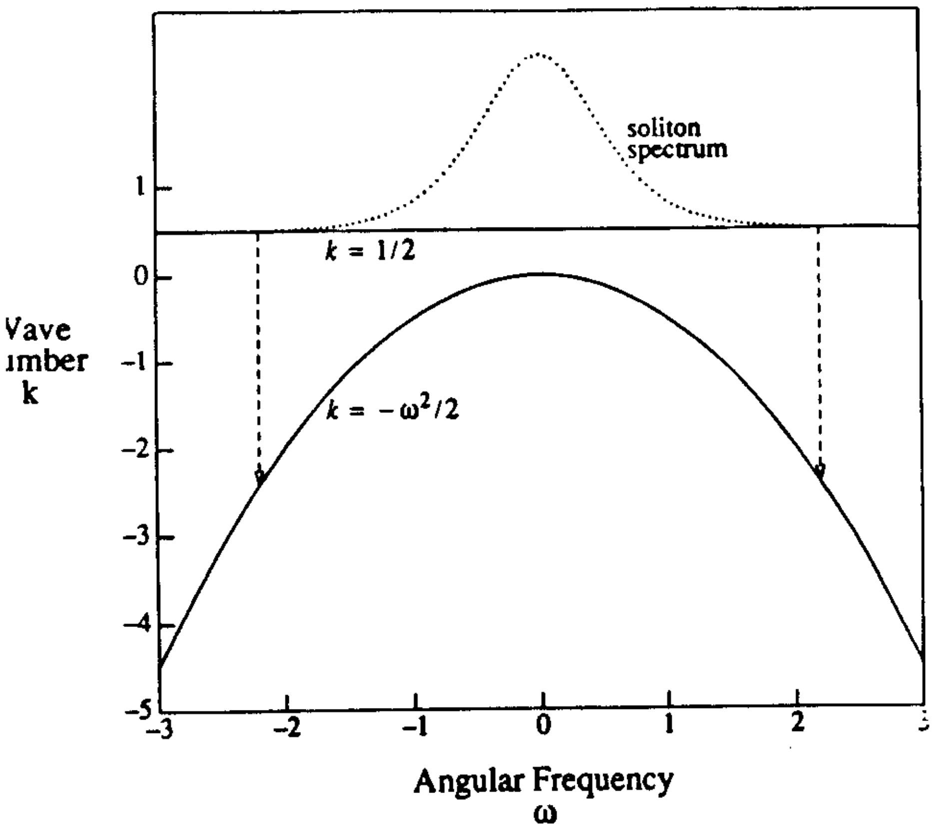
Dotted curve: initial pulses; solid curve: after 9000 km





Note: For $\tau = 35$ and 50 ps ($z_0 = 480$ and 980 km, respectively), the pulses at 9000 km are virtually indistinguishable from those at input.

Radiation from a Soliton
The Phase Matching Condition

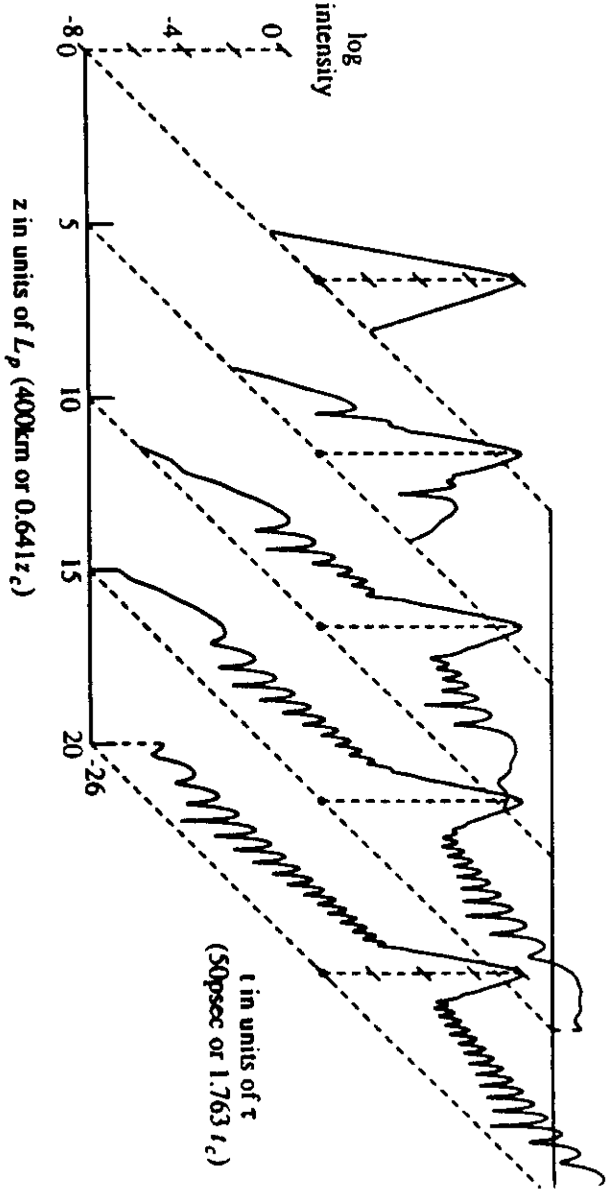


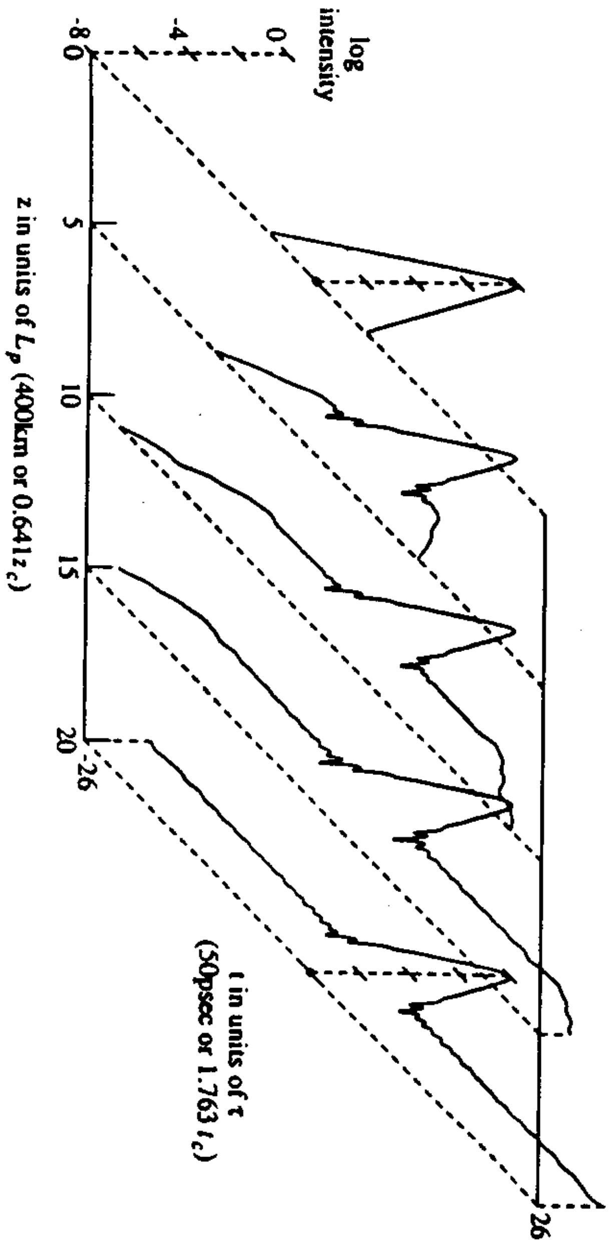
Dispersion curves for the soliton (k=1/2) and for purely dispersive radiation (k=- ω^2). Dashed line represents the wave vector of the spatial perturbation needed to phase match the soliton frequency component to the dispersive radiation field.

$$\Gamma_{rad.loss} = \frac{1}{4\Omega}\left[\pi k A_k \,sech(\pi \frac{\Omega}{2})\right]^2$$

J P Gord

Radiation from a Soliton
Due to a Periodic Perturbation
A(z) = 0.5 sin(9.8 z)



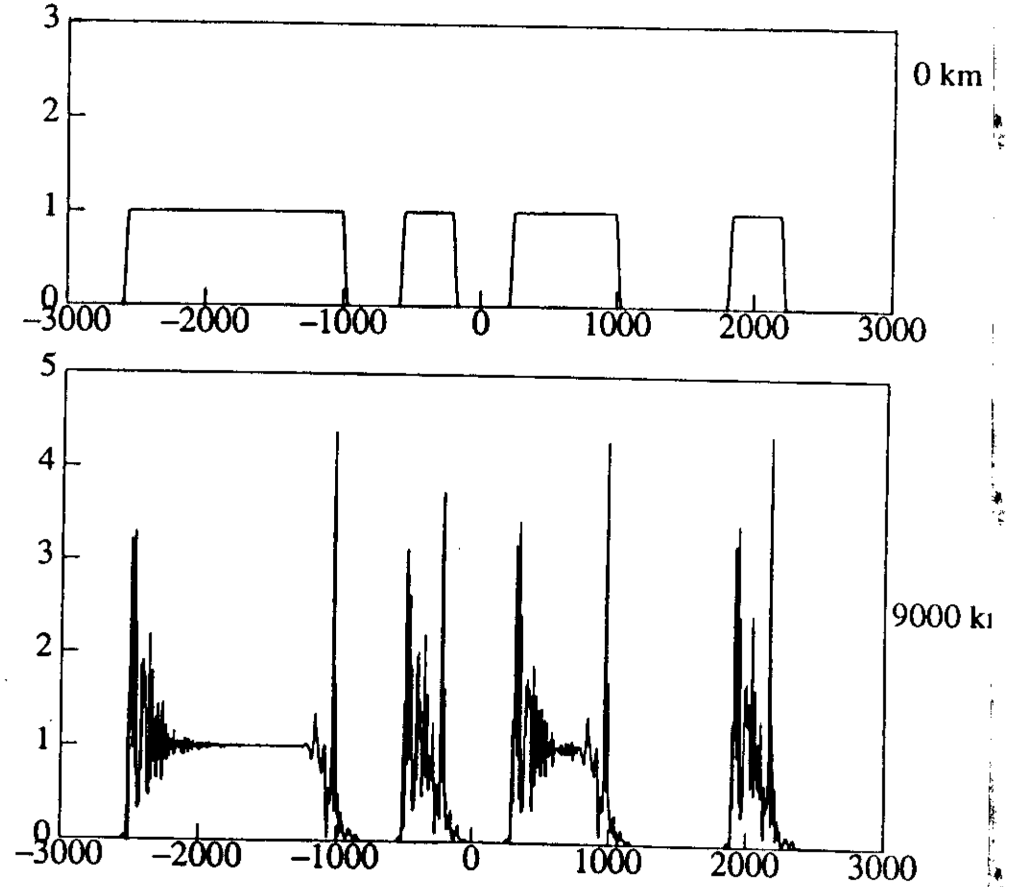


Radiation from a Soliton
Due to a Periodic Perturbation
with Corrected Input
$A(z) = 0.5\cos(9.8z)$

J.P. Gordon.

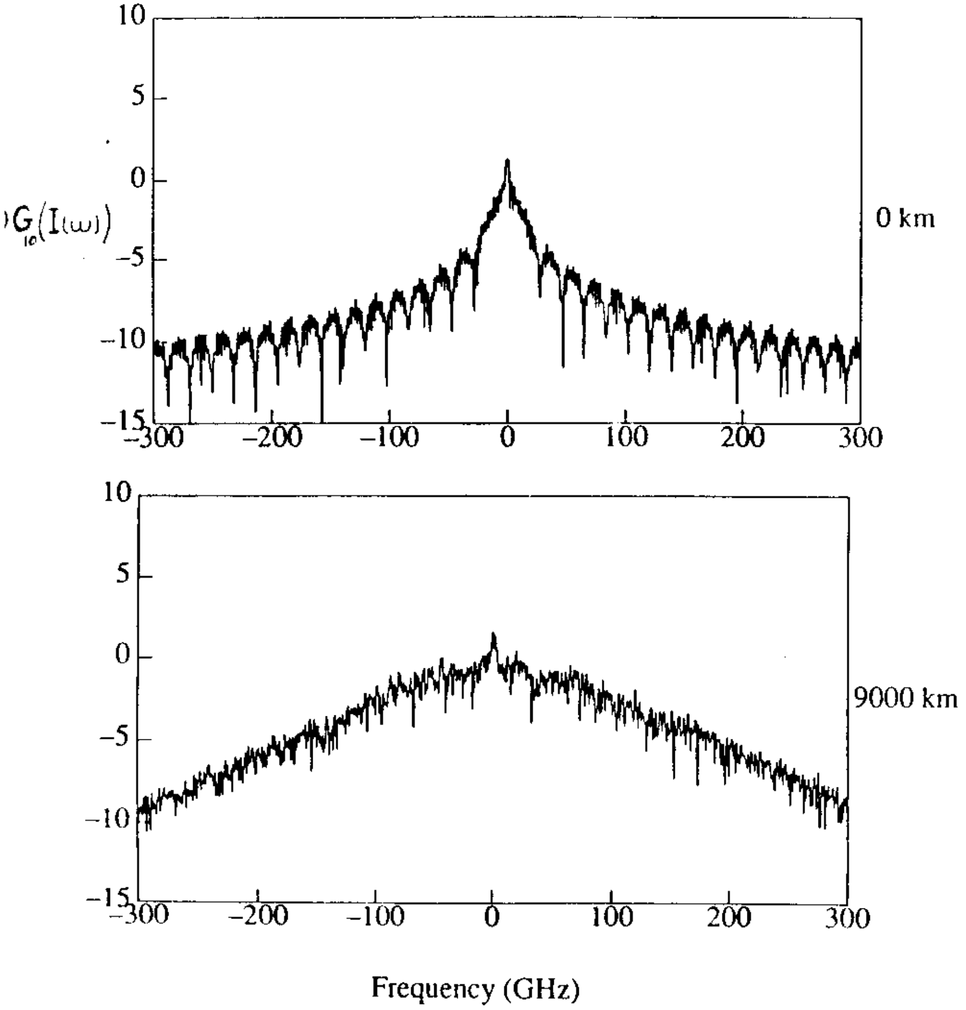
Computer Simulation
of
Transmission of NRZ Signals
2.5 GHz

Amplifier Spacing 33 km
Initial Power 1mW
Randomly Varying D, ($\bar{D}$=0)



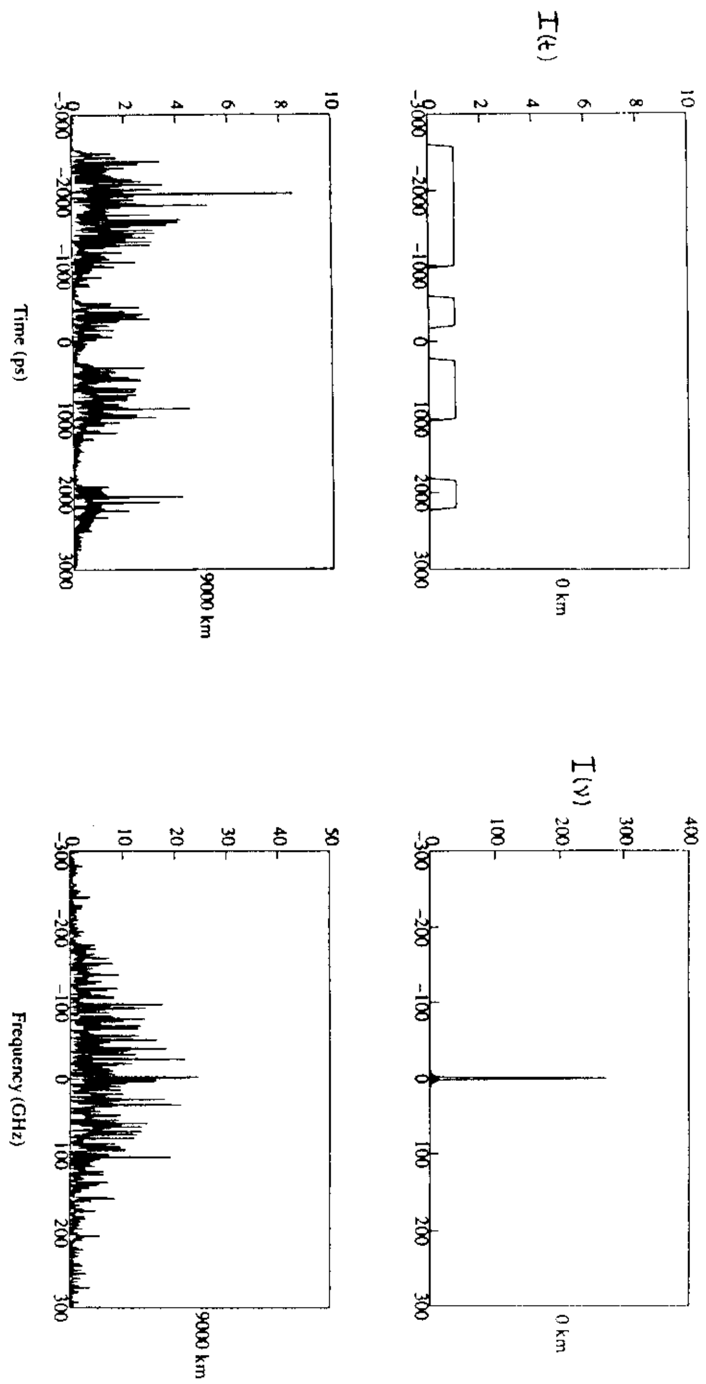
Spectra of NRZ Pulse Train from Computer Simulations

Amplifier Spacing 33 km
Initial Power 1mW
Randomly Varying D, ($\overline{D}$ =0)

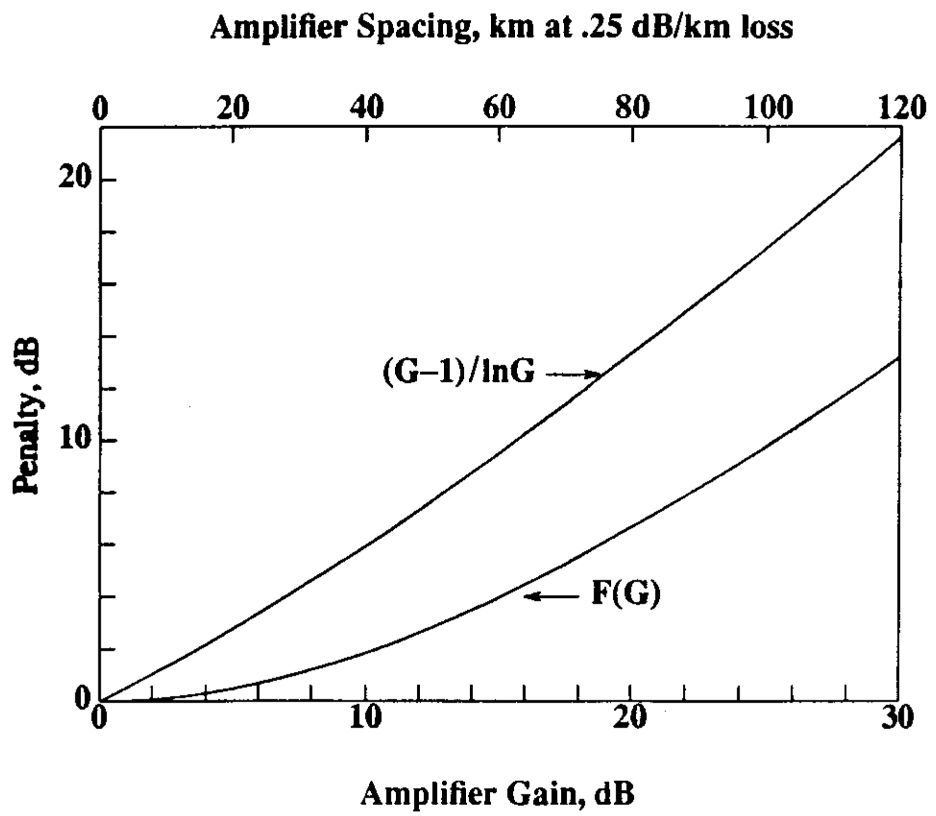


Computer Simulations of 2.5 GHz NRZ Transmission

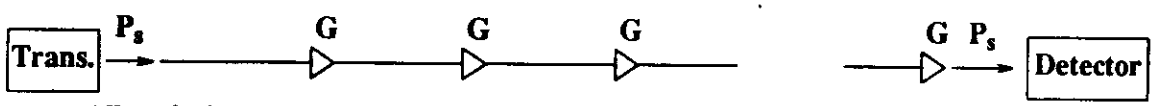
P_0= 4 mW, $\overline{D}$=0, 33km Amplifier spacing



NOISE PENALTIES VS AMPLIFIER GAIN



AMPLIFIED SPONTANEOUS EMISSION NOISE



All optical system with N amplifiers of gain G each preceded by 1/G fiber loss factor.

In all-optical transmission, detector noise tends to be insignificant compared to ASE noise.

One can easily show that the ASE spectral density (power per unit bandwidth), $P(\nu)$, at the output of the last amplifier in the chain, is

$$P(\nu) = \alpha Z\, h\nu\, \beta \frac{(G-1)}{\ln G}$$

where α is the fiber loss coefficient, Z the system length, $h\nu$ the photon energy, and β the amplifier excess spontaneous emission factor.

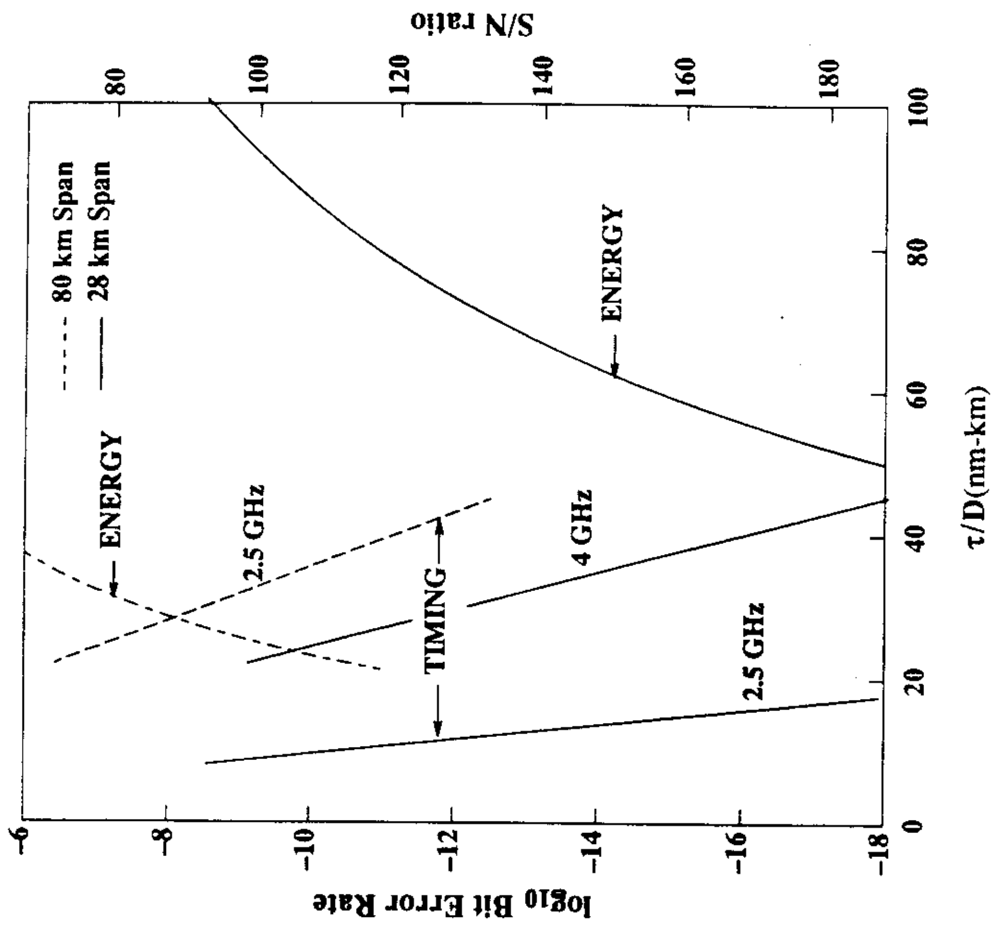
For solitons, however, where the path-average signal power is fixed, S/N ratio is most conveniently calculated by comparing with the path-averaged $P(\nu)$.
Since the ratio of path-average to peak power in each fiber span is $(G-1)/(G \ln G)$, the path-average $P(\nu)$ is

$$\bar{P}(\nu) = \alpha Z\, h\nu\, \beta\, F(G)$$

where the function $F(G) = \dfrac{(G-1)^2}{G(\ln G)^2}$ represents an important noise penalty.

ERROR RATES AT 9000 KM

Assumes 0.25dB/km loss, λ_s =1532 nm, and β=1.5
(erbium amlifiers)



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 Z, there is a Gaussian distribution in arrival times with the following variance:

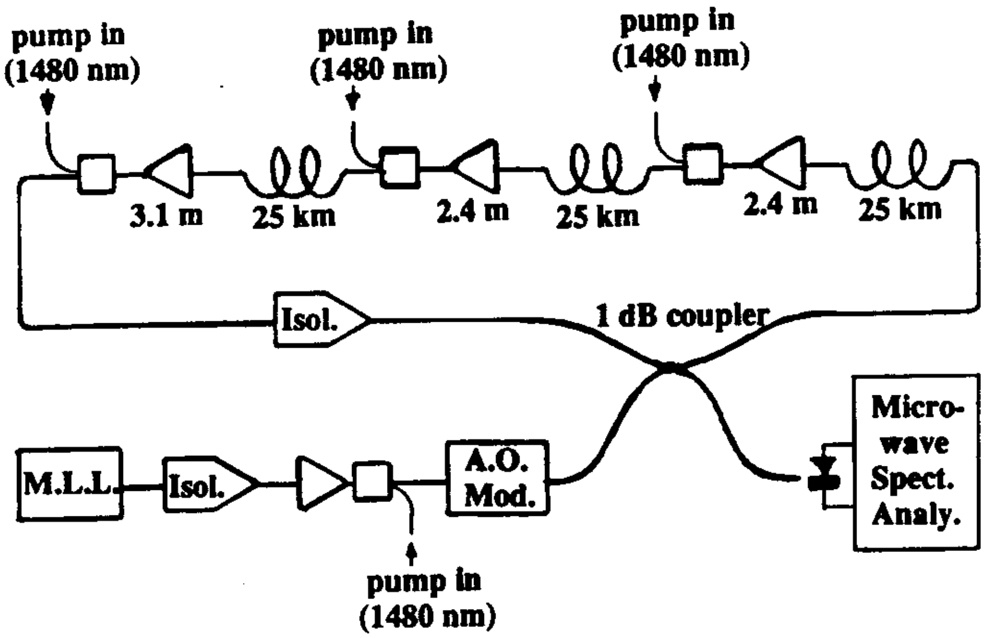
$$\sigma^2 = 4138\, \beta F(G)\, \frac{\alpha_{loss}}{A_{eff}}\, \frac{D}{\tau}\, Z^3$$

where α_{loss} is in km^{-1}, D in ps/nm/km, Z in thousands of km, τ in ps, A_{eff} in μm^2, G and β are the amplifier gain and excess spontaneous emission factor, respectively, and where

$$F(G) = \frac{(G-1)^2}{G(\ln G)^2}$$

Example: Let τ=50 ps, D=1 ps/nm/km, A_{eff}=35 μm^2, α_{loss}=0.0576/km (0.25 dB/km), F =1.24 (span between amplifiers = 28 km), and $\beta \sim 1.5$. Then, for 9000 km, one obtains:

The Loop Experiment



SOLITON POWERS

For $\tau = 50$ ps solitons at $D = 1.38$ ps/nm/km:

Path-average power: P_{sol} ~660 μW

At amplifier output:

P_{pk} ~1.8 mW

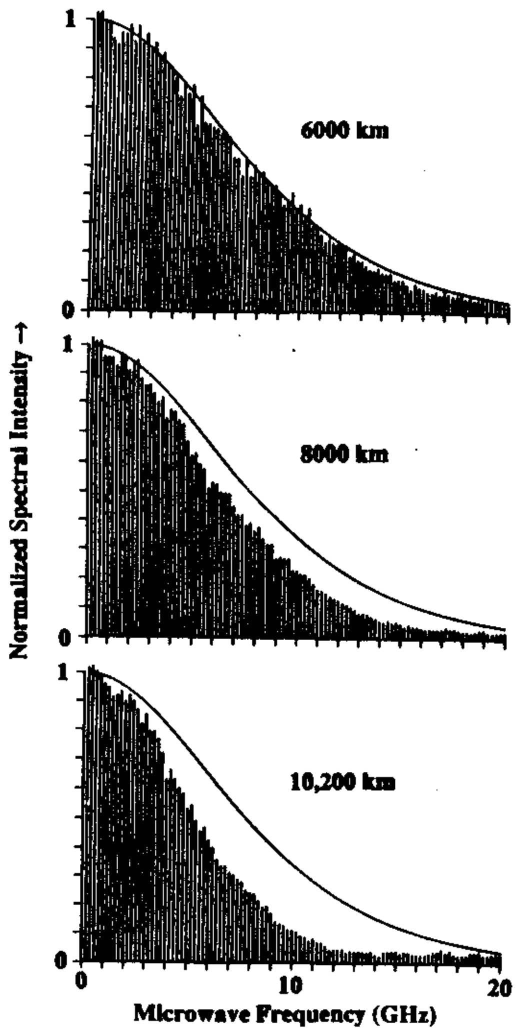
$\bar{P}$ into one bit period at 2.5 Gbit/s: ~250 μW

Measured ASE noise power referred to 2.5 GHz: ~0.8 μW

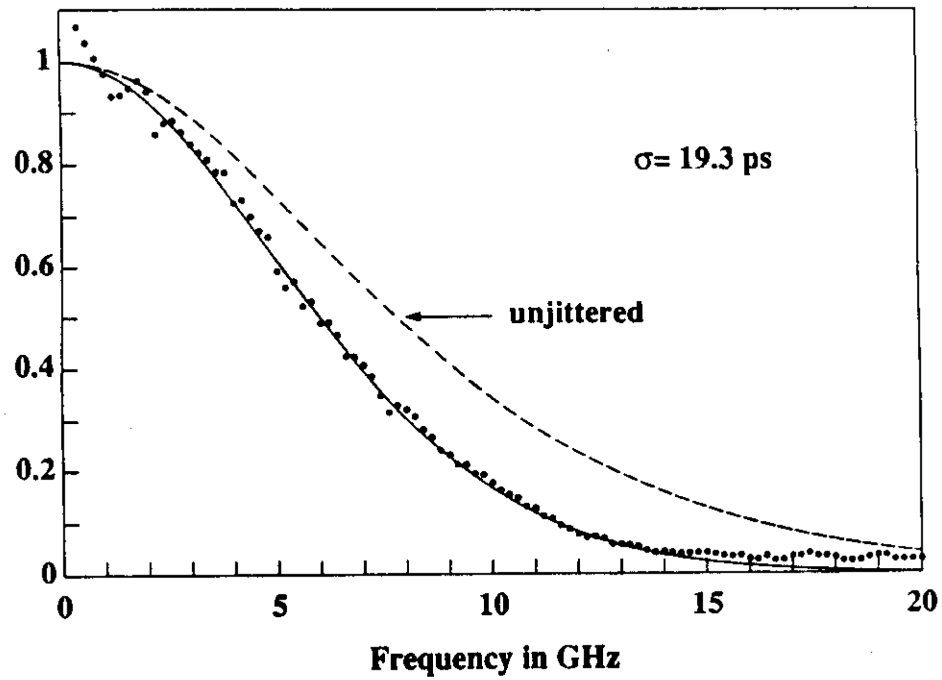
S/N ratio > 250

Experimental Data
Microwave Spectra of the Soliton Pulse Train

Showing the evolution of the soliton spectrum as the pulse train moves down the fiber.



Soliton Propagation Experiment
9000 km Data



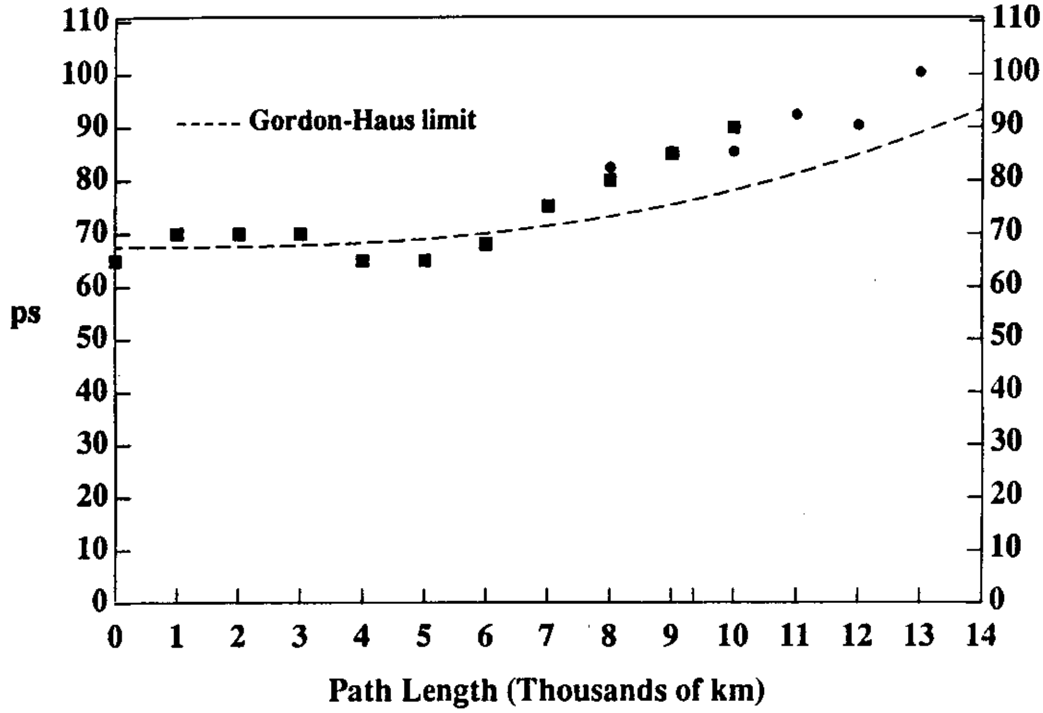
The solid curve is obtained by multiplying the dashed curve by the gaussian:

$$e^{-\frac{1}{2}(2\pi f\sigma)^2}$$

where σ is chosen for best fit to the data.

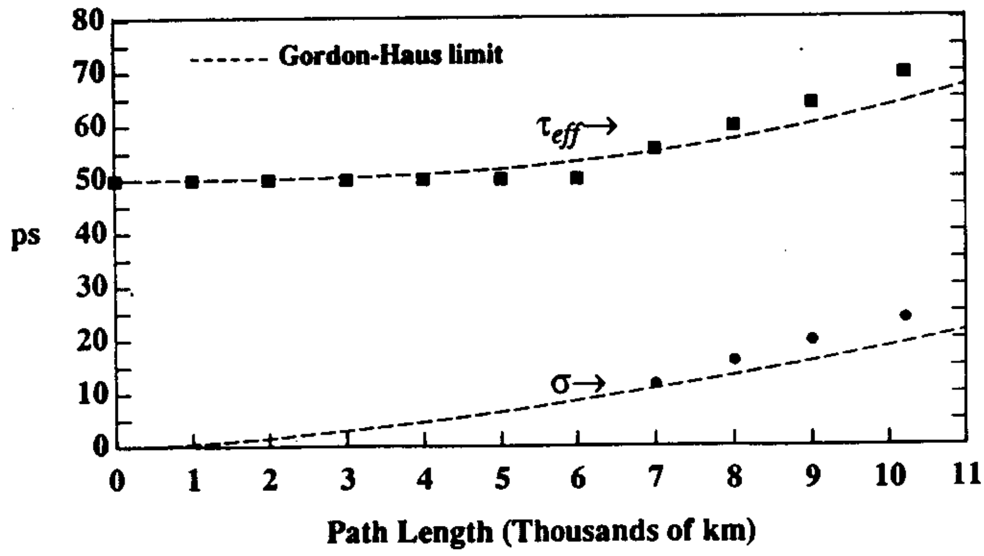
SOLITON TRANSMISSION EXPERIMENT USING MODE LOCKED LASER DIODE SOURCE

1.2 GHz pulse repetition rate

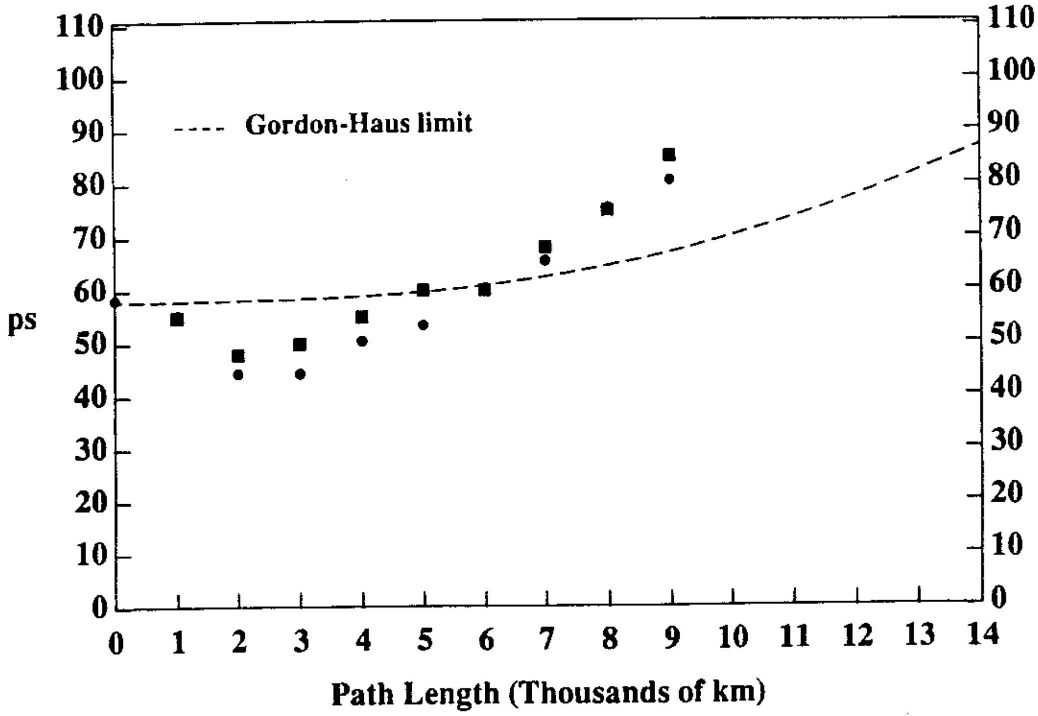


SOLITON TRANSMISSION EXPERIMENT EFFECTIVE PULSE WIDTH AND JITTER VS DISTANCE

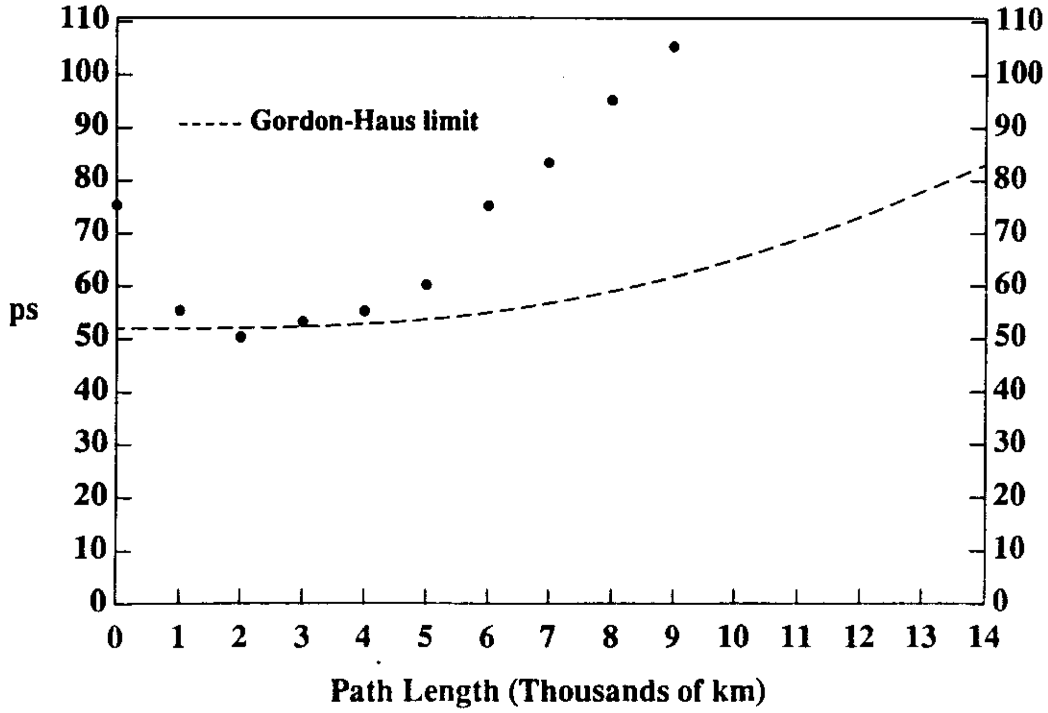
Theoretical curves are for the conditions of experiment, viz., β ~1.5, 0.25 dB/km loss, 25 km amp spacing, etc.



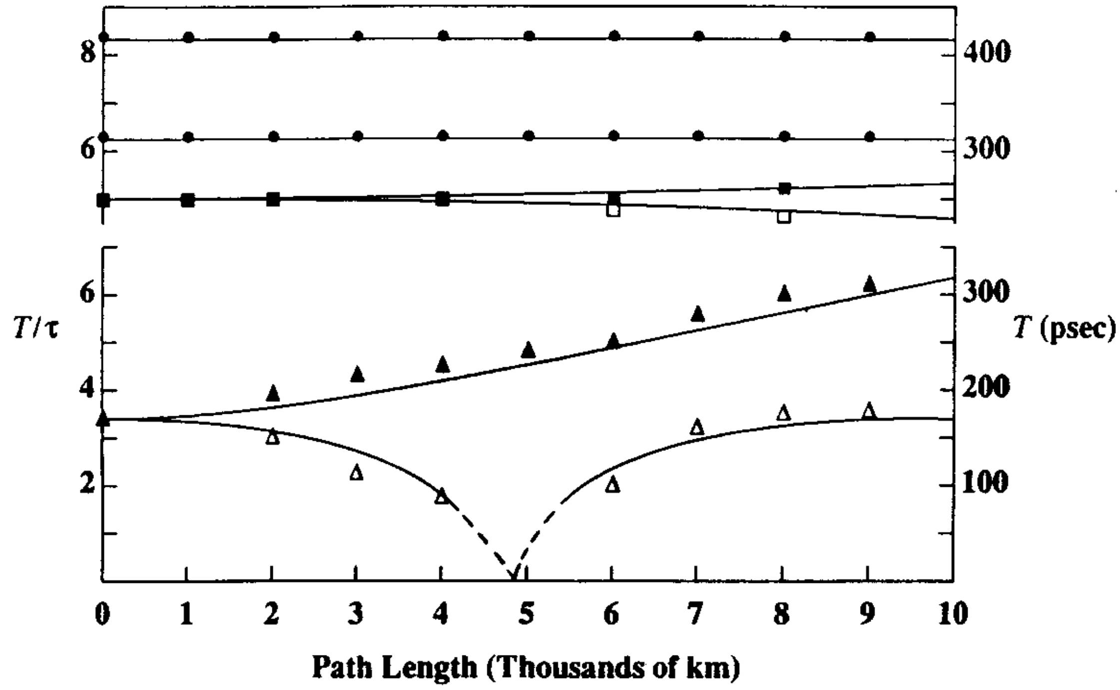
SOLITON TRANSMISSION EXPERIMENT USING
MODE LOCKED LASER DIODE SOURCE
2.4 Gbits/s pulse repetition rate
110011001100... pattern imposed by modulator following laser (boxes)
110000110000... pattern imposed by modulator following laser (bullets)



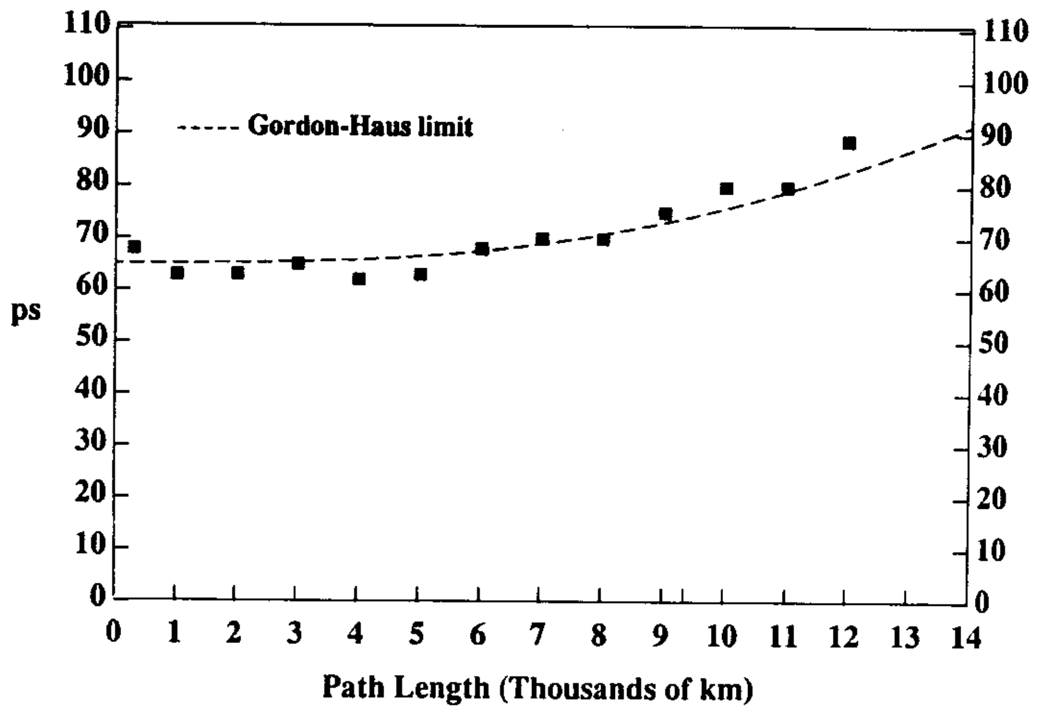
SOLITON TRANSMISSION EXPERIMENT USING
GAIN SWITCHED AND OPTICALLY FILTERED LASER DIODE SOURCE
2.4 Gbits/s pulse repetition rate
101010... pattern imposed by modulator following laser



SOLITON PAIR INTERACTION VS DISTANCE

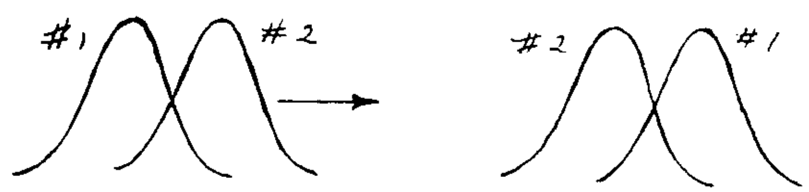


SOLITON TRANSMISSION EXPERIMENT USING MODE LOCKED LASER DIODE SOURCE
2.4 GHz pulse repetition rate



SOLITON-SOLITON COLLISIONS IN WDM

Solitons of a higher freq. channel overtake and pass through those of a lower freq. channel:



(#1 at $f_0+\Delta f$; #2 at f_0)

Collision length, L_{coll}, begins and ends where solitons overlap at their half pwr. points:

$$L_{coll} = 0.6298\,\frac{z_0}{\tau\Delta f} = \frac{2\tau}{D\,\Delta\lambda}$$

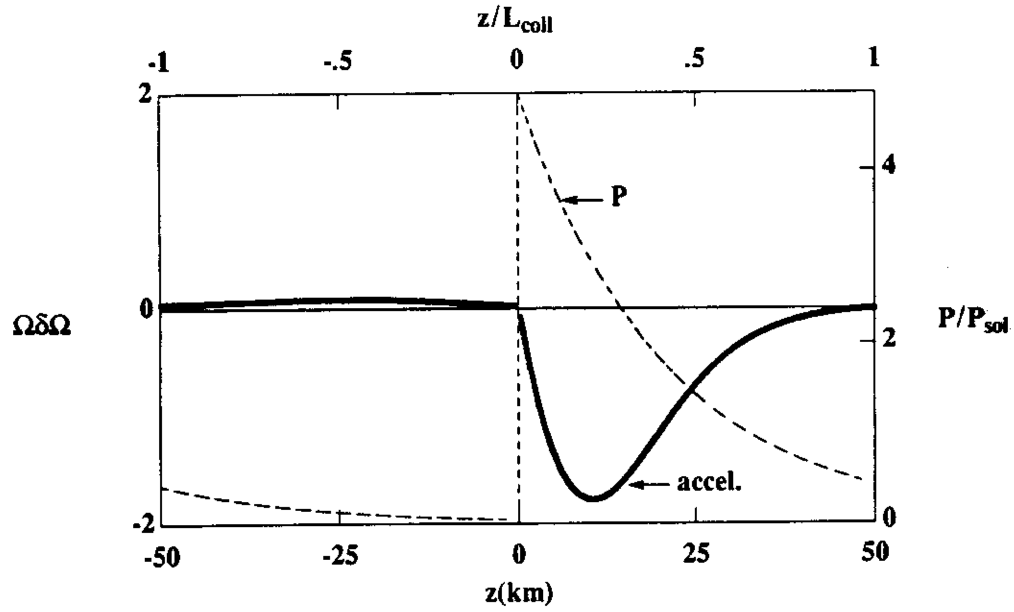
Ex: for $\tau = 50$ ps, $D = 1$ ps/nm/km and $\Delta f = 0.125$ THz ($\Delta\lambda = 1$ nm at 1550 nm), $L_{coll} = 100$ km

[In soliton units, solitons have frequencies $+\Omega$ and $-\Omega$, respectively, where Ω = radians/t_c. ($\Delta f/2 = \frac{\Omega}{2\pi t_c}$). Ω is also time per unit distance traveled, ie, it is a reciprocal velocity.]

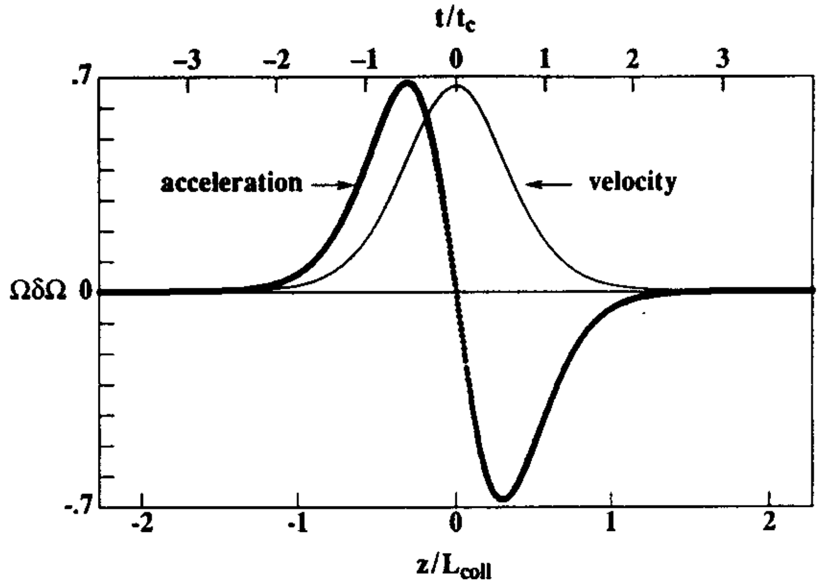
SUMMARY OF 10000 KM EXPERIMENT:

- **Measured timing jitter agrees well with that predicted theoretically.**
- **Measured S/N ratio ~250**
- **No measurable polarization dispersion.**
- **No measurable interaction between pulses separated by $\geq 5\tau$.**

ACCELERATION OF COLLIDING SOLITONS
COLLISION CENTERED AT AMPLIFIER (1 AMP/100 km)



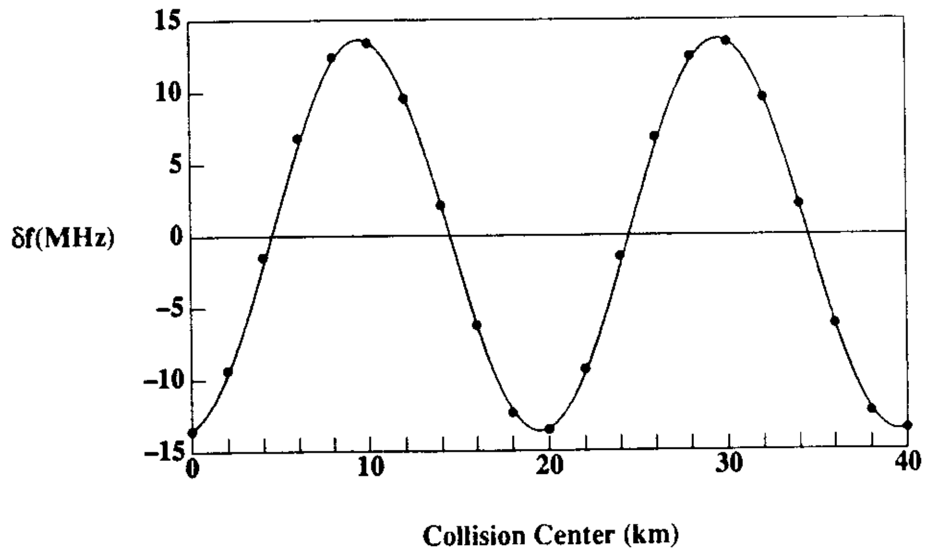
ACCELERATION & VELOCITY SHIFT DURING COLLISION OF SOLITONS
IN LOSSLESS AND OTHERWISE UNPERTURBED FIBER



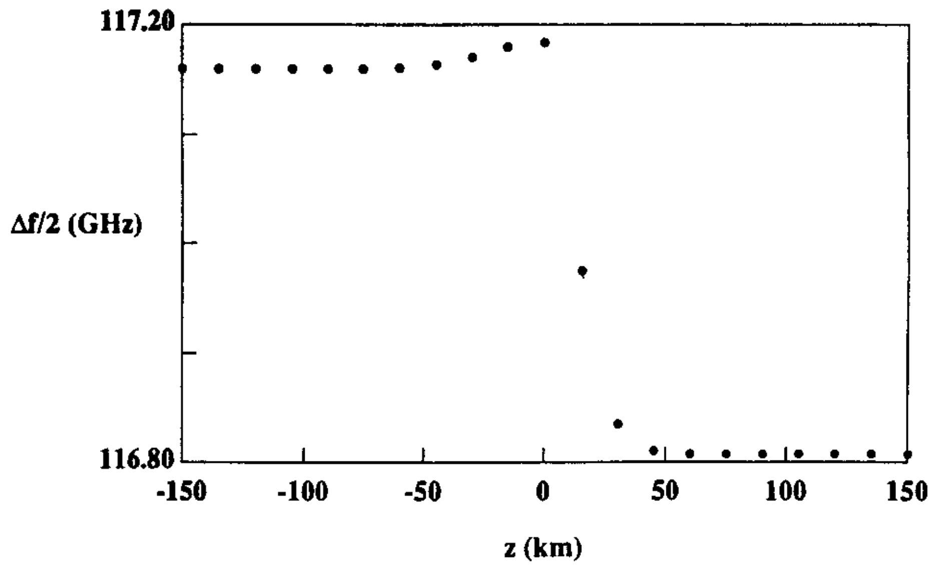
For $\tau \Delta f > 1$, pulses are shifted in time by $\delta t = 0.1786 \dfrac{1}{\tau (\Delta f)^2}$

Ex: for $\tau = 50$ ps and $\Delta f = 0.03$ THz ($\Delta\lambda \cong .25$nm at 1550 nm), $\delta t = 4$ ps.

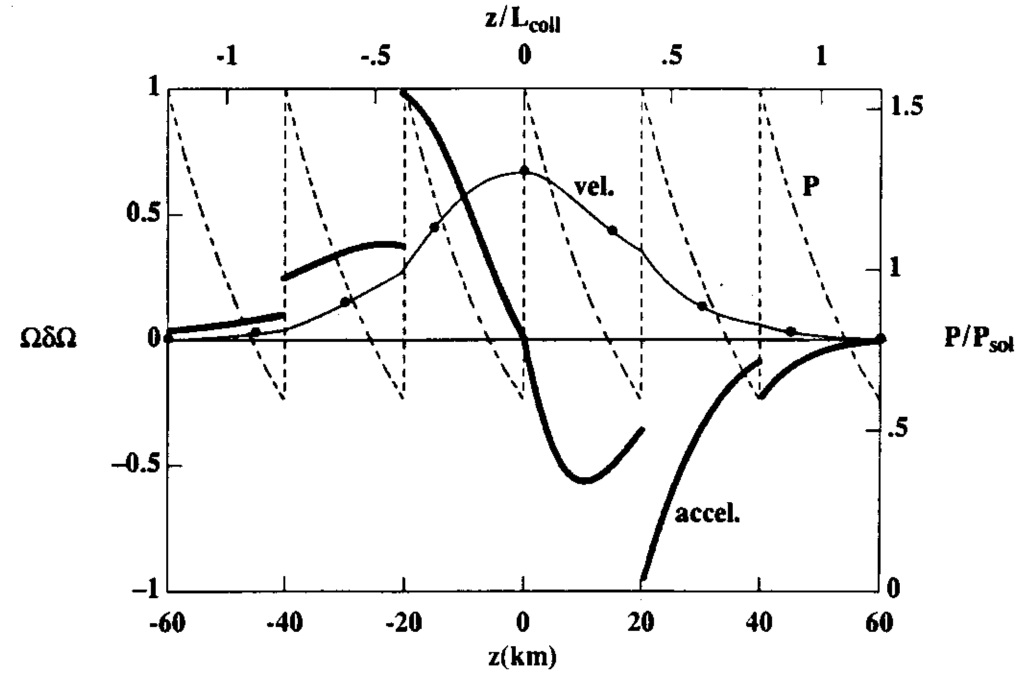
δf OF SOLITONS vs COLLISION CENTER
LUMPED AMPS AT 0,20,40, etc. km and L_{coll} = 20 km.



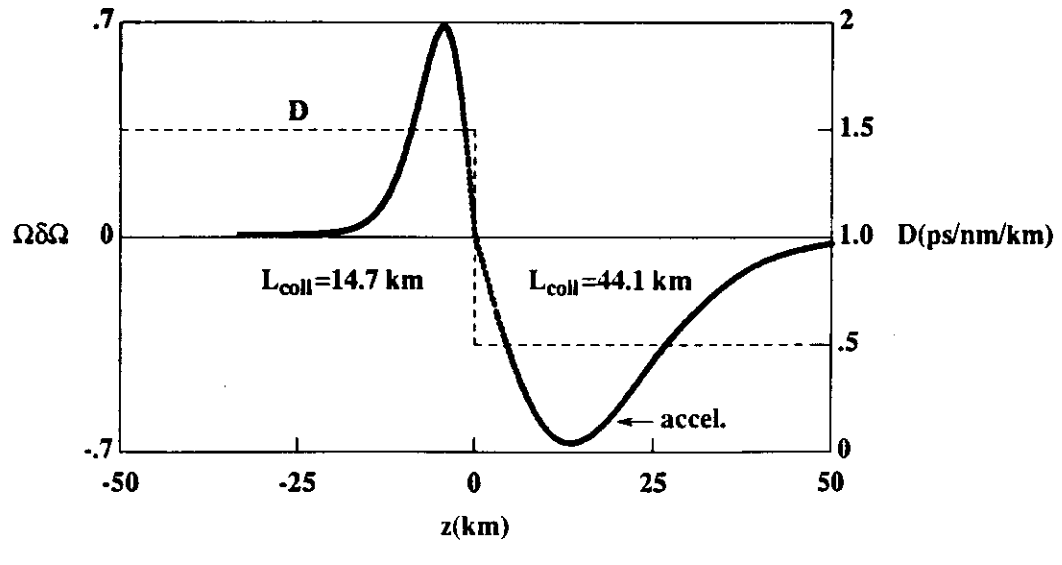
VELOCITY (Δf/2) OF COLLIDING SOLITONS
COLLISION CENTERED AT AMPLIFIER, 1 AMP/100 km



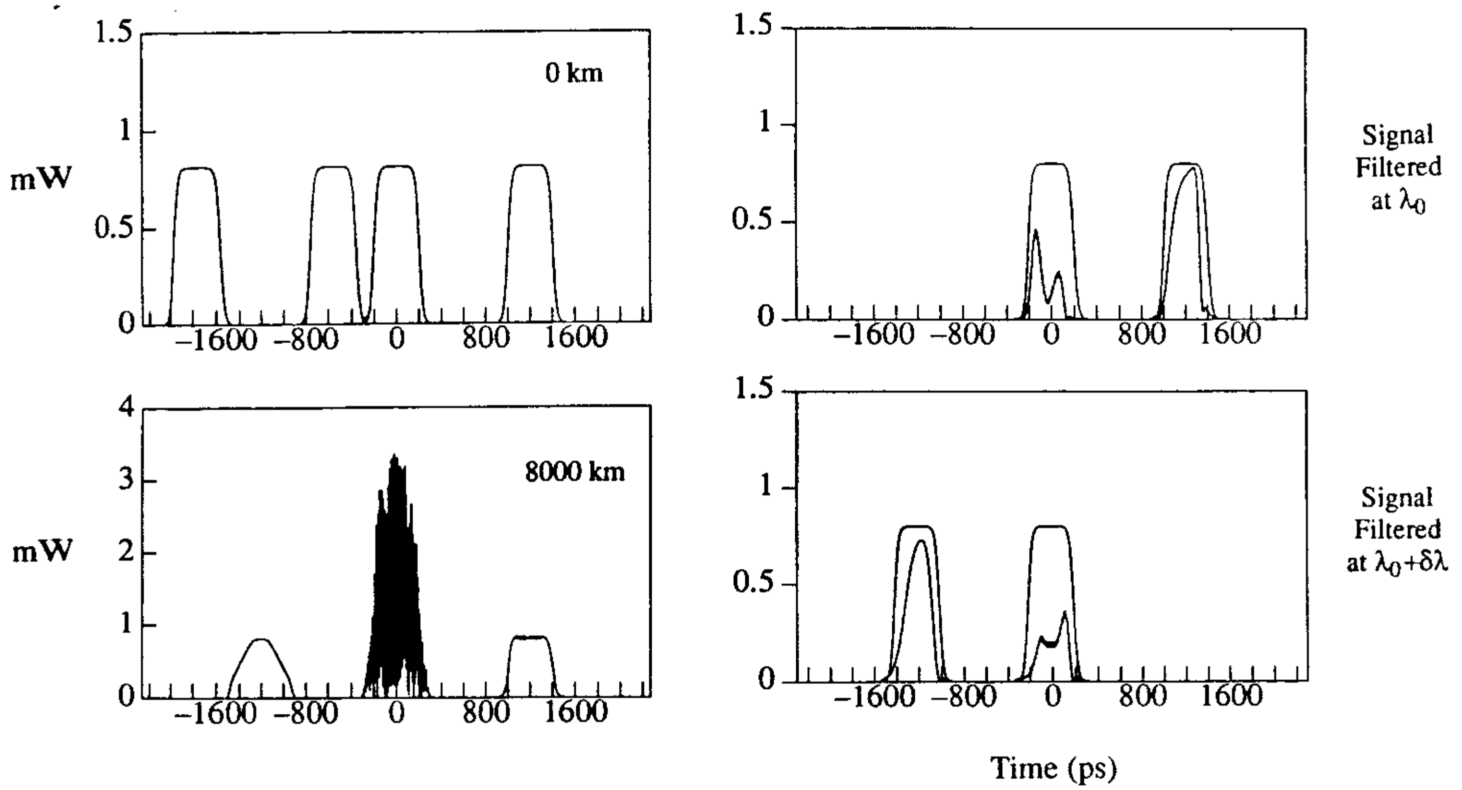
ACCELERATION AND VELOCITY SHIFT OF SOLITONS COLLIDING IN SYSTEM WITH LUMPED AMPS EVERY 20 km



ACCELERATION OF SOLITONS COLLIDING IN LOSSLESS FIBER COLLISION CENTERED ABOUT A STEP CHANGE IN D

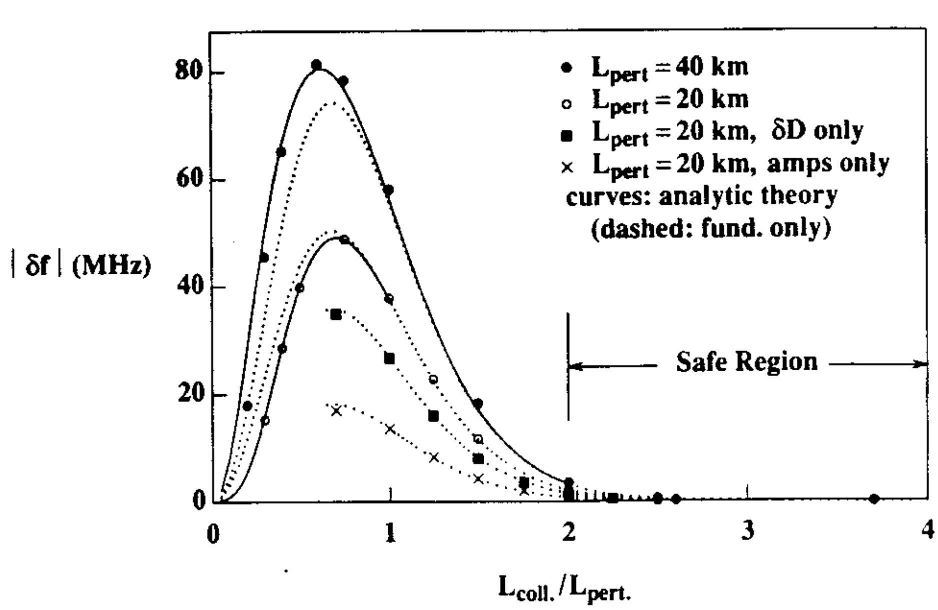


2.5 GBit WDM
0.8 mW
$\delta\lambda$=1.4nm
34 km amplifier spacing

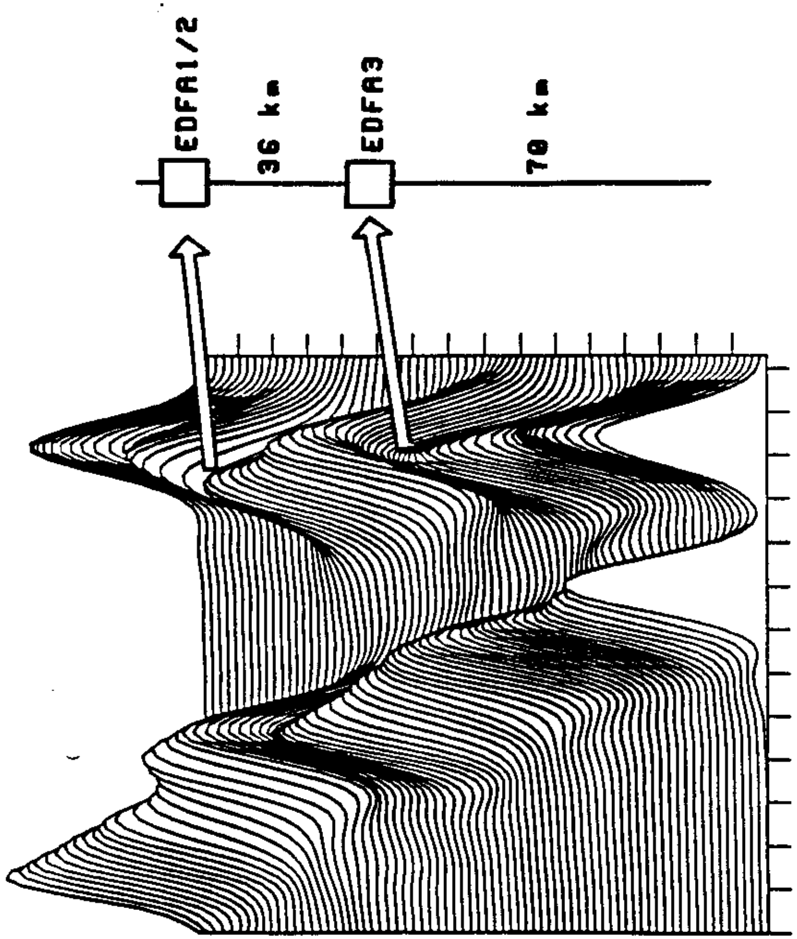


δf OF COLLIDING SOLITONS VS L_{coll}/L_{pert}

lumped amps every 20 km and $\delta D = \pm 0.5$ ps/nm/km about $\bar{D} = 1$

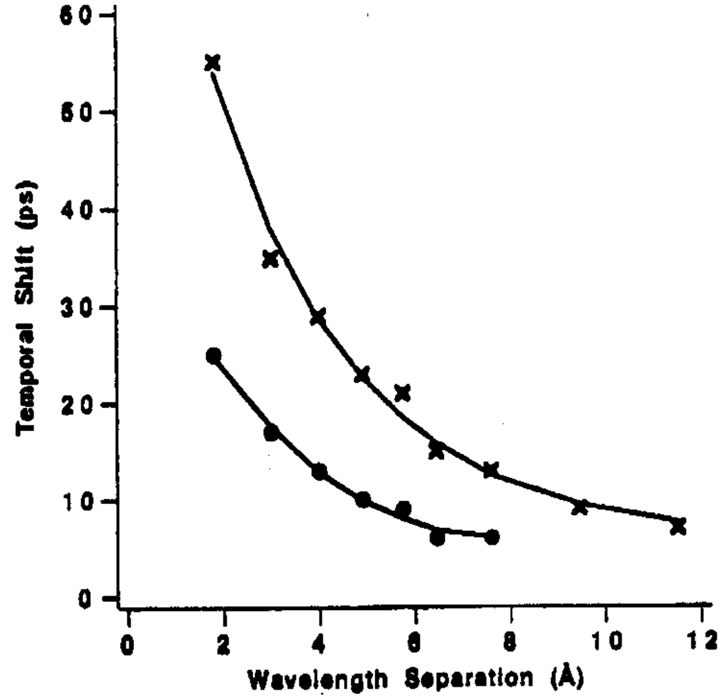


Soliton Collisions
Effects of Amplifiers on Collisions
Experimental Data



Data of Andrekson and Olsson (Bell Laboratories)

Temporal Shift due to a Collision
Experimental Data



$$\delta t = \pm 0.1786 \frac{1}{\tau (\Delta f)^2}$$

Data of Andrekson and Olsson (Bell Laboratories)

WDM WITH 50 PS SOLITONS

Z = 9000 km

4 Gbits/s per channel

$\bar{D}$ (ps/nm/km)	$\Delta\lambda_{min}$ (nm)	Δt (ps)	$\Delta\lambda_{max}$ (nm)	No. of channels	$\bar{P}_{sig.}$/chan. at amp. outputs (μW)	Total bidirectional capacity (GBits/s)
1.0	**.27**	**±19.0**	**1.08**	**5**	**125**	**40**

RULES FOR WDM CHANNEL SPACING

The requirement $L_{coll} \geq 2L_{pert}$ determines the maximum allowable channel spacing:

$$\Delta f_{max} = 0.31 \frac{z_0}{\tau L_{pert}} \quad \text{or} \quad \Delta\lambda_{max} = \frac{\tau}{DL_{pert}}$$

Pulses of the *i*th channel will tend to suffer a range of collisions with the *j*th channel, from none to a maximum given by $N_{ij} = Z\tau/(L_{coll}^{ij}T)$, where Z is the total system length and T is the bit period. There will then be a spread of arrival times about the mean, given by multiplying the time shift per collision by $N_{ij}/2$, and summing over all channels $j \neq i$, of

$$\Delta t_i = \pm 0.1418 \frac{Z}{z_0} \frac{\tau}{T} \sum_{j \neq i} \frac{1}{(\Delta f)_{ij}}$$

Thus, the max allowable Δt sets a limit on the *minimum* allowable Δf.
[Note: the minimum Δf may instead be determined by the requirement $\tau \Delta f > 1$.]

RESULTS

Solitons

- Resist distortion due to perturbations with spatial period much less than z_0.

- For lumped amplifier schemes the soliton peak power is adjusted so that the span averaged power is the soliton power.

- Bit rates in excess of 5 GHz are possible with very low error rates.

- Wavelength Division Multiplexing can be done.

- Fiber birefringence will not affect solitons so long as the polarization parameter (in $ps/km^{1/2}$) $\leq .3D^{1/2}$

NRZ at λ_0

- Bit rates and peak power severely limited by fiber nonlinear index, for acceptable error rates:
  - Transmission limited to single channel at $\leq$ 2.5 GBit/s
  - Peak powers less than 1.0 mW
  - Amplifier spans must be less than 50 km, less than 30 km for optimum performance

- Nonlinearity results in pattern dependent signal distortion.

- Polarization and dispersion fluctuations contribute to signal degradation.

- WDM, very difficult, if at all possible. Cross phase modulation between channels severely degrades the signal.

- Signal degradation depends weakly on the pulse envelope shape.

SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLITONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS
SOLUTIONS