SOLITONS IN OPTICAL FIBERS AND THEIR APPLICATION TO TELECOMMUNICATIONS

Princeton Plasma Physics Laboratory Colloquium Talk
Wednesday Afternoon, April 30, 2008

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THE NONLINEAR SCHRODINGER EQUATION

$$-i\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u - i(\alpha/2)u$$

chromatic dispersion

based on $n = n_0 + n_2 I$

CLASSICAL SOLITON:

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

SOLITON UNITS:

Length	*Time*	*Power*
$z_c = 0.322\frac{2\pi c}{\lambda^2}\frac{\tau^2}{D}$	$\frac{\tau}{1.7627...}$	$P_{sol} = \frac{A_{eff}}{2\pi n_2}\frac{\lambda}{z_c} \propto \frac{D}{\tau^2}$

(For $\tau = 20$ ps, $D = 0.5$ ps/nm-km, and $\lambda = 1556$ nm, $z_c \sim 200$ km.)

$$(1.7627... = 2\cosh^{-1}\sqrt{2})$$

THE NLS EQN: ACTION OF THE DISPERSIVE TERM

To get action of dispersive term alone, turn off NL term, so eqn. becomes:

$$\frac{\partial u}{\partial z} = \frac{i}{2}\frac{\partial^2 u}{\partial t^2}$$

The problem is most naturally solved in the frequency domain, where eqn. becomes:

$$\frac{\partial \tilde{u}}{\partial z} = -\frac{i}{2}\,\omega^2\,\tilde{u}$$

and where the general solution is:

$$\tilde{u}(z,\omega) = \tilde{u}(0,\omega)\,e^{-i\frac{\omega^2 z}{2}}$$

Thus, the dispersive term merely rearranges the phase relations among existing frequency components; it adds no new ones.

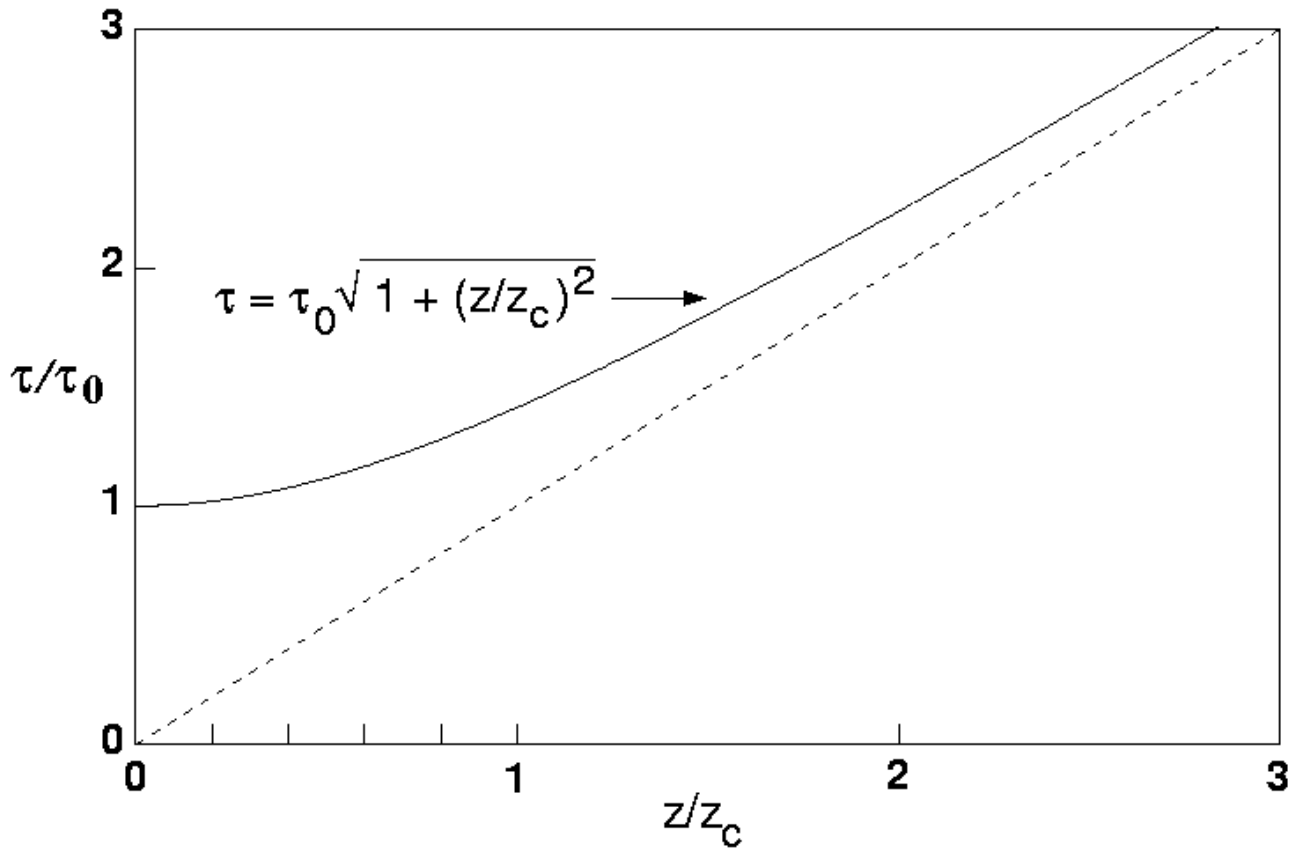
To get the spreading of the pulse, must transform back to the time domain.

Example: Let $u(0,t) = e^{-t^2/2}$ for which $\tilde{u}(0,\omega) = e^{-\omega^2/2}$.

$$u(z,t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\tilde{u}(0,\omega)\,e^{-i\frac{\omega^2 z}{2}}\,e^{-i\omega t}\,d\omega = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}e^{-\frac{\omega^2}{2}(1+iz)}\,e^{-i\omega t}\,d\omega = e^{-\frac{t^2}{2(1+iz)}}$$

Thus, intensity envelope $|u|^2 = e^{-t^2/(1+z^2)} = e^{-(2t/\delta t)^2}$, where $\delta t/2 = \sqrt{1+z^2}$.

DISPERSIVE BROADENING OF A GAUSSIAN PULSE VS Z
(Minimum spectral width at origin)



THE NLS EQN: ACTION OF THE NON-LINEAR TERM

To get action of NL term alone, turn off dispersive term, so eqn. becomes:

$$\frac{\partial u}{\partial z} = i|u|^2 u$$

The problem is most naturally solved in the time domain, where gen. soln. is:

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

The NL term modifies $\phi(t)$, but not the intensity envelope.

Thus, it only adds new frequency components.

To get spectral spreading, must transform back to the frequency domain.

Example: Again, let $u(0,t) = e^{-t^2/2}$.

$$\tilde{u}(z,\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} u(0,t)\, e^{i|u|^2 z}\, e^{i\omega t}\, dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-t^2/2}\, e^{i z e^{-t^2}}\, e^{i\omega t}\, dt$$

For $z >> 1$, this integral produces a multi-peaked spectrum, where the number of peaks and the over-all spectral width increase directly with z.

However, for $z << 1$, the integral is approximately

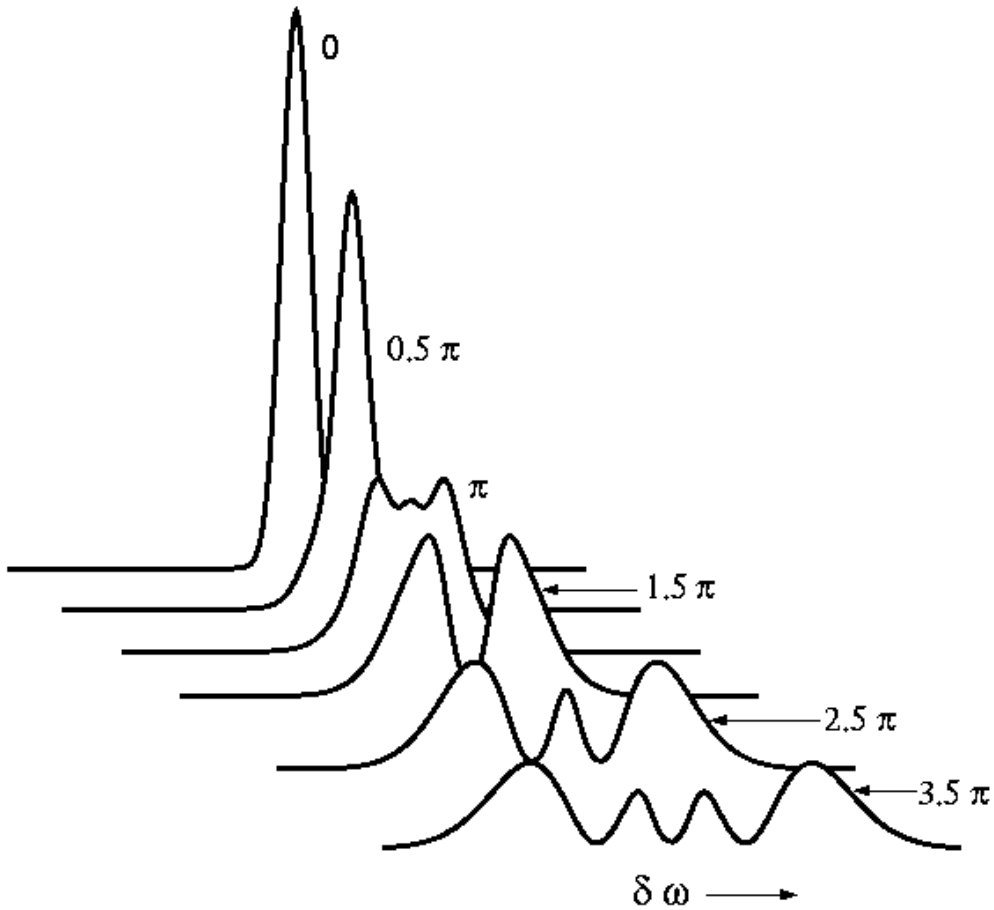
$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-t^2/2}(1 + iz\, e^{-t^2})\, e^{i\omega t}\, dt = \tilde{u}(0,\omega) + iz\, \tilde{v}(\omega)$$

Note that once again, the new component is in quadrature with the original pulse.

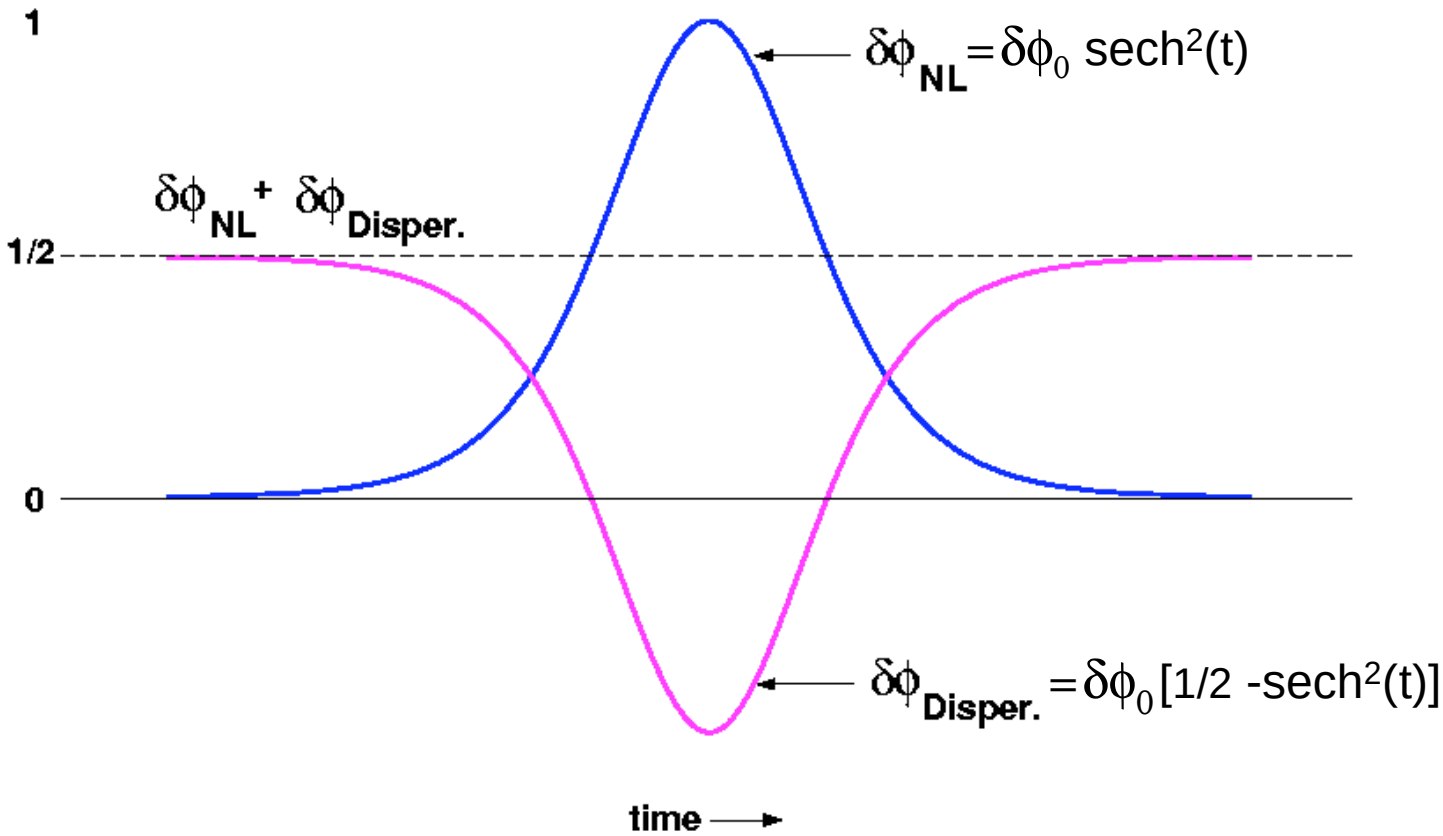
Thus, the increase in net spectral width scales only as z^2.

SPECTRAL BROADENING OF A GAUSSIAN PULSE AT ZERO DISPERSION

(Peak non-linear phase shift indicated next to each spectrum.)

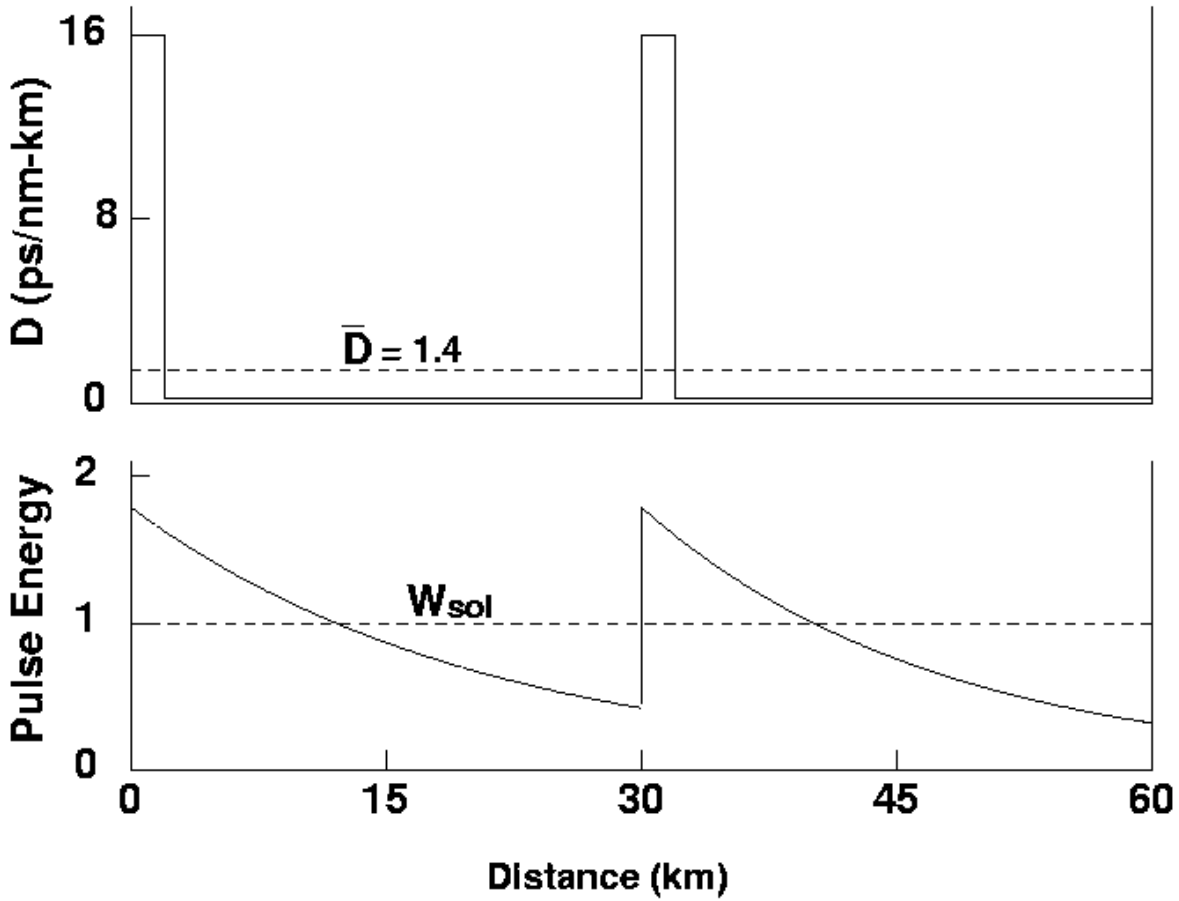


THE DISPERSIVE AND NON-LINEAR PHASE SHIFTS OF A SOLITON

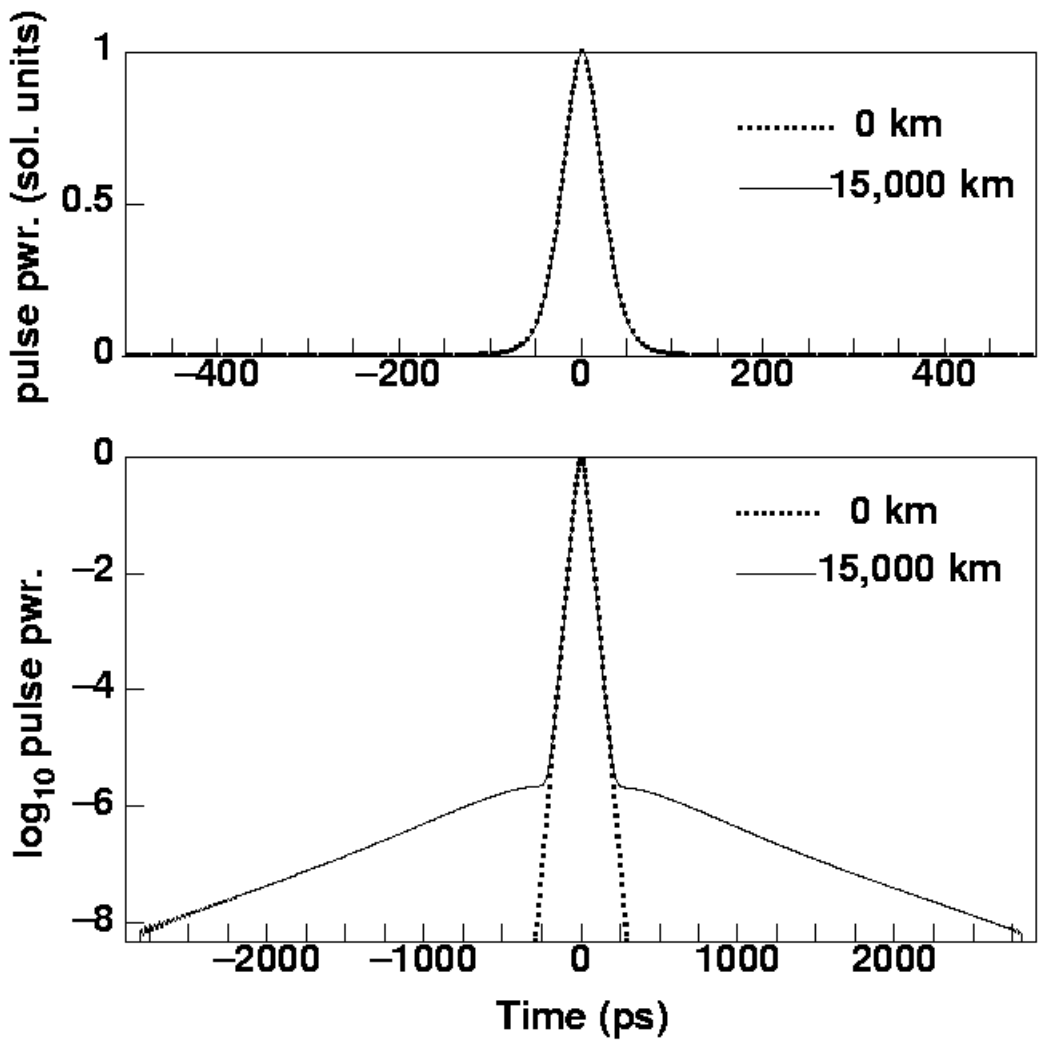


Note that the dispersive and non-linear phase shifts sum to a constant.

PULSE ENERGY AND FIBER DISPERSION IN SAMPLE OF TRANSMISSION LINE USED FOR TEST OF "PATH-AVERAGE" SOLITONS



SIMULATED TRANSMISSION THRU SYSTEM WITH LUMPED AMPS AND PERIODICALLY VARYING DISPERSION



Limitations Imposed by Amplifier Spontaneous Emission

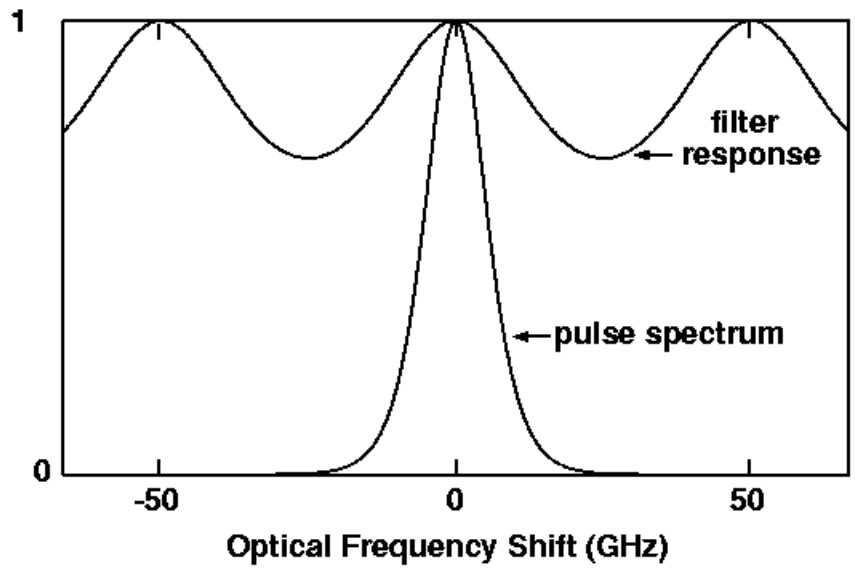
Optical amplification is always accompanied by spontaneous emission. This “ASE” noise, which grows in direct proportion to the transmission distance, can bring about errors in the digital transmission in two ways:

1. Noise energy, if big enough, can make an empty bit slot (a “0”) look like a “1”, and noise fields can subtract enough energy from a “1” to make it look like a “0”. The severity of this amplitude jitter increases monotonically with the N/S (noise to signal) energy ratio, which, for solitons, scales as Z / W_{sol}, where Z is the total transmission distance, and W_{sol} the pulse energy.

2. In the Gordon-Haus effect, certain components of the noise field can add to the solitons and modify their central frequencies. The resultant frequency shifts, multiplied by the dispersion remaining to the end of the path, results in a random distribution of pulse arrival times, or timing jitter. The variance of the Gaussian distribution of arrival times scales as $Z^3 W_{sol}$.

The combination of amplitude and timing jitters limits the distance for error-free transmission, and the maximum possible such distance corresponds to one particular value of W_{sol}. (Hence for one particular value of D/t.)

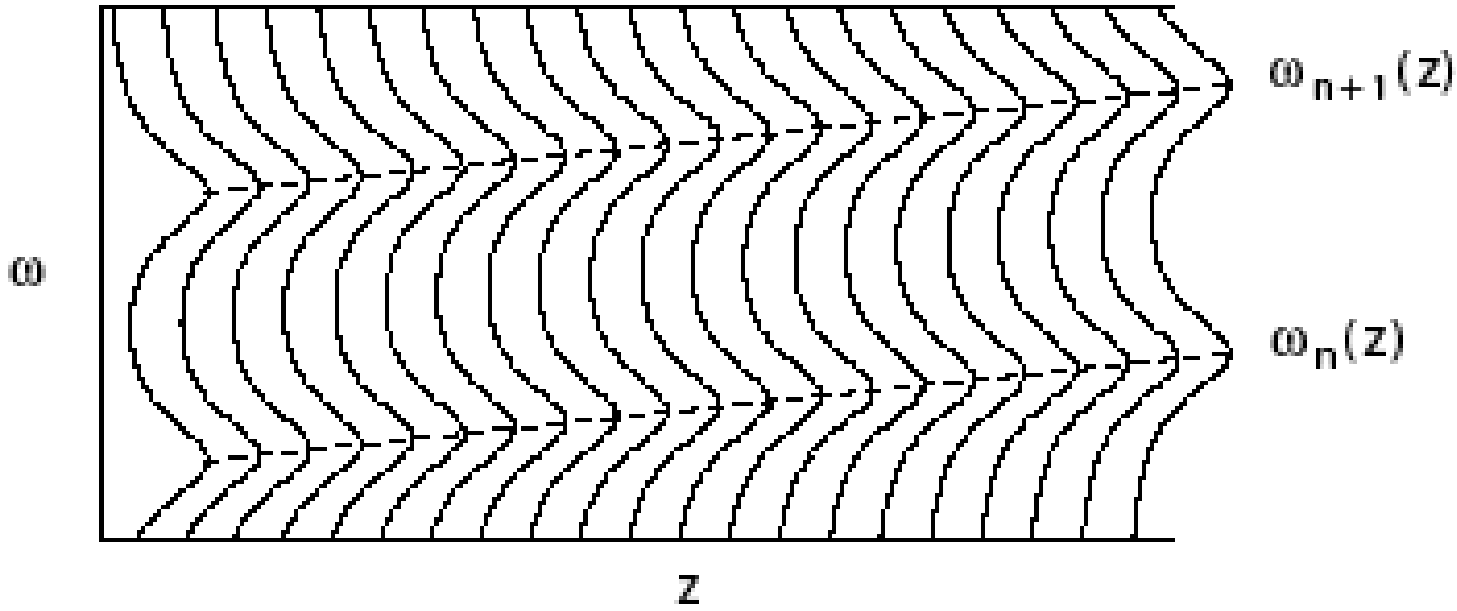
FREQUENCY-GUIDING FILTERS
(Typically, low-finesse F-P etalons, one per span)



Filters:

- Reduce freq. and timing jitter by “guiding” pulse spectra back to filter peaks.
- Reduce amplitude jitter because filter loss increases as pulse energy (BW).
- Are compatible with dense WDM.
- Work only with solitons!

Sliding-Frequency Guiding Filters



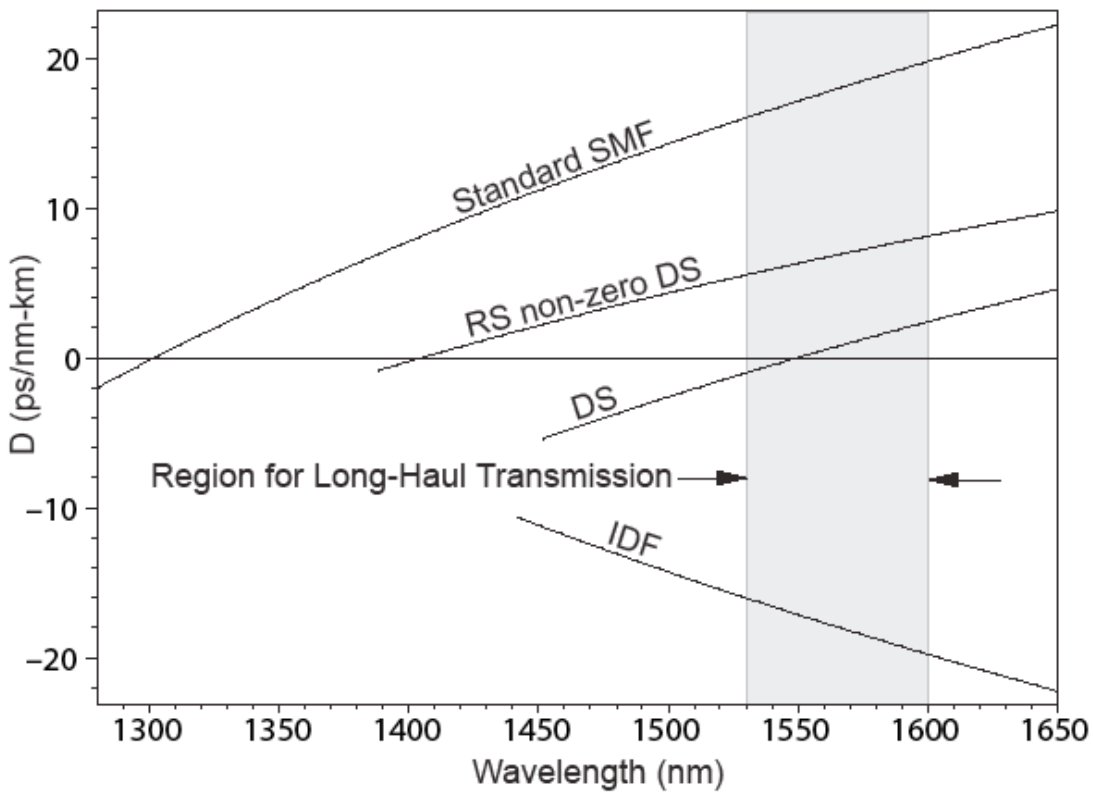
Through action of the non-linear term, solitons can generate the new frequency components required for them to follow the sliding-frequency filters.

The noise, however, being linear stuff, cannot follow, so it is highly attenuated.

The scheme enabled error-free transmission at 10 Gbit/s over more than 40,000 km (the circumference of the earth)!

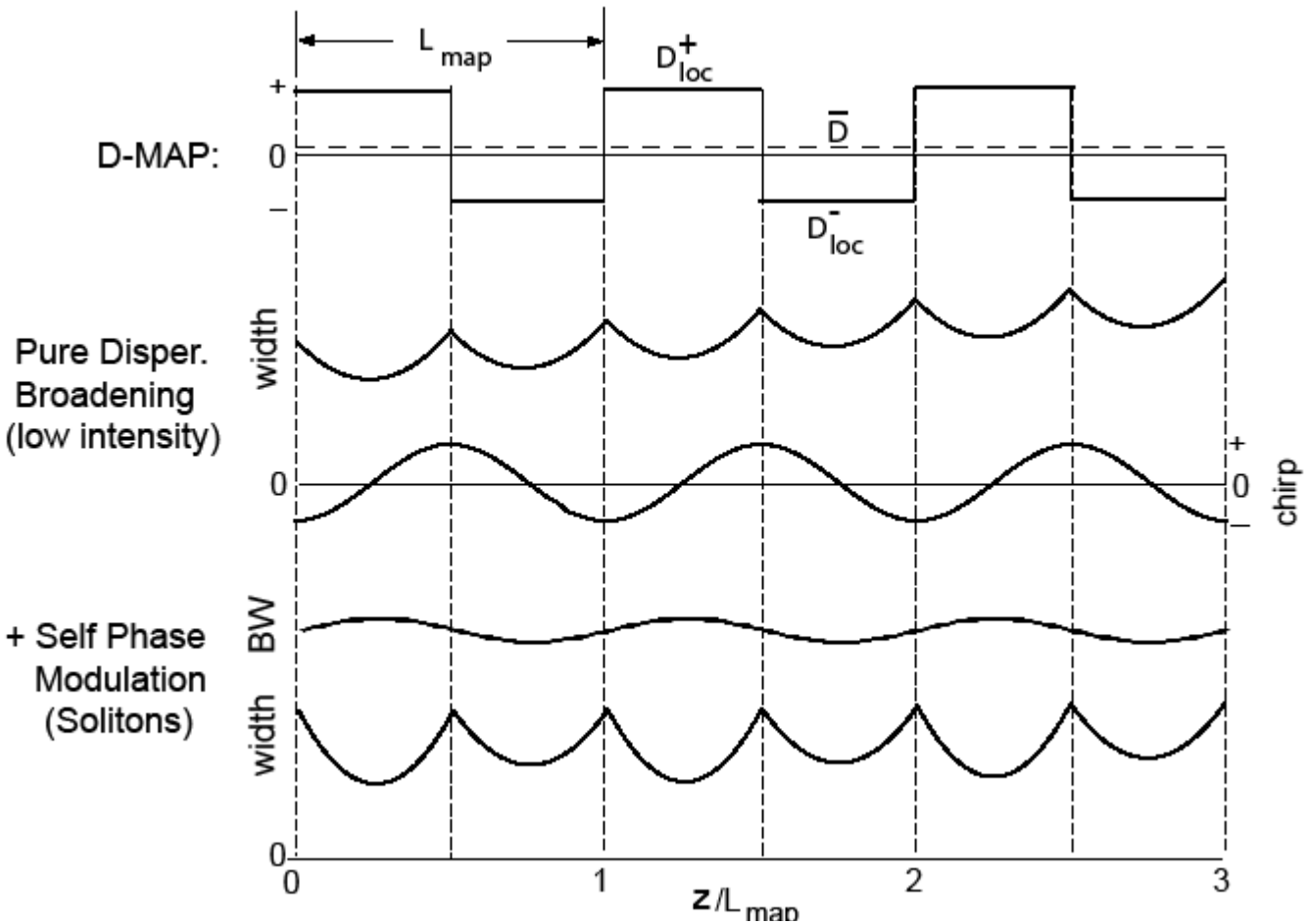
Problems with Solitons for Dense WDM

- The dispersion of fiber varies too rapidly with wavelength to maintain the small, optimal D value required for solitons over the large wavelength bands (many tens of nm) required for “dense” (many channel) WDM.



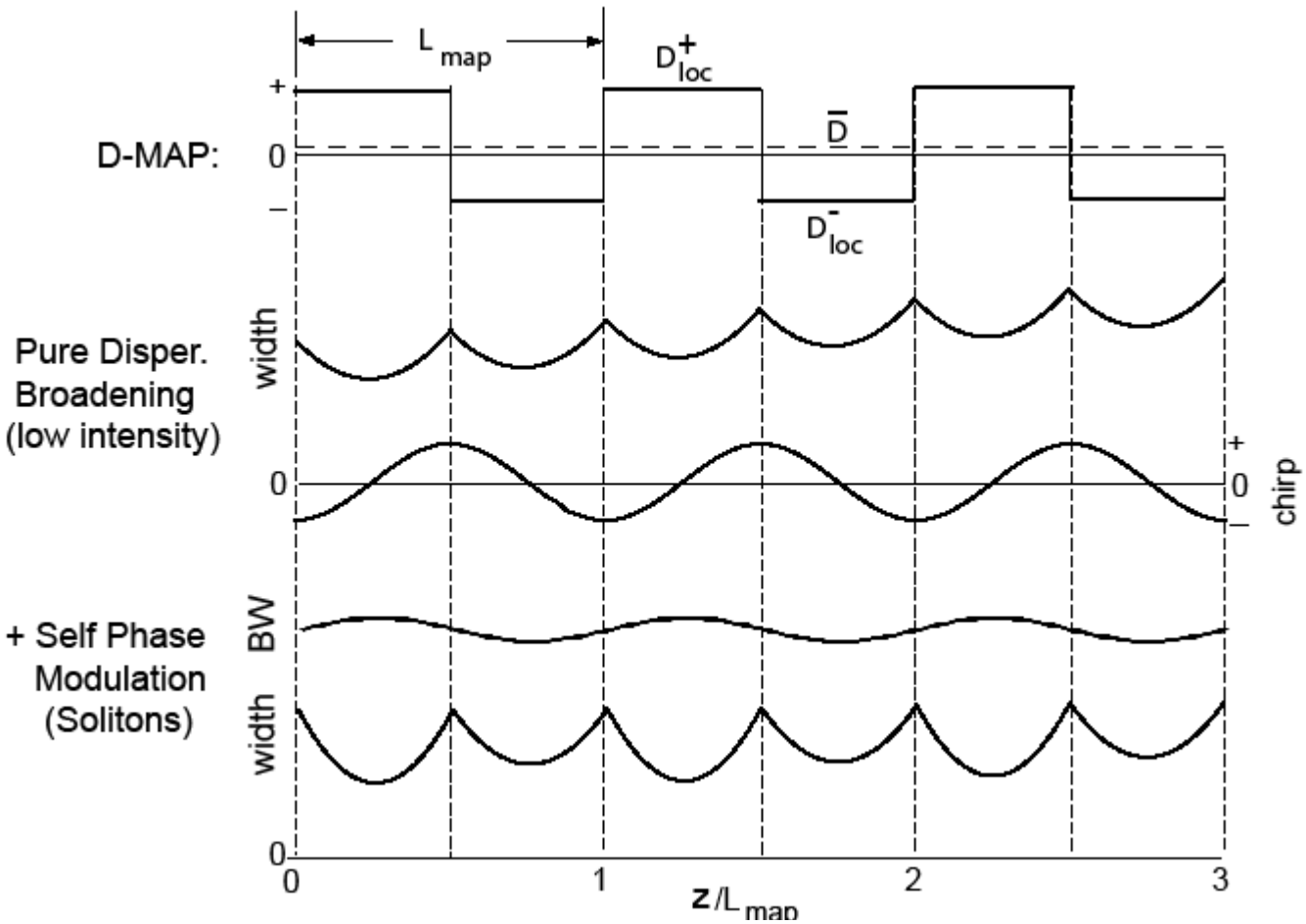
- For path-average solitons, four-wave mixing between adjacent channels can produce significant interference with yet other channels.

Dispersion-Managed Solitons in a Nutshell



Non-linear and dispersive phase shifts cancel each other over each L_{map}. Pulse shape is Gaussian, however, since D_{loc} dominates in each segment.

Dispersion-Managed Solitons in a Nutshell



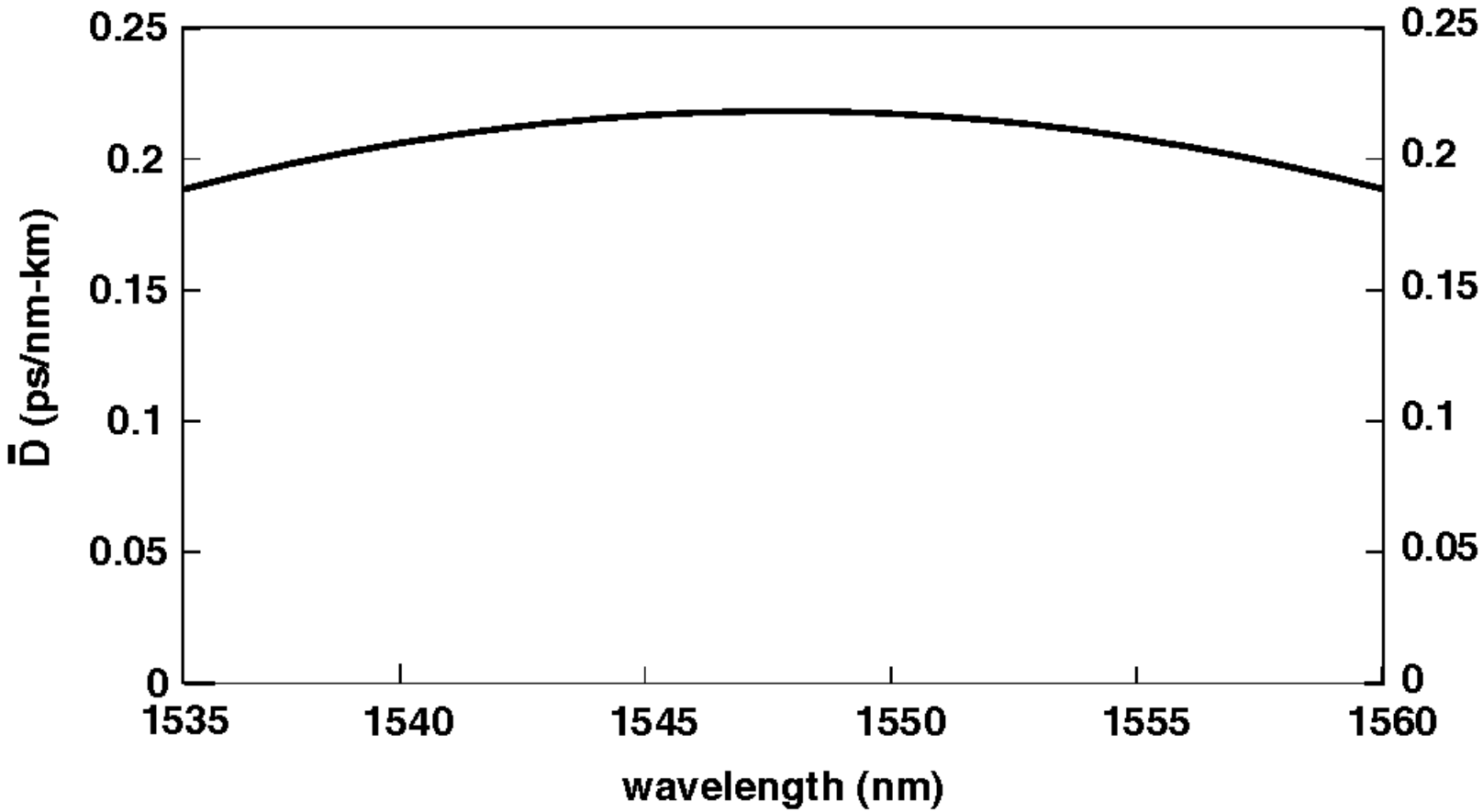
Since dispersive phase shift scales as D x (BW)^2, variation of BW in map makes ϕ_{disp} several times larger than anticipated from D alone. Therefore pulse energy must correspondingly be several times larger.

Parameters of Some Fiber Types Suitable for Use in Dispersion-managed WDM Transmission

FIBER TYPE	D(ps/nm-km) (@ 1555 nm)	S(ps/nm^2) ($\partial D/\partial\lambda$)	D/S (nm)	A_{eff} (μm^2)
Standard	+16.7	+0.056	298	80
low-slope DS	+6.6	+0.045	147	50
IDF	-17.7	-0.057	310	35
hi-slope DCF	-105	-0.35	300	20
ultra-slope DCF	-115	-0.78	147	18

Note that “Standard” and “IDF” fibers make a slope-compensating pair, as do “low-slope DS” and “ultra-slope DCF”.

$\bar{D}$ OF TWRS SPANS + ULTRA-SLOPE DCF (FROM RELATIVE TIME-OF-FLIGHT MEASUREMENTS)



ADVANTAGES OF DISPERSION-MANAGED SOLITONS OVER ORDINARY SOLITONS

- D-map can be made from fiber combinations yielding nearly constant path-average dispersion ($\overline{D}$) over a large wavelength span, as required for "dense" WDM.

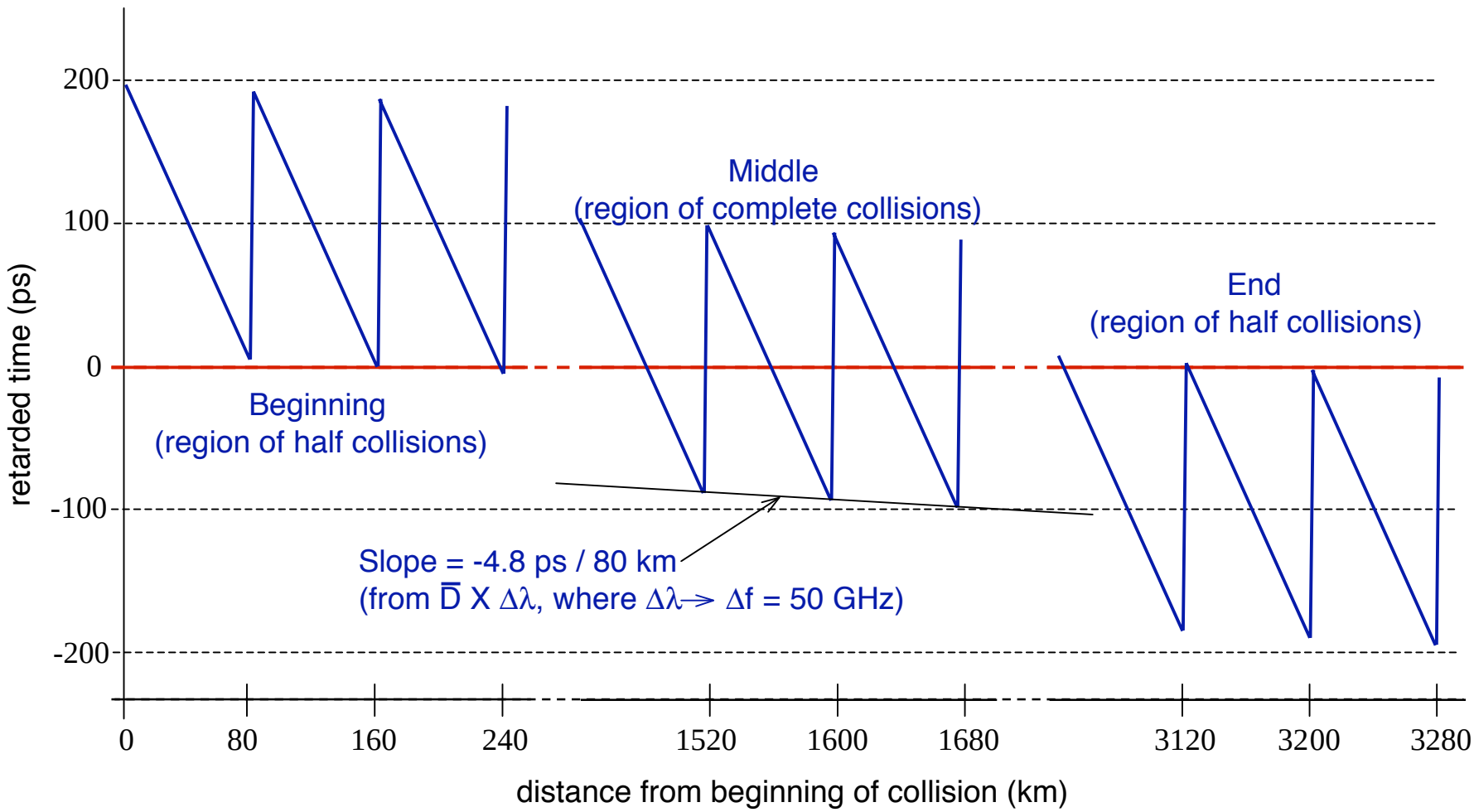
- D_{local} can be made large enough to guarantee negligible 4-wave mixing between pulses of adjacent WDM channels.

- Can get adequate soliton pulse energy with several times smaller $\overline{D}$. This tends to make the Gordon-Haus jitter relatively unimportant.

RELATIVE MOTION IN RETARDED TIME OF COLLIDING, DISPERSION-MANAGED SOLITONS

Blue line shows motion of higher-frequency (+50 GHz) pulse relative to lower-frequency pulse (fixed at t = 0).

D-map = 80 km of D = +6 ps/nm-km + DCF; $\overline{D}$ = +0.15 ps/nm-km.

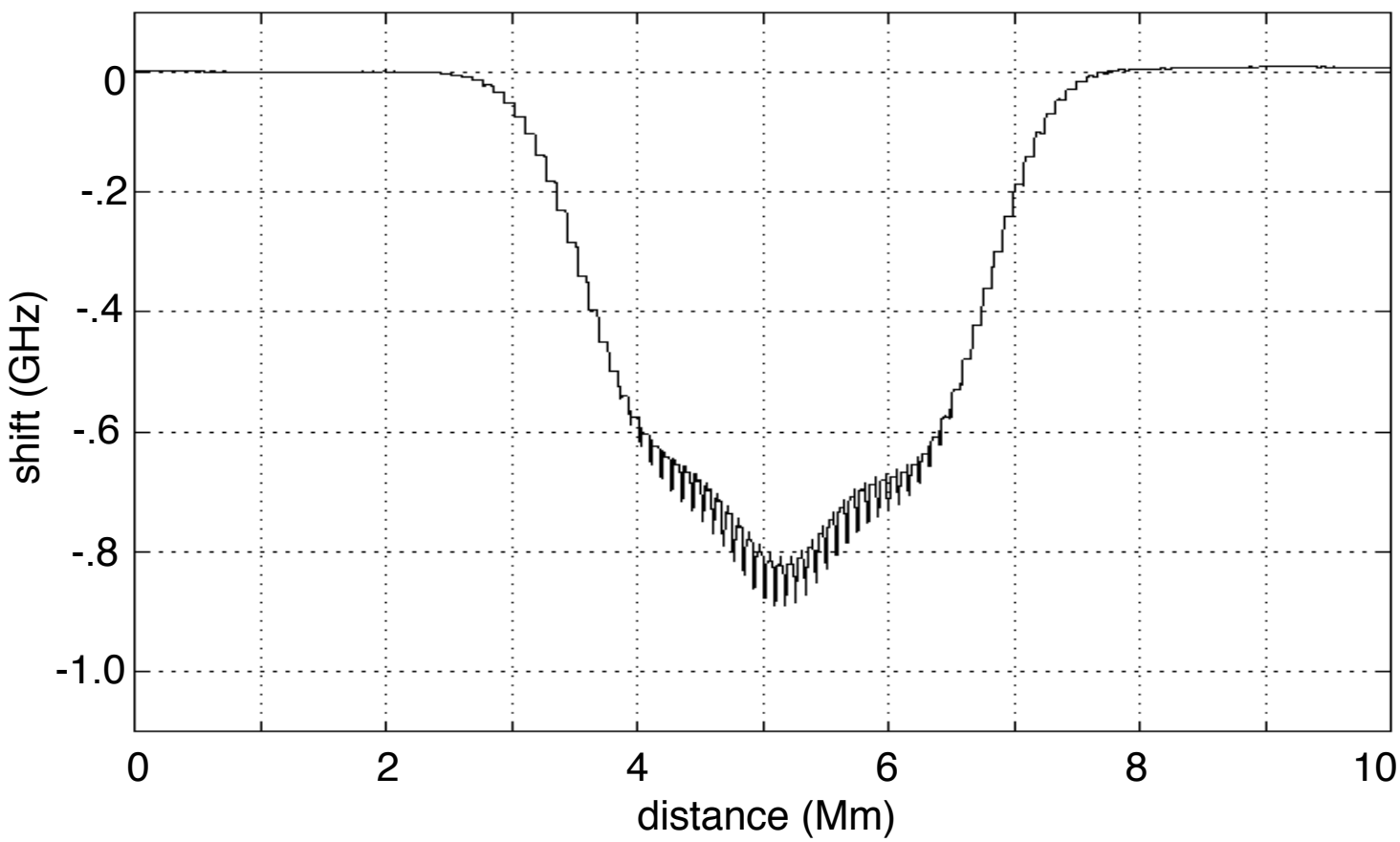


FREQUENCY SHIFT OF THE LOWER-FREQUENCY ONE OF TWO COLLIDING, DISPERSION-MANAGED SOLITONS

Solitons separated by 50 GHz and orthog. polarized

D-map = 80 km of D = +6.0 ps/nm-km + DCF; D = +0.15 ps/nm-km.

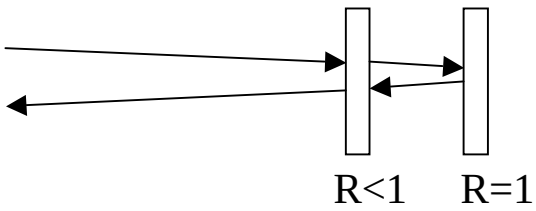
Backward Raman pumped at end and at mid-span; DCF at end.

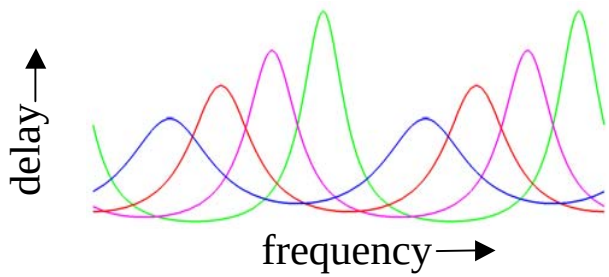


REDUCTION IN THE COLLISION-INDUCED TIMING JITTER BY THE USE OF PERIODIC GROUP DELAY COMPENSATORS

Recently, periodic group delay (PGD) dispersion compensators have become available commercially. In the next few slides, we shall show how the use of these devices to compensate a modest fraction of the span dispersion can effect a drastic reduction in the collision-induced timing jitter.

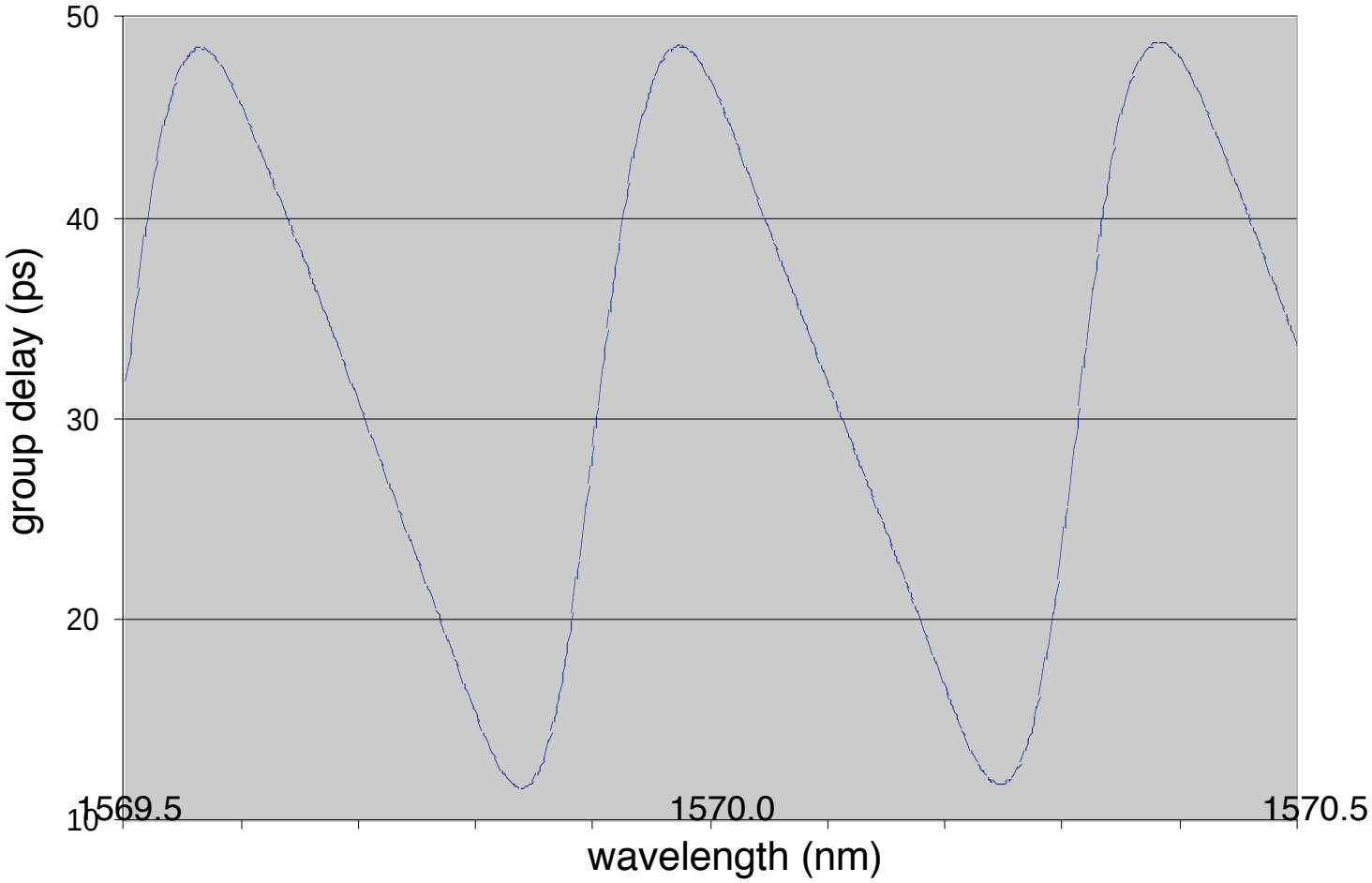
The most successful of the PGD devices are based on a cascade of Gires-Tournois etalons:





Note that these act as “all pass” filters, i.e., they are 100% reflective for all wavelengths, but that the effective delay time varies with frequency, and that the peak delay depends on the reflectivity of the front mirror. A number of these devices, cascaded together, can provide a low insertion loss element whose delay characteristics tend to look like the ideal on the next slide.

MEASURED GROUP DELAY OF PGD MODULE*

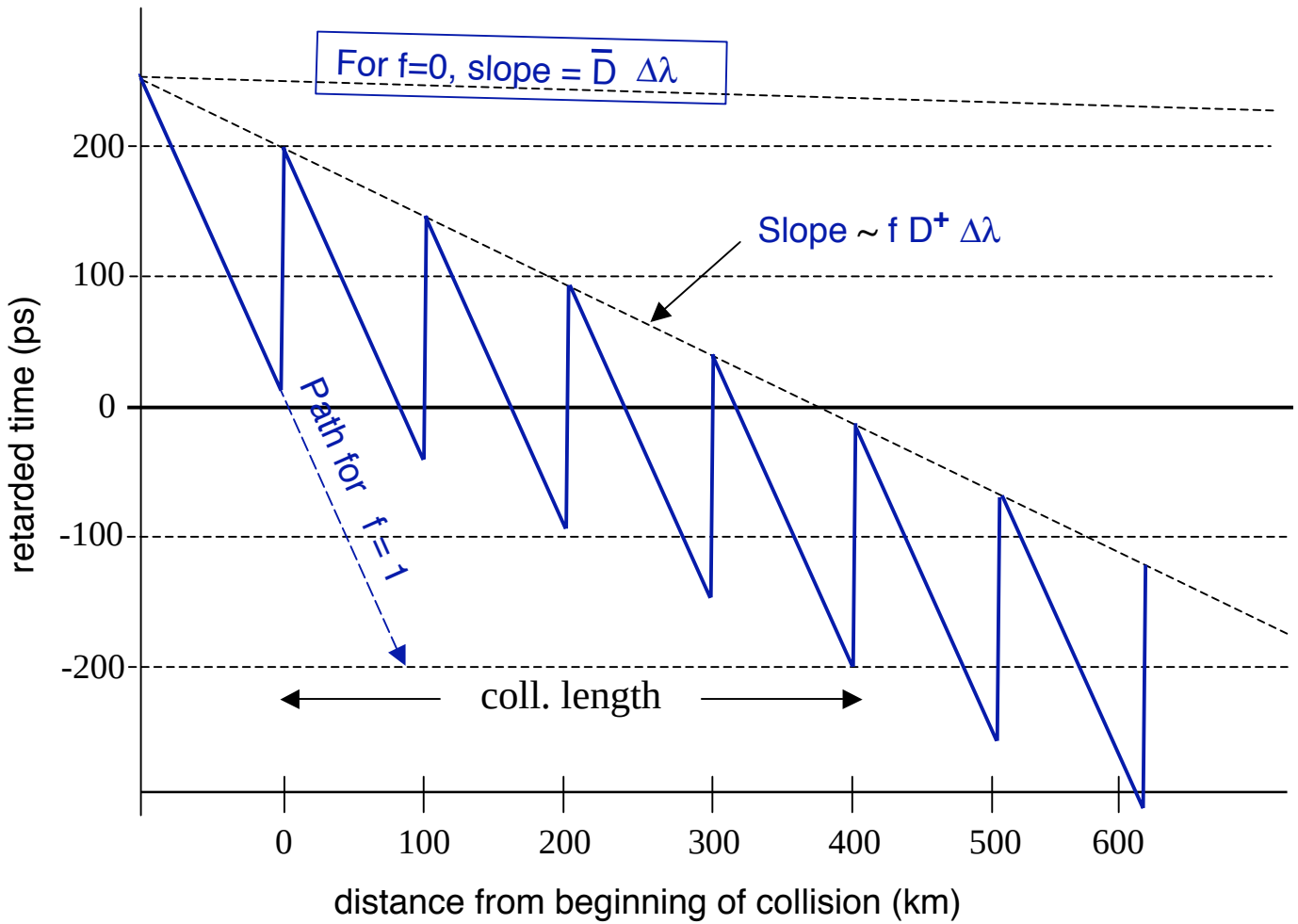


Note that the mean group delay is the same for all channels.

***Avanex "power-shaper"**

RELATIVE MOTION IN RETARDED TIME OF COLLIDING, DISPERSION-MANAGED SOLITONS

D-map = 100 km of D = +6 ps/nm-km, with fraction (1-f) of its dispersion compensated by DCF and fraction f compensated by a PGD-device

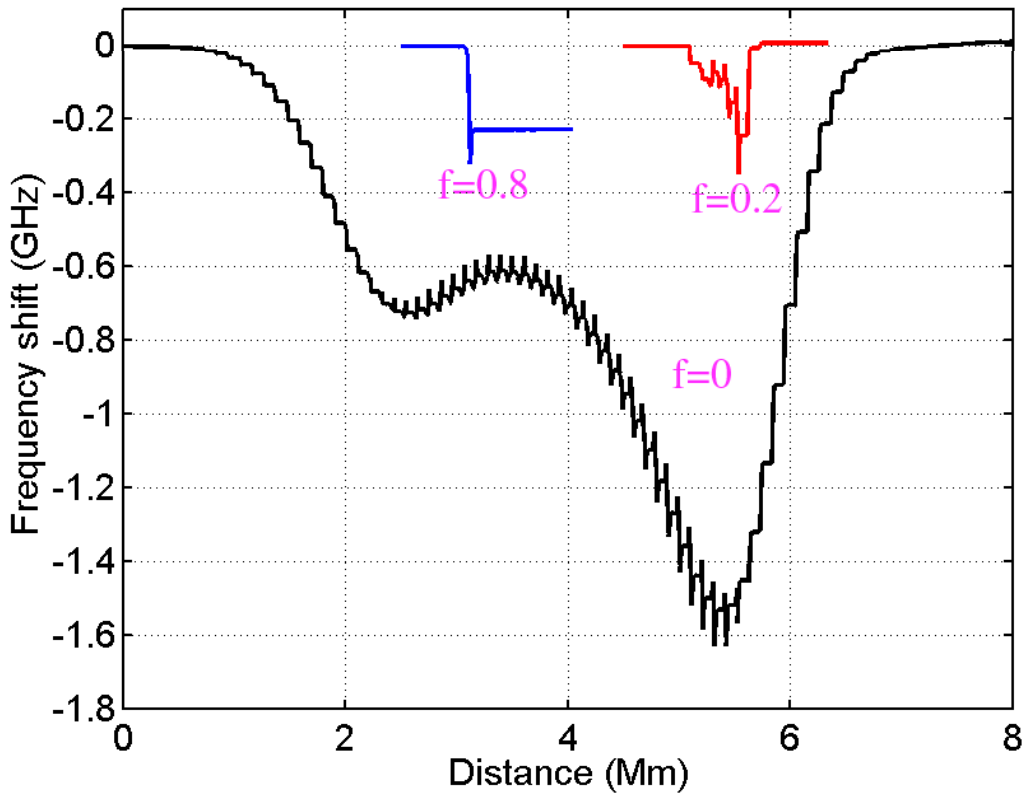


FREQUENCY SHIFT OF THE LOWER-FREQUENCY ONE OF TWO COLLIDING, DISPERSION-MANAGED SOLITONS for different values of the parameter f

Solitons separated by 50 GHz and co-pol.

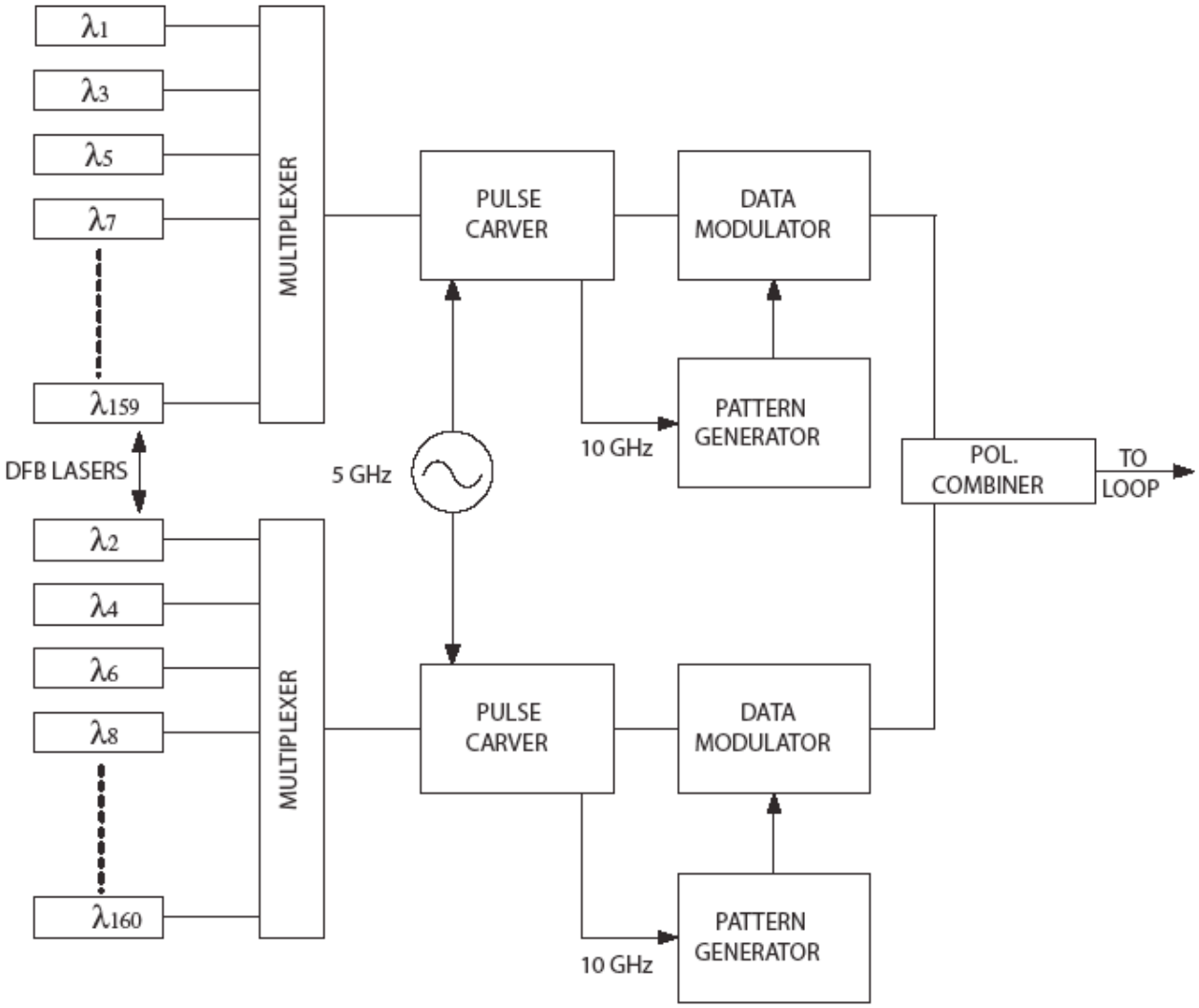
D-map = 100 km of D = +6.0 ps/nm-km + DCF; D = +0.15 ps/nm-km.

Backward Raman pumped at end only; DCF at end.

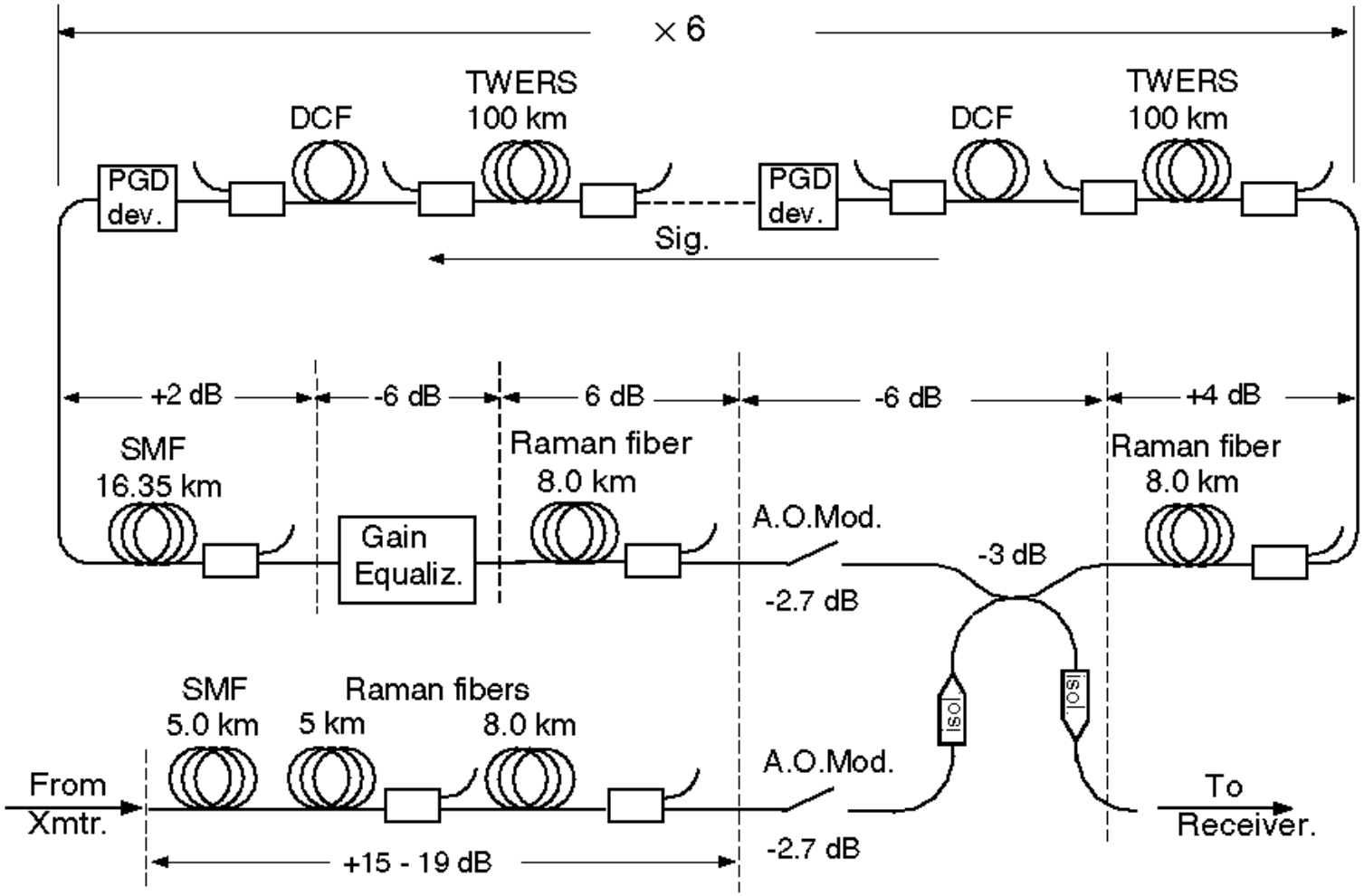


Note that for f=0.2, (just as for f=0), the collision is “frequency preserving”, i.e., the freq. shift returns essentially to zero after the collision, but that this is not so for f=0.8

160 WDM-Channel Soliton Pulse Generator

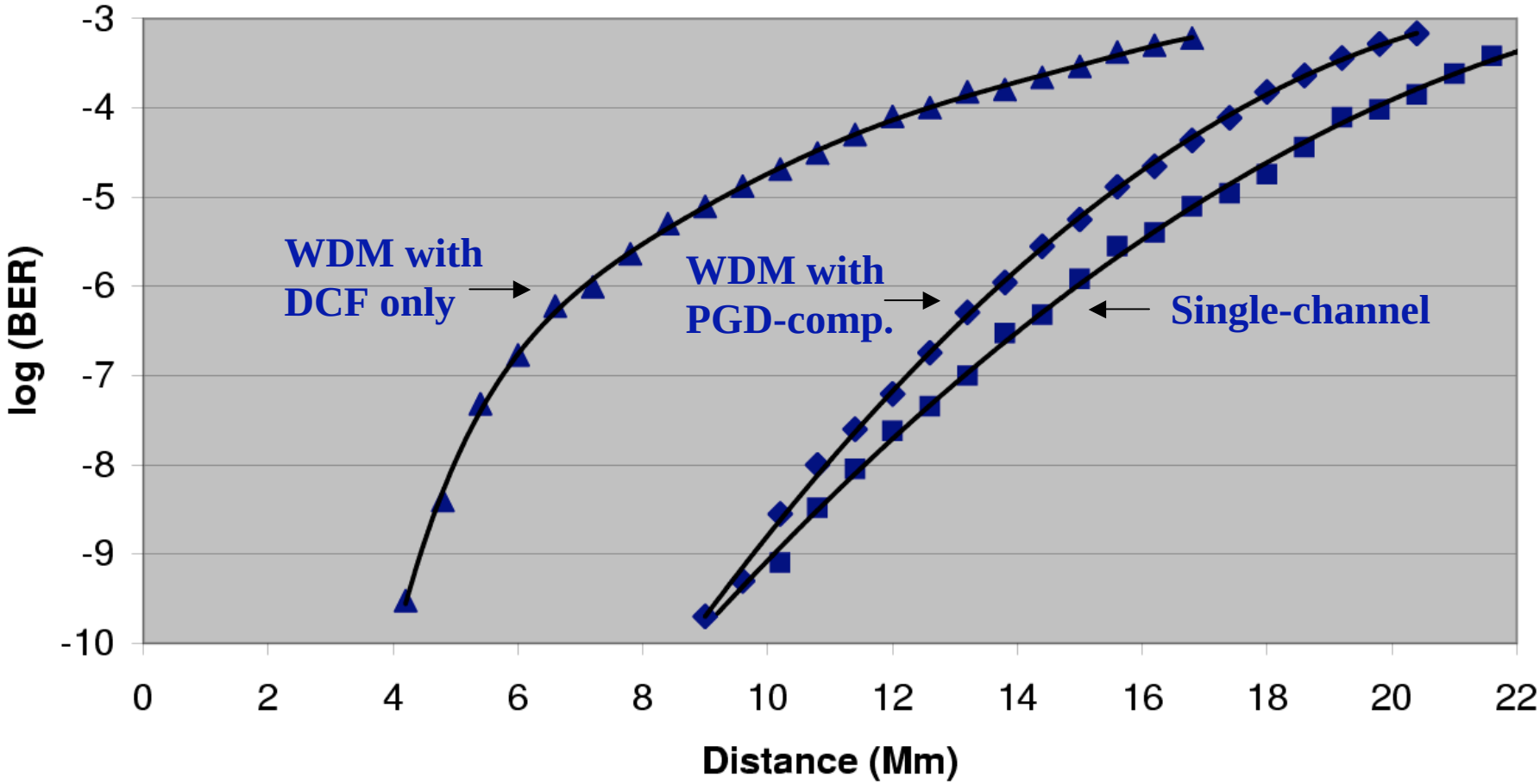


RECIRCULATING LOOP CONFIGURATION

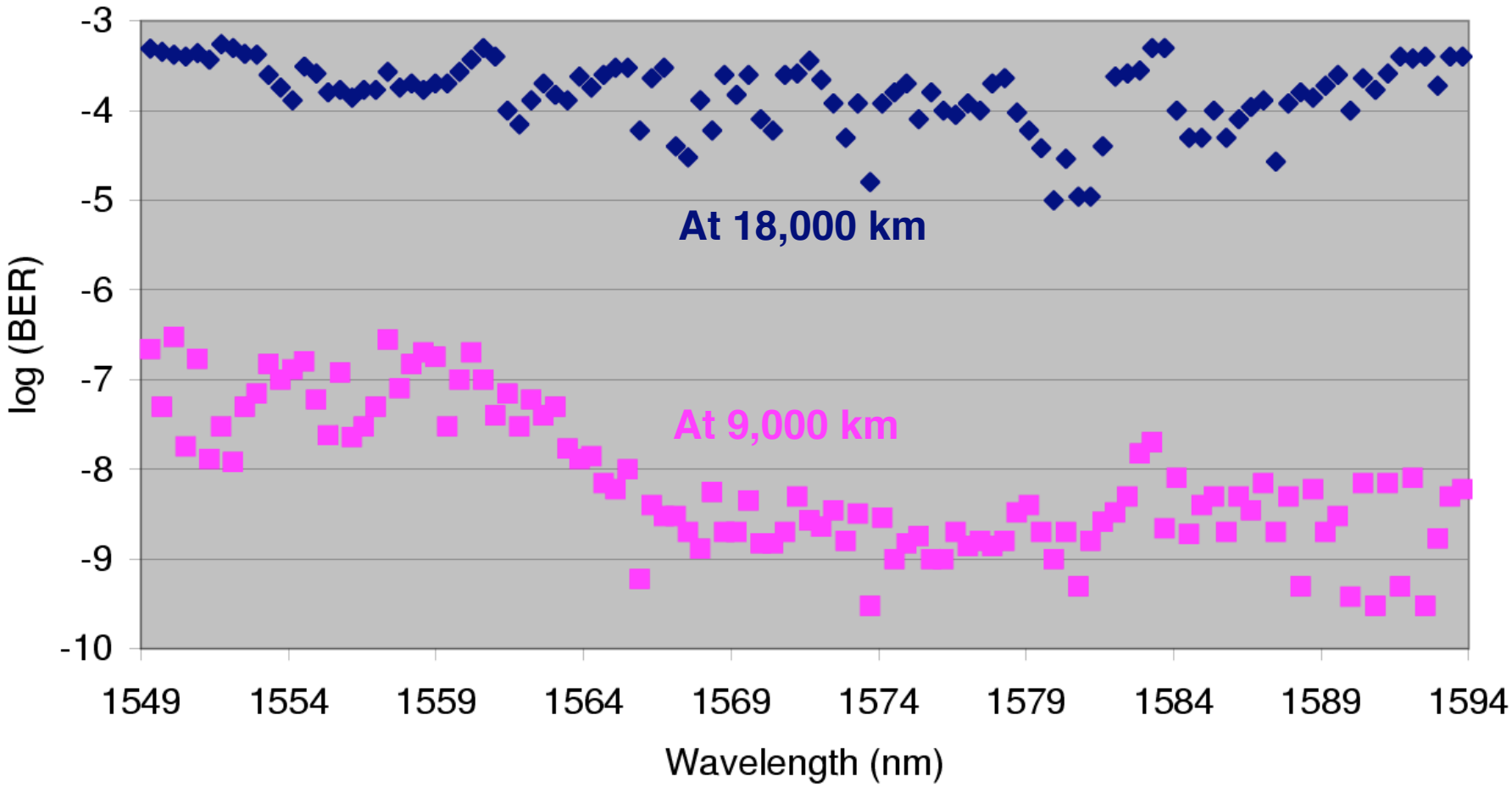


Two-stage, all-Raman Preamp

MEASURED BER vs DISTANCE FOR "TYPICAL" WDM CHANNEL
50 GHz Channel Spacing



BER vs WAVELENGTH for 109- CHANNEL (1.09 Tbit/s) WDM



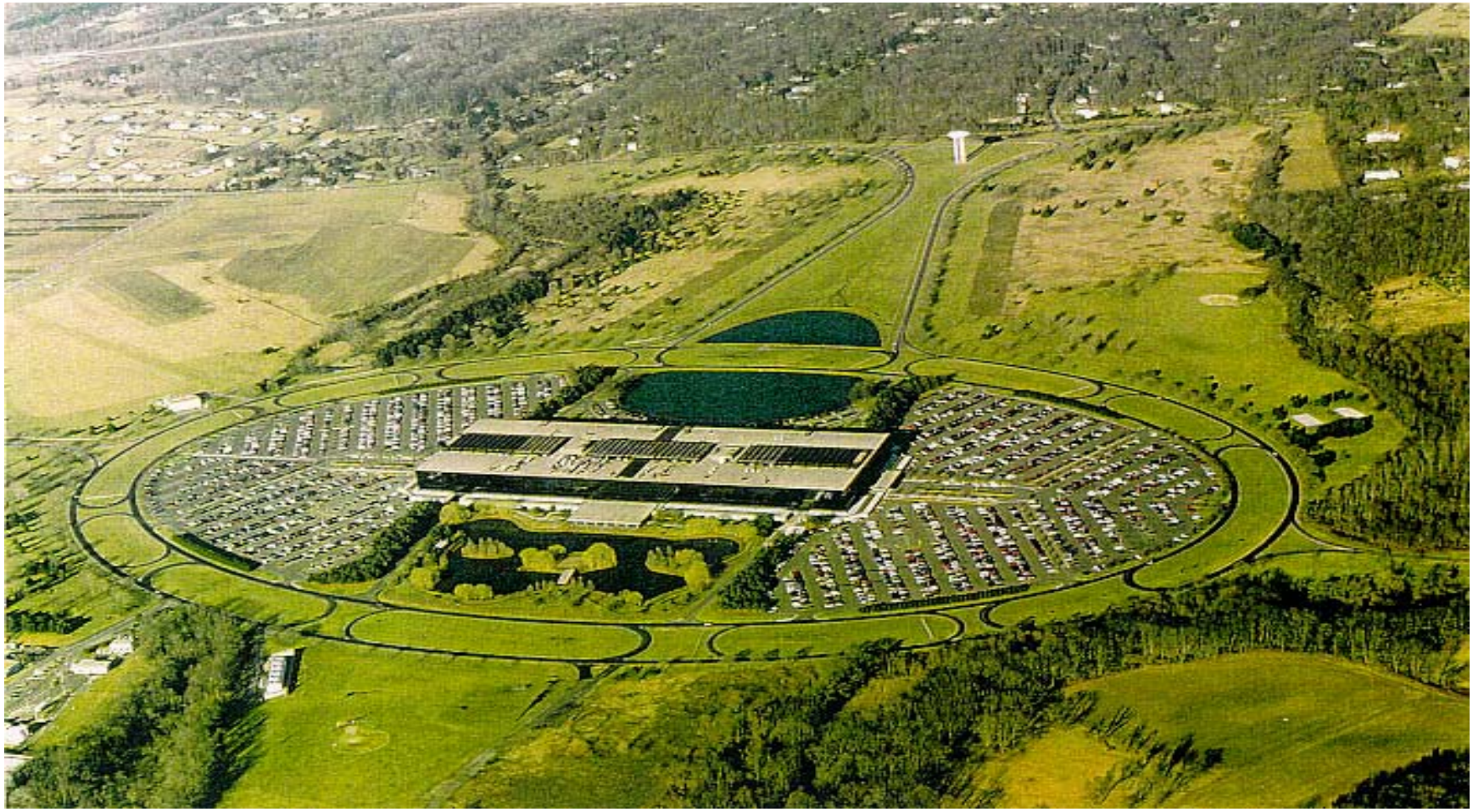
Lucent's LambdaXtreme:
First US Commercial Soliton-based System

- LambdaXtreme is an all-optical, all-Raman amplified, dense WDM system capable of handling up to 160 channels of 10 Gbit/s each, based on dispersion-managed solitons. It will handle paths of up to 4000 km without the use of electronic regeneration.

- In early 2004, Verizon ordered a $100,000,000 system that became operational in early 2005. The Verizon systems contains over 20,000 km of fiber path and covers most of the continental US.

- Qwest has ordered an even bigger, more expensive version of LambdaXtreme that is still under construction.

Bell Telephone Laboratories
Holmdel, NJ



Bell Labs, Holmdel
Interior View