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

H4.SMR/842-4

Conference on
Ultrafast Transmission Systems in Optical Fibres

13 - 17 February 1995

Long Distance Soliton Transmission Using Sliding Frequency Guiding Filters

P.V. Mamyshev - L.F. Mollenauer

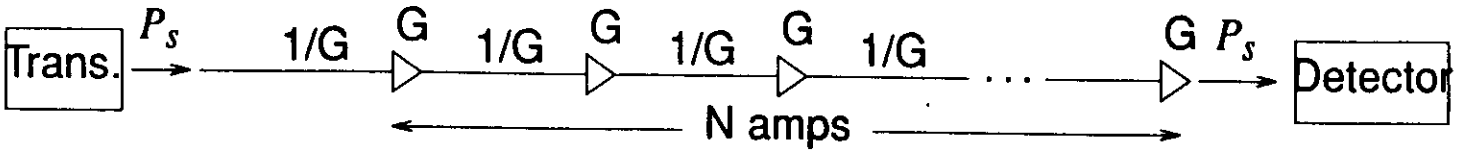
AT&T Bell Laboratories
Holmdel, New Jersey
U.S.A.

SOLITON TRANSMISSION

PROBLEMS:

1. **GORDON-HAUS EFFECT**
2. **ACOUSTIC EFFECT**
3. **ENERGY FLUCTUATIONS** (ASE NOISE, NONSOLITON COMPONENTS)
4. **PULSE-TO-PULSE INTERACTION**

SPONTANEOUS EMISSION NOISE: GROWTH AND EFFECTS
BROADBAND TRANSMISSION LINE



Noise Power/Unit Bandwidth

Each amplifier contributes $P(\nu) = (G-1)\,h\nu\, n_{sp}$.

Noise at system output is $P(\nu) = N(G-1)\,h\nu\, n_{sp}$

Gordon Haus Effect

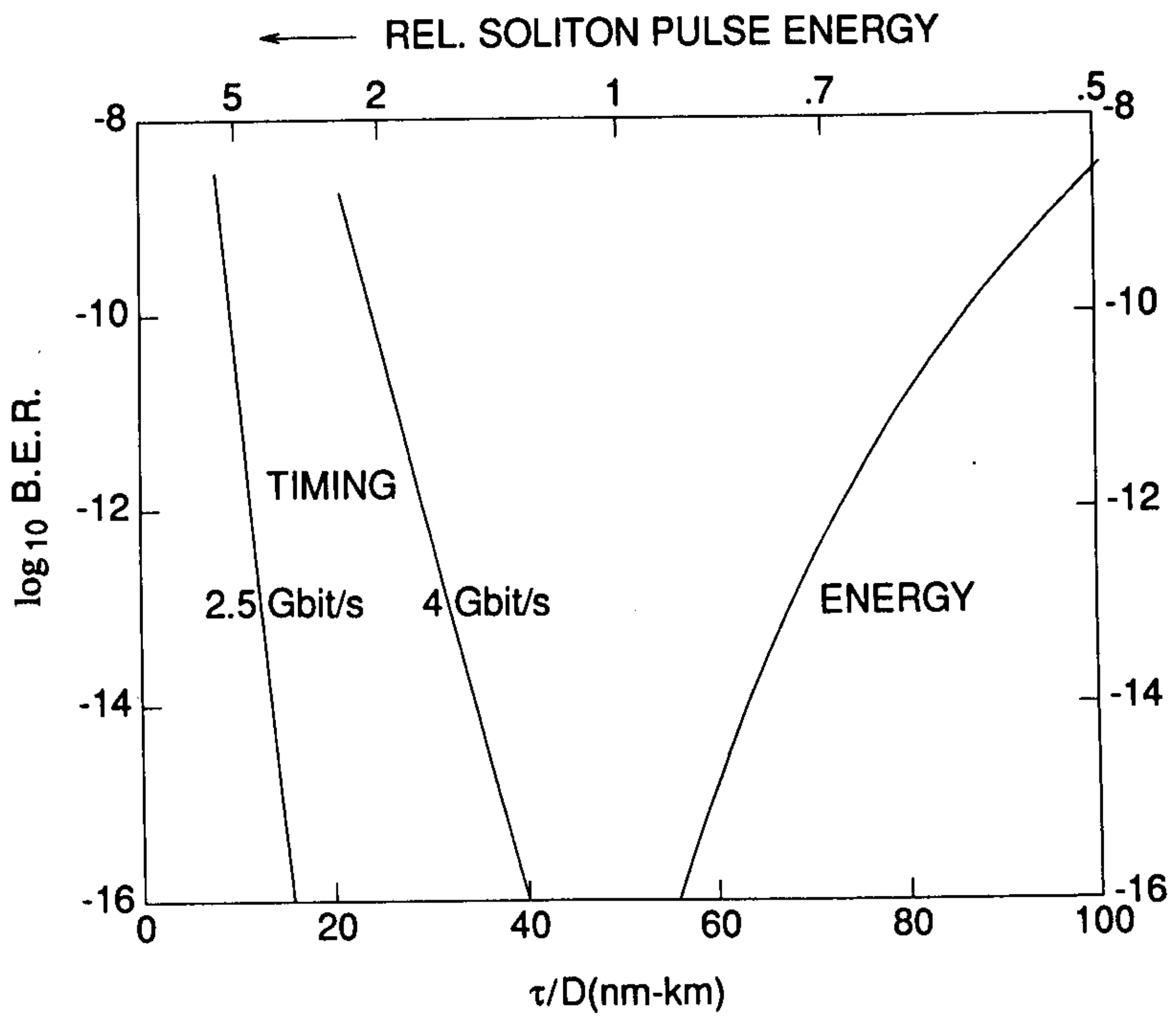
Spontaneous emission modulates the soliton frequencies (velocities) at random.

Resultant variance of Gaussian distribution in arrival times at Z is:

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

where α_{loss} is in km^{-1}, D in ps/nm-km, Z in Mm, τ in ps, A_{eff} in $\mu\mathrm{m}^2$.

BIT ERROR RATES IN SOLITON TRANSMISSION AT 9000 km
BROADBAND TRANSMISSION LINE, 30 km AMPLIFIER SPACING

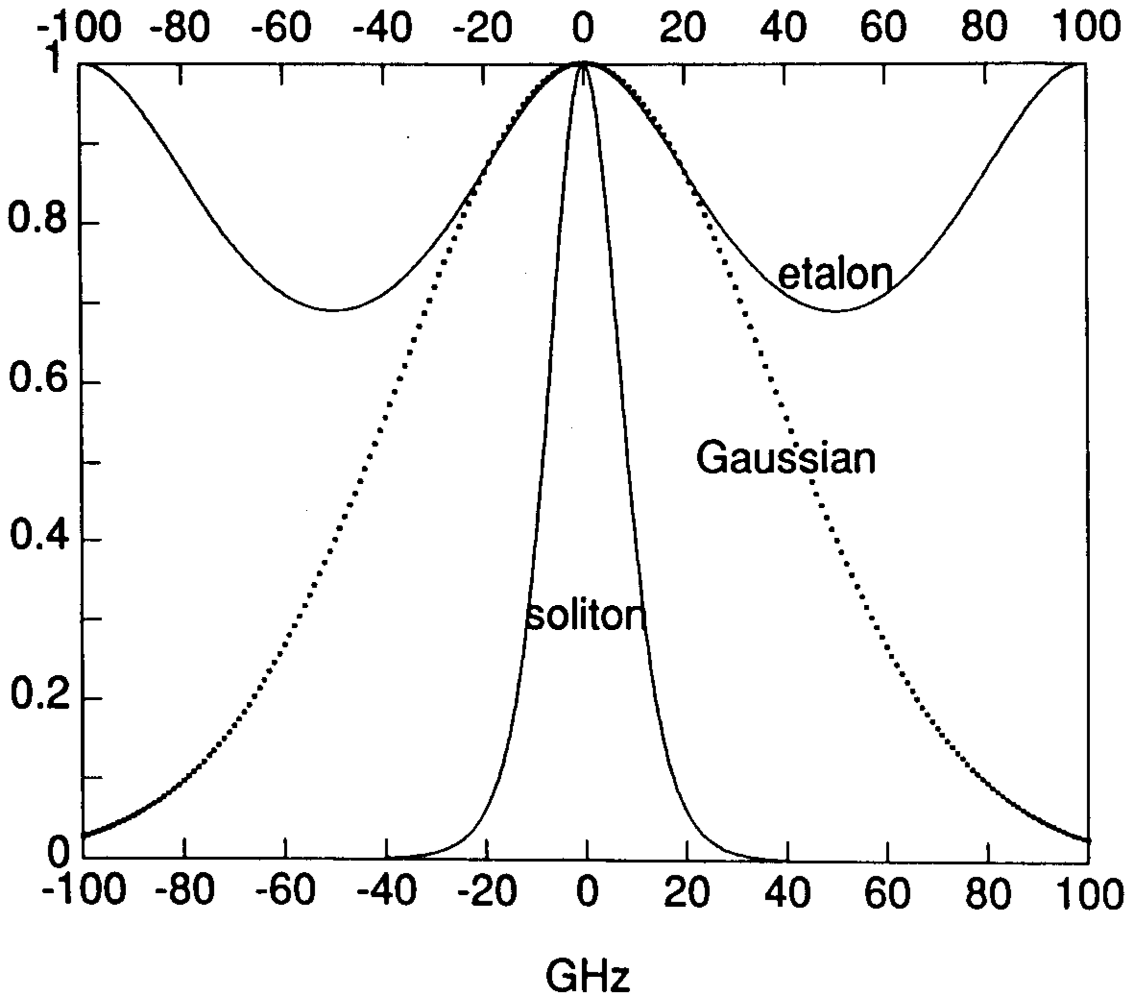


ORIGINAL PAPERS ON FREQUENCY GUIDING FILTERS

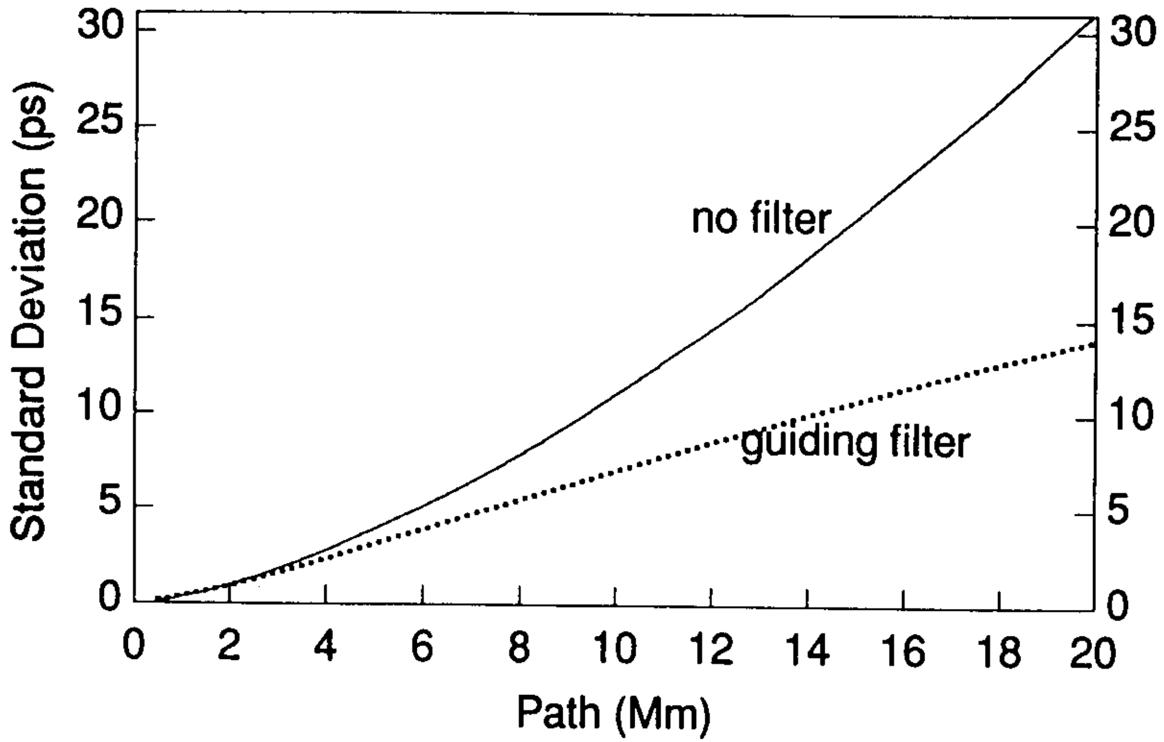
[1] A. Mecozzi, J. D. Moores, H. A. Haus, and Y. Lai, "Soliton transmission control," *Opt. Lett.* **16**, 1841 (received Aug. 1, 1991, pub. Dec. 1, 1991)

[2] Y. Kodama and A. Hasegawa, "Generation of Asymptotically Stable Optical Solitons and Suppression of the Gordon-Haus Effect," *Opt. Lett.* **17**, 31 (received Aug. 5, 1991, pub. Jan. 1, 1992)

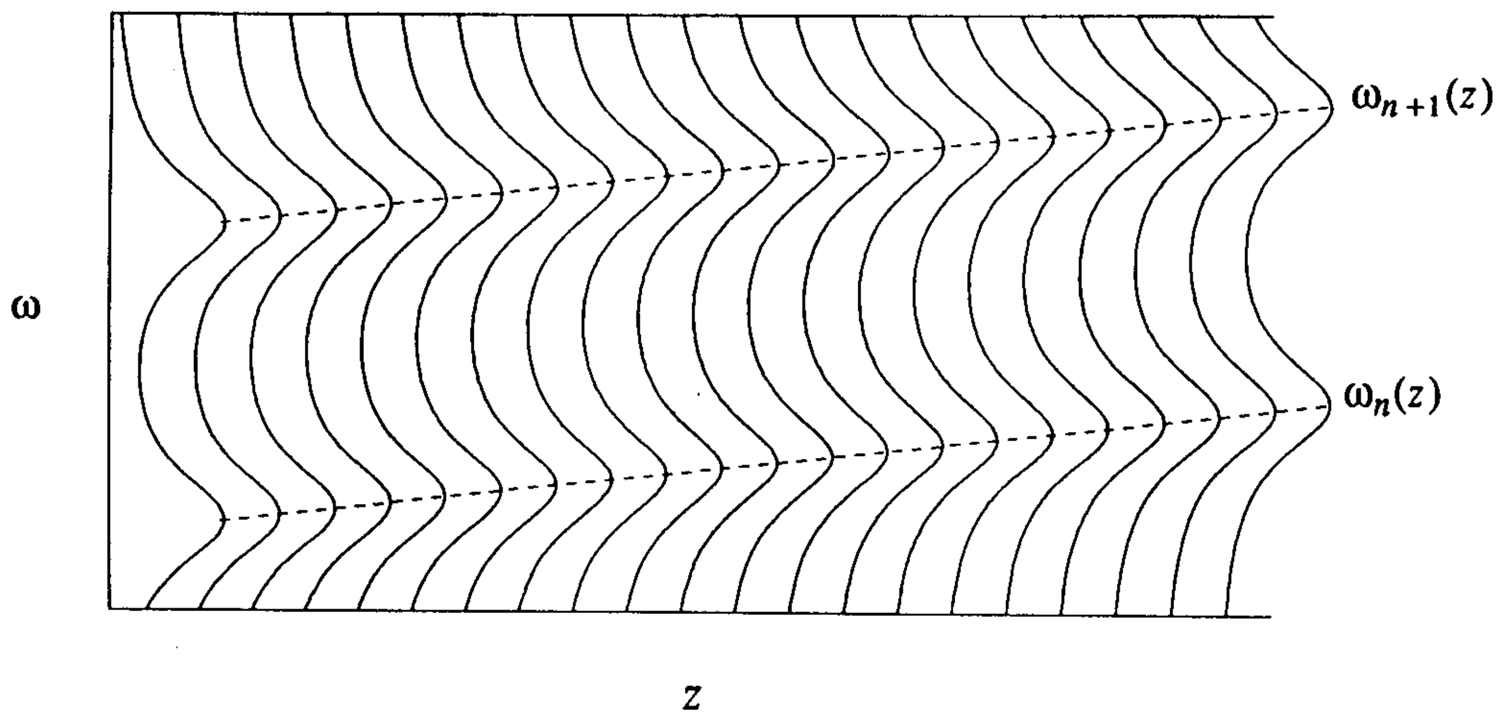
SPECTRUM OF 20 ps SOLITON COMPARED WITH GAUSSIAN AND ETALON FREQUENCY-GUIDING FILTERS



DECREASE OF JITTER IN PULSE ARRIVAL TIMES WITH OPTIMUM STRENGTH, FIXED-FREQUENCY FILTERS



THE SLIDING-FREQUENCY GUIDING FILTER:
Filter Frequency Response vs Distance



The sliding-frequency guiding filter: an improved form of soliton jitter control

L. F. Mollenauer, J. P. Gordon, and S. G. Evangelides

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received July 20, 1992

By gradually translating the peak frequency of guiding filters along its length, we create a fiber transmission line that is substantially opaque to noise while remaining transparent to solitons. This trick allows the use of stronger filters, and hence greater jitter reduction, without incurring the usual penalty of exponentially rising noise from the excess gain required to overcome filter loss.

PRACTICAL EXAMPLE

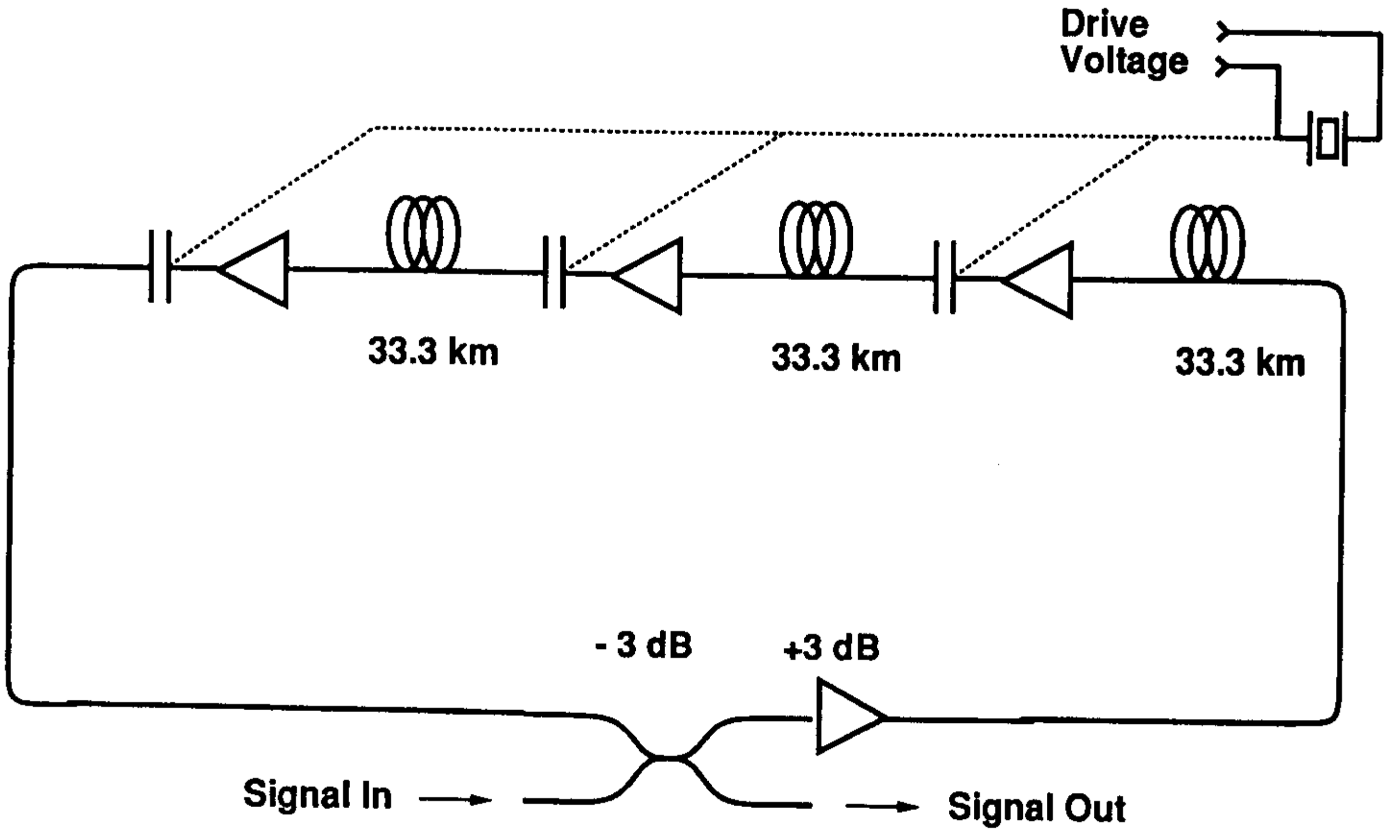
Filters: one 1.5(2) mm gap, R = 9% etalon every 33(50) km

Pulse width	16 ps
D	0.5 ps/nm-km
z_c	130 km
Sliding rate	~7-14 GHz/Mm

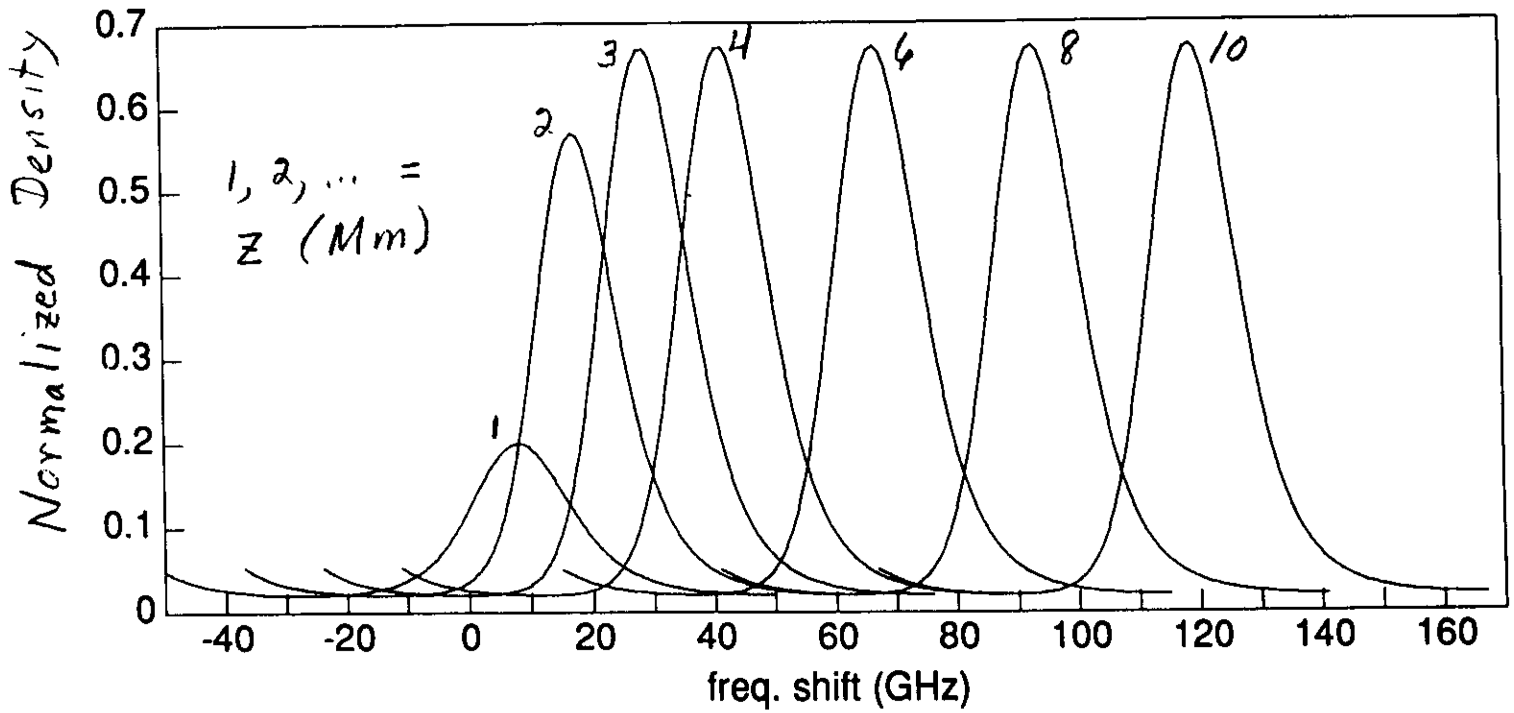
Soliton pwr.	3.6 mW(path av.)
Time av. pwr.	0.6 mW(span input, 10 Gbit/s)

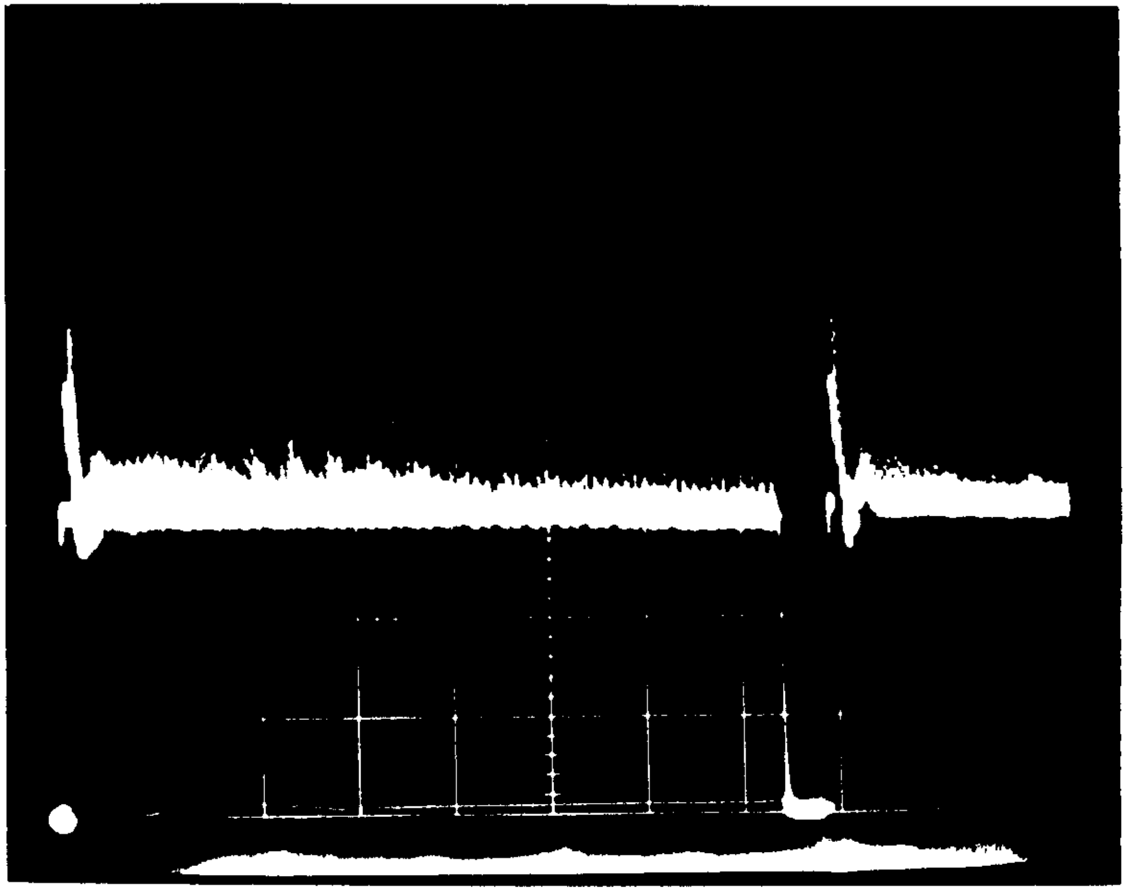
Recirculating Loop with Sliding -Frequency Filters

(Filters are 75 or 100 GHz FSR etalons with R=9%)

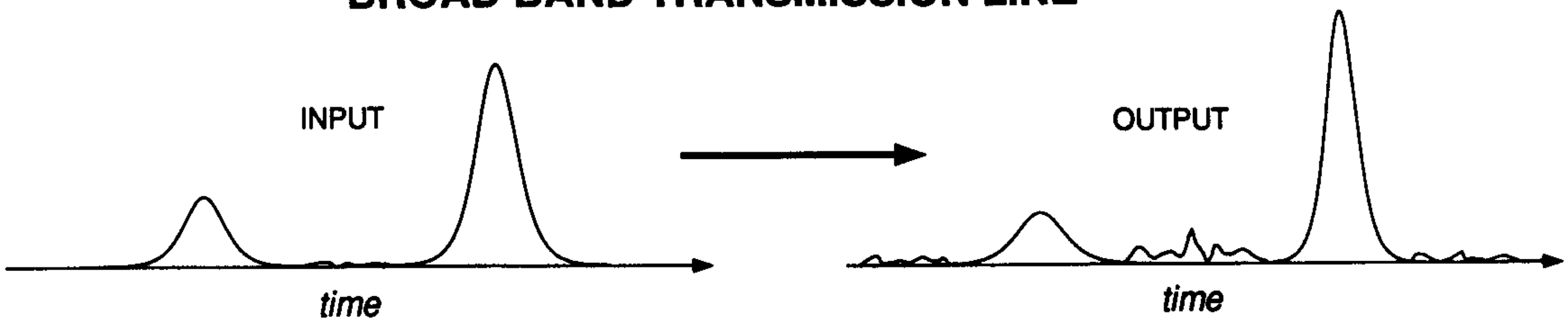


NOISE SPECTRAL DENSITY VS FREQUENCY AND DISTANCE
TRANS., R=9%, 75 GHz FSR ETALONS SLIDING AT 13 GHz/Mm
ONE ETALON FILTER PER 50 KM; alphar = 1.4/Mm

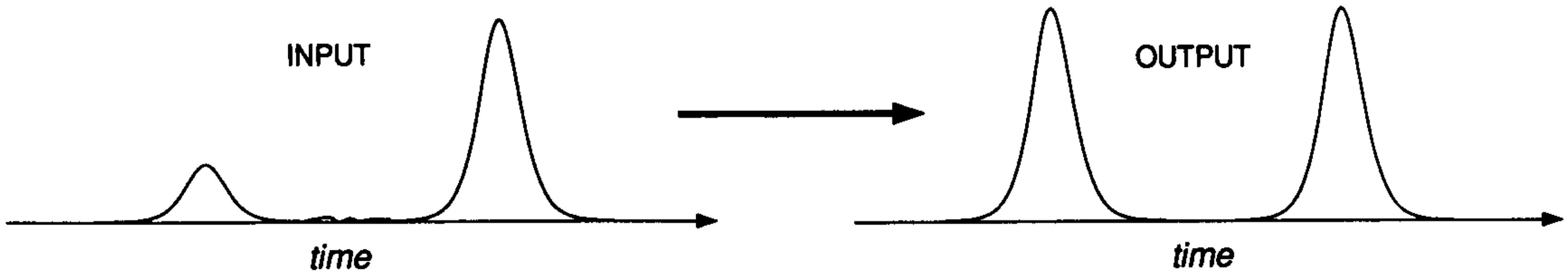




BROAD BAND TRANSMISSION LINE



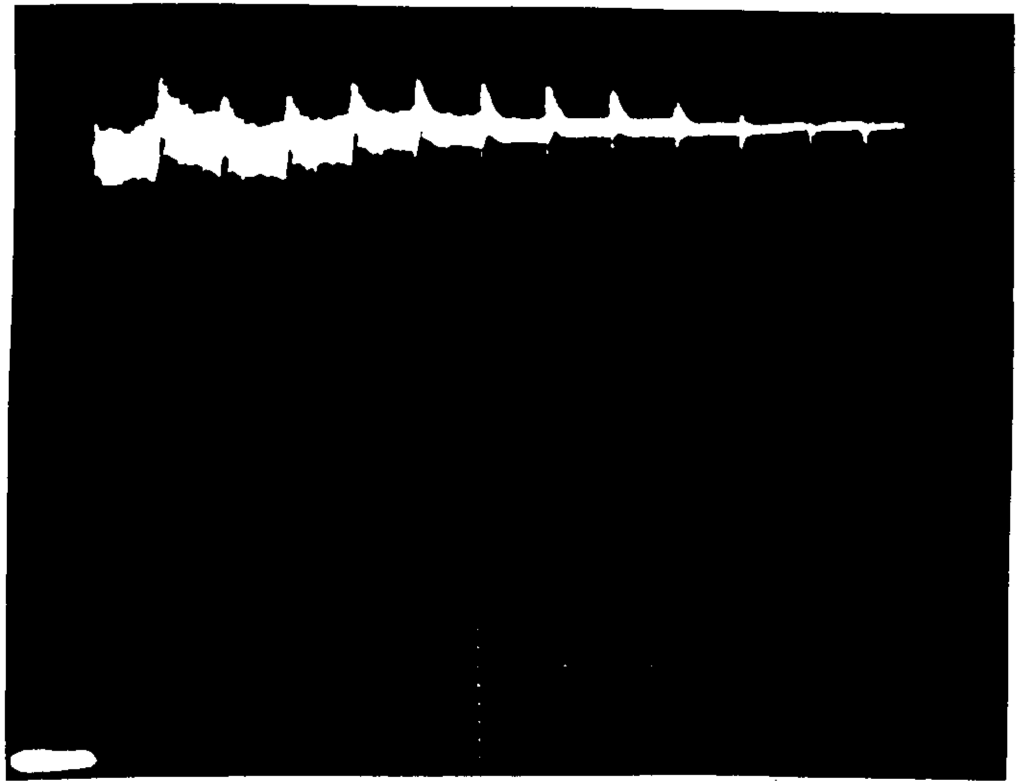
FILTERED TRANSMISSION LINE



THE PARAMETERS OF SOLITONS (PULSE WIDTH, INTENSITY) IN FILTERED TRANSMISSION LINE ARE DETERMINED BY THE TRANSMISSION LINE ONLY (NOT BY THE INPUT SIGNAL!)

SLIDING-FREQUENCY GUIDING FILTERS AS AMPLITUDE NOISE EATERS

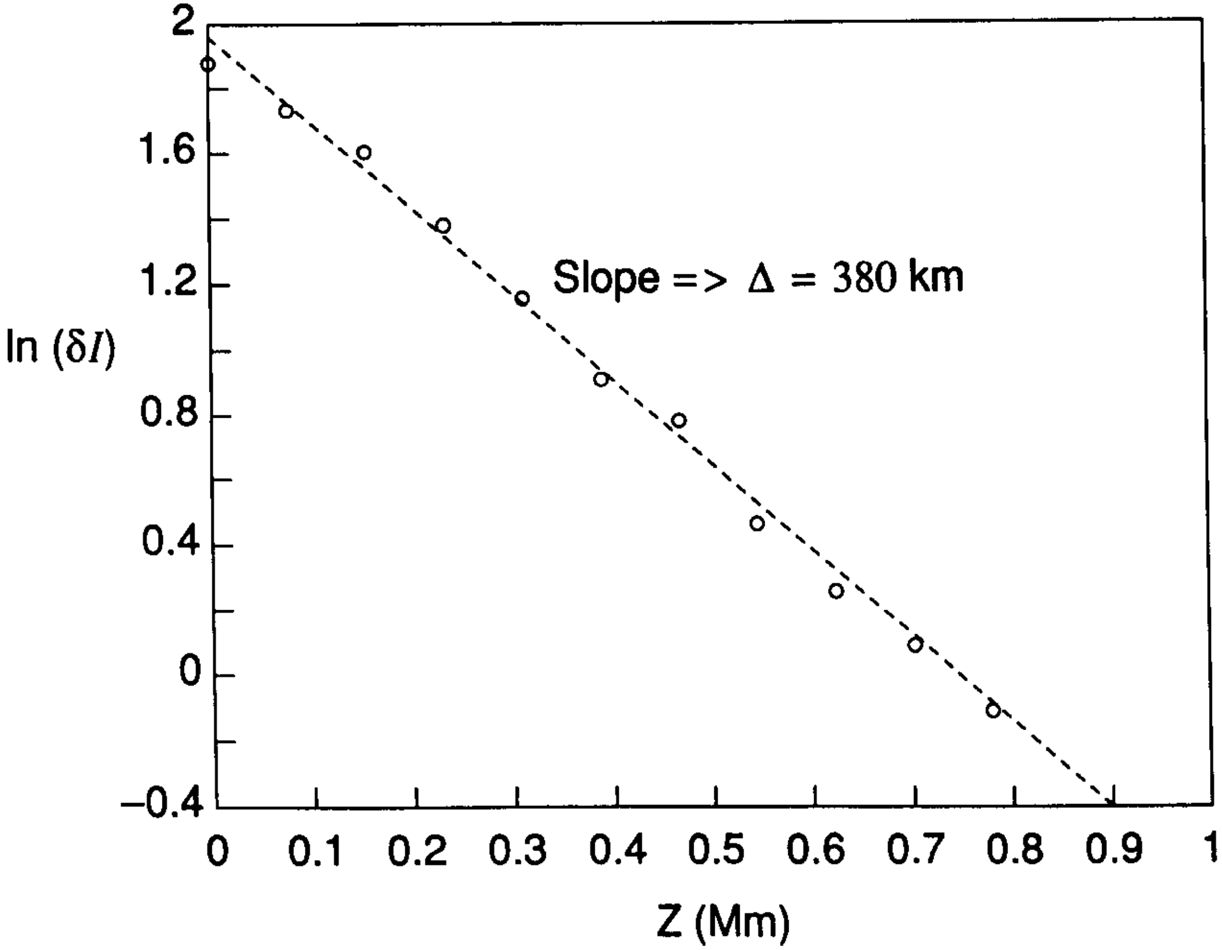
NOTE GREAT REDUCTION IN SOURCE AMPLITUDE NOISE AFTER ONLY ~6 ROUND TRIPS (PASSAGE THROUGH 18 FILTERS):



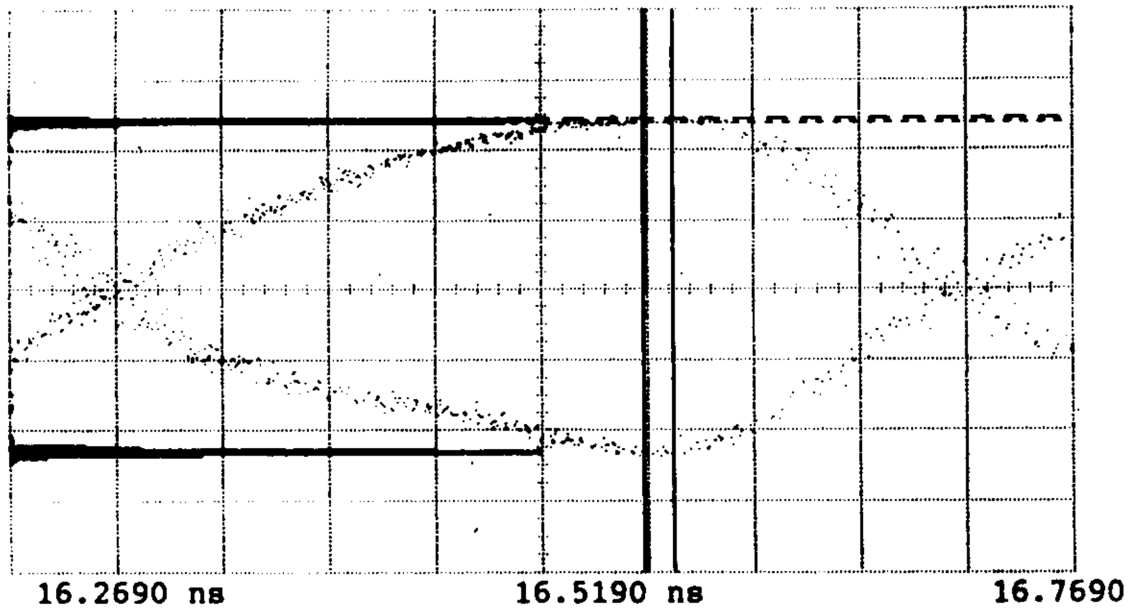
← 1000 km →

IMPLIED DAMPING LENGTH = 380 km.

Experimentally measured amplitude damping parameter



MEASUREMENT OF Q FACTOR AT 20 Mm
(Sliding filters; D = .45 ps/nm-km; τ = 16 ps)

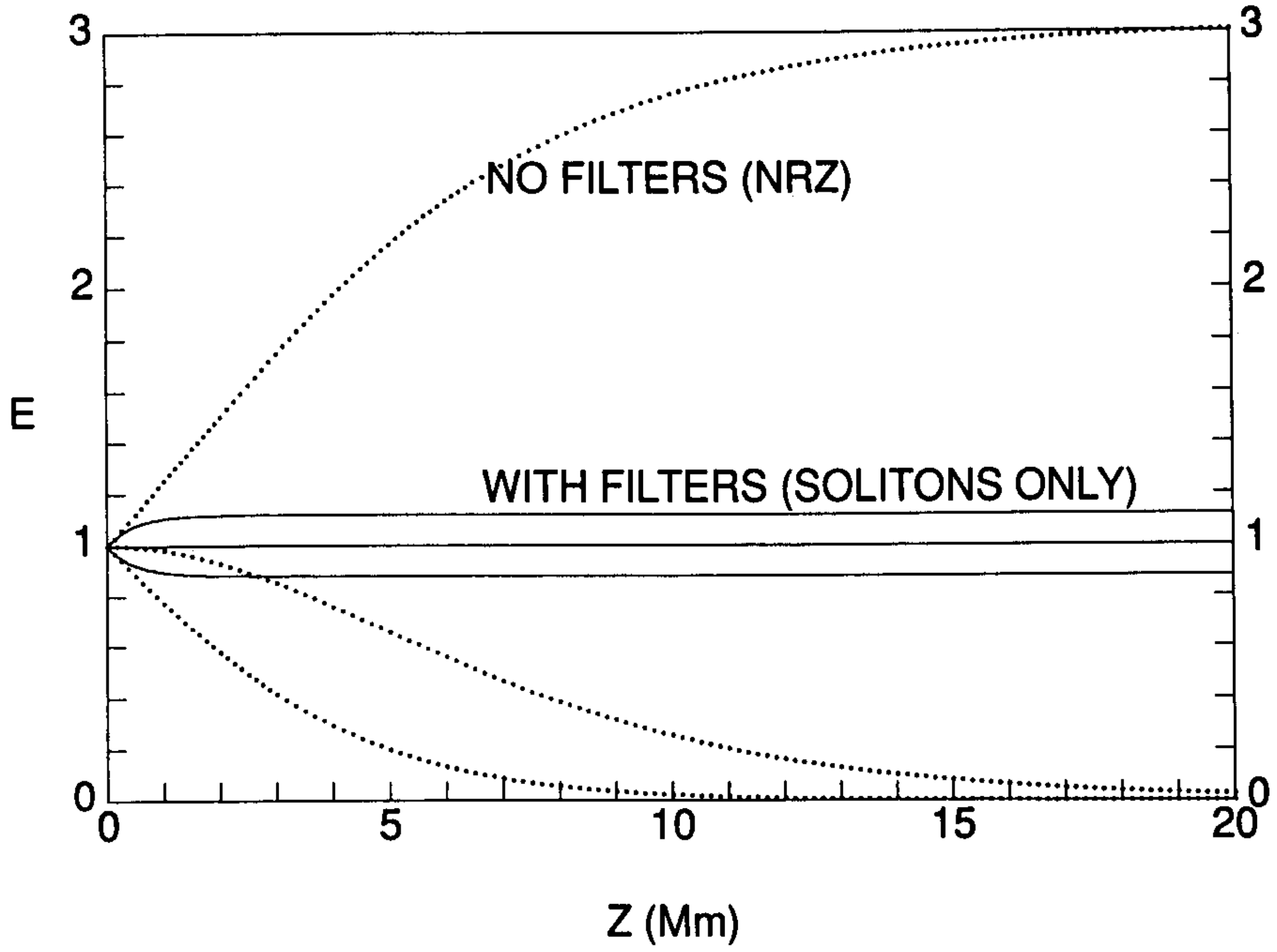


$V_1 - V_0 = 240\ mV; \quad \sigma_1 = 2.16\ mV; \quad \sigma_0 = 1.83\ mV.$

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0} = 60$$

Conclusion: We have Q factor to burn!

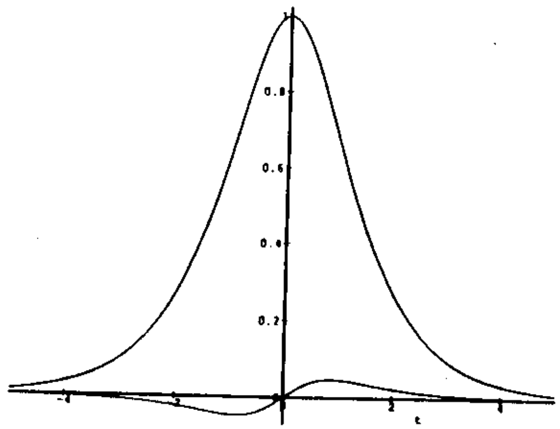
WDM CHANNEL STRENGTHS VS DISTANCE WITH AND WITHOUT FILTERS
THREE CHANNELS WITH RELATIVE GAINS OF +1, 0, and -1 dB/Mm.



THE GORDON-HAUS EFFECT: OUTLINE OF PROOF

At each amplifier, addition of the noise field component $\delta u = i\,a\,u_{sol}\tanh(t)$ shifts the soliton's frequency by

$$\delta\Omega = \frac{2}{3}a$$



The net time shift of a given pulse is:

$$\delta t = \sum_{amps} \delta\Omega_n z_n$$

where z_n is distance from nth amp. to the end.

Get variance of δt by summing variances of the (independent) δt_n:

$$\langle \delta t^2 \rangle = \langle \delta\Omega^2 \rangle_{amp} \sum_{amps} z_n^2 = \langle \delta\Omega^2 \rangle_{amp} \frac{Z^3}{3L_{amp}}$$

(It can be shown that $\langle \delta\Omega^2 \rangle_{amp} = \frac{1}{3}\frac{(G-1)n_{sp}h\nu}{W_{sol}}$.)

THE GORDON-HAUS EFFECT: BROAD-BAND VS FILTERED TRANSMISSION LINES

Get variance of δt by summing variances of the (independent) δt_n:

For broad-band transmission line, one has:

$$\langle \delta t^2 \rangle = \langle \delta\Omega^2 \rangle_{amp} \sum_{amps} z_n^2 = \langle \delta\Omega^2 \rangle_{amp} \frac{Z^3}{3L_{amp}}$$

where z_n is the distance from the nth amp. to the end.

Filters reduce the z_n to the filter-damping length, Δ, so one then has:

$$\langle \delta t^2 \rangle = \langle \delta\Omega^2 \rangle_{amp} \sum_{amps} \Delta^2 = \langle \delta\Omega^2 \rangle_{amp} \frac{\Delta^2 Z}{L_{amp}}$$

Ex: For 10,000 km line, root mean square value of z_n ~7000 km.

But with sliding-frequency filters, Δ is typically ~400 km.

THE GORDON-HAUS EFFECT: BROAD-BAND VS FILTERED TRANSMISSION LINE

BROAD-BAND LINE:

$$\sigma^2{}_{GH} = 6.8 n_{sp} F(G) \frac{Z^3 D}{\tau}$$

The pulse jitter increases when τ decreases.

FILTERED LINE:

$$\frac{Z^3}{3} \to \Delta^2 Z, \qquad \text{and} \qquad \Delta = \frac{3}{2\eta} z_c \sim \frac{\tau^2}{\eta D}$$

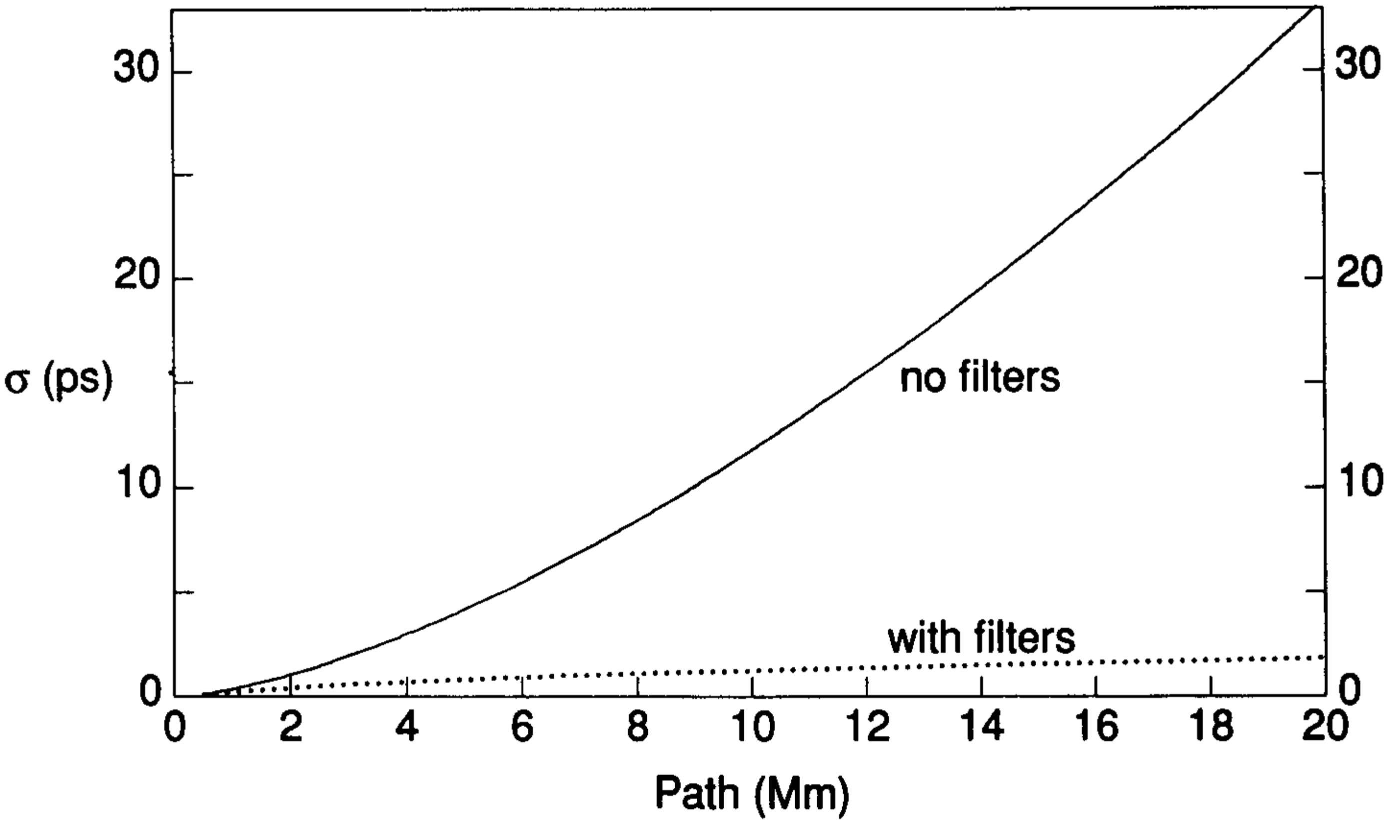
$$\sigma^2{}_{GH} = 3.21\ 10^{-7} n_{sp} F(G) \frac{Z\tau^3}{\eta^2 D}$$

The pulse jitter decreases when τ decreases!

STANDARD DEVIATION OF JITTER IN PULSE ARRIVAL TIMES

16 ps pulse, D = 0.5 ps/nm-km, n_{sp} = 1.6

Effective damping length ≈400 km



THE ACOUSTIC EFFECT: BROAD-BAND VS FILTERED TRANSMISSION LINE

BROAD-BAND LINE:

$$\sigma_a = 8.6 \frac{D^2}{\tau} \frac{Z^2}{2} (R - 0.99)^{1/2}$$

The pulse jitter increases when τ decreases.

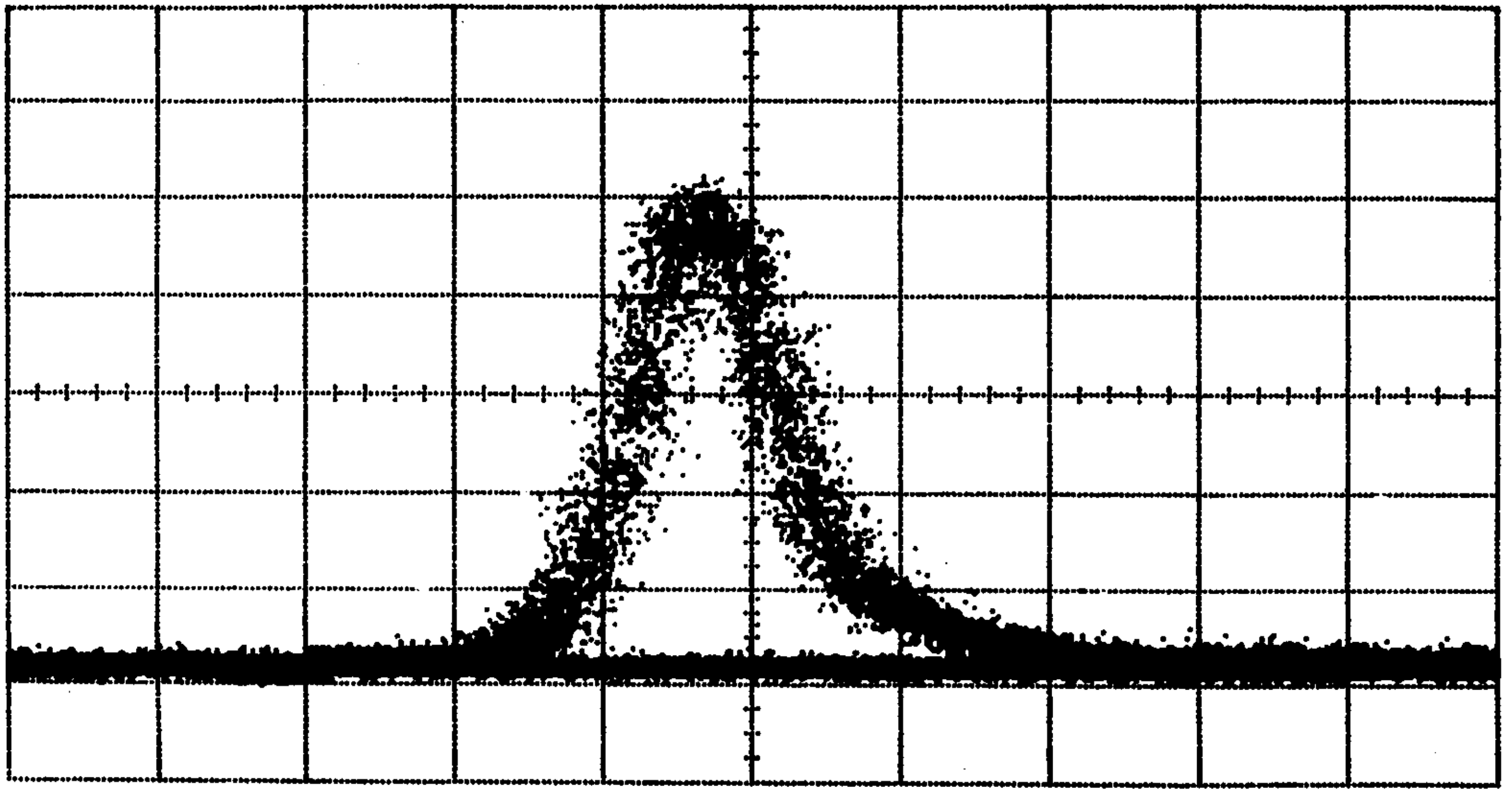
FILTERED LINE:

$\frac{Z^2}{2} \rightarrow Z\Delta,$ and $\Delta = \frac{3}{2\eta} z_c \sim \frac{\tau^2}{\eta D}$

$$\sigma_a = 3.26 \; 10^{-3} \frac{D\tau Z}{\eta} (R - 0.99)^{1/2}$$

The pulse jitter decreases when τ decreases!

EYE DIAGRAM OF 20 ps SOLITONS AFTER 10 Mm TRANSMISSION USING SLIDING-FREQUENCY, GUIDING FILTERS



20 ps per division

Measurement of timing jitter in filter-guided soliton transmission at 10 Gbits/s and achievement of 375 Gbits/s-Mm, error free, at 12.5 and 15 Gbits/s

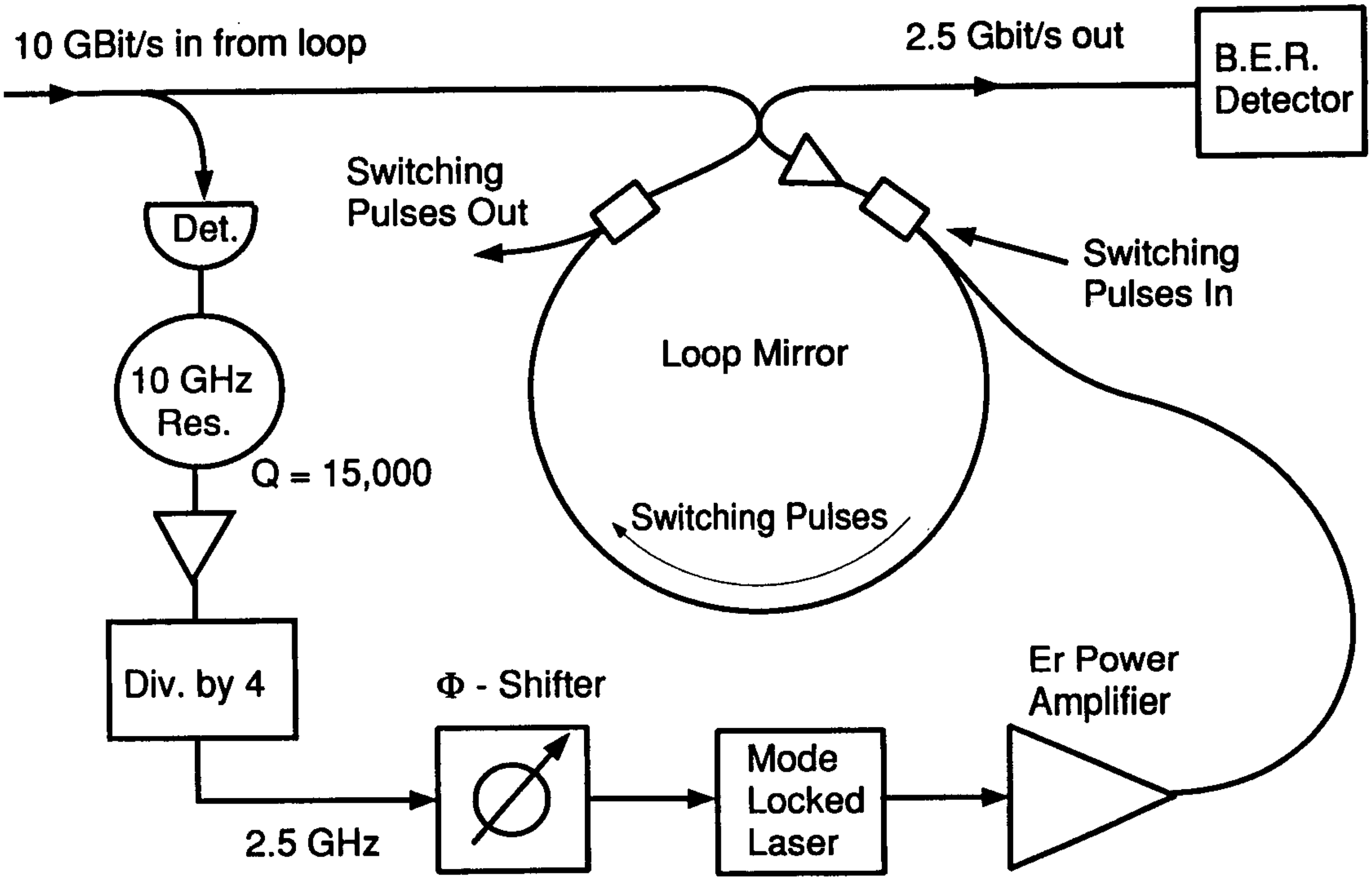
L. F. Mollenauer, P. V. Mamyshev, and M. J. Neubelt

AT&T Bell Laboratories, Holmdel, New Jersey 07733

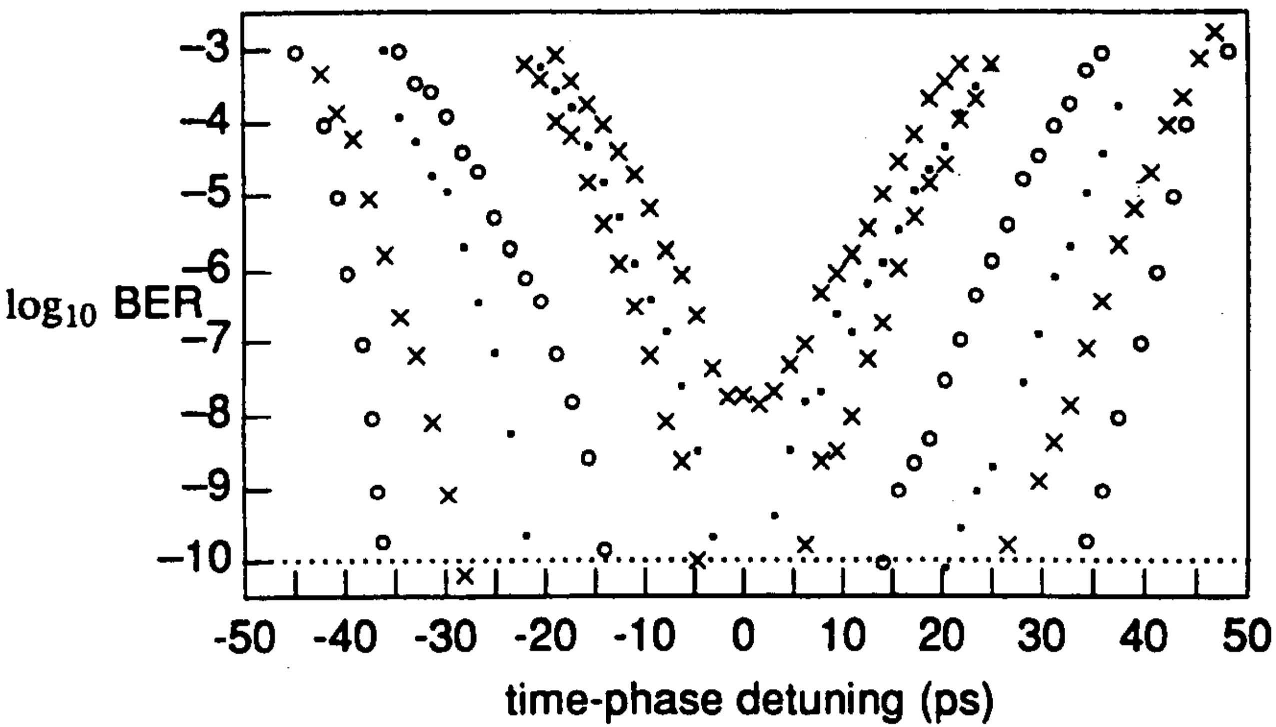
Received January 7, 1994

We report on extensive measurement, as a function of distance, of the timing jitter in sliding-frequency-filter-guided soliton transmission at 10 Gbits/s. The measured jitter is separated into a sliding-filter-damped, Gordon–Haus term, a similarly damped acoustic term, and a recently predicted contribution from scatter in pulse polarizations. Measured error-free (bit-error rate $<10^{-10}$) distances at 10, 12.5, and 15 Gbits/s are 35, 30, and 25 Mm, respectively.

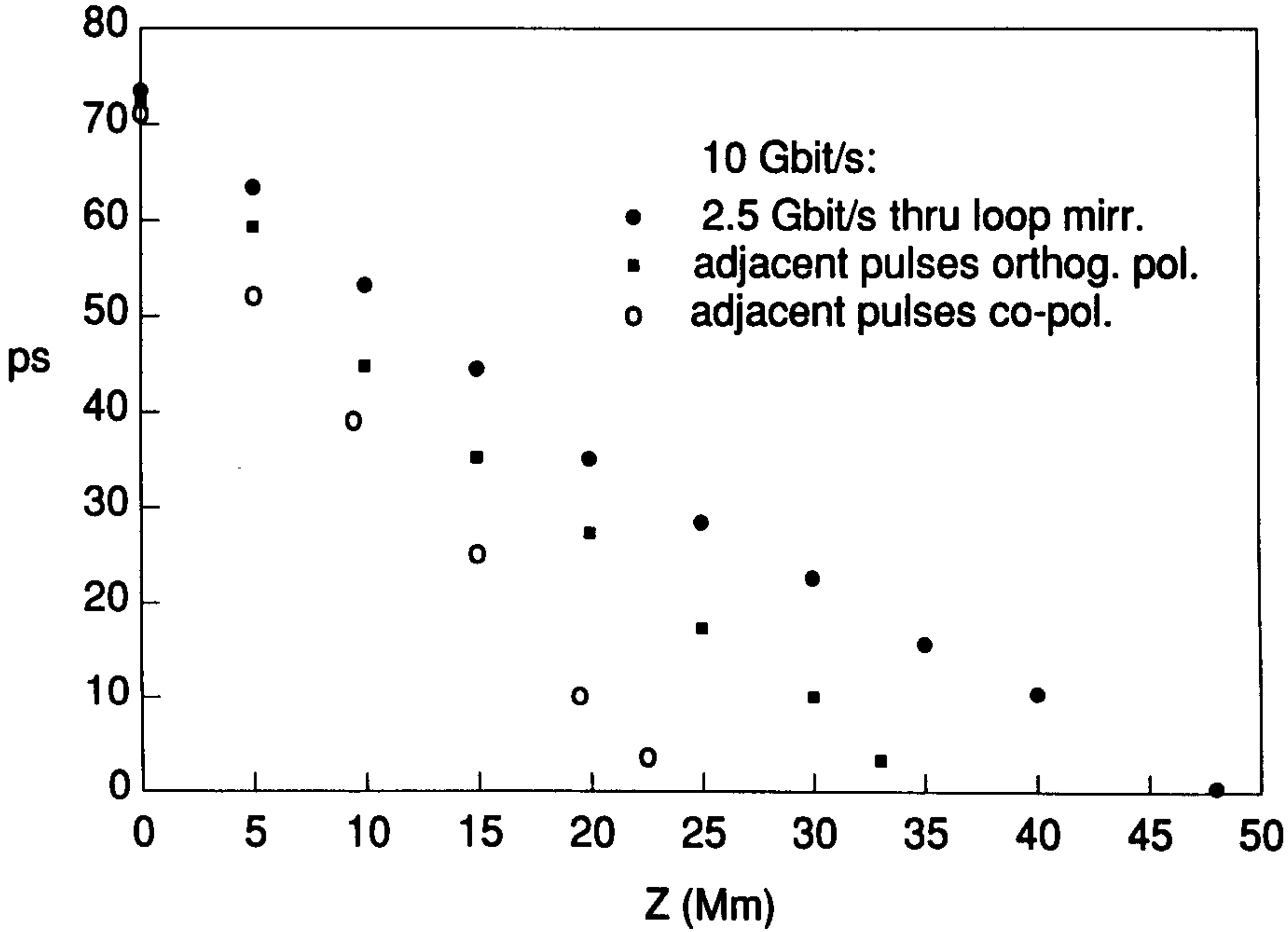
BIT-ERROR-RATE DETECTION SCHEME



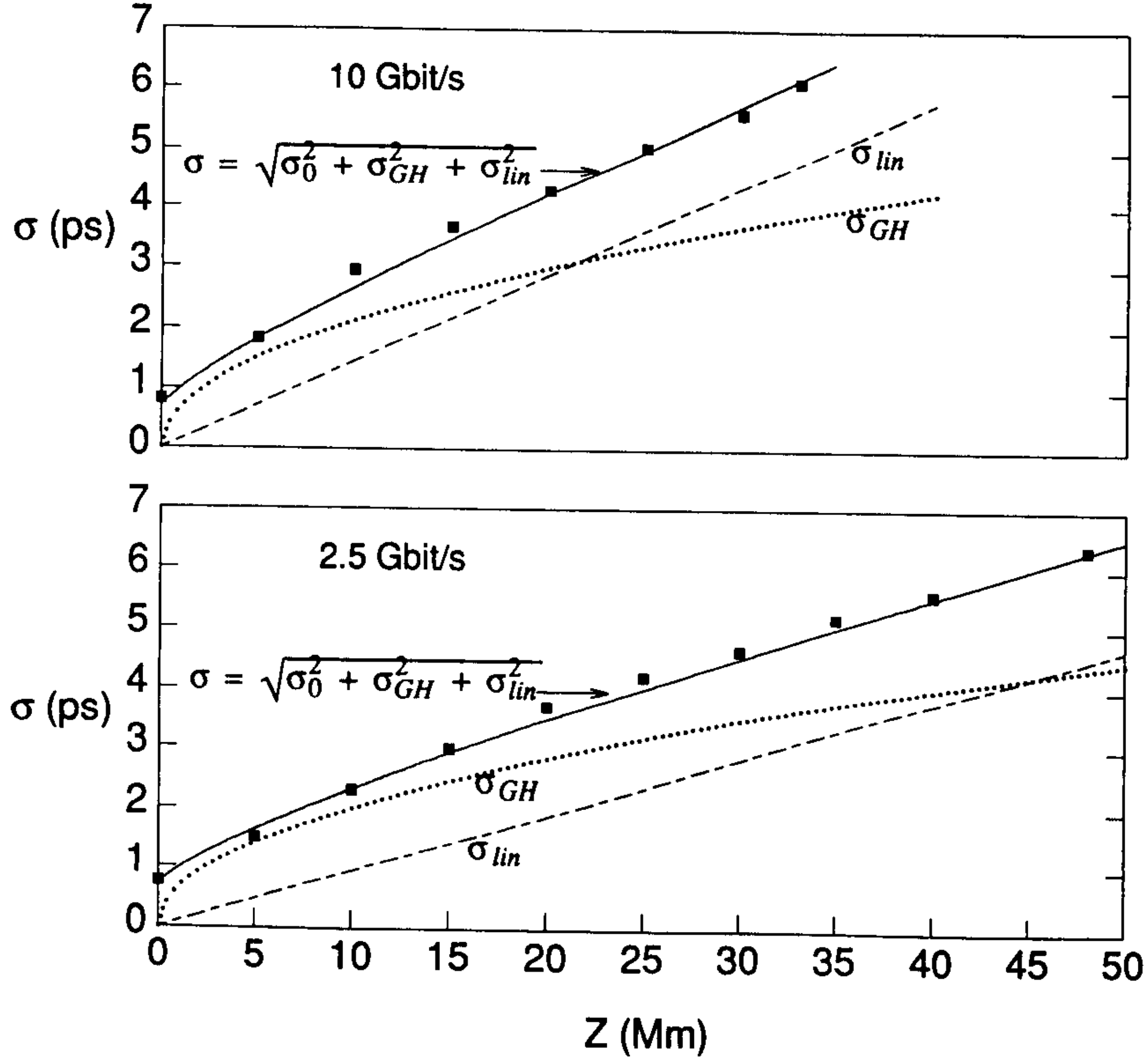
BER AT 0, 5, 9.5, 15, 19.5, 22.5, and 24.5 Mm VS
LOOP MIRROR PHASE ADJUSTMENT



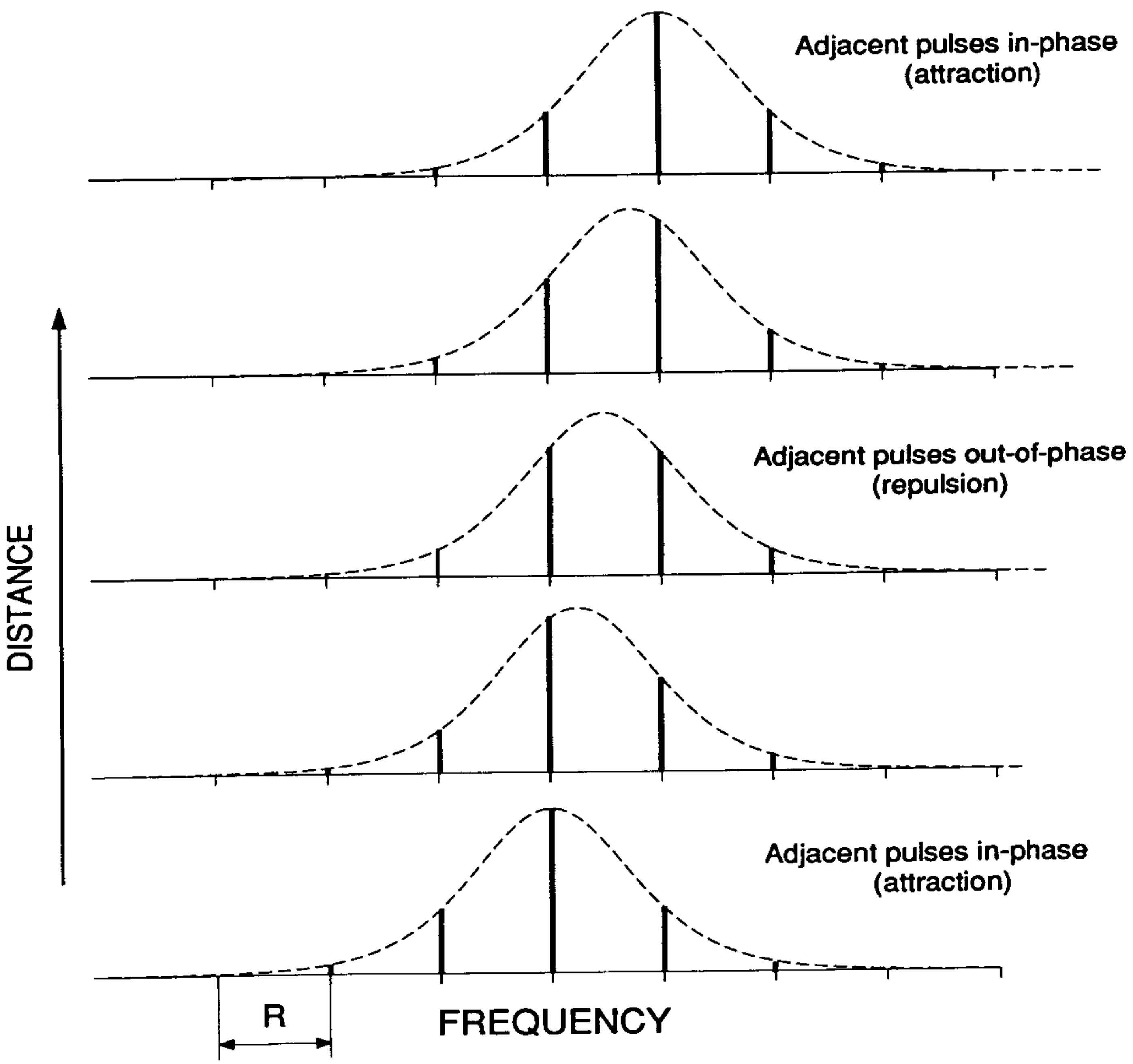
PHASE MARGIN AT 10^{-10} BER VS Z



STD. DEV. OF JITTER USING SLIDING FREQ. FILTERS



SOLITON PULSE TRAIN SPECTRUM EVOLUTION

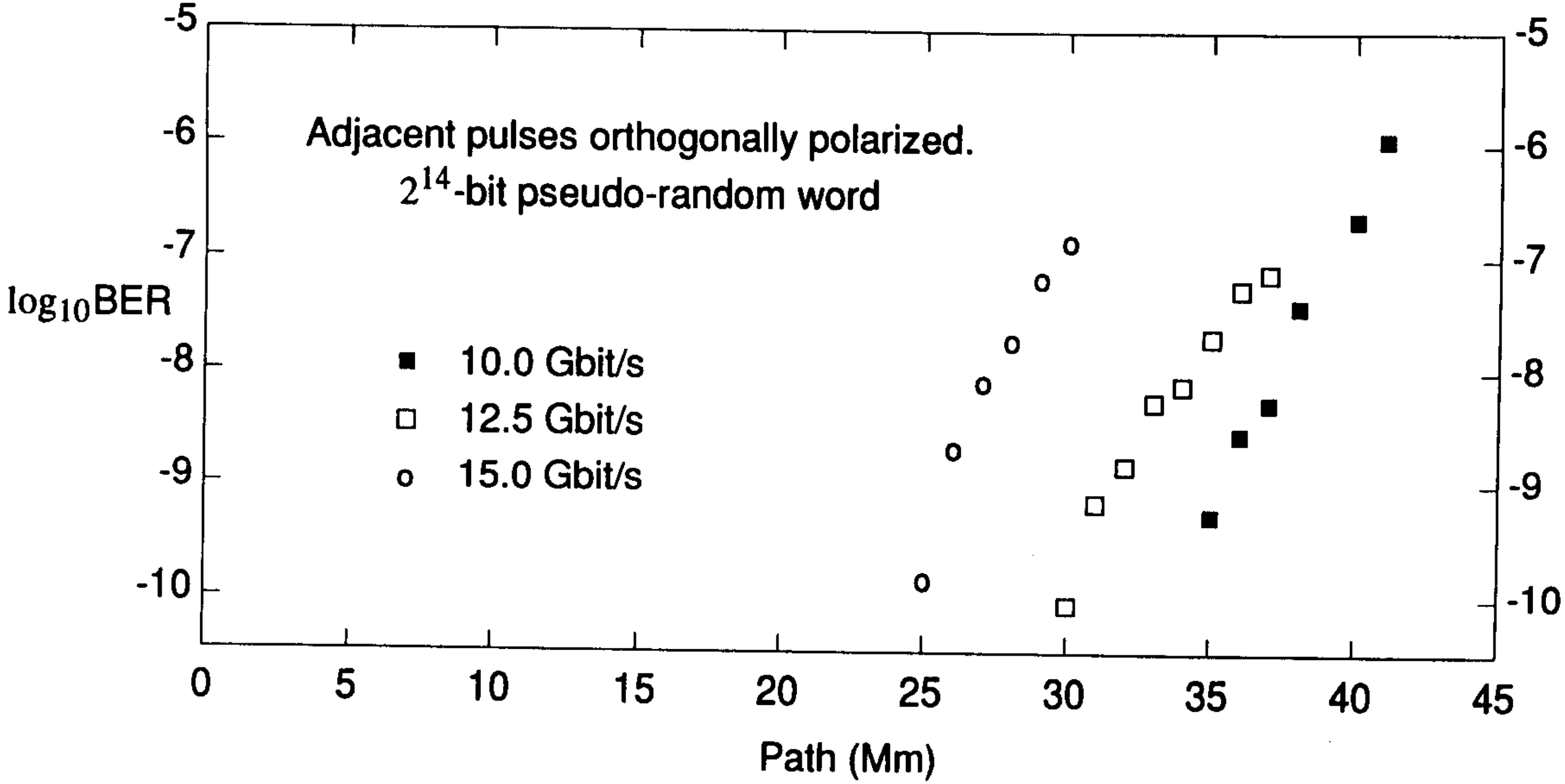


REPULSION AND ATTRACTION OF ADJACENT SOLITONS ALTERNATE WITH DISTANCE WITH A PERIOD OF **Z=R/F'**

R PULSE TRAIN REPETITION RATE

F' SLIDING RATE

MEASURED BIT-ERROR-RATE IN SOLITON TRANSMISSION at 10, 12.5, & 15 Gbit/s



Stability of soliton propagation with sliding-frequency guiding filters

P. V. Mamyshev and L. F. Mollenauer

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received July 25, 1994

We report on extensive experimental measurement of the allowable range of soliton pulse energies for stable, error-free propagation with sliding-frequency guiding filters, as a function of both filter strength and sliding rate, and on interpretative numerical analysis. The most important result is our discovery of an upper bound and related optimum value for the filter strength; at the optimum, the allowed range of pulse energies is nearly two to one.

COMPUTATION OF "DIMENSIONLESS" FILTER STRENGTH, SLIDING RATE, AND EXCESS GAIN PARAMETERS FROM REAL WORLD QUANTITIES

With filters, the simplified propagation equation in soliton units is:

$$\frac{\partial u}{\partial z} = i\left(\frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u\right) + \frac{1}{2}\left[\alpha - \eta\left(i\frac{\partial}{\partial t} - \omega_f\right)^2\right]u$$

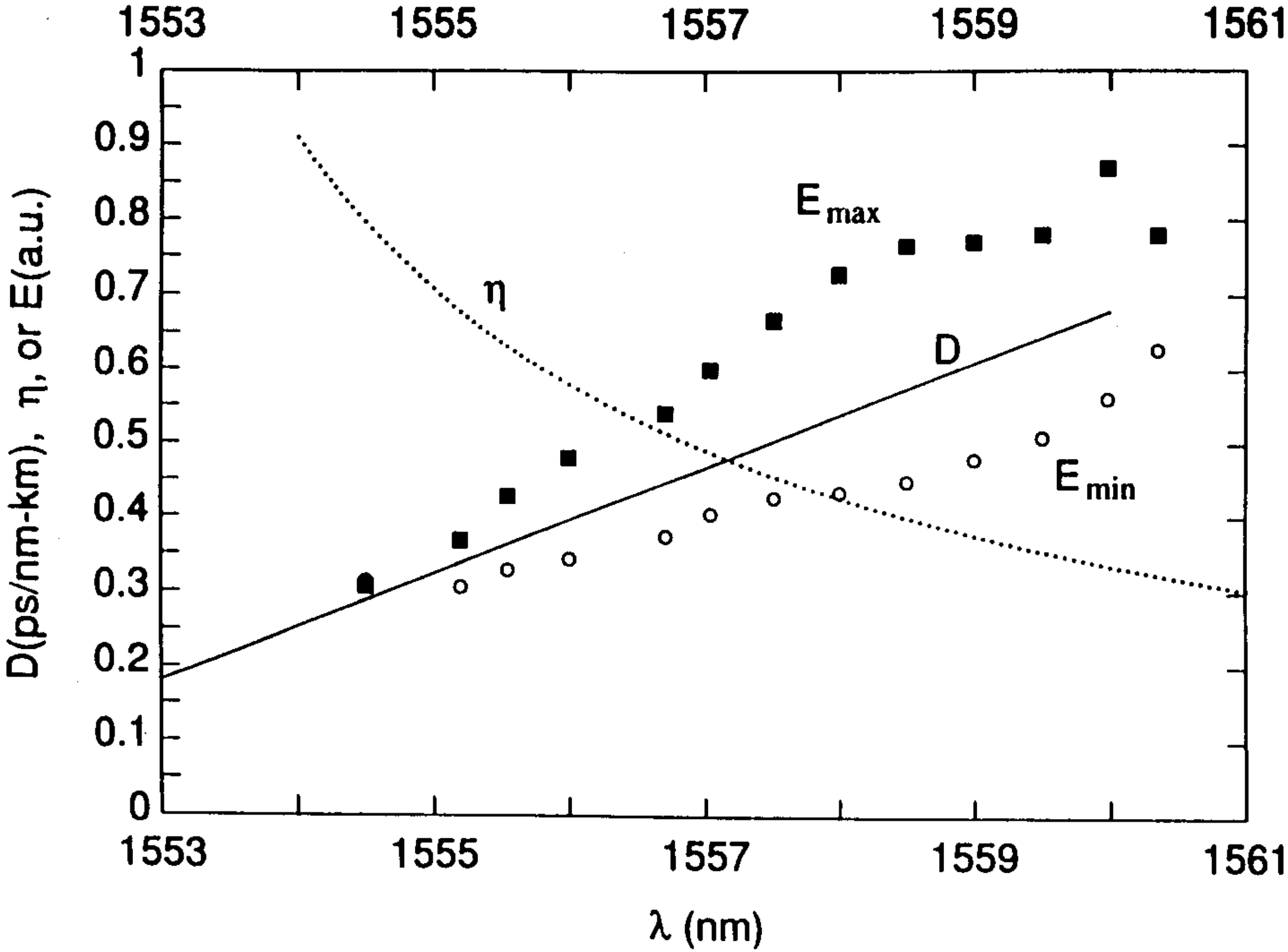
When using etalon filters with mirror spacing d, reflectivity R, spaced L_f apart, η, ω'_f and α are computed as:

$$\eta = \frac{8\pi R}{(1-R)^2}\left(\frac{d}{\lambda}\right)^2 \frac{1}{DL_f}$$

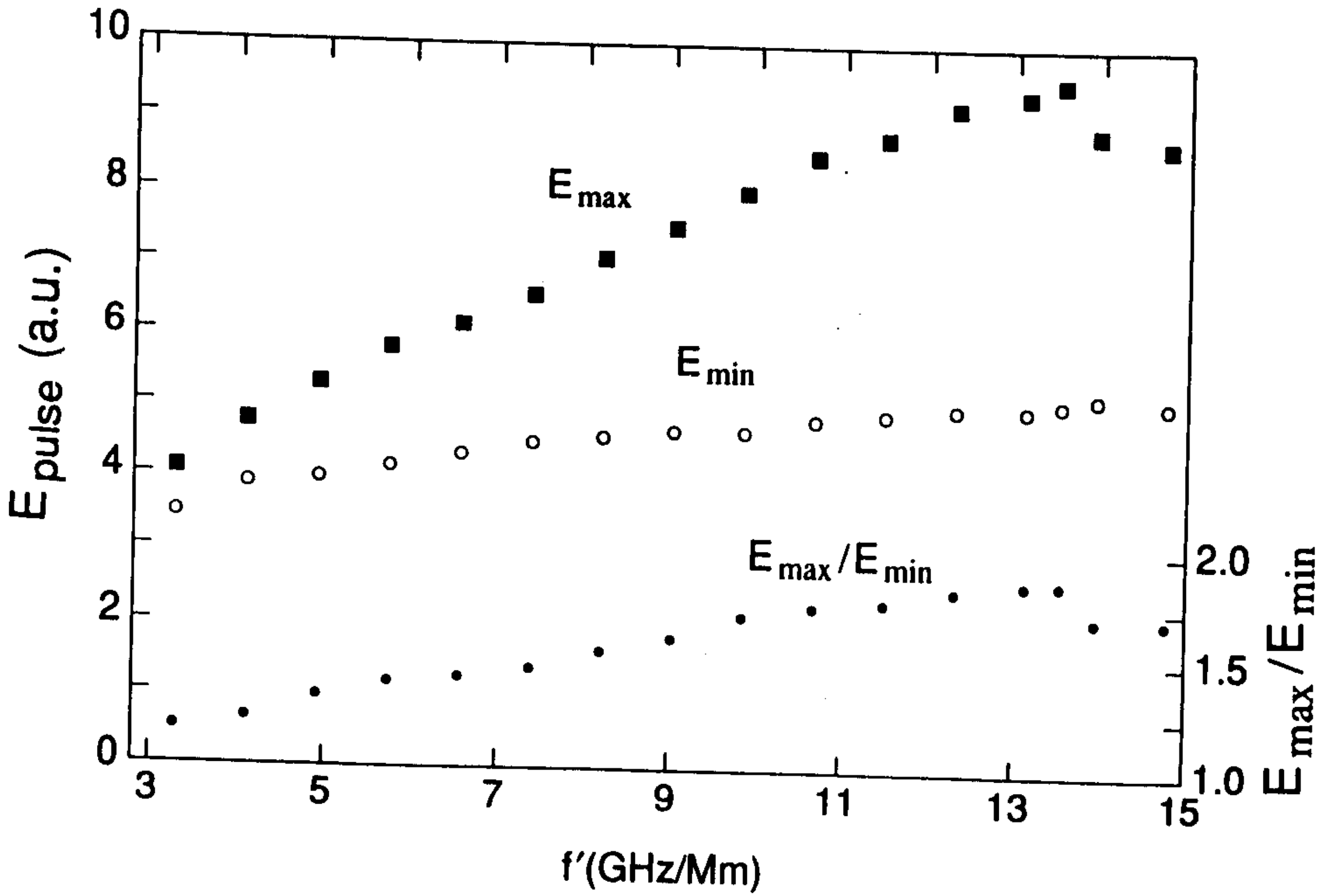
$$\omega'_f = 4\pi^2 f' c t_c{}^3/(\lambda^2 D)$$

$$\alpha = \alpha_R t_c{}^2 2\pi c/(\lambda^2 D)$$

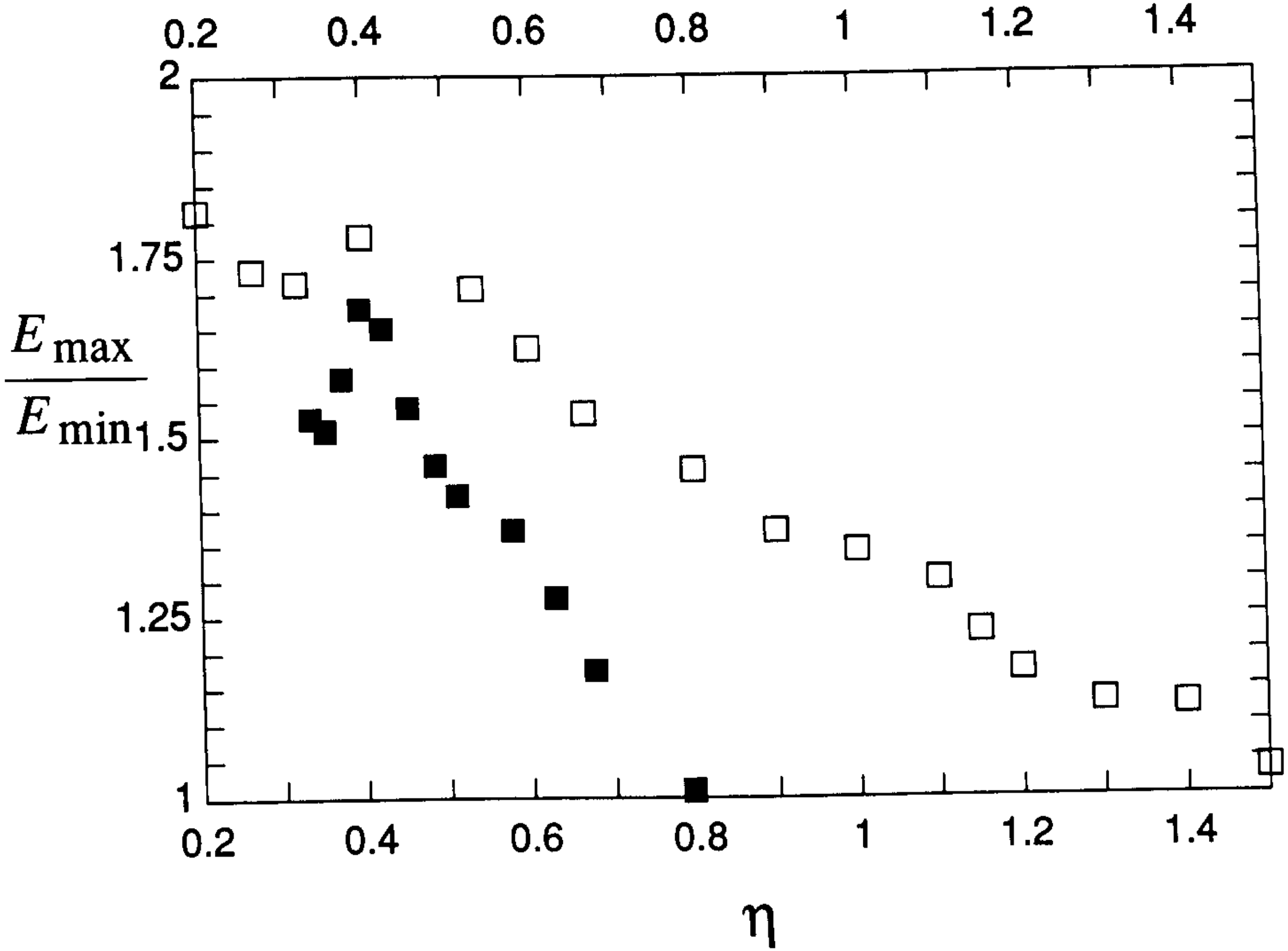
SOLITON PULSE ENERGY RANGE FOR ERROR FREE TRANSMISSION
SLIDING RATE = 13 GHz/Mm (OPTIMUM RATE)



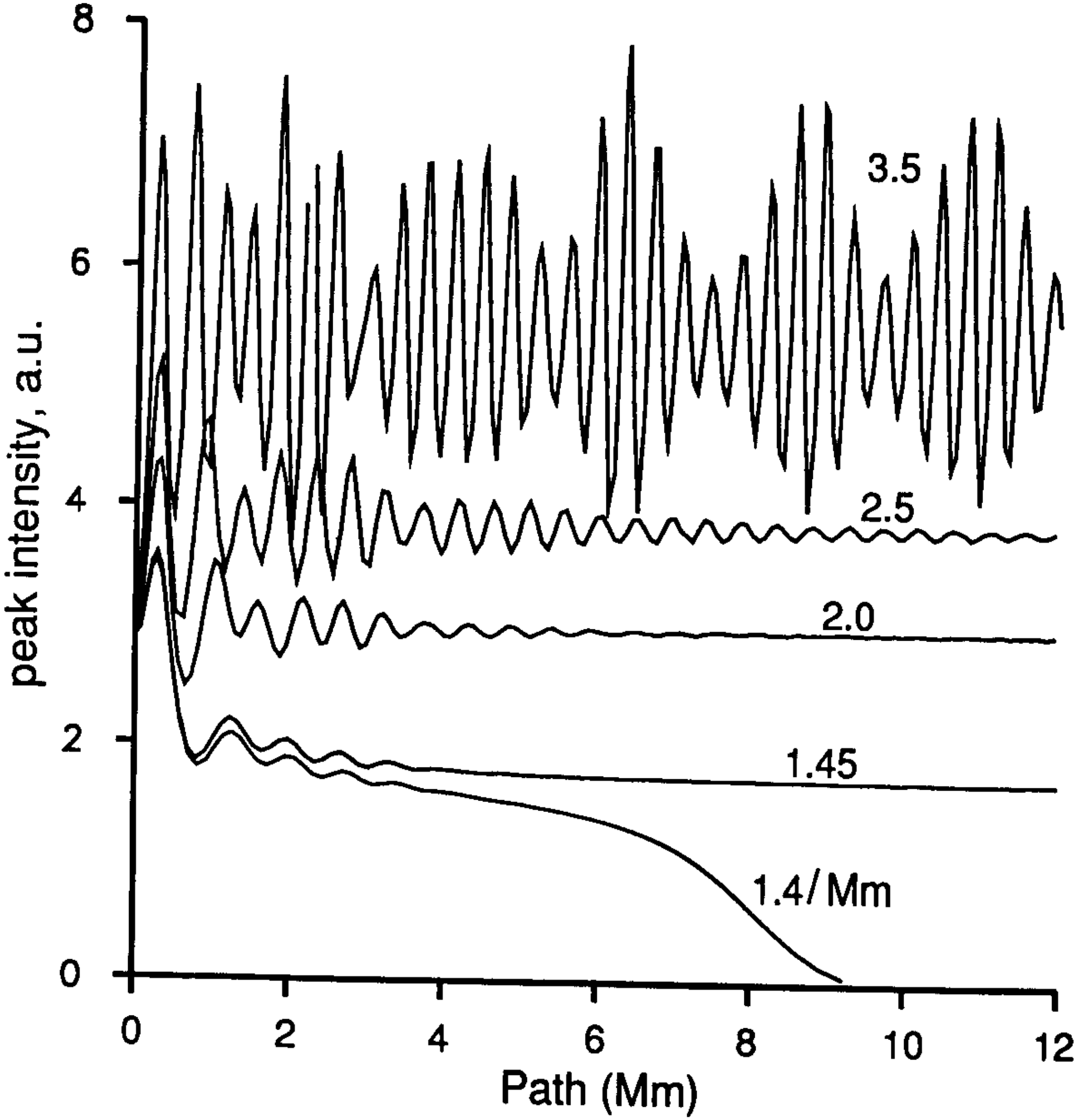
SOLITON ENERGY RANGE FOR ERROR FREE TRANS. VS SLIDING RATE
FILTER STRENGTH PARAMETER η = 0.4 (OPTIMUM VALUE)

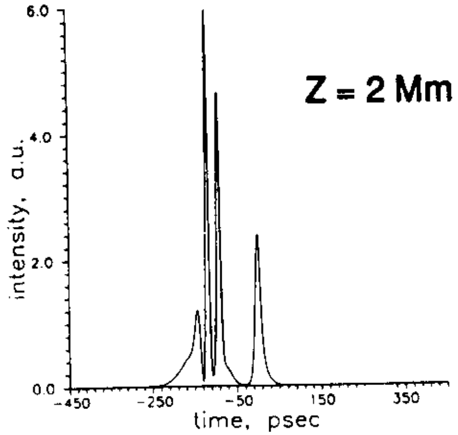


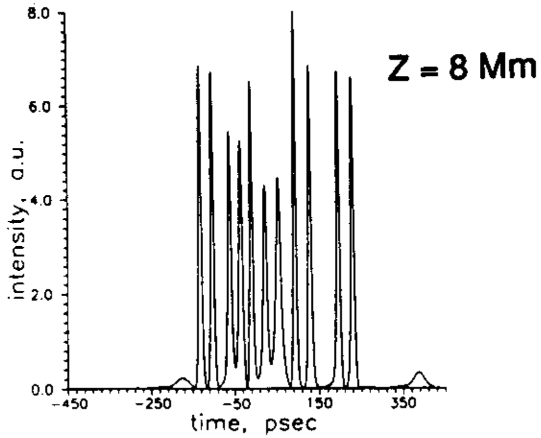
STABILITY RANGE VS FILTER STRENGTH PARAMETER;



SOLITON PEAK INTENS. VS. PATH FOR VARIOUS EXCESS GAINS

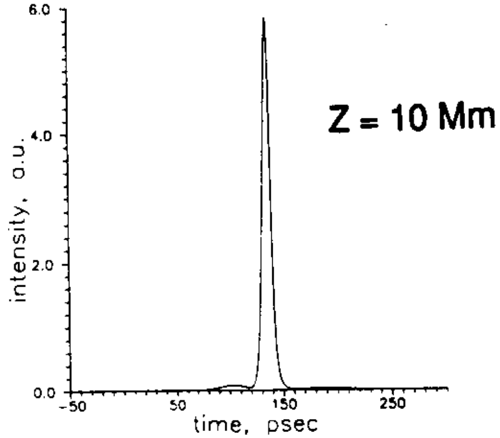






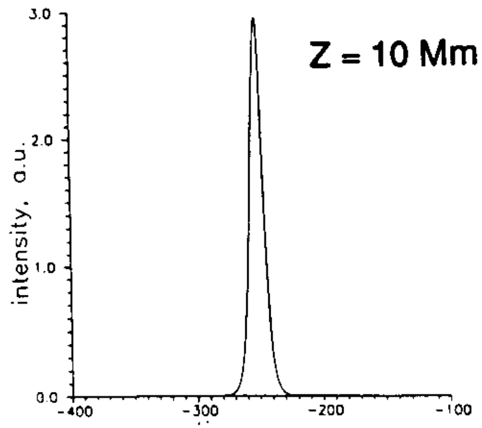
Over the upper limit

$\alpha = 4.5$ /Mm



Near the upper limit

$\alpha = 3.5$ /Mm



Stable region

$\alpha = 2$ /Mm

Dual-wavelength source of high-repetition-rate, transform-limited optical pulses for soliton transmission

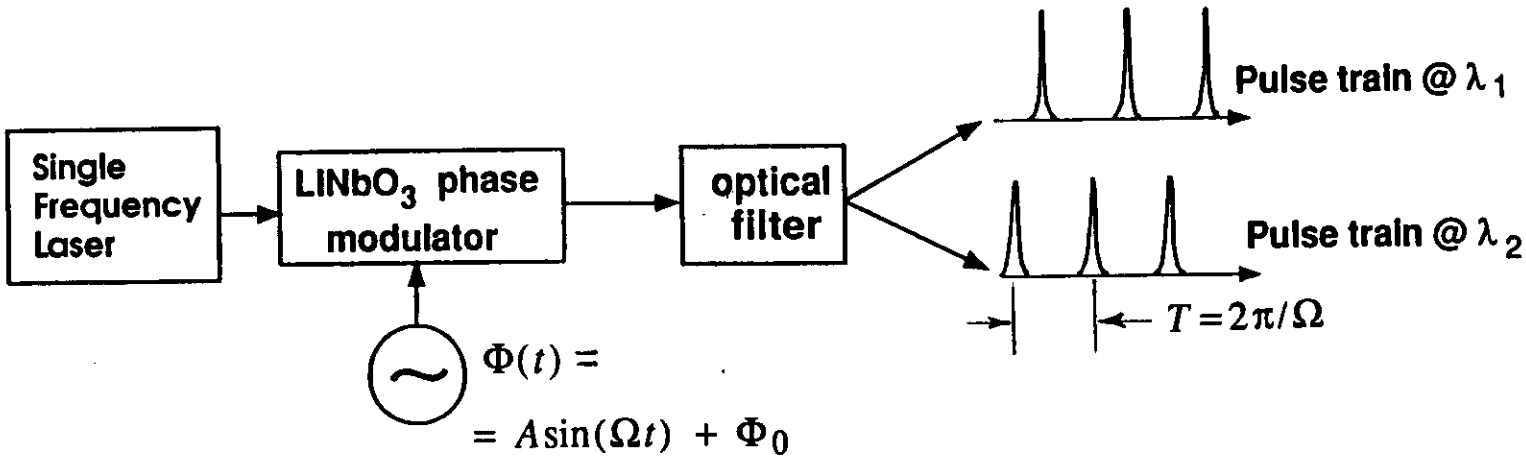
P. V. Mamyshev

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received June 3, 1994

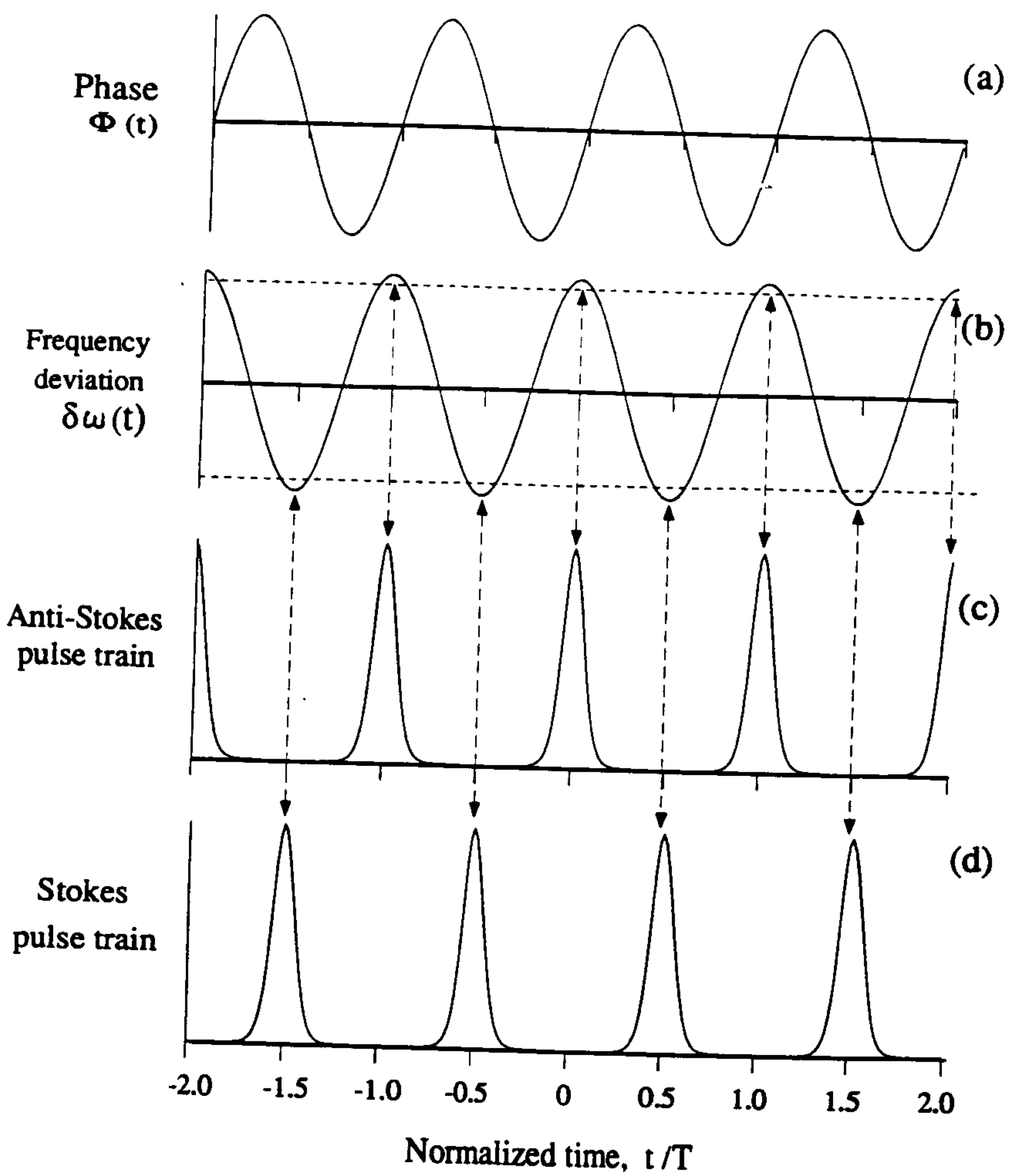
I show how removal of the central optical frequencies from the output of an externally phase-modulated, single-frequency laser results in a dual-wavelength source of high-quality pulse trains for wavelength-division-multiplexed soliton transmission and describe successful experimental demonstration of such sources in the 2.5–12.6-Gbit/s range.

Dual-wavelength source of high-repetition-rate, transform-limited optical pulses for soliton transmission

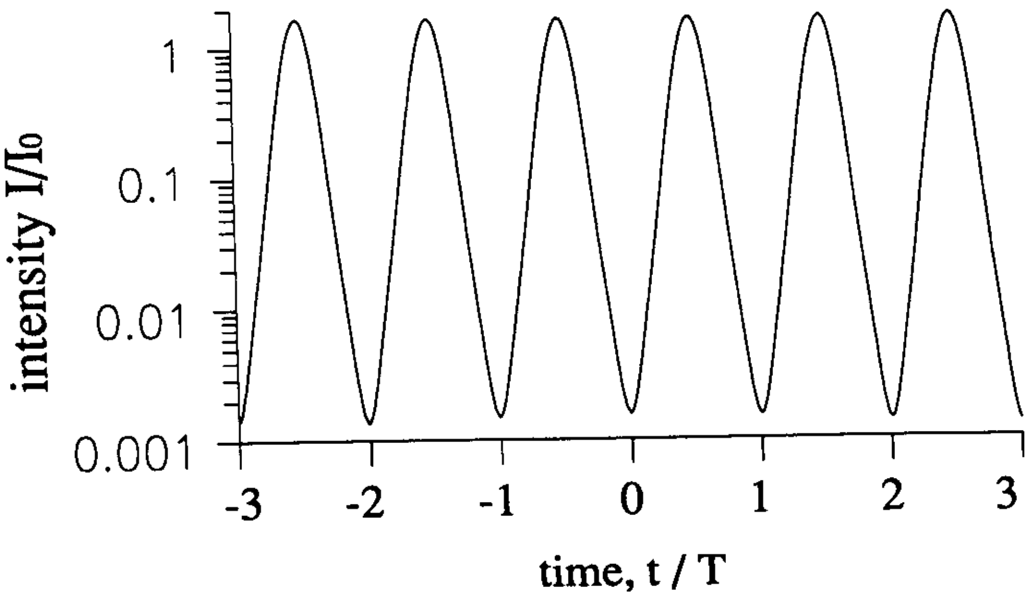


$$\Phi(t) = A\sin(\Omega t) + \Phi_0$$

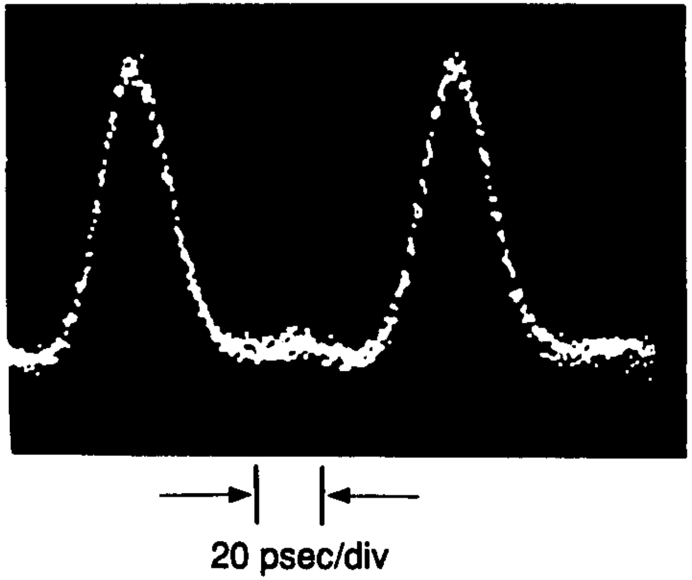
$$\delta\omega(t) \equiv \omega(t) - \omega_0 = \frac{\partial\Phi}{\partial t} = A\Omega\cos(\Omega t)$$



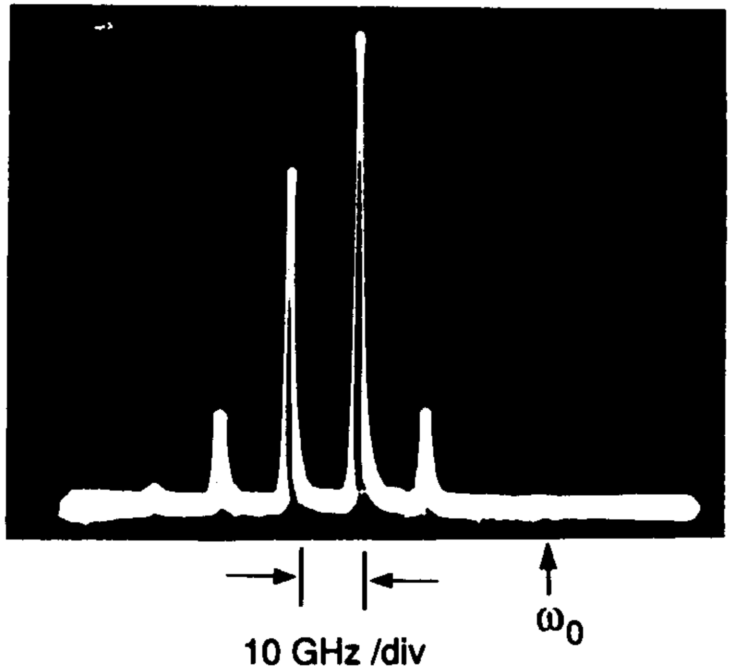
Log intensity plot of pulses:
shows essentially Gaussian shape



Experimental test at 10 GHz:

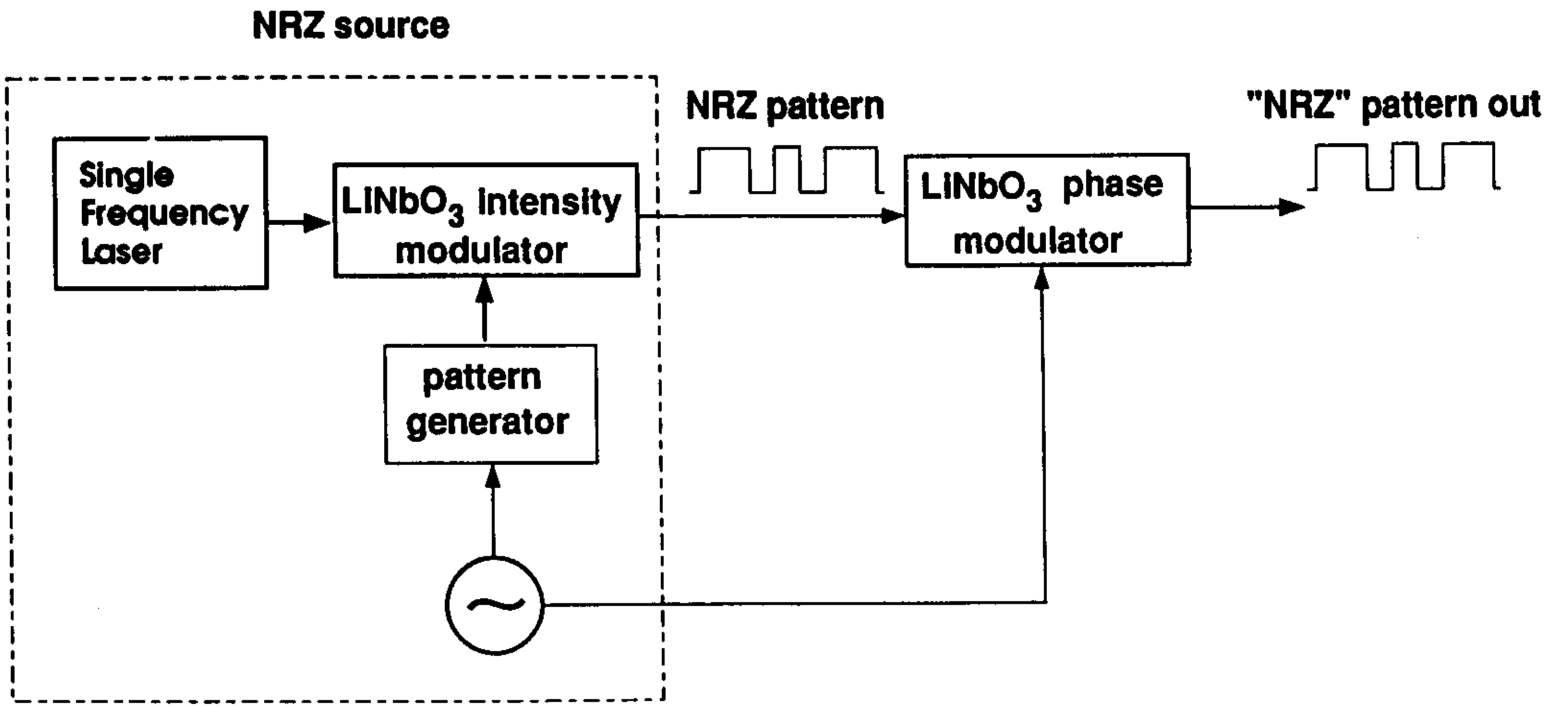


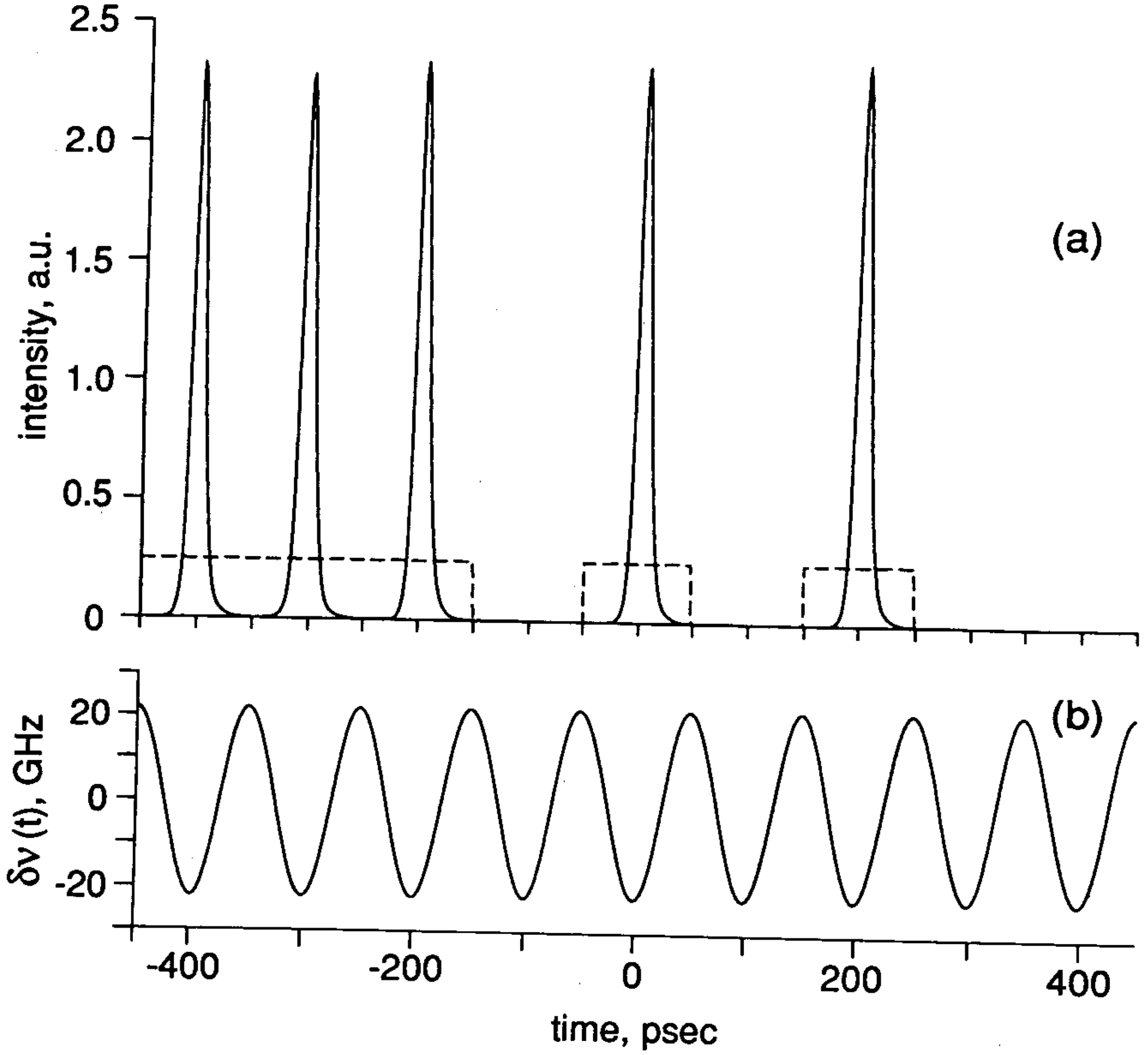
Pulses



Spectrum

"NRZ" soliton source

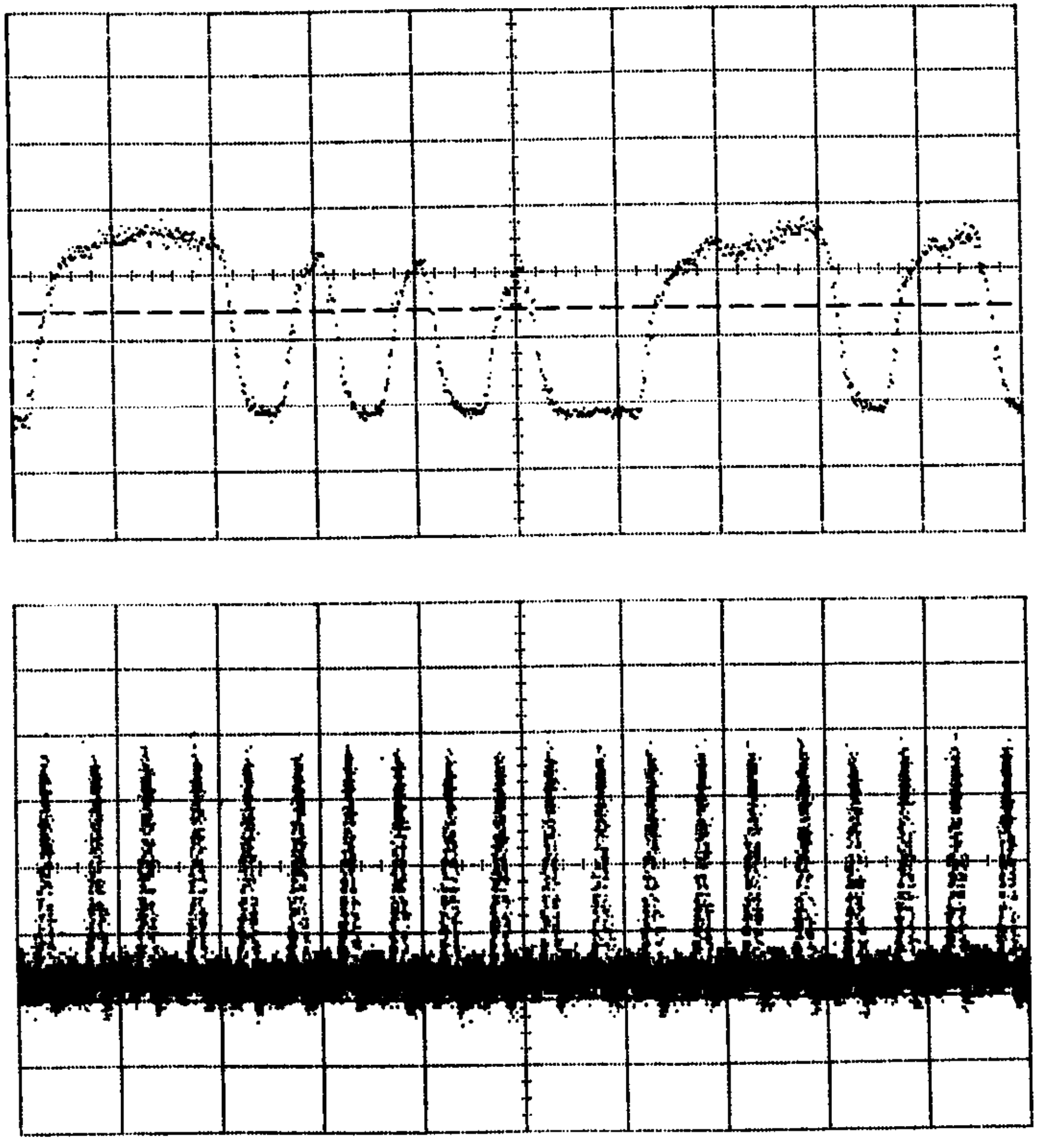



2.5
2.0
1.5
1.0
0.5
0
intensity, a.u.
(a)
20
0
-20
δν (t), GHz
(b)
-400
-200
0
200
400
time, psec

"NRZ" TO SOLITON CONVERSION BY FILTERED TRANS. LINE

"NRZ" DATA IN

DATA OUT AT 10 Mm
(EYE DIAGRAM)



200 ps/div

NONLINEAR Guided WAVE PHENOMENA - 91

Ultra long nonlinear fiber optics data transmission using dual-frequency laser sources.

P.V. Mamyshev, S.V. Chernikov, A.M.Prokhorov.

General Physics Institute, Academy of Sciences of the USSR
38 Vavilov Street, Moscow 117942, USSR

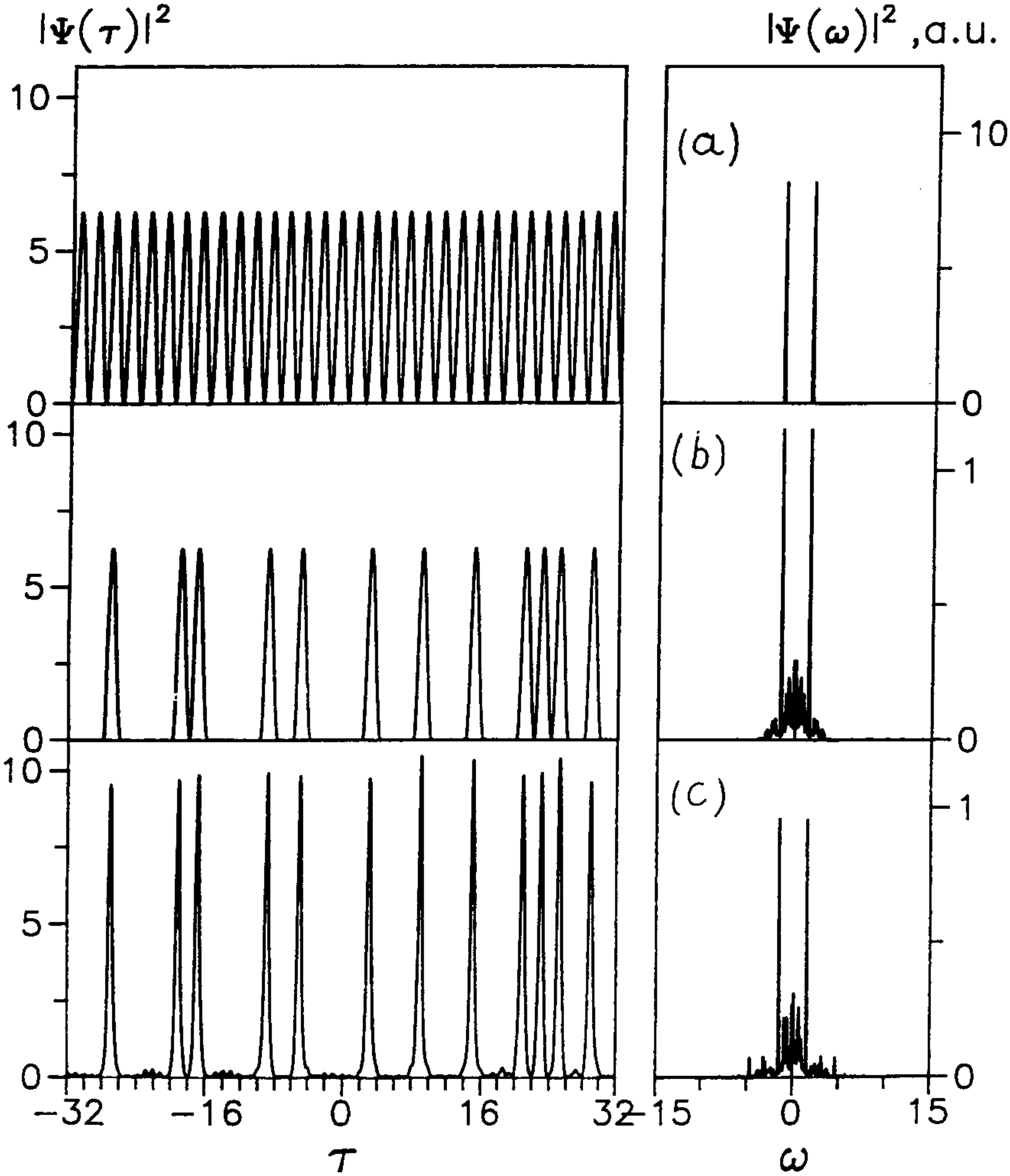
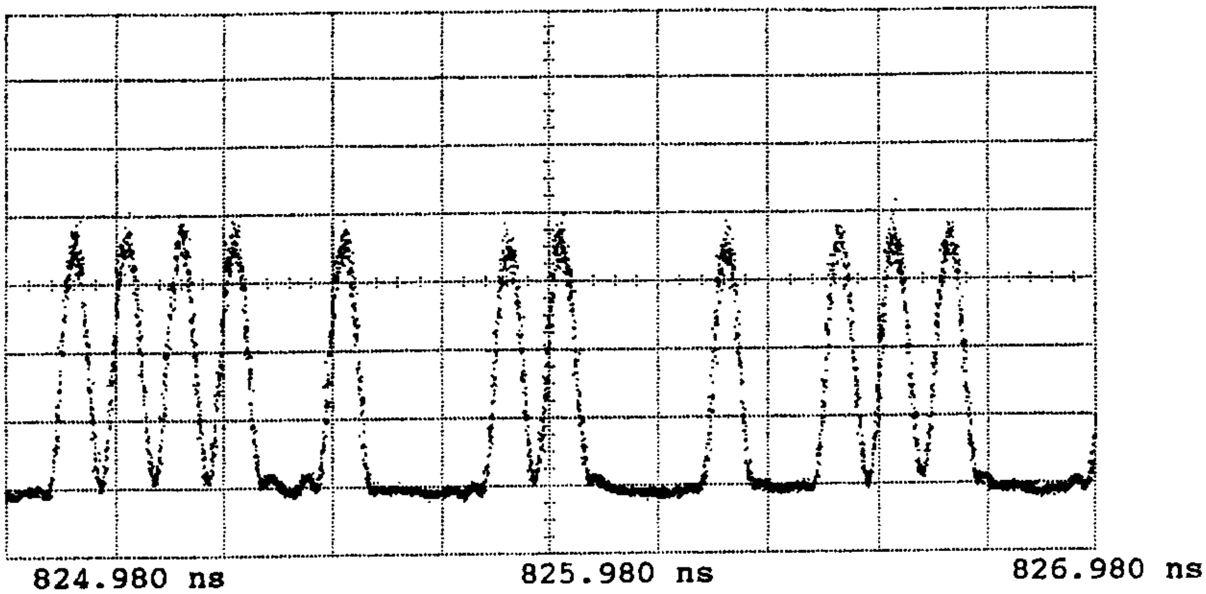


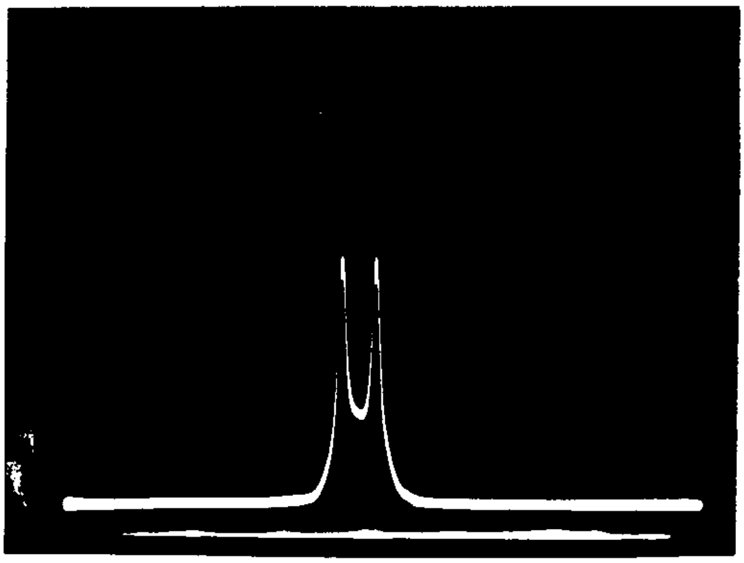
Figure 1 (a) The dual-frequency signal before data coding



Ch. 4 = 35.00 mVolts/div
Timebase = 200 ps/div

Offset = 112.5 mVolts
Delay = 825.980 ns

Trigger on External at Pos. Edge at 3.000 mVolts



ULTRA LONG DISTANCE SOLITON TRANSMISSION WITH SLIDING-FREQUENCY GUIDING FILTERS: SUMMARY

S. F. filters + fiber nonlinearity form an optical regenerator which

- is strictly passive
- is uniquely compatible with WDM
- enables greater transmission rate than any other mode.

NB: Filters work only with solitons!
("Linear" pulses are highly dispersed by filters.)

For other transmission modes,
the effects of fiber nonlinearity tend to be severely limiting.

Here, however, they are used to maximum benefit!

ADDED BENEFITS OF SLIDING-FREQUENCY GUIDING FILTERS

Filters do more than reduce timing and amplitude jitter.
In addition, they:

- Equalize relative signal amplitudes of WDM channels.
- Reduce soliton pair interactions, so pulses can be packed closer together.
- Remove dispersive wave radiation from imperfect input pulses.