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/842-15

Conference on
Ultrafast Transmission Systems in Optical Fibres

13 - 17 February 1995

Upgrading the Installed Fibre Base

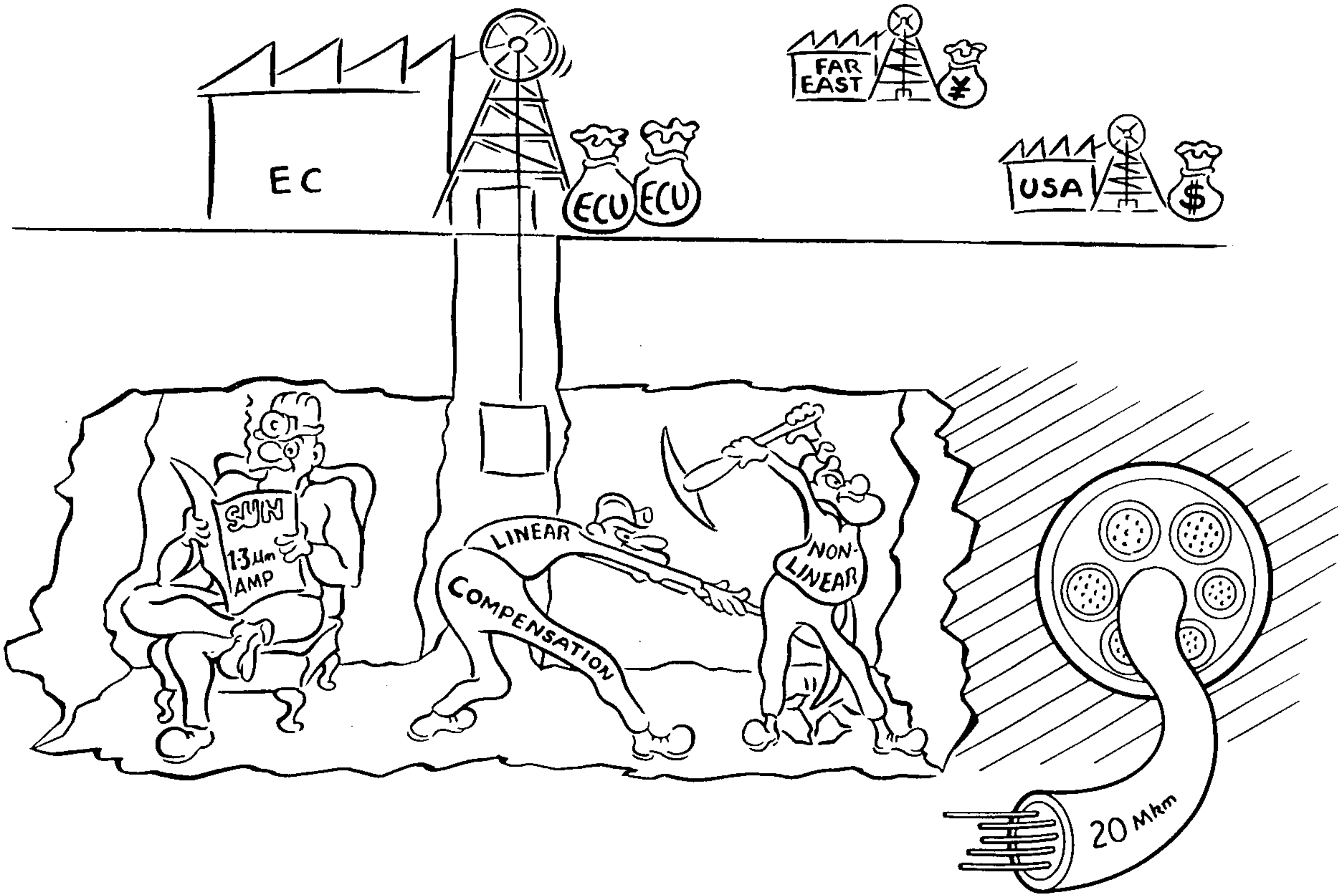
R.I. Laming

Optoelectronics Research Centre
Southampton University
Southampton, United Kingdom

Acknowledgements

MN Zervas
A Royset
SY Set
I Goncharenko
D Hewak
B Samson
S Barcelos
DN Payne

THE FIBRE GOLD MINE



1.3μm NETWORK UPGRADE

- Loss compensation at 1.3μm
  - Doped fibre amplifiers
  - Raman amplifiers
  - ➡ Soliton transmission at 1.3μm

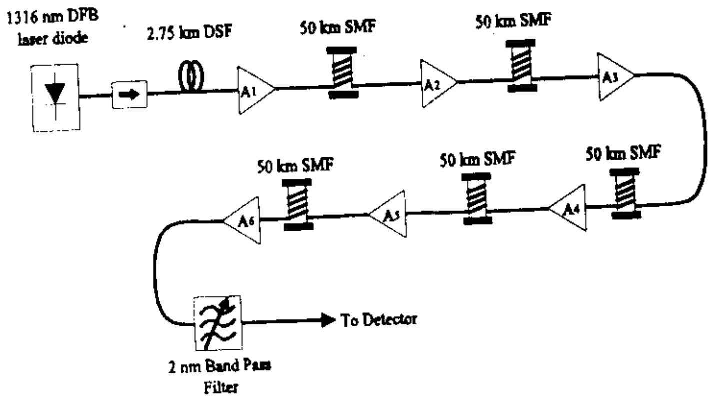
- Dispersion compensation for 1.5μm
  - Solitons
  - Source pre-chirp
  - Equalizing fibre
  - Chirped fibre gratings
  - Phase conjugation

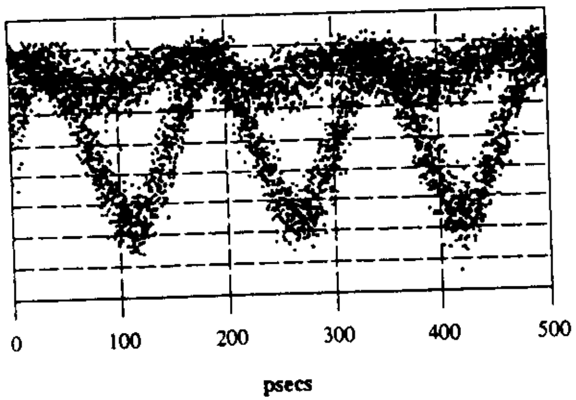
1.3μm SOLITON TRANSMISSION ON STANDARD FIBRE

The issues:

- Fibre loss
- Fibre dispersion
- Polarisation mode dispersion
- Amplifiers - spacing
  - power

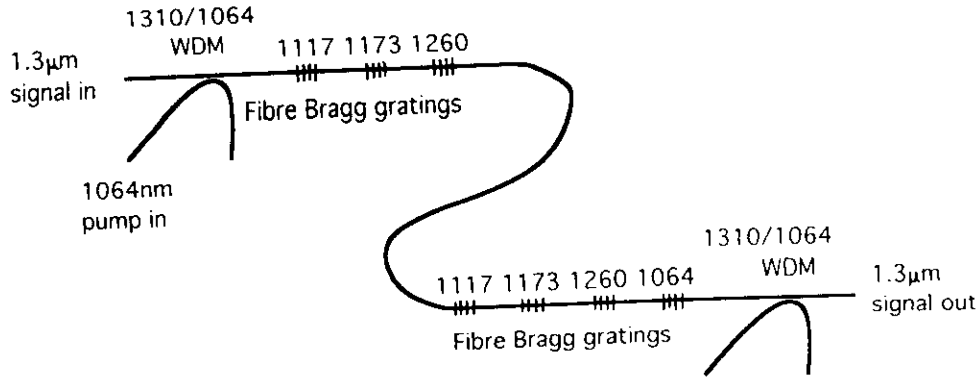
6.5 Gbit/s, 1316nm SOLITON TRANSMISSION OVER 250km OF STANDARD FIBRE USING SEMICONDUCTOR QUANTUM WELL AMPLIFIERS

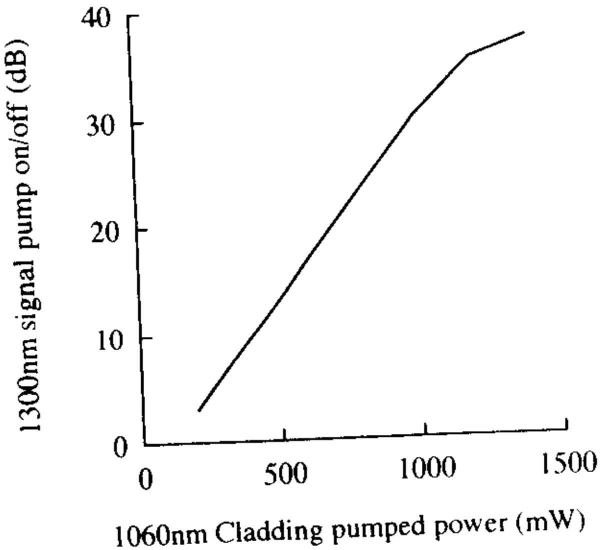




Liedenbaum et al, ECOC '94

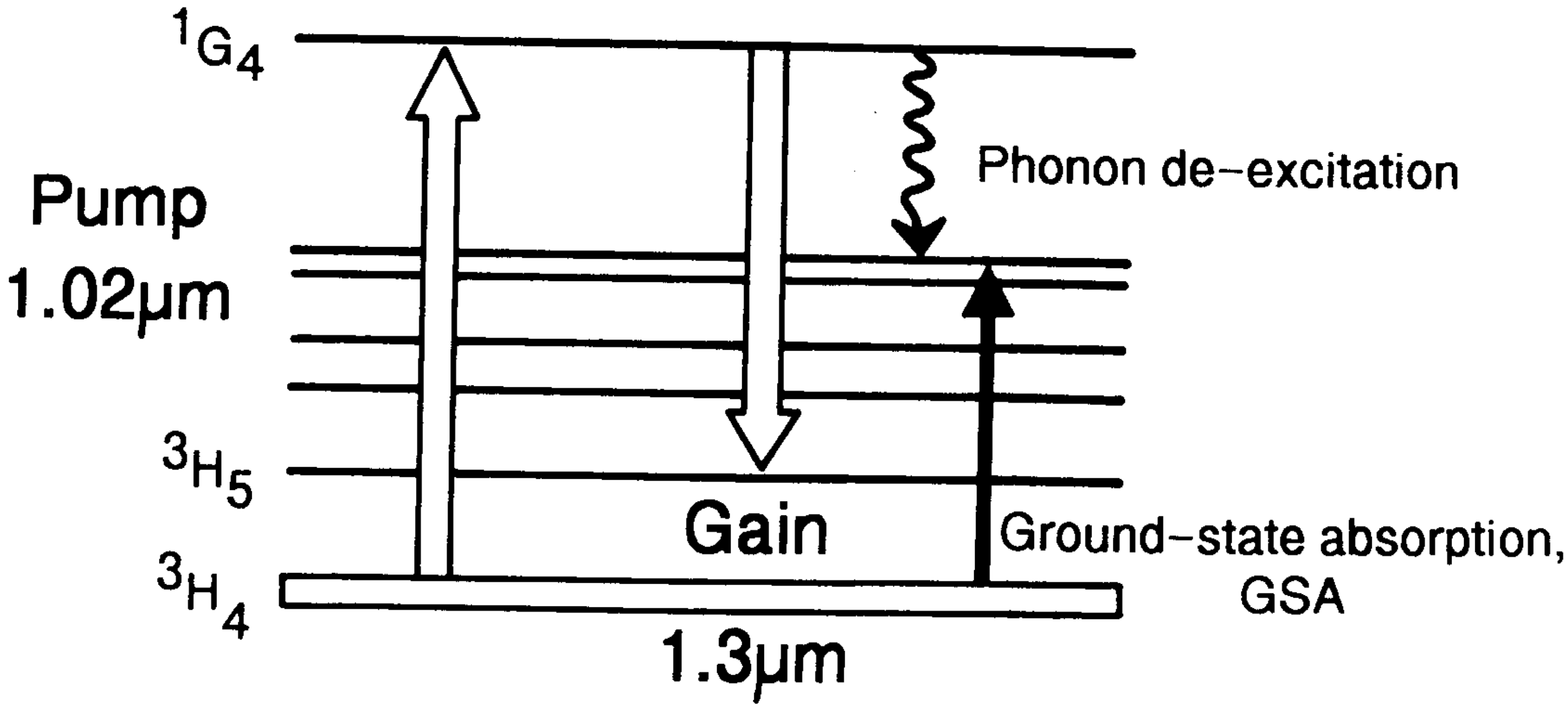
1.3μm AMPLIFIERS - RAMAN CASCADE



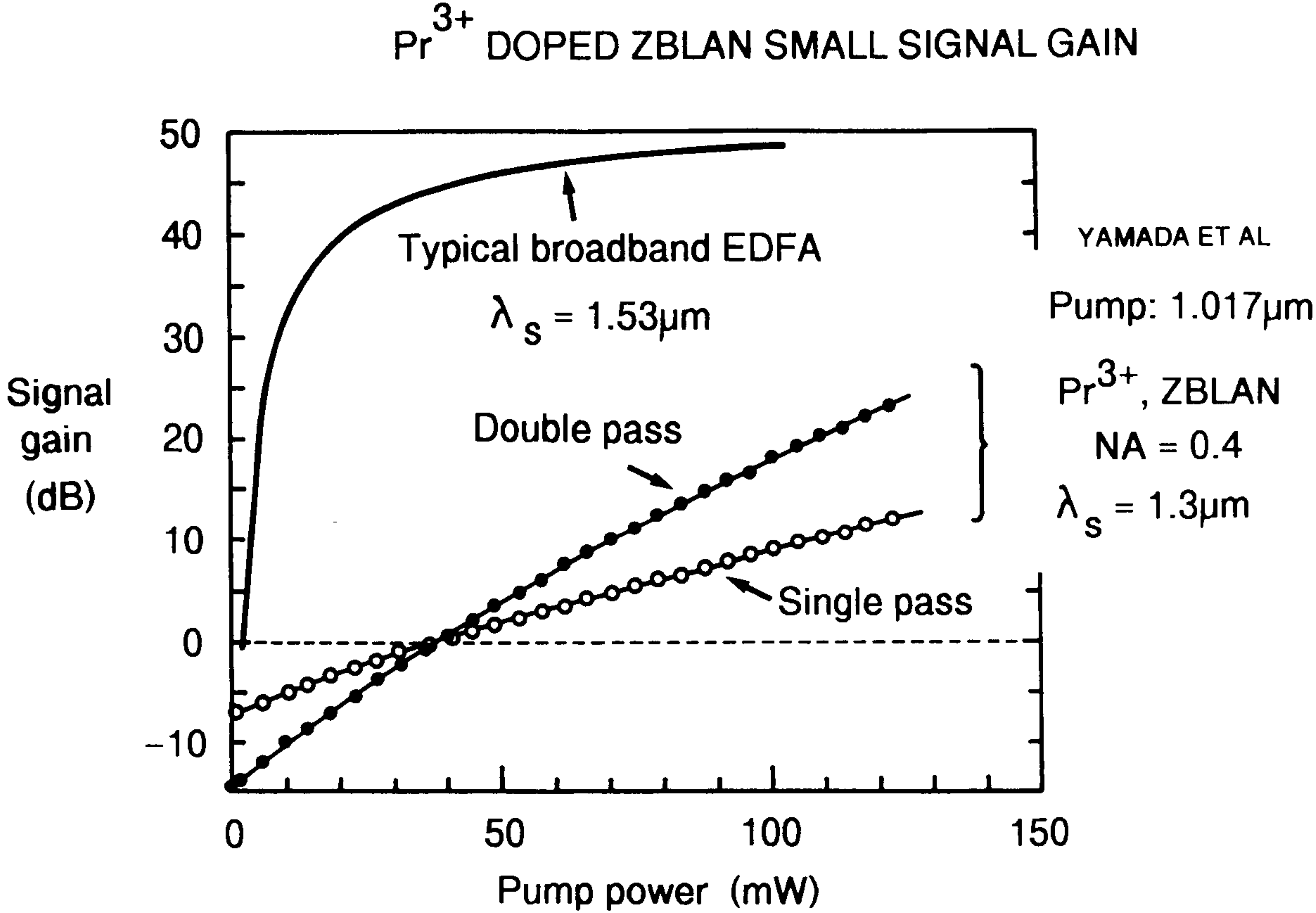


S Grubb et al, OAA '94

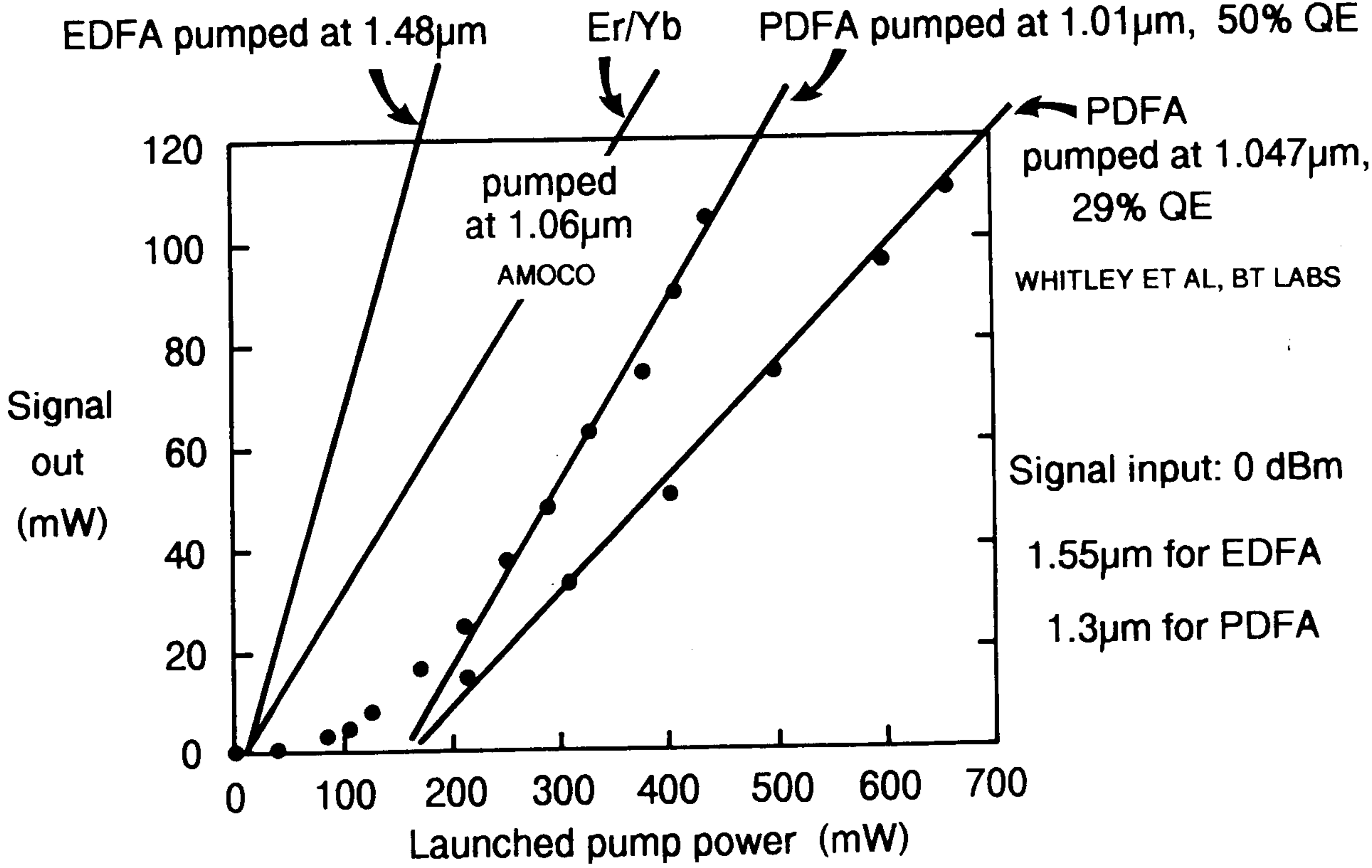
Pr^{3+} DOPED ZBLAN ENERGY LEVEL DIAGRAM

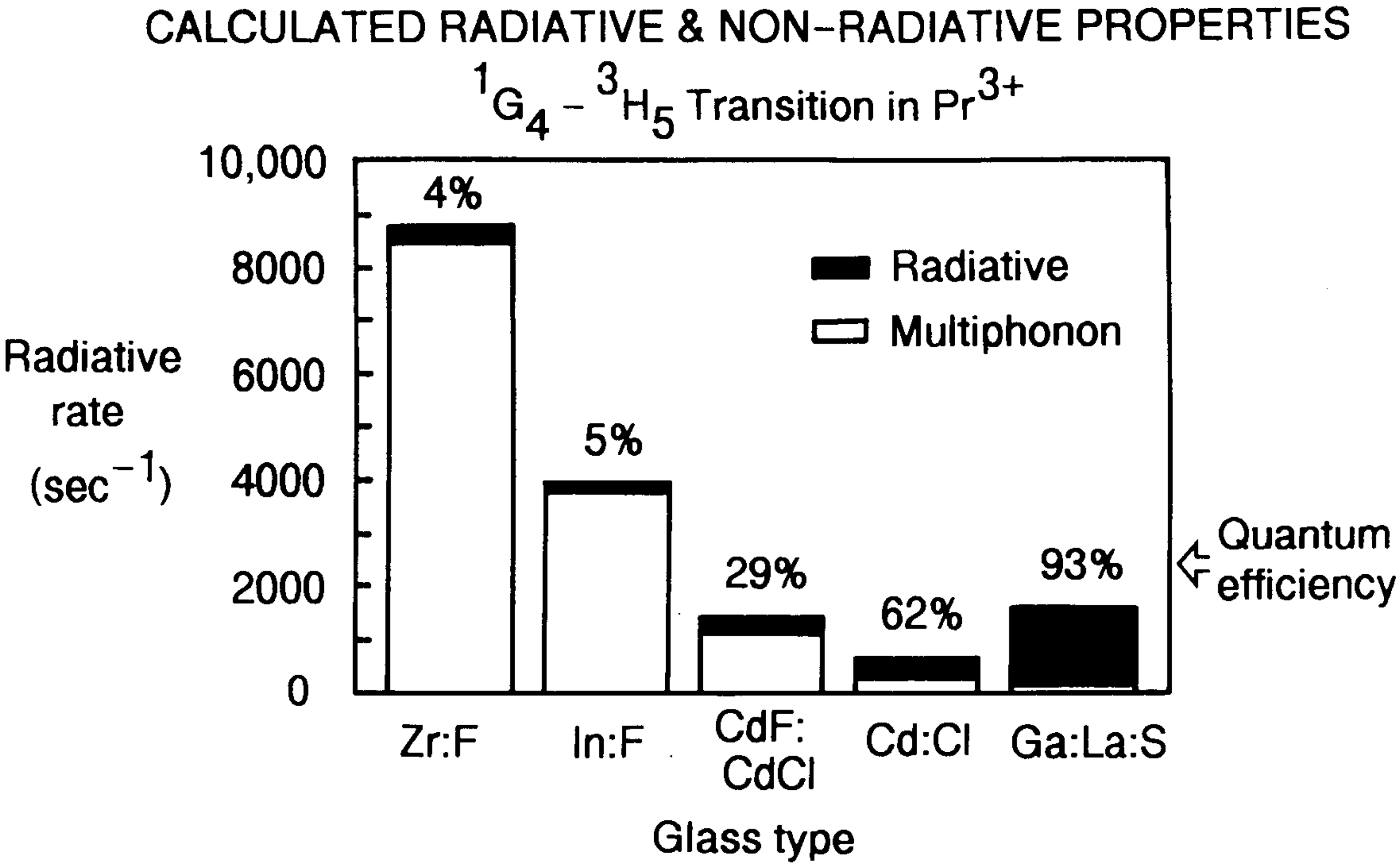


Non-radiative decay ➔ Quantum efficiency ~ 4%


Pr3+ DOPED ZBLAN SMALL SIGNAL GAIN
50
40
30
20
10
0
−10
Signal
gain
(dB)
Typical broadband EDFA
λ s = 1.53μm
Double pass
Single pass
0
50
100
150
Pump power (mW)
YAMADA ET AL
Pump: 1.017μm
Pr3+, ZBLAN
NA = 0.4
λ s = 1.3μm

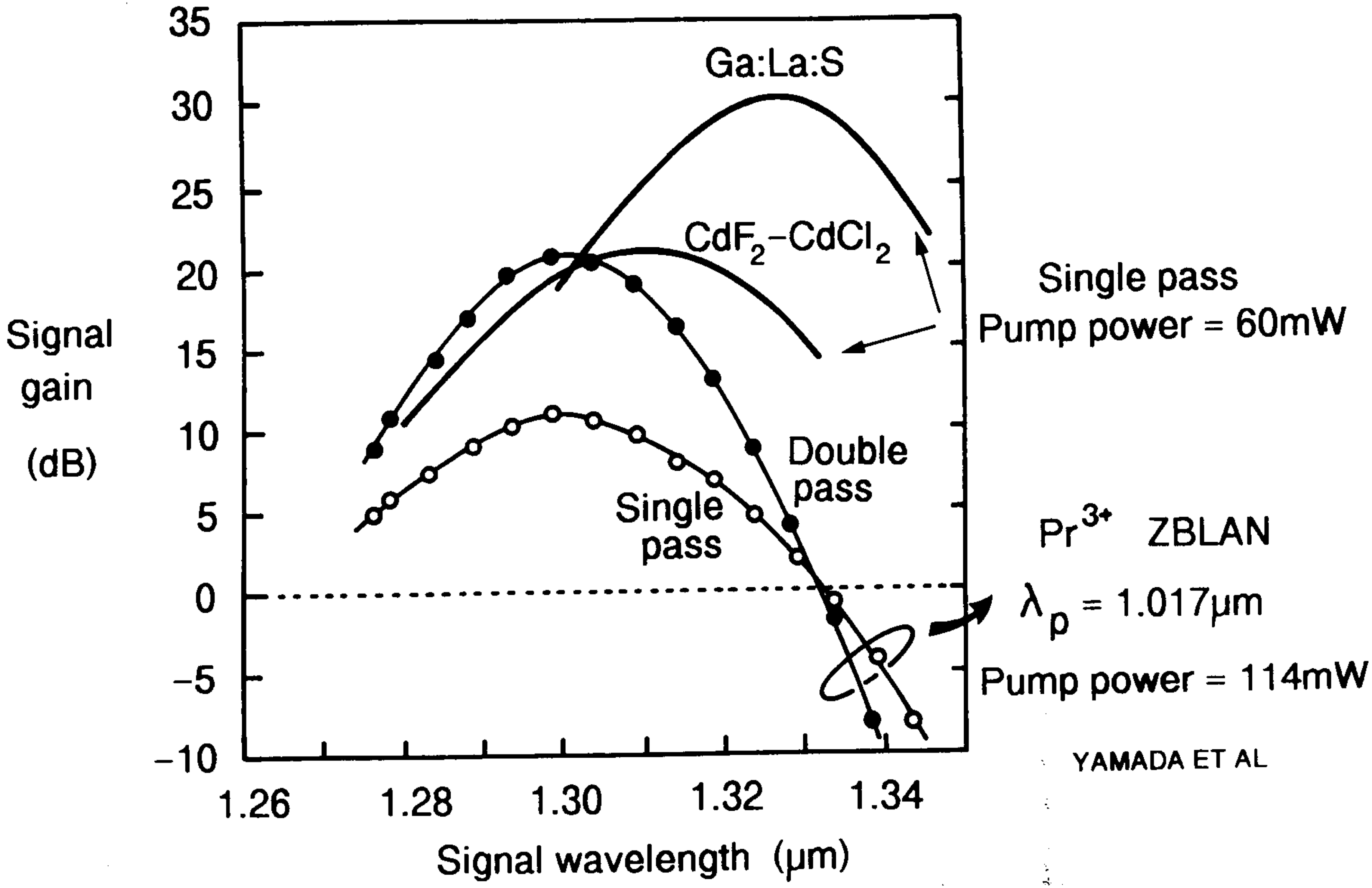
POWER AMPLIFICATION





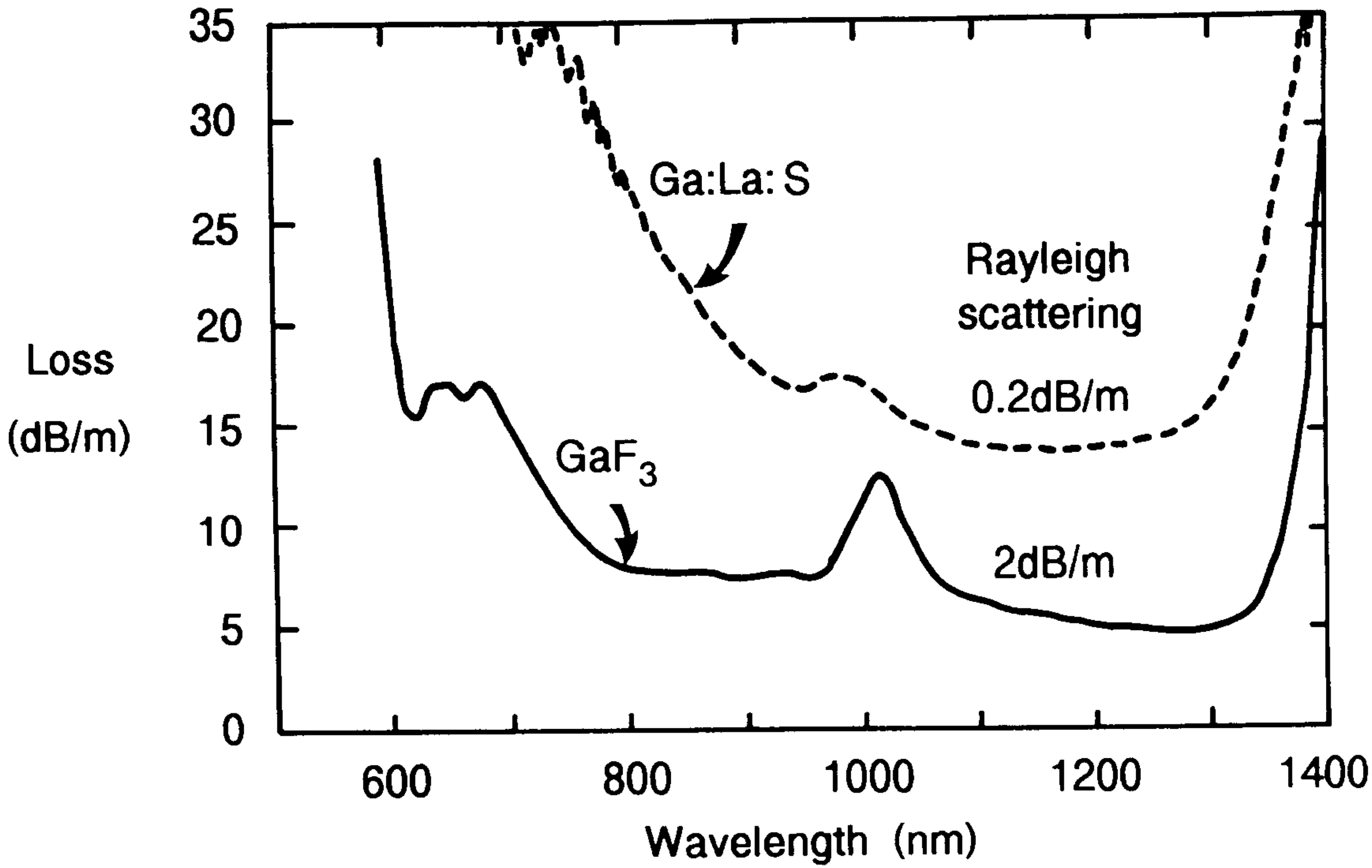
CALCULATED RADIATIVE & NON–RADIATIVE PROPERTIES
$^1G_4 - {}^3H_5$ Transition in Pr^{3+}
10,000
8000
6000
4000
2000
0
Radiative rate (sec^{-1})
4%
5%
29%
62%
93%
Radiative
Multiphonon
Quantum efficiency
Zr:F
In:F
CdF: CdCl
Cd:Cl
Ga:La:S
Glass type

SMALL SIGNAL GAIN SPECTRA OF Pr^{3+} DOPED AMPLIFIER

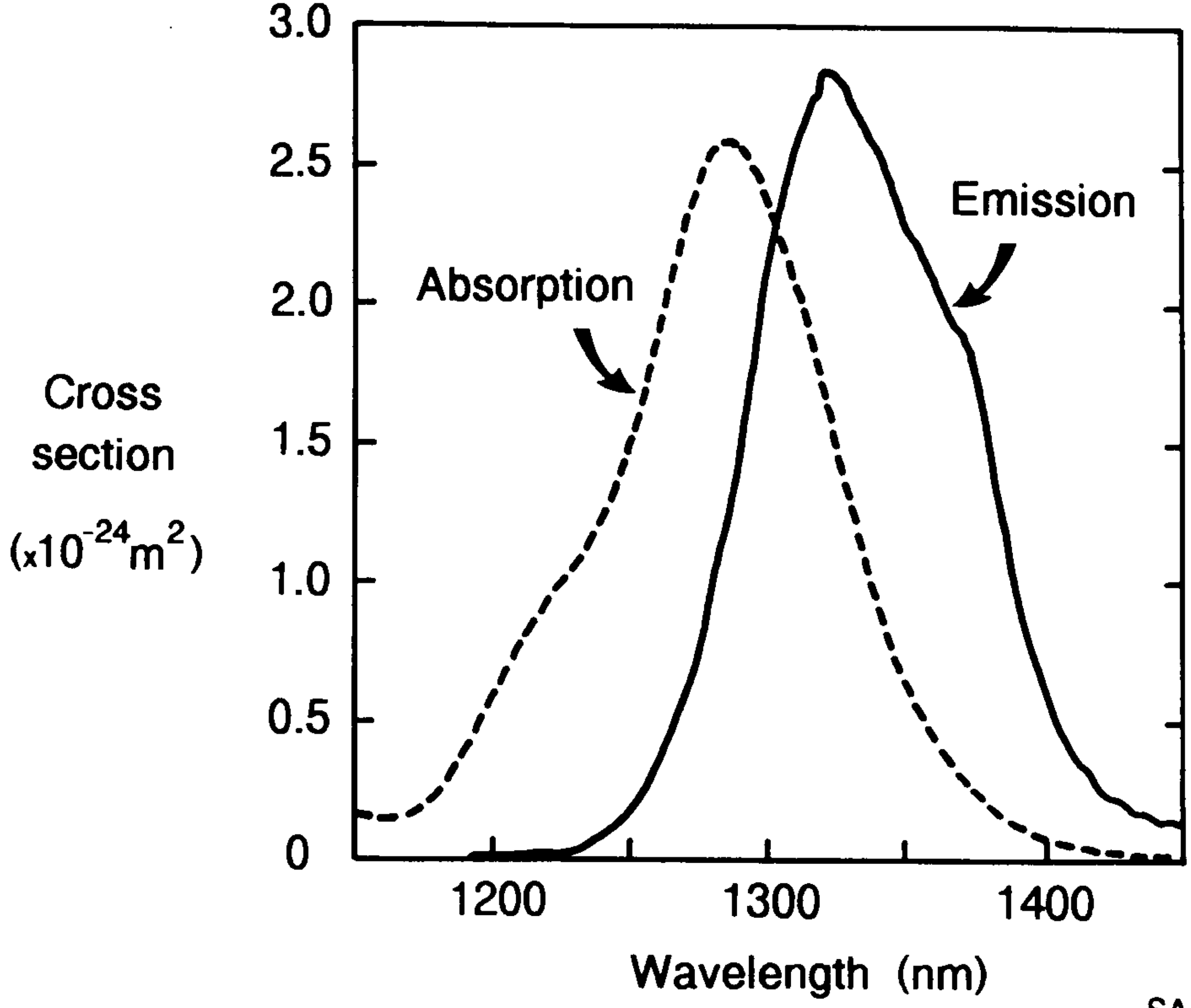


YAMADA ET AL

LOSS SPECTRA OF EARLY SOUTHAMPTON FIBRES



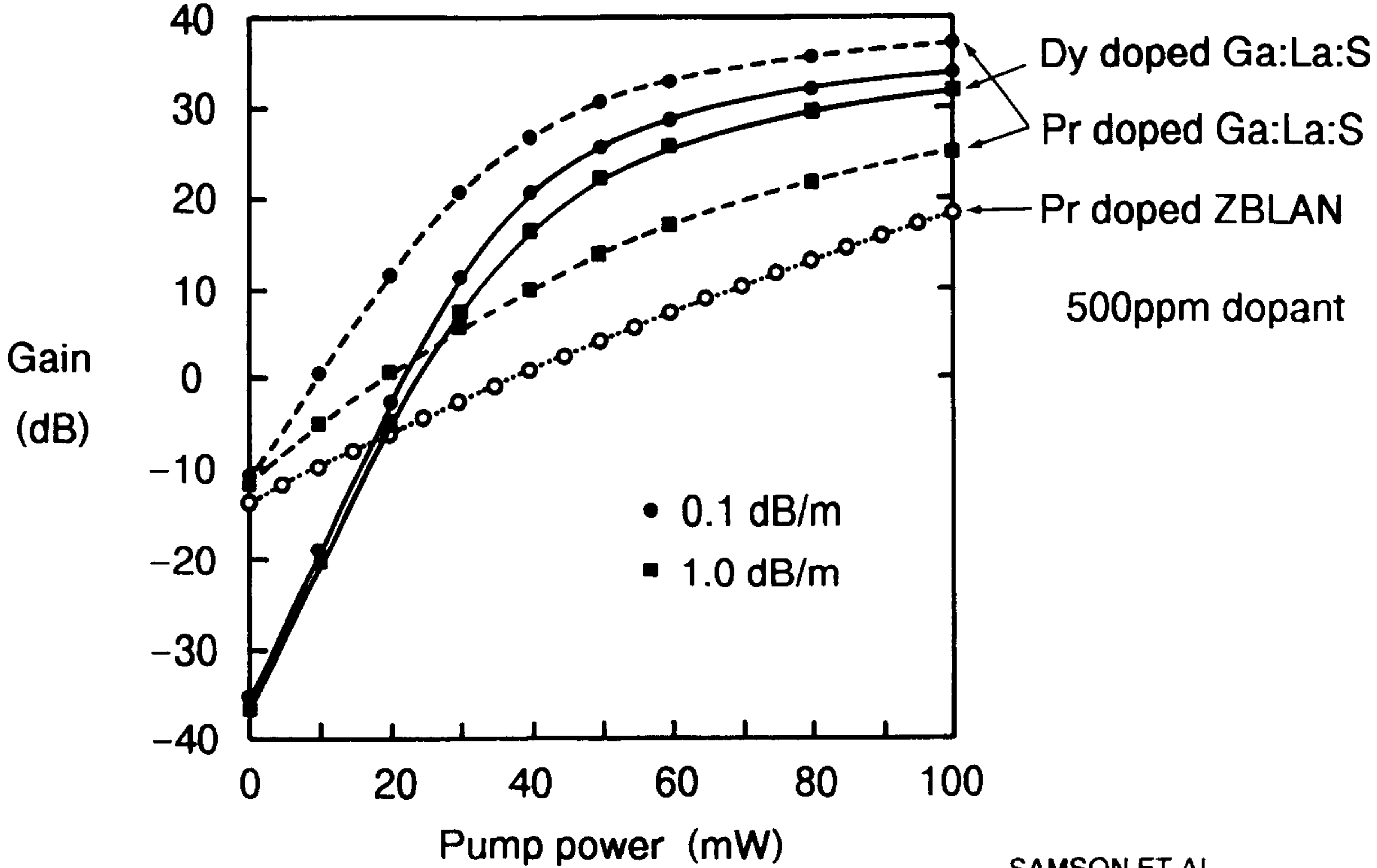
Dy^{3+} EMISSION AND ABSORPTION CROSS-SECTIONS



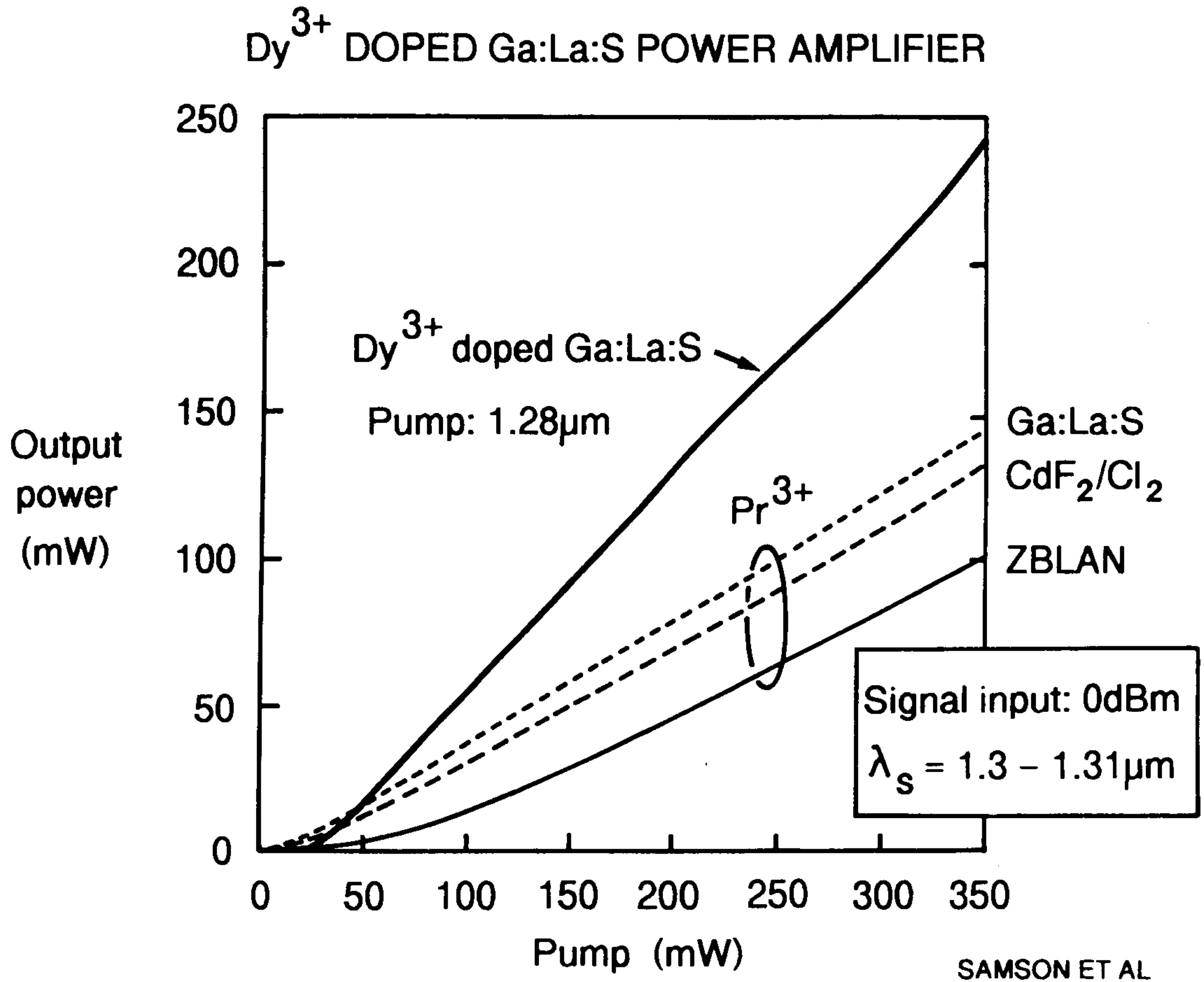
SAMSON ET AL

COMPARISON OF Dy^{3+} and Pr^{3+} DOPED GaLaS and Pr^{3+} DOPED ZBLAN

Showing the effect of background loss

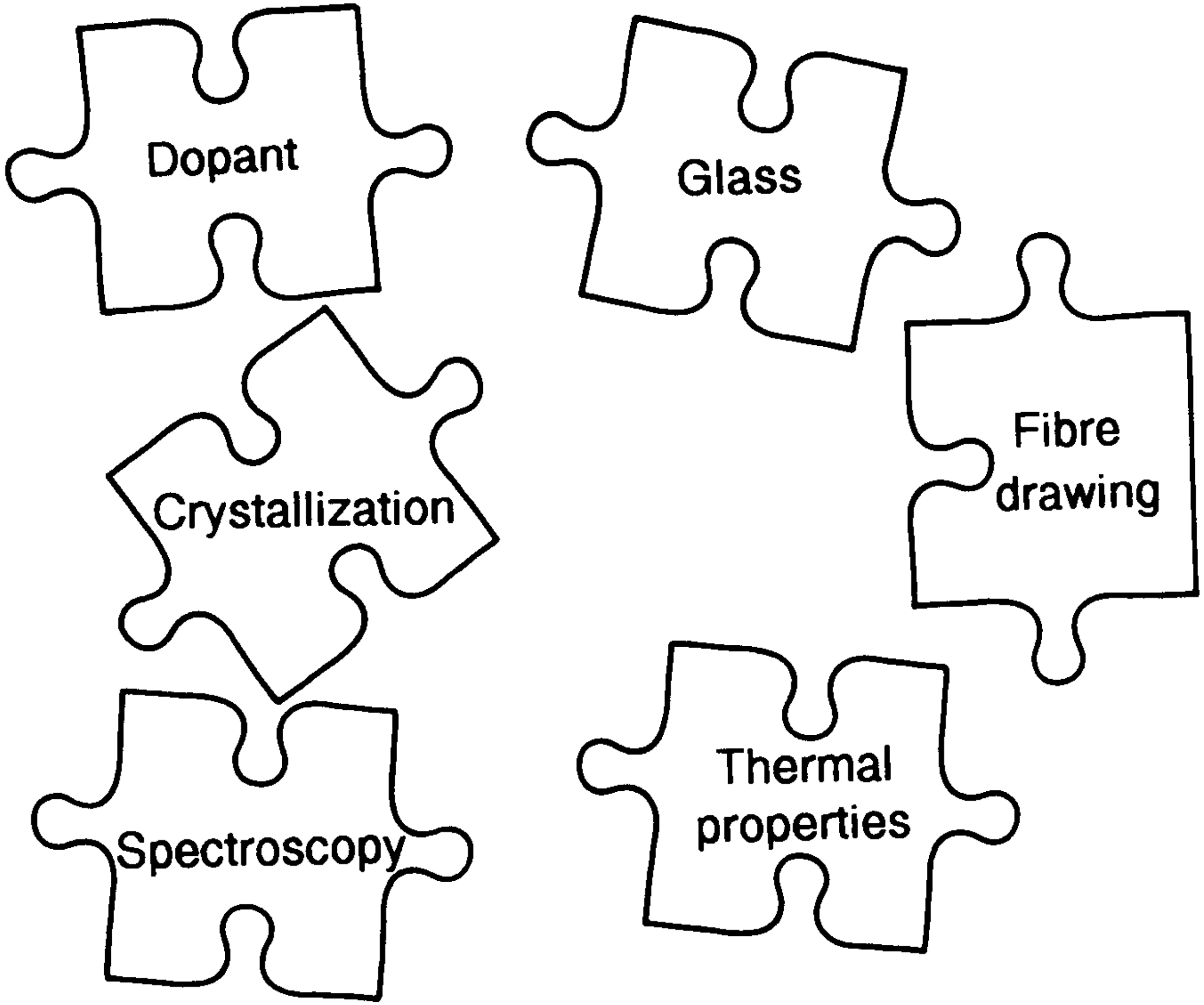


SAMSON ET AL



Dy3+ DOPED Ga:La:S POWER AMPLIFIER
Output power (mW)
Pump (mW)
Dy3+ doped Ga:La:S
Pump: 1.28μm
Pr3+
Ga:La:S
CdF2/Cl2
ZBLAN
Signal input: 0dBm
λs = 1.3 – 1.31μm
0
50
100
150
200
250
300
350

SAMSON ET AL


Dopant
Glass
Crystallization
Fibre drawing
Spectroscopy
Thermal properties

PROSPECTS FOR 1.3μm AMPLIFIERS

- Pr^{3+} ZBLAN - 1.02/1.047μm pump
  Reasonable power amplifier, Poor small signal gain

Commercially available !!

- Pr^{3+} doped low phonon energy glasses;
  Chalcogenides & Mixed halides - 1.02μm pump
  Significantly improved small signal gain, Improved power amplifier

Chalcogenide preferred !!

- Dy^{3+} doped Chalcogenide - 1.28μm pump
  Excellent power amplifier, Good small signal gain

Potential problems with bottlenecking to be overcome !!

SOLITON TRANSMISSION OVER STEP INDEX FIBRE

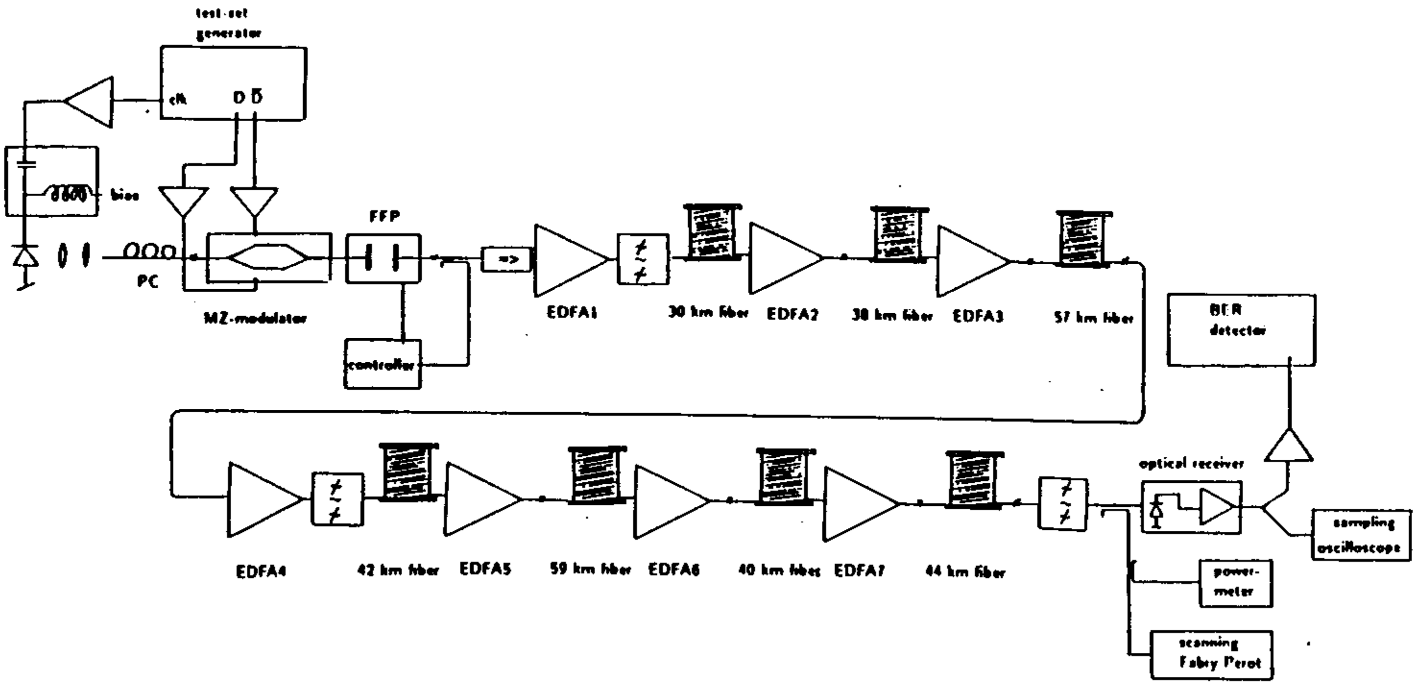
Problems

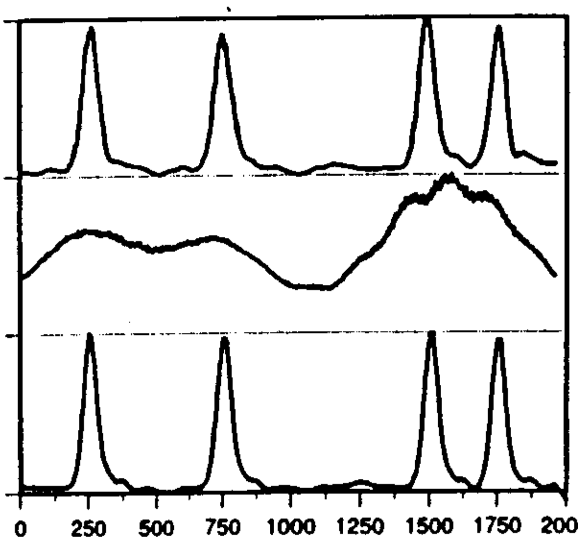
- Soliton period
- Amplifier spacing
- Gordon Haus jitter

Solutions

- Partial dispersion compensation
- Soliton filtering
- Temporal control

SOLITON TRANSMISSION AT 1.55μm IN STANDARD FIBRE





4 Gbit/s
55 ps pulses
8.6 mW peak power
70 km soliton period
40 km amp spacing

B. Christensen et al, ECOC '93

SOLITON TRANSMISSION ON STANDARD FIBRE USING SATURABLE ABSORPTION AND SPECTRAL FILTERING

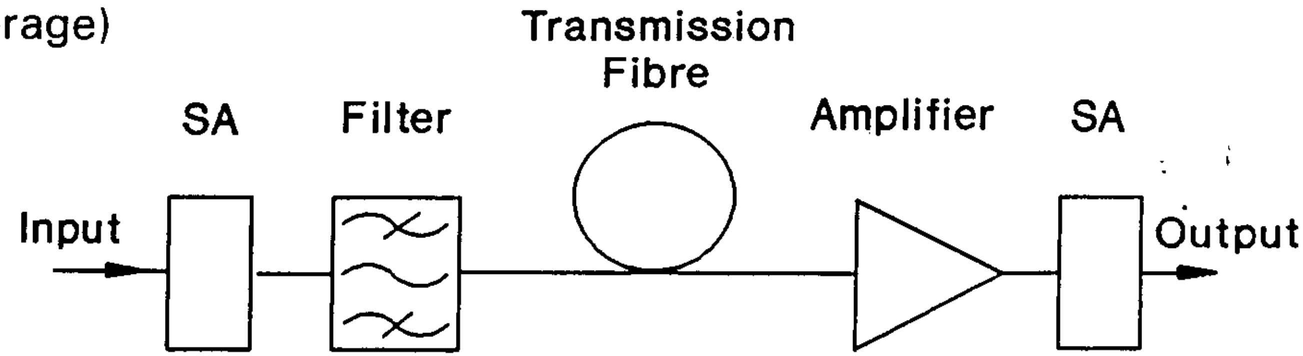
Dispersion 17 ps/nm.km

8 Gbit/s, MSR = 4.5:1
soliton pulsewidth 28ps
(40 mW peak, 10 mW average)

Amp spacing 40 km
(3 soliton periods)

Filter bandwidth 30 GHz

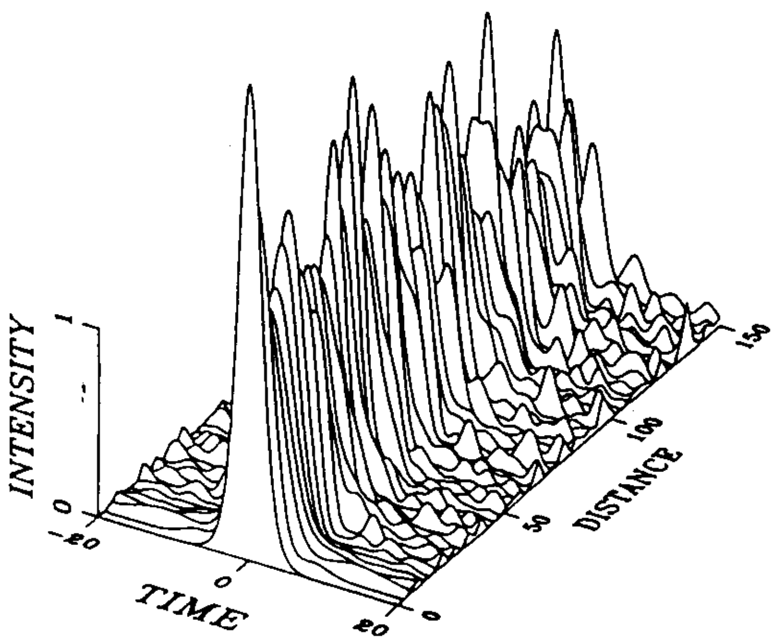
Amp gain 12 dB



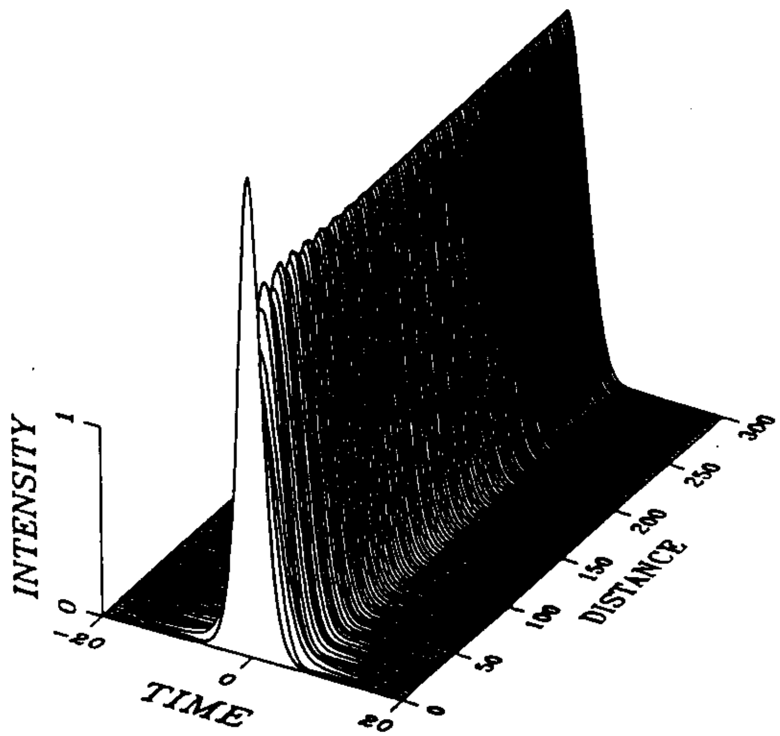
For 10Gbit/s amp
spacing ~25 km

A. Grudinin et al, Southampton University

Pulse dynamics along transmission system



No control



Filter + Saturable absorber

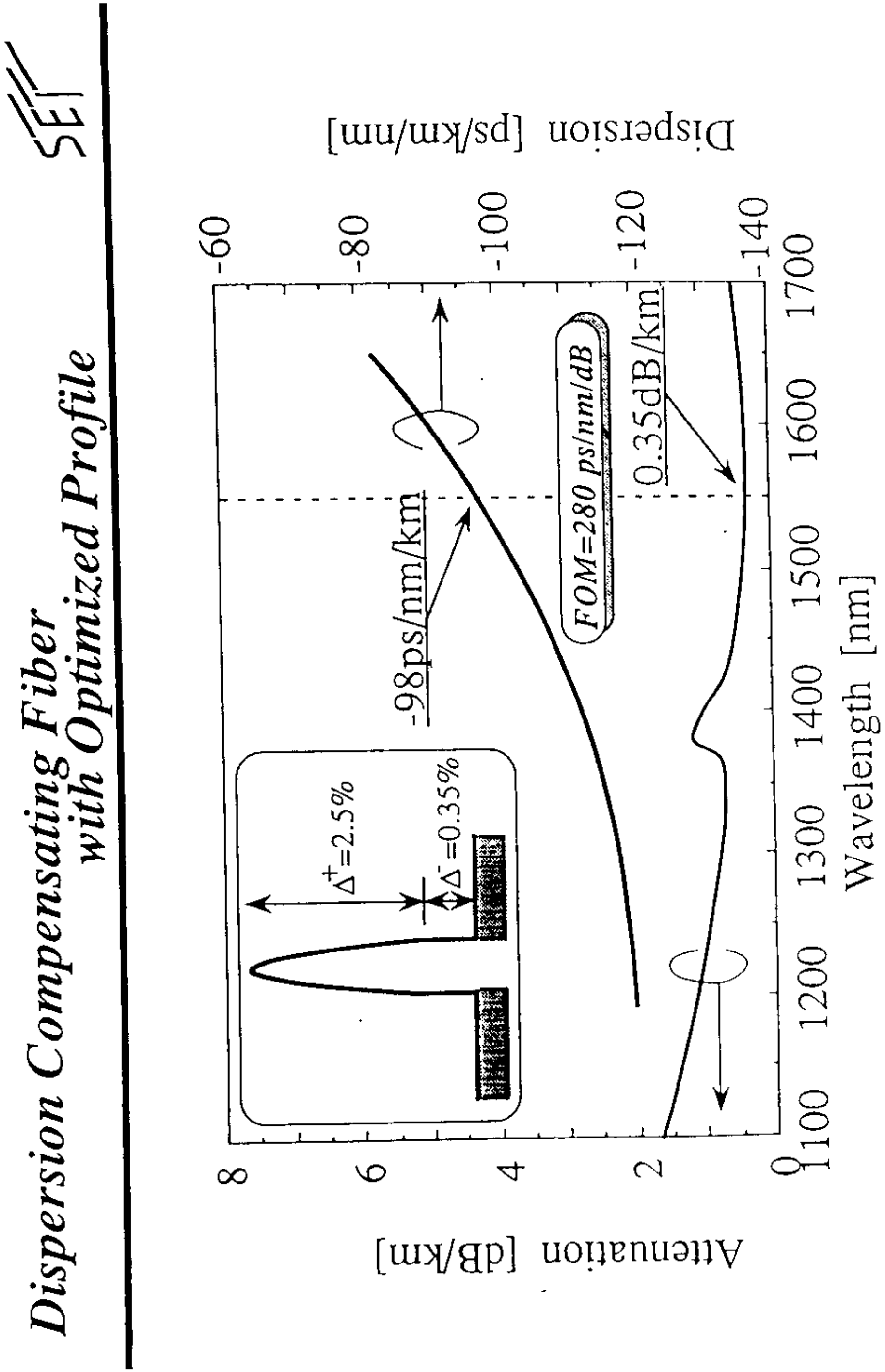
DISPERSION EQUALISING FIBRE

Advantages

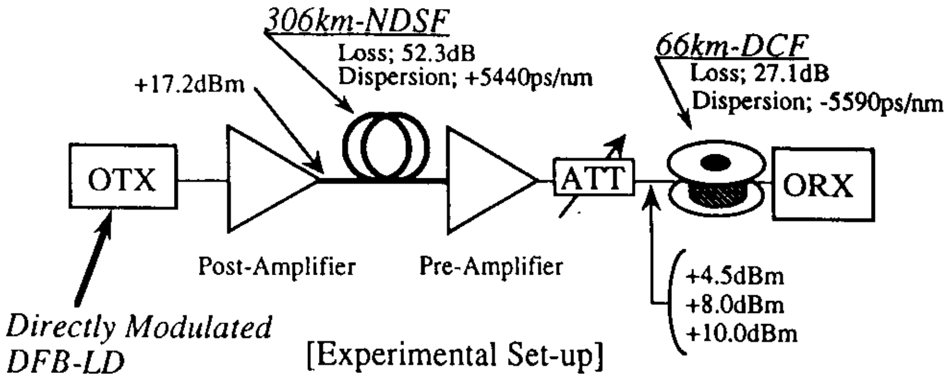
- Broad bandwidth
- Simple
- Fibre compatability

Disadvantages

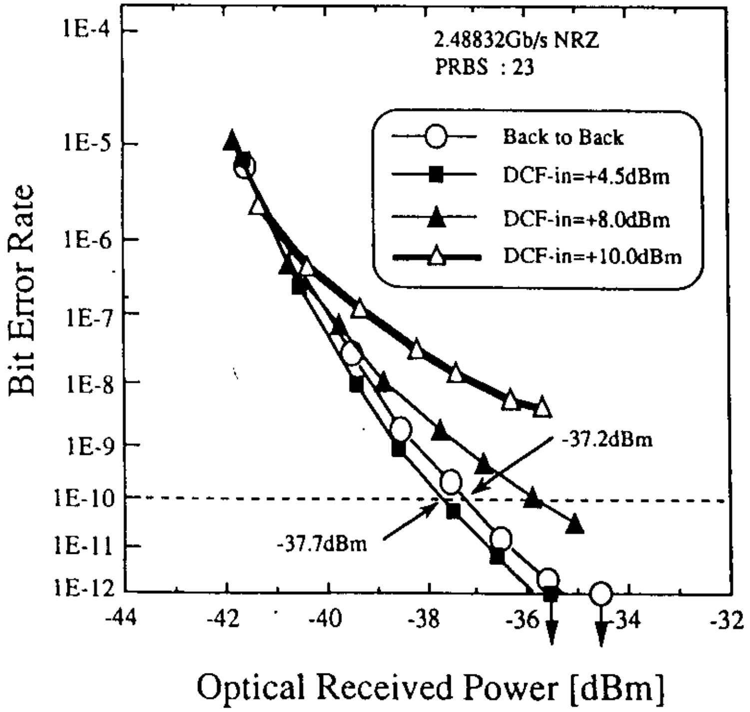
- Loss
- Size



2.4Gb/s, 306km Repeaterless Transmission Experiment using DCF



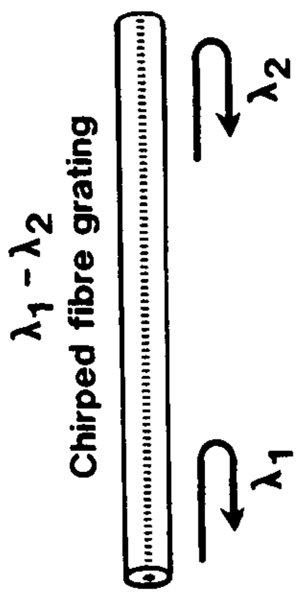
[Experimental Set-up]

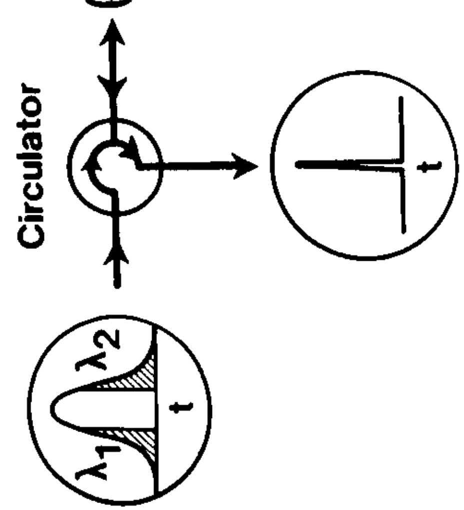


[Bit Error Rate Characteristics]

FUTURE FIBRE DEVICES

Dispersion compensators?





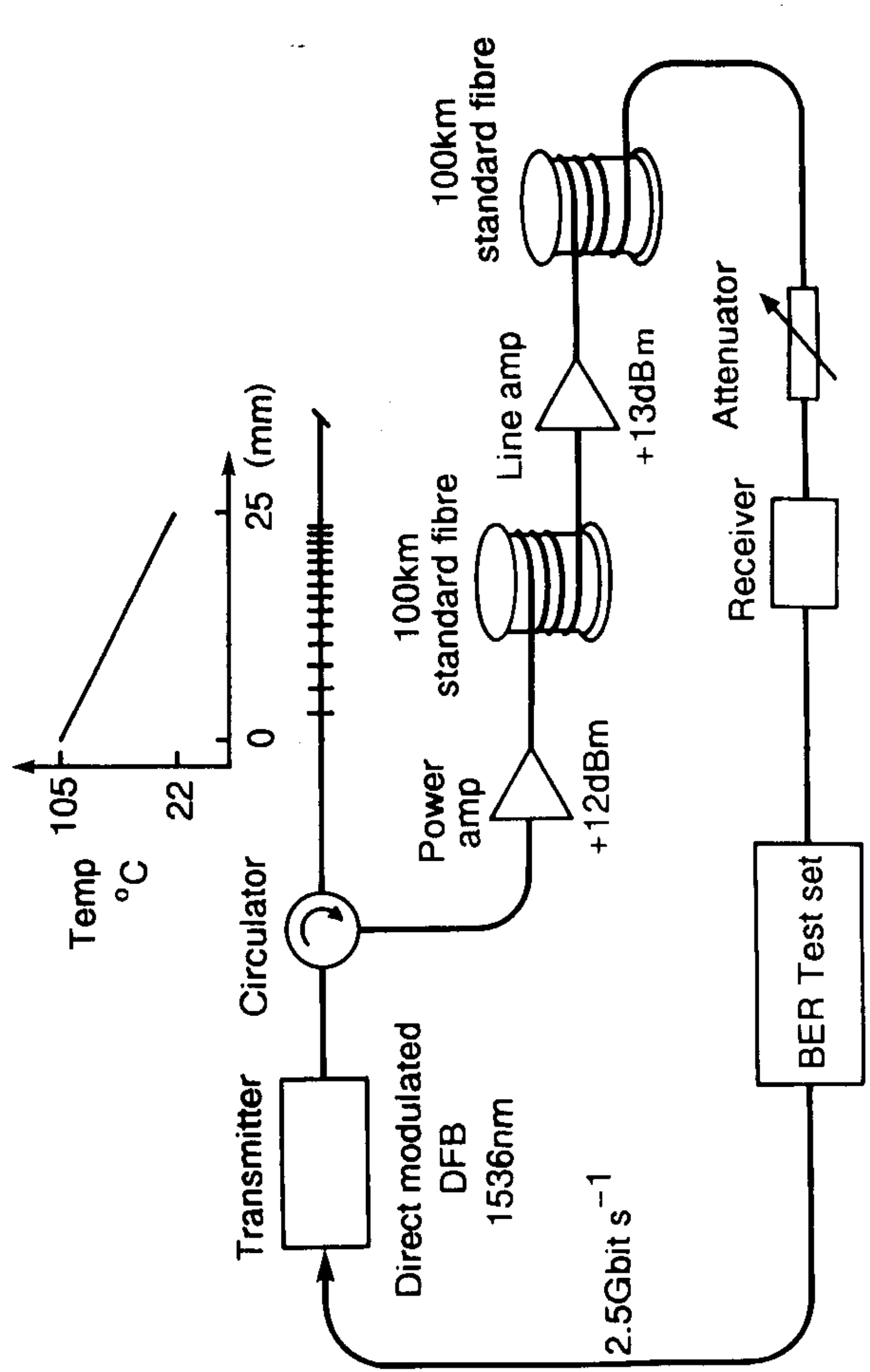
- To compensate 100km of 17ps/nm.km fibre: Need 17cm/nm
- Difficult to write gratings > 1cm at present

CHIRPED FIBRE GRATINGS

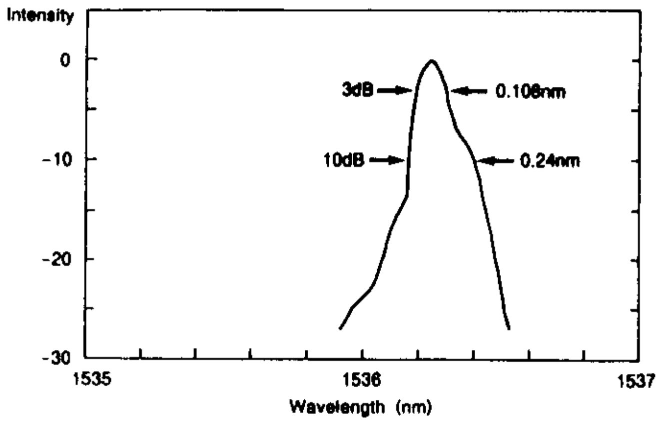
Advantages
- Low loss
- Compact
- Higher order dispersion
- Narrowband

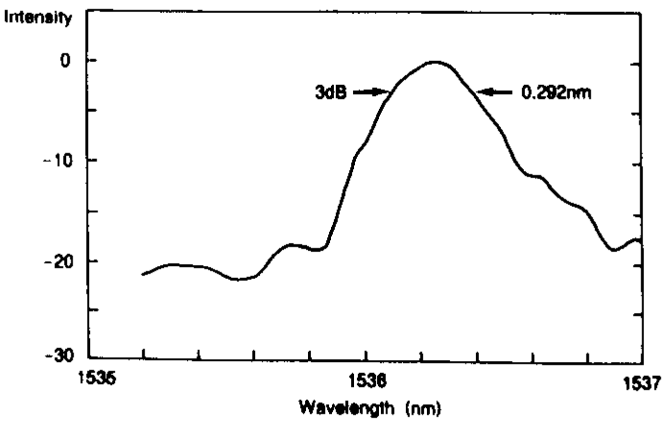
Disadvantages
- Dispersion profile
- Narrowband

Experimental setup



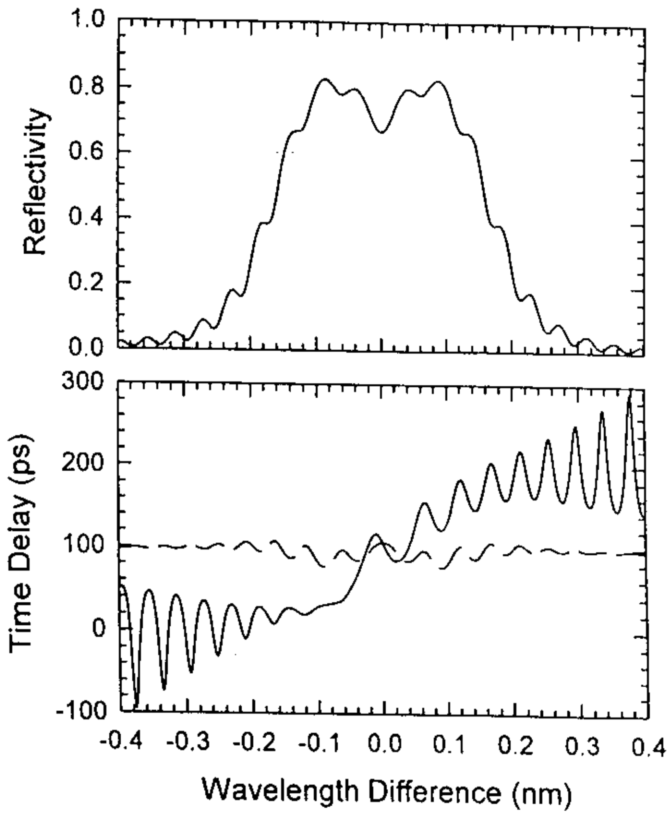
TRANSMITTER AND GRATING REFLECTION SPECTRA





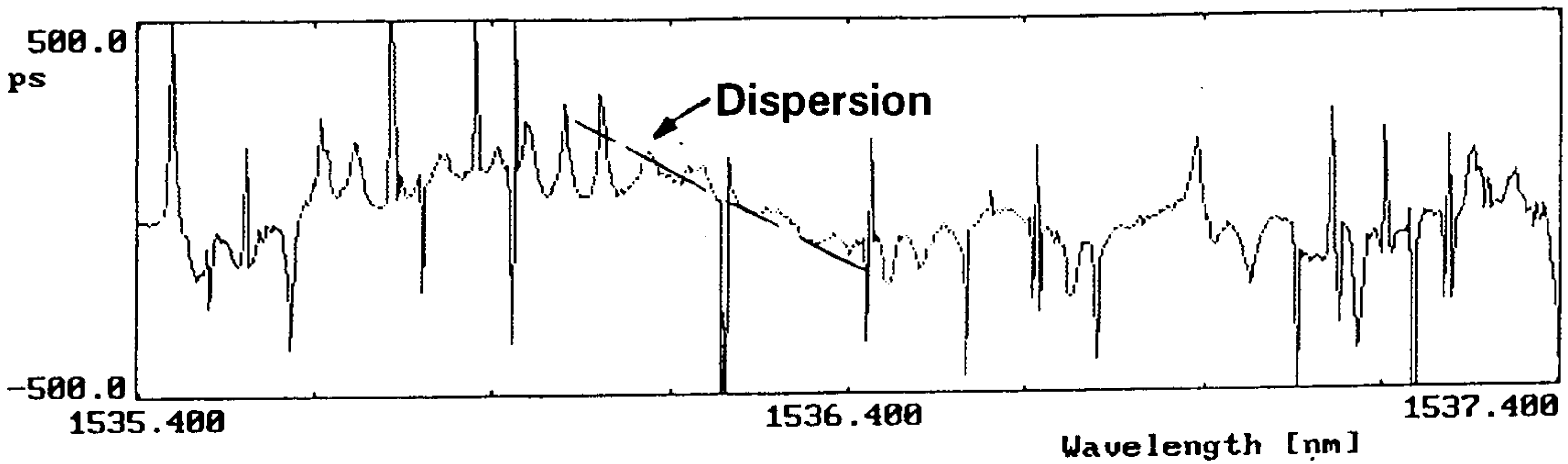
Reflection and Transmission of a Chirped Grating

Lamda= 1552nm Grating Length= 20mm $h_0 = 3x10^{-5}$ C= 0.006

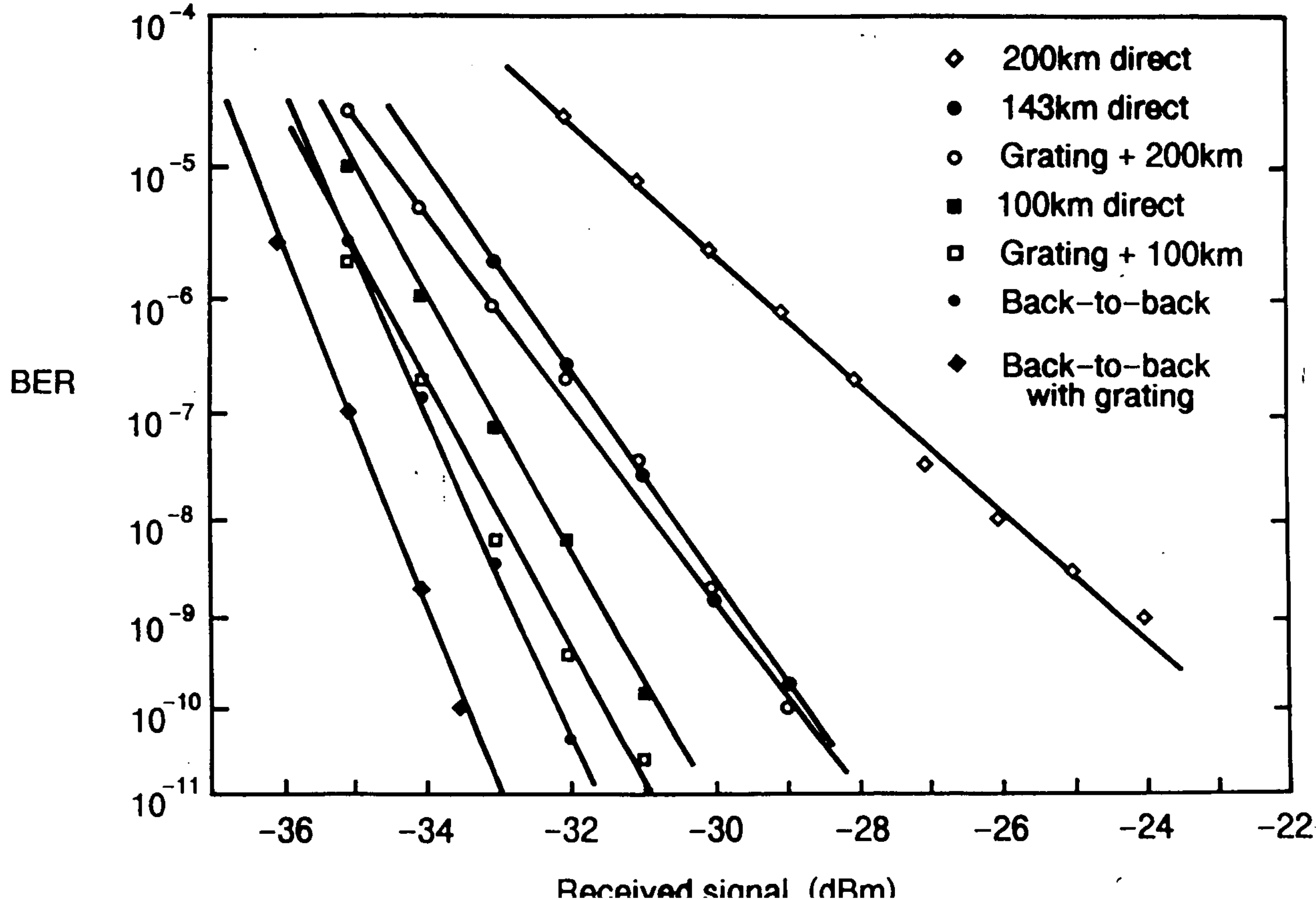


z:\user\mnz\grat1\fig35.spw

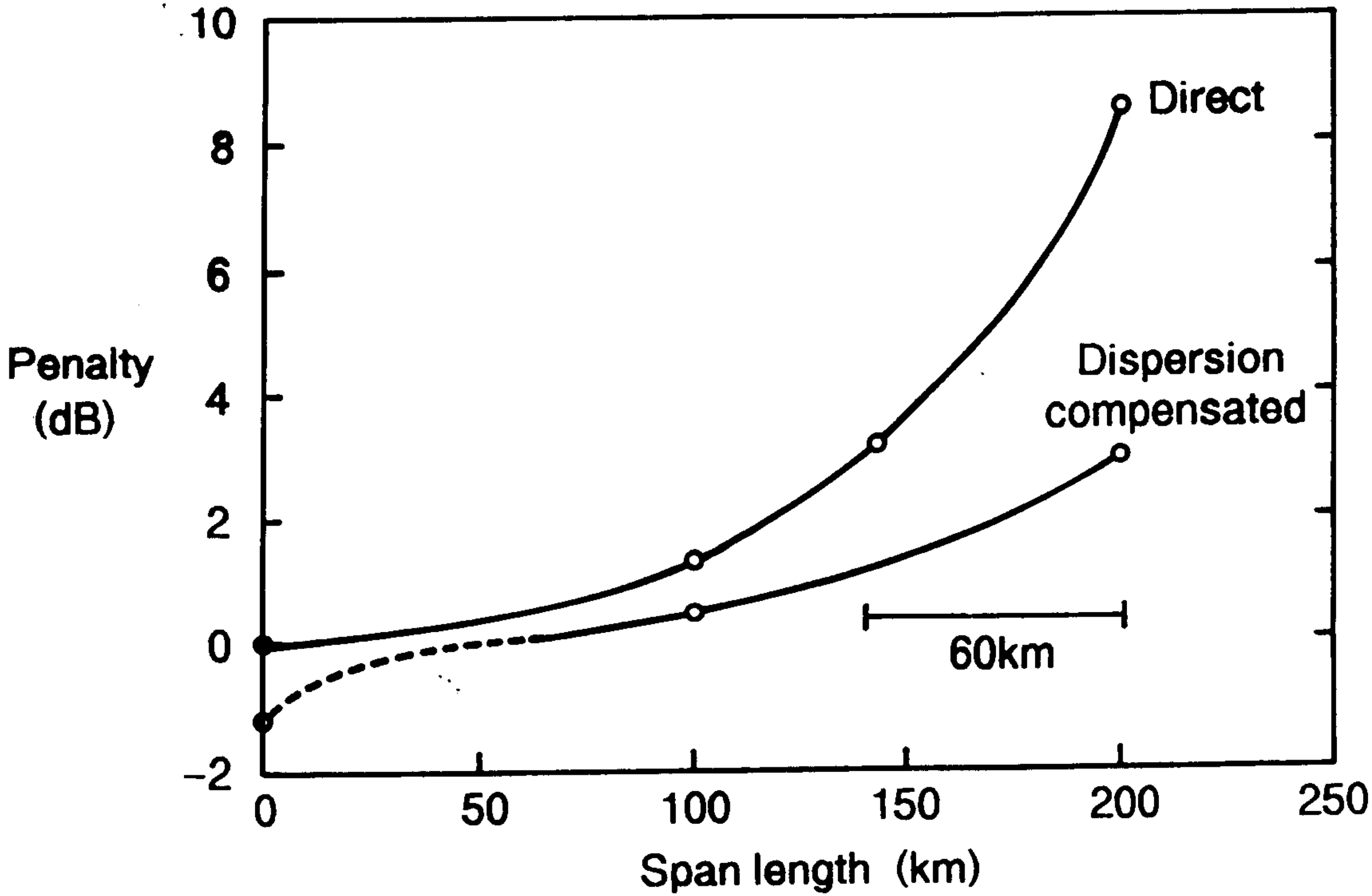
MEASURED DELAY CHARACTERISTICS OF THE GRATING



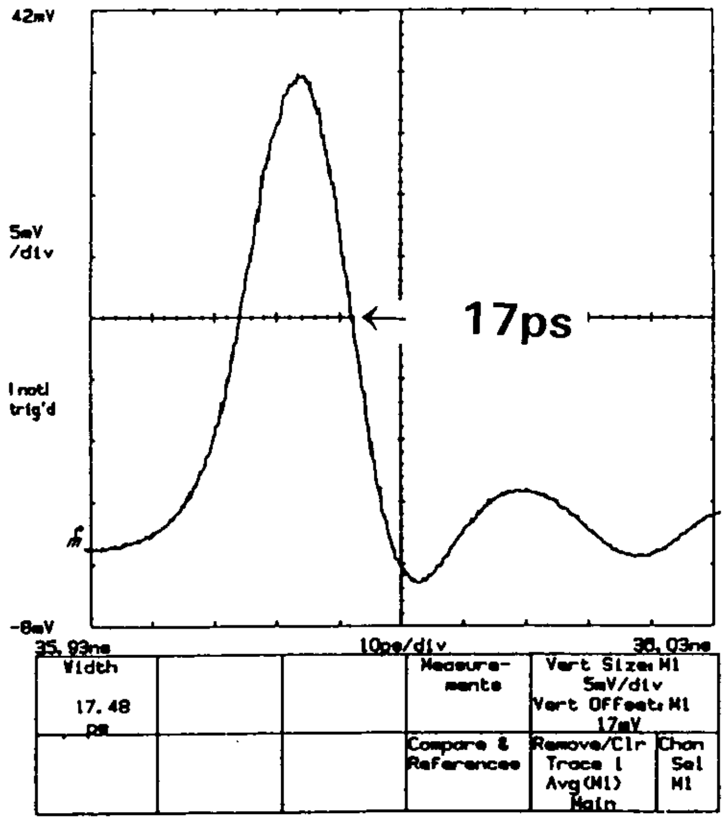
BER for 2.5Gbit/s system

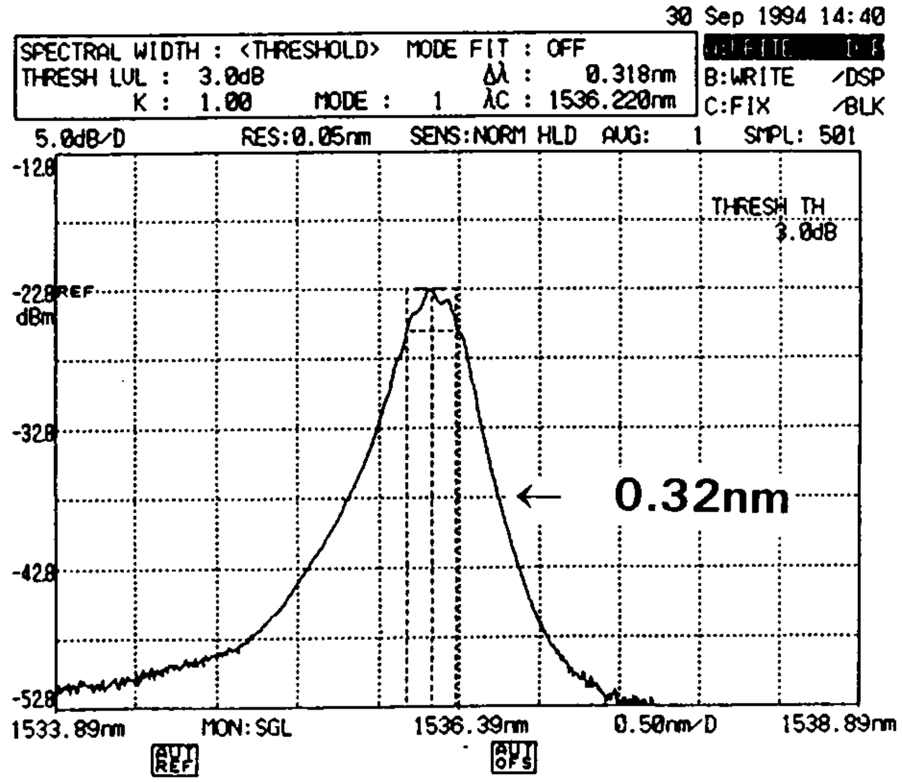


Receiver penalty due to dispersion



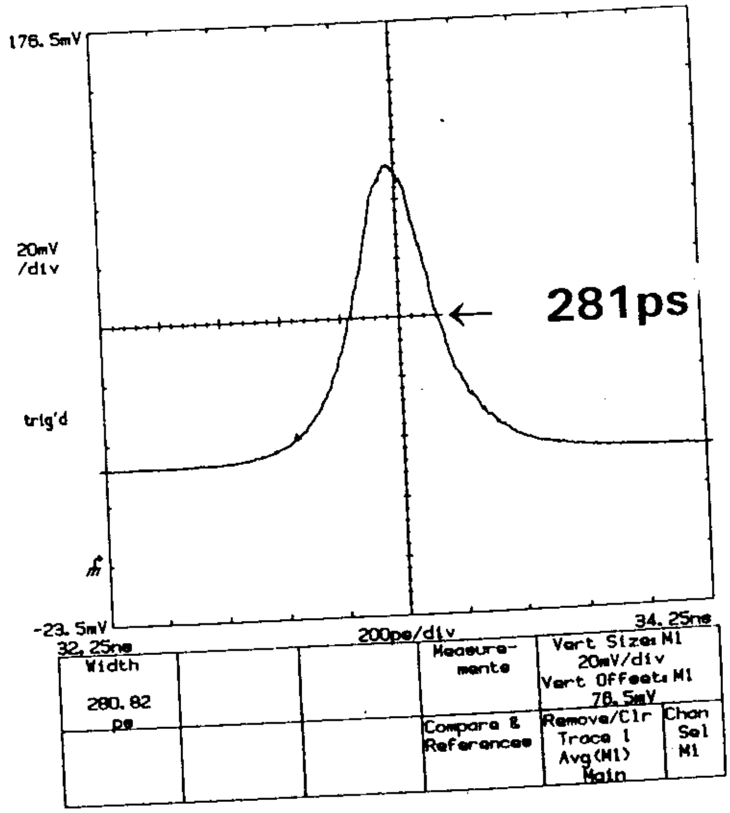
SOURCE DATA


42mV
5mV
/div
I not
trig'd
-8mV
17ps
35.93ns
10ps/div
38.03ns
Width
17.48
ps
Measure-
ments
Vert Size: M1
5mV/div
Vert Offset: M1
17mV
Compare &
References
Remove/Clr
Trace 1
Avg(M1)
Main
Chan
Sel
M1

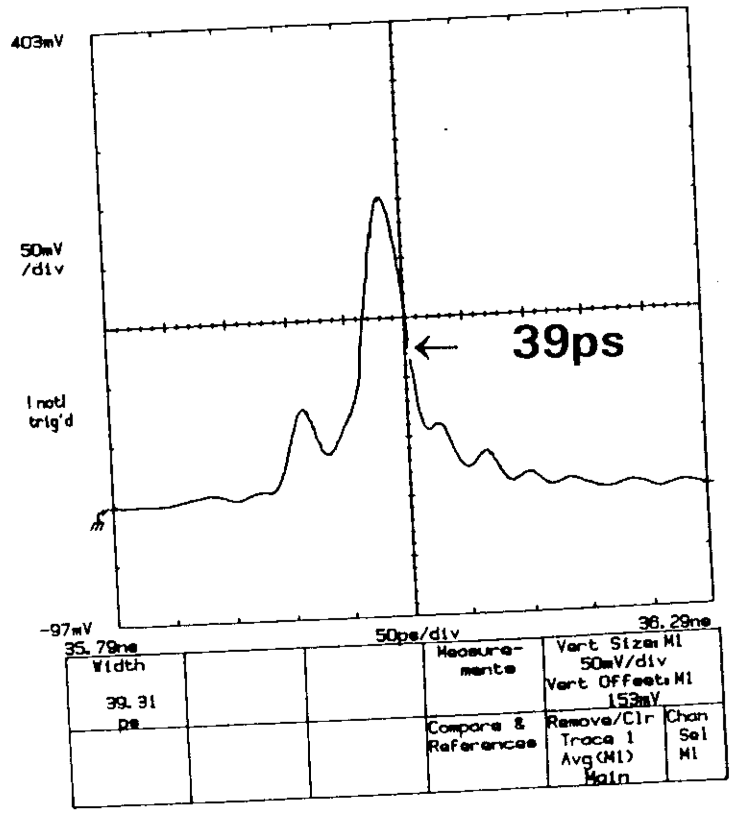

30 Sep 1994 14:40
SPECTRAL WIDTH : <THRESHOLD> MODE FIT : OFF
THRESH LVL : 3.0dB Δλ : 0.318nm
K : 1.00 MODE : 1 λC : 1536.220nm
B:WRITE /DSP
C:FIX /BLK
5.0dB/D RES:0.05nm SENS:NORM HLD AVG: 1 SMPL: 501
-12.8
-22.8 REF
dBm
-32.8
-42.8
-52.8
THRESH TH
3.0dB
0.32nm
1533.89nm
MON:SGL
1536.39nm
0.50nm/D
1538.89nm
AUT
REF
AUT
OFS

PROPAGATION THROUGH 50 km STANDARD FIBRE

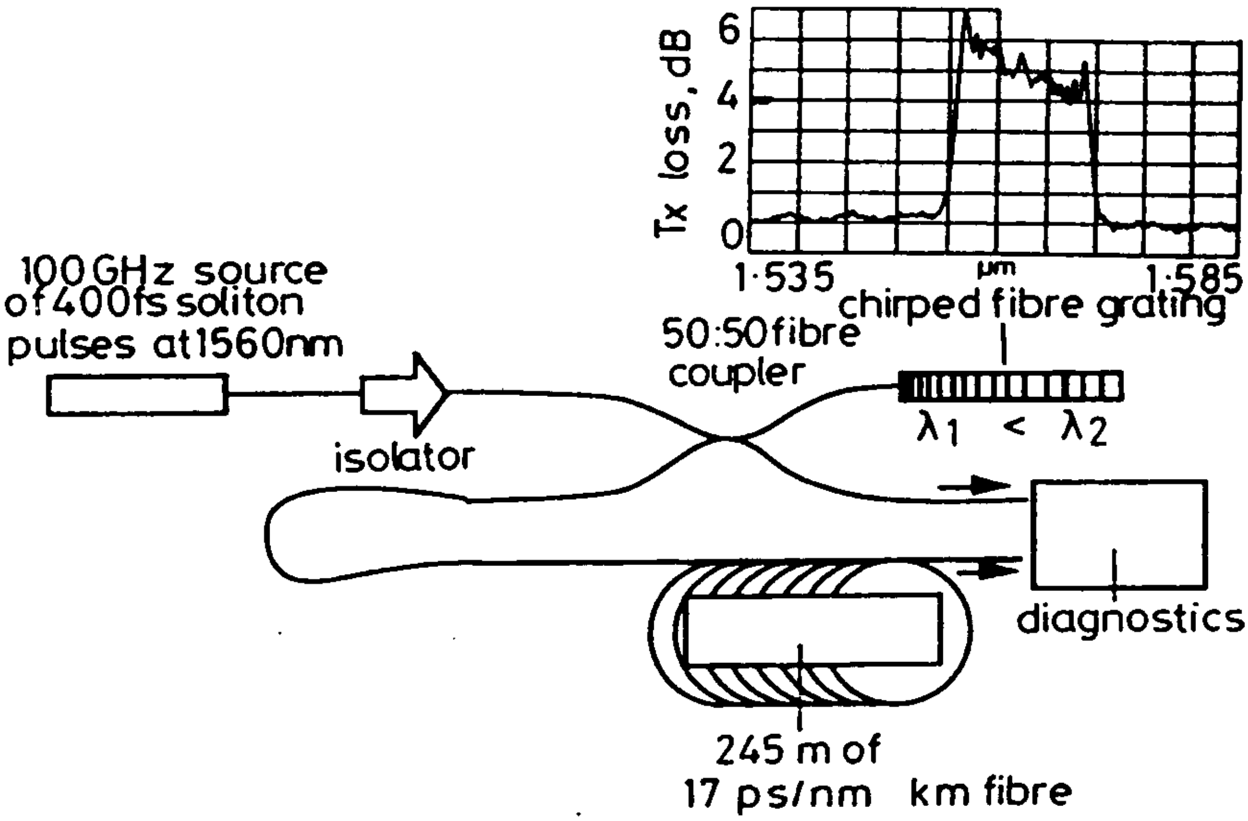
Uncompensated

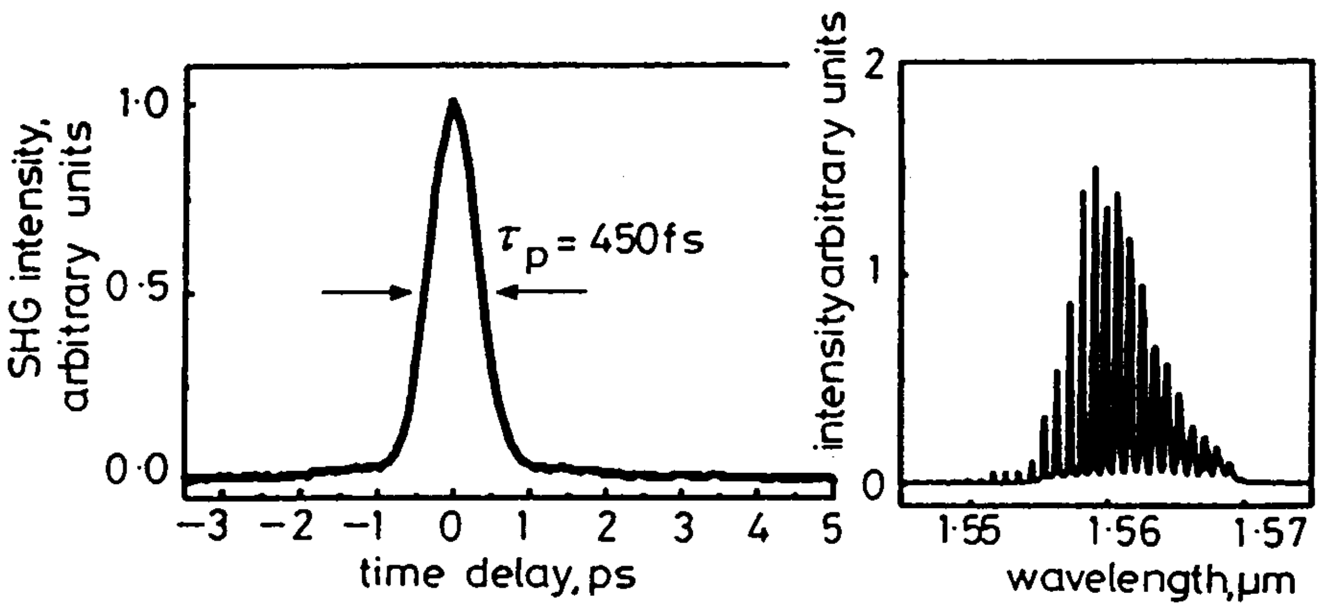


Compensated



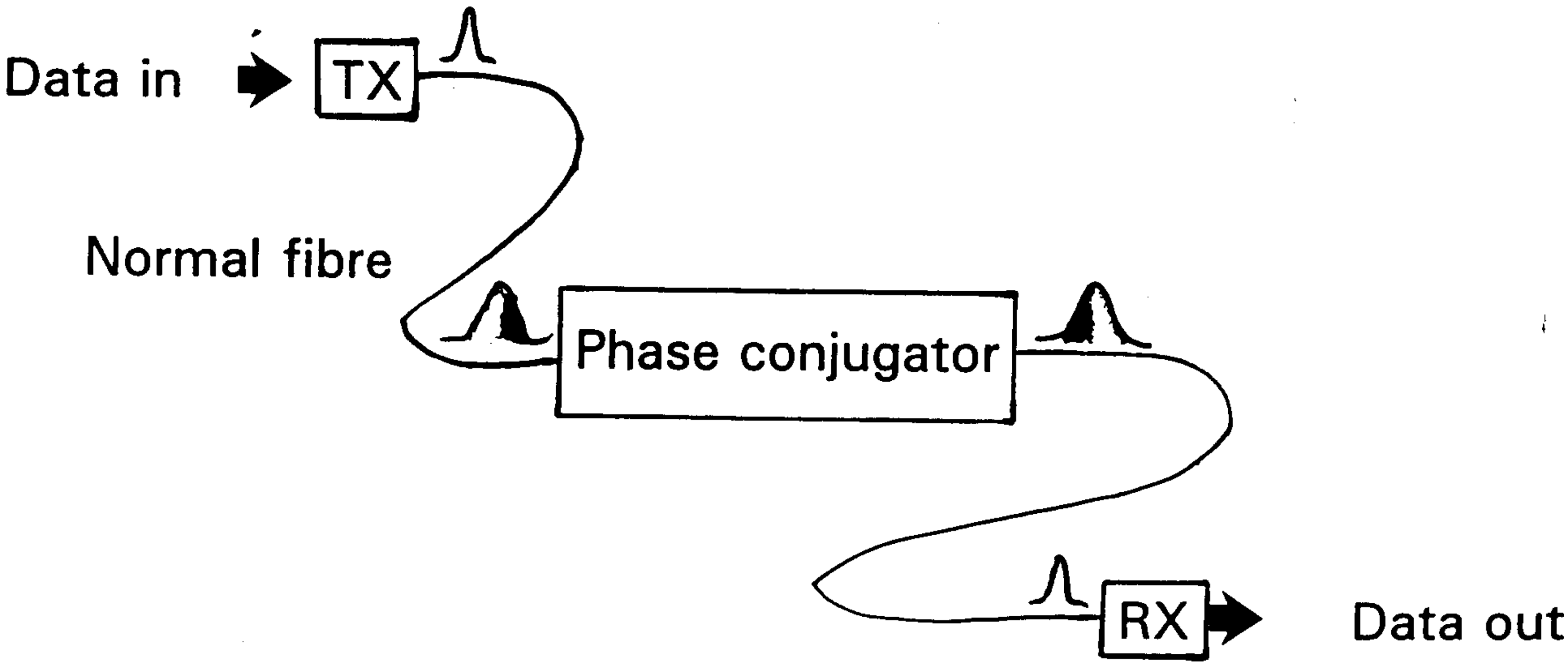
CHROMATIC DISPERSION COMPENSATION OF 400 fs PULSES





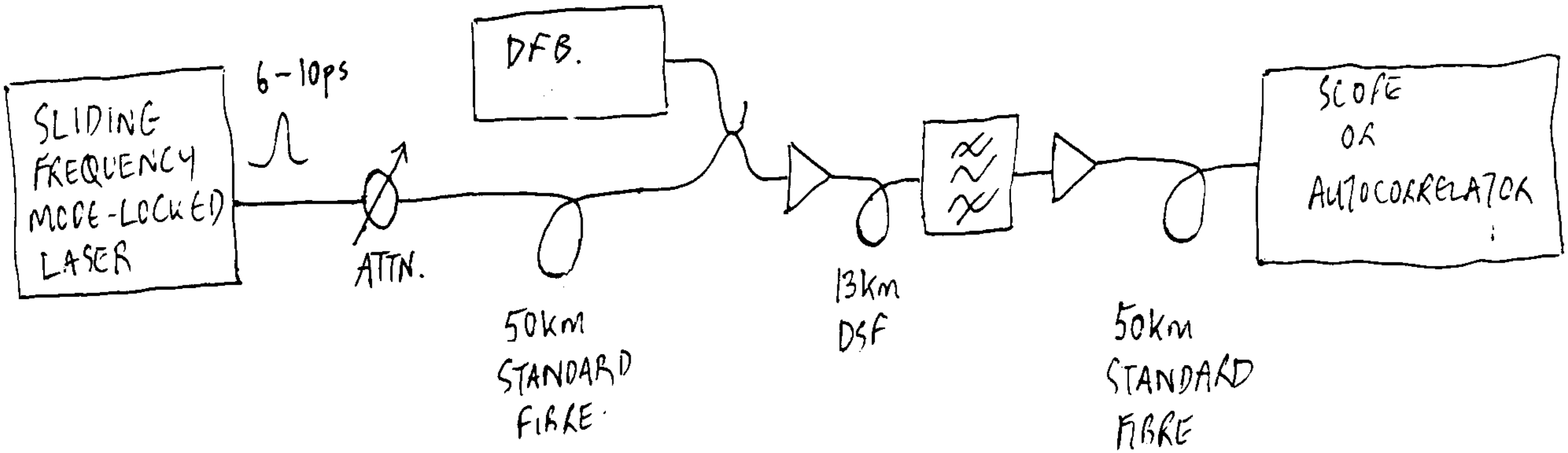
R. Kashyap et al, Electr. Lett., '94

DISPERSION COMPENSATION BY PHASE CONJUGATION



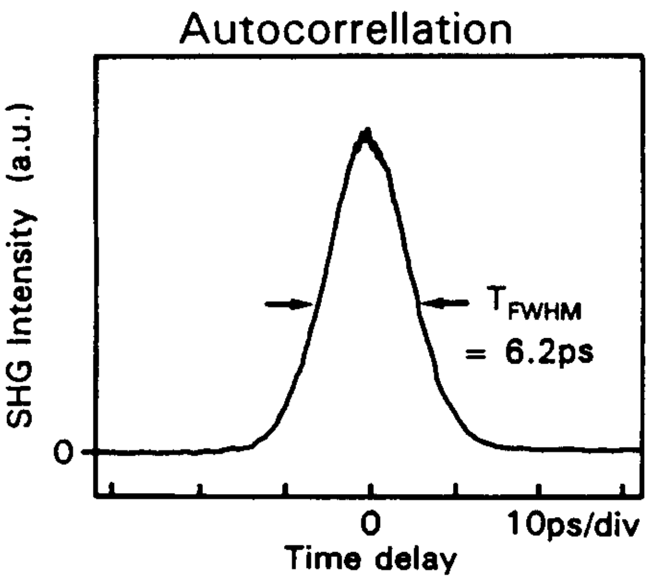
A. Yariv, Opt. Lett., 1979

MPSI EXPERIMENTS

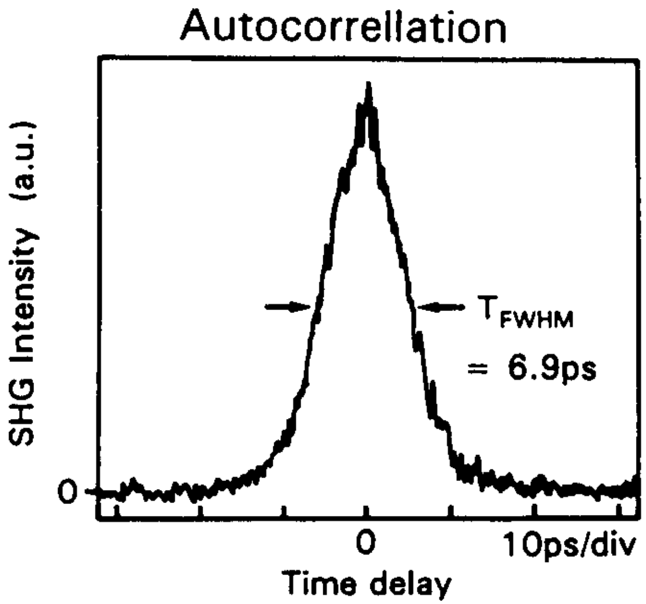


TRANSMISSION OVER 50km OF STANDARD FIBRE

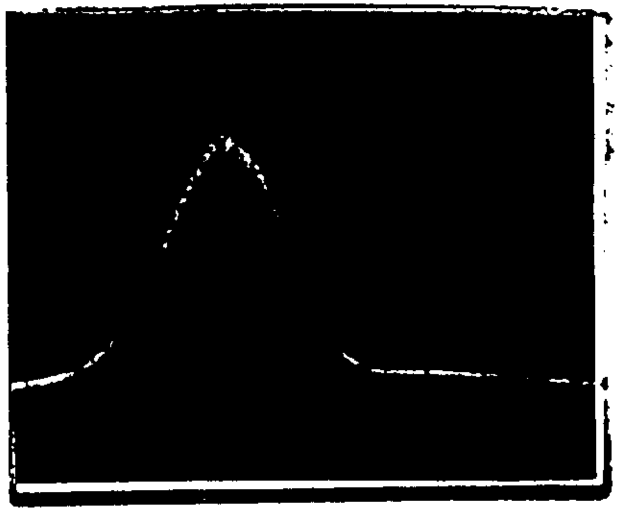
Input pulse



Output pulse
with compensation



Output pulse
without compensation



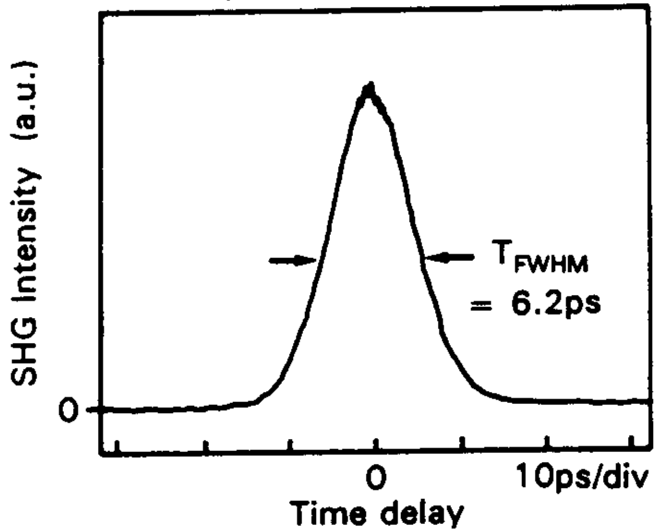
200ps/div

detector/scope response 320ps

TRANSMISSION OVER 50km OF STANDARD FIBRE

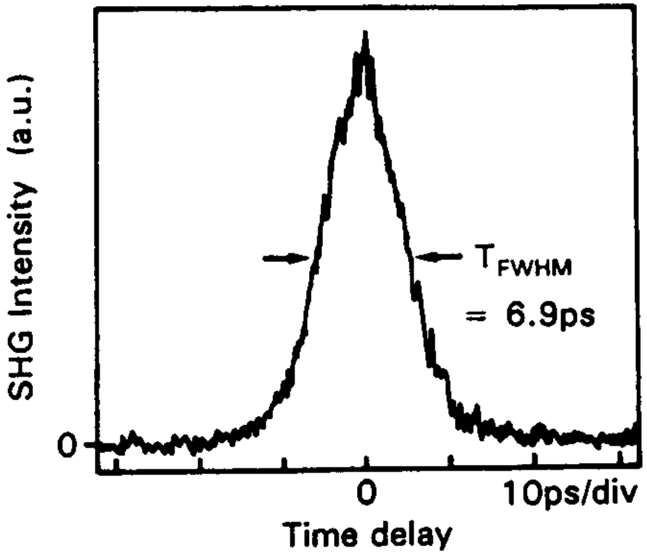
Input pulse

Autocorrellation

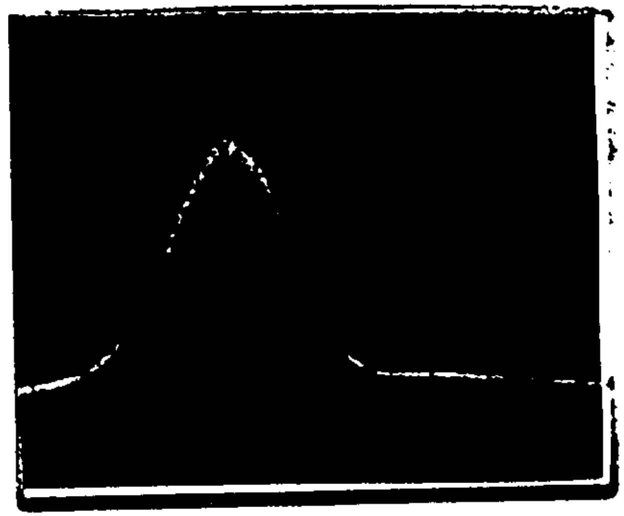


Output pulse with compensation

Autocorrellation



Output pulse without compensation

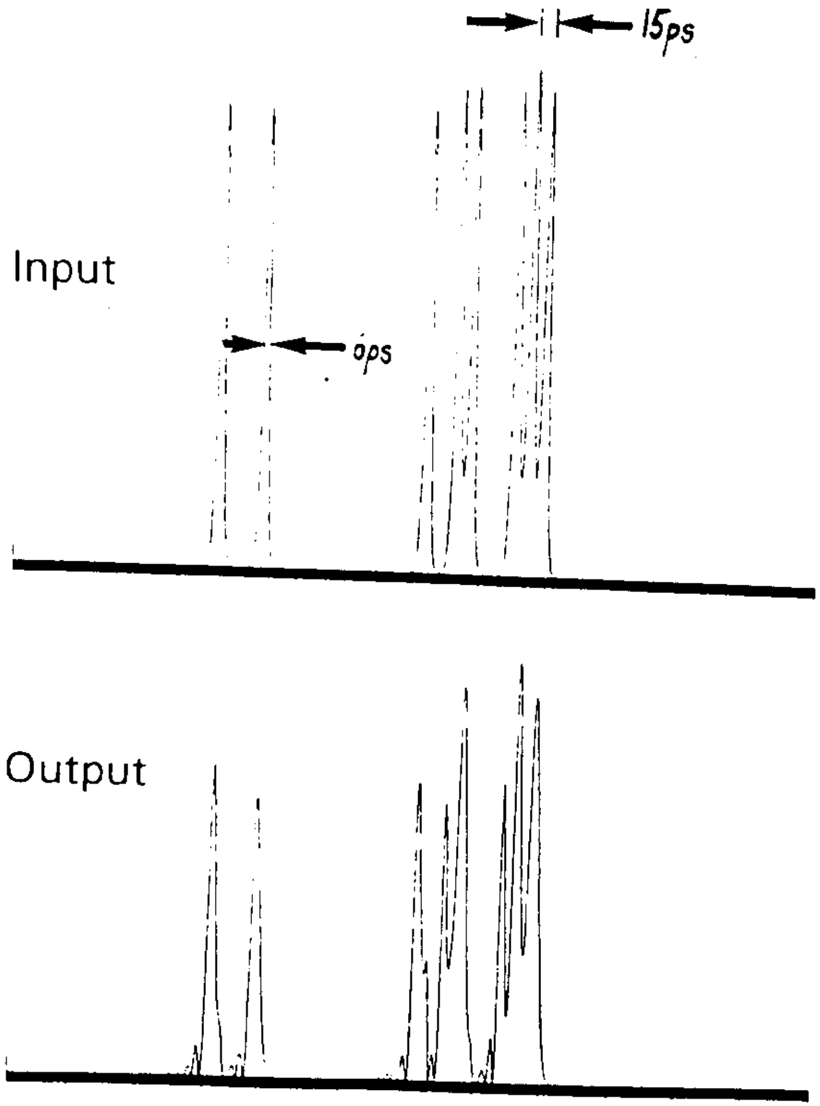


200ps/div

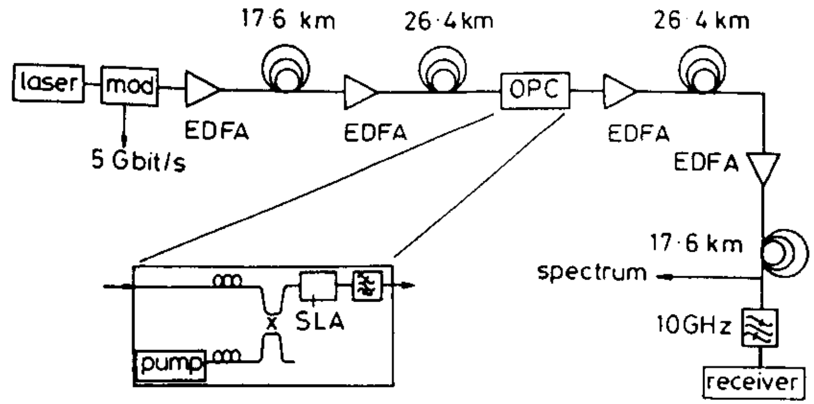
detector/scope response 320ps

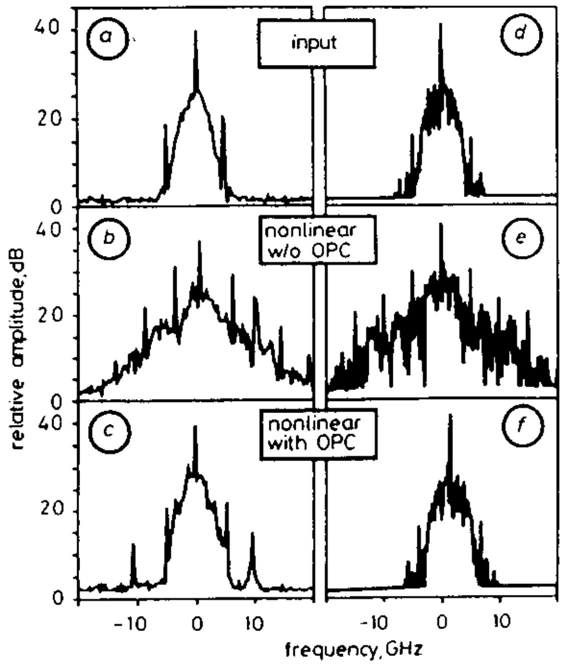
66 Gbit/s, 6ps PULSES OVER 2000km

Domino Taverner



COMPENSATION OF FIBRE NONLINEARITY WITH MPSI





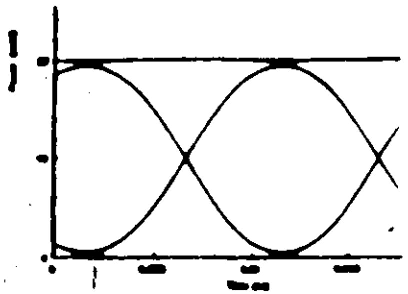
Kikuchi et al, OAA '93

Pieper et al, Electr. Lett., '94

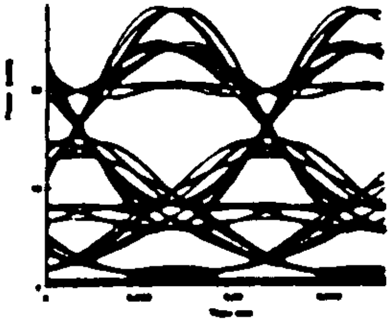
LONG-HAUL NRZ TRANSMISSION

C. Kurtzke and A. Gnauck

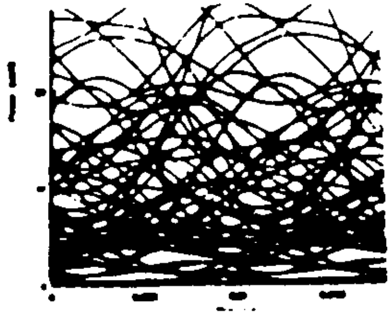
100Gbit/s



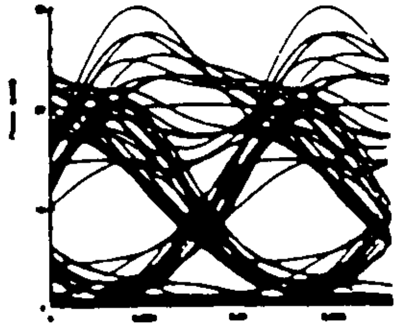
0km



10km

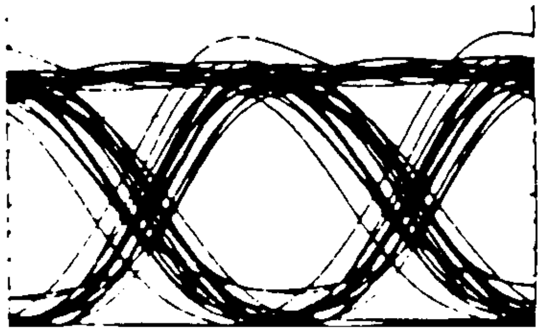


25km

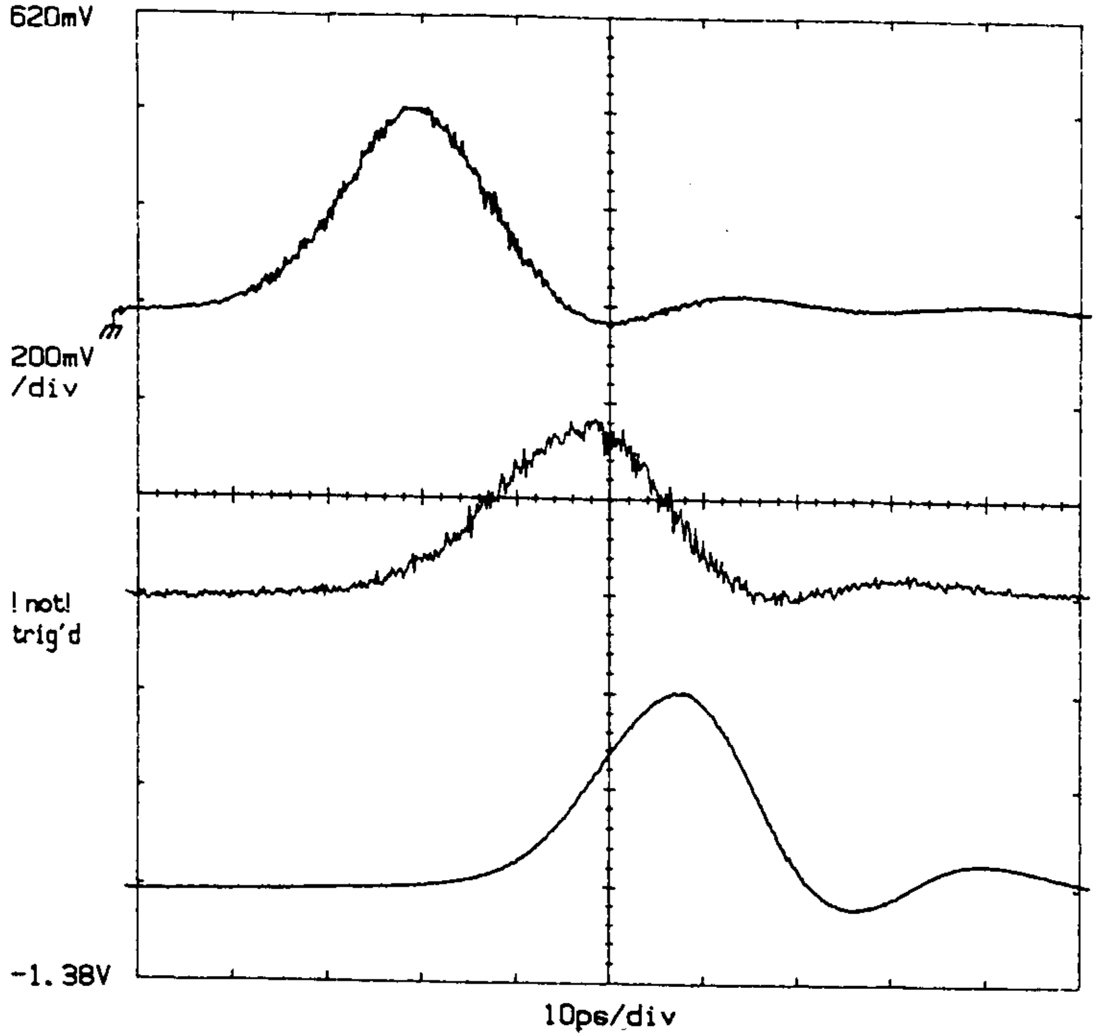


1000km
with compensation

20Gbit/s over 10,000km with compensation
Including noise and dispersion fluctuations



MPSI PULSE TRANSMISSION EXPERIMENTS

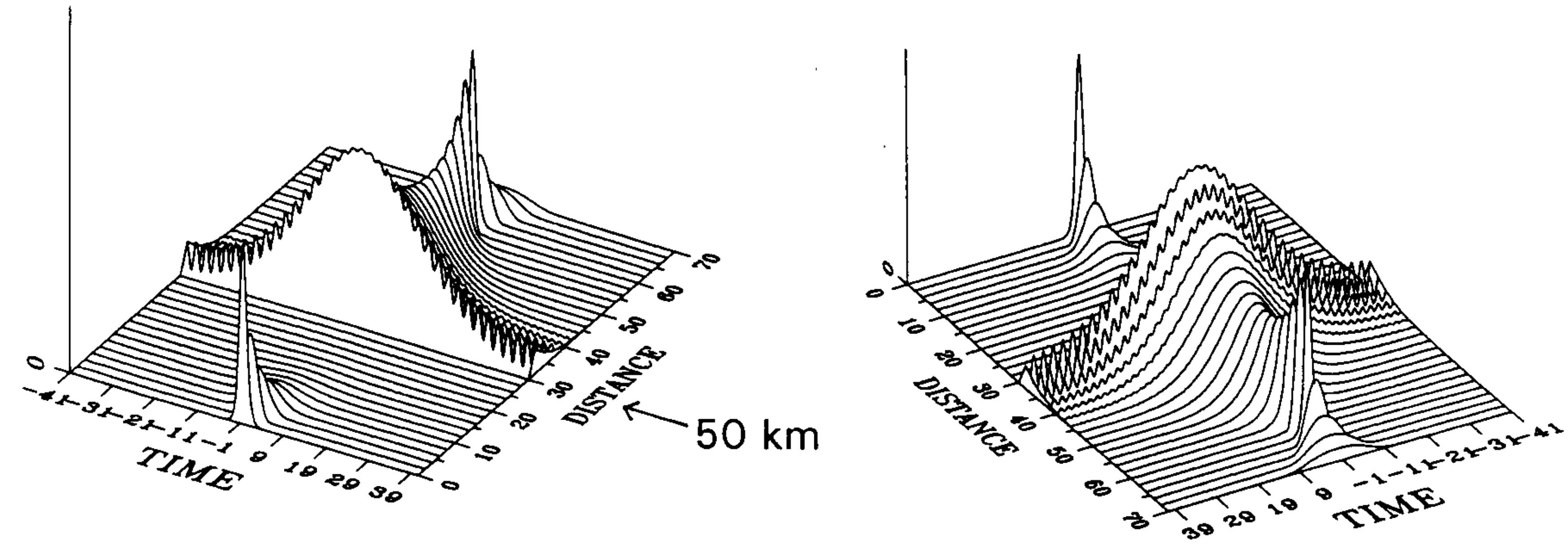


source pulse

transmitted data
50km + MPSI + 50km

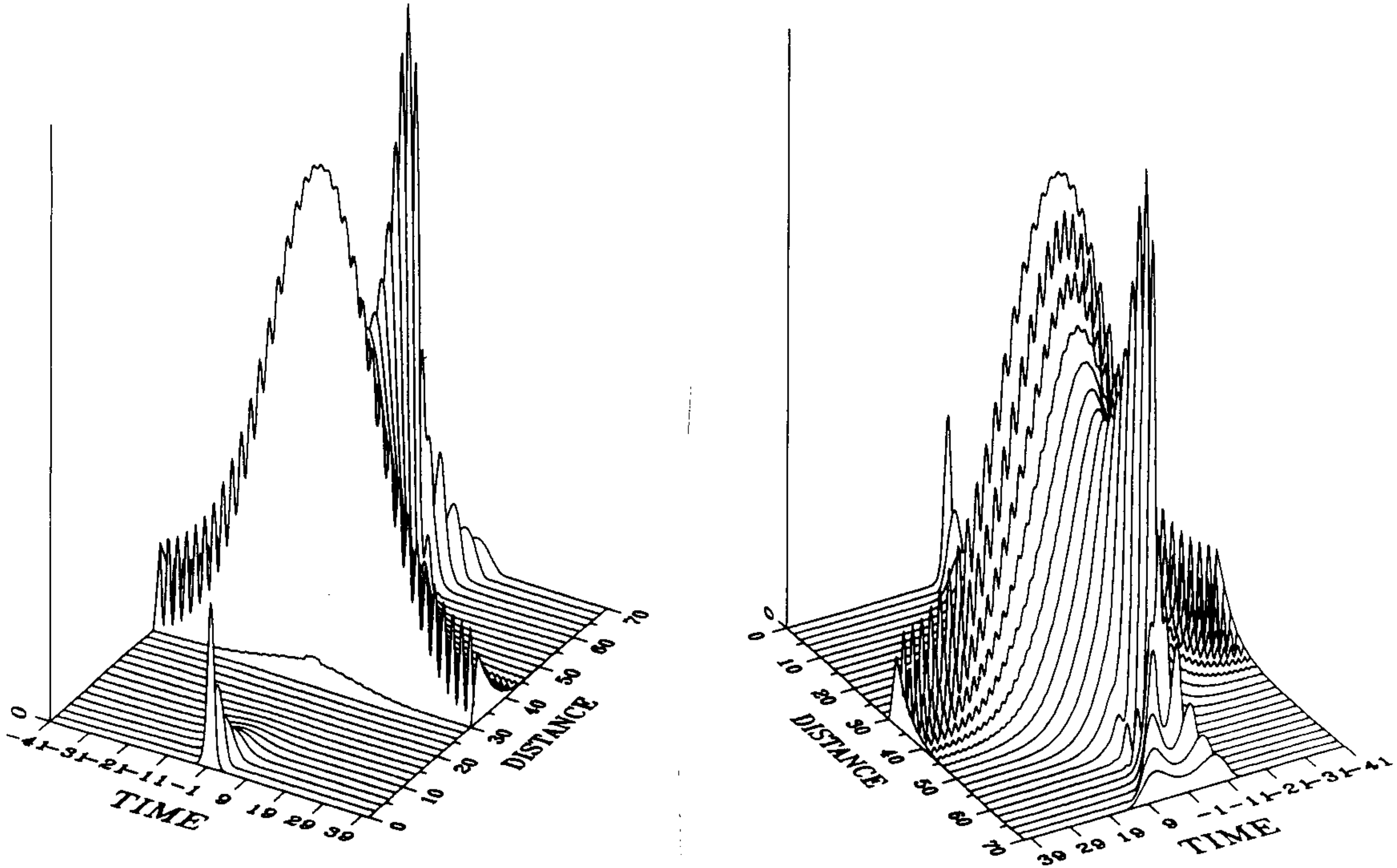
transmitted data
50km + MPSI + 51.5km

SIMULATION OF PULSE TRANSMISSION WITH MPSI;
pulse powers in the linear regime

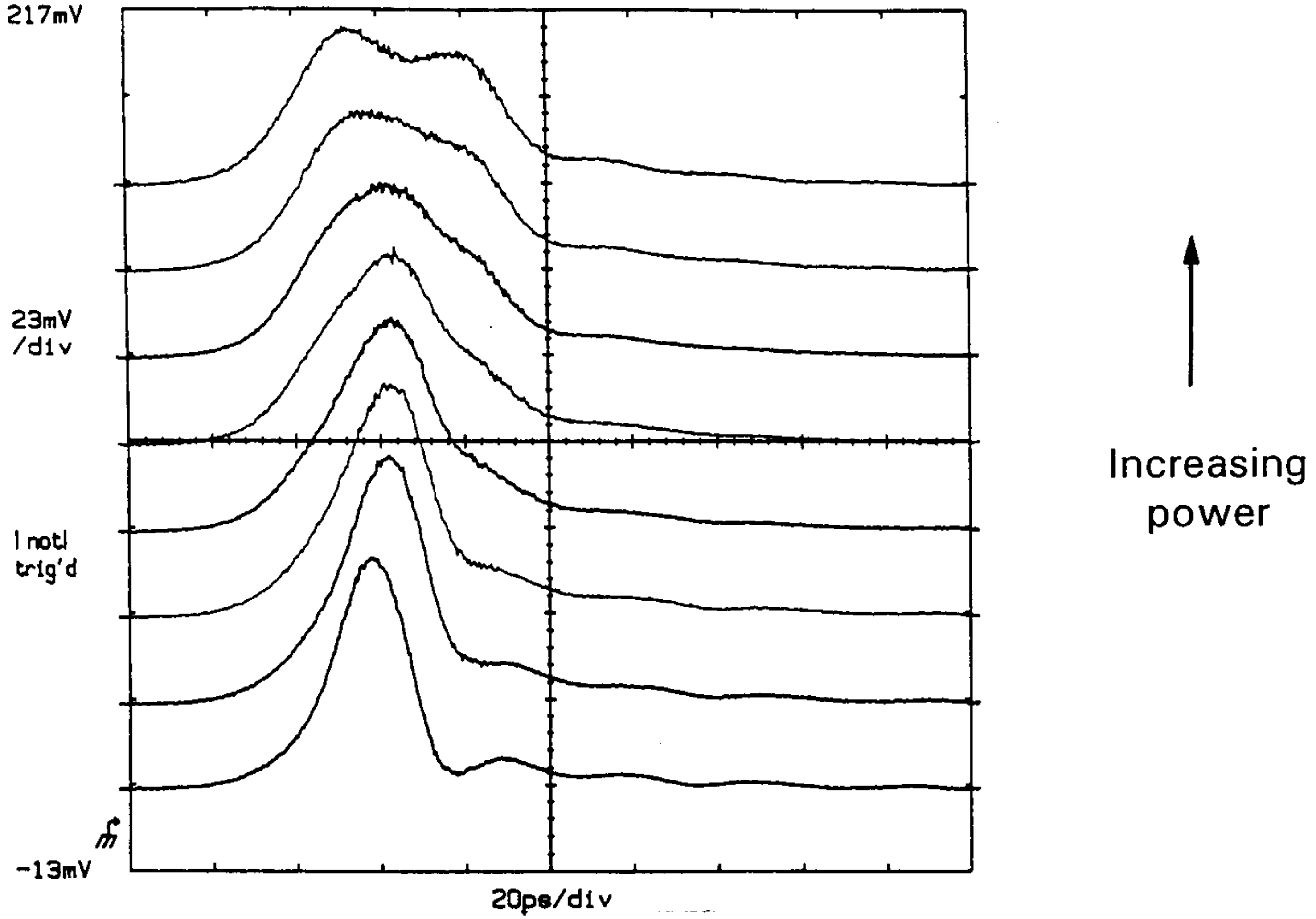


Source 10 ps FWHM @ 1535nm
Dispersion 16 ps/nm.km

SIMULATION OF PULSE TRANSMISSION WITH MPSI;
pulse powers in the second span in the nonlinear regime



TRANSMITTED PULSES AFTER 101.5km WITH INCREASING POWER IN SECOND SPAN



DISPERSION-COMPENSATION USING MPSI

CONCLUSIONS :

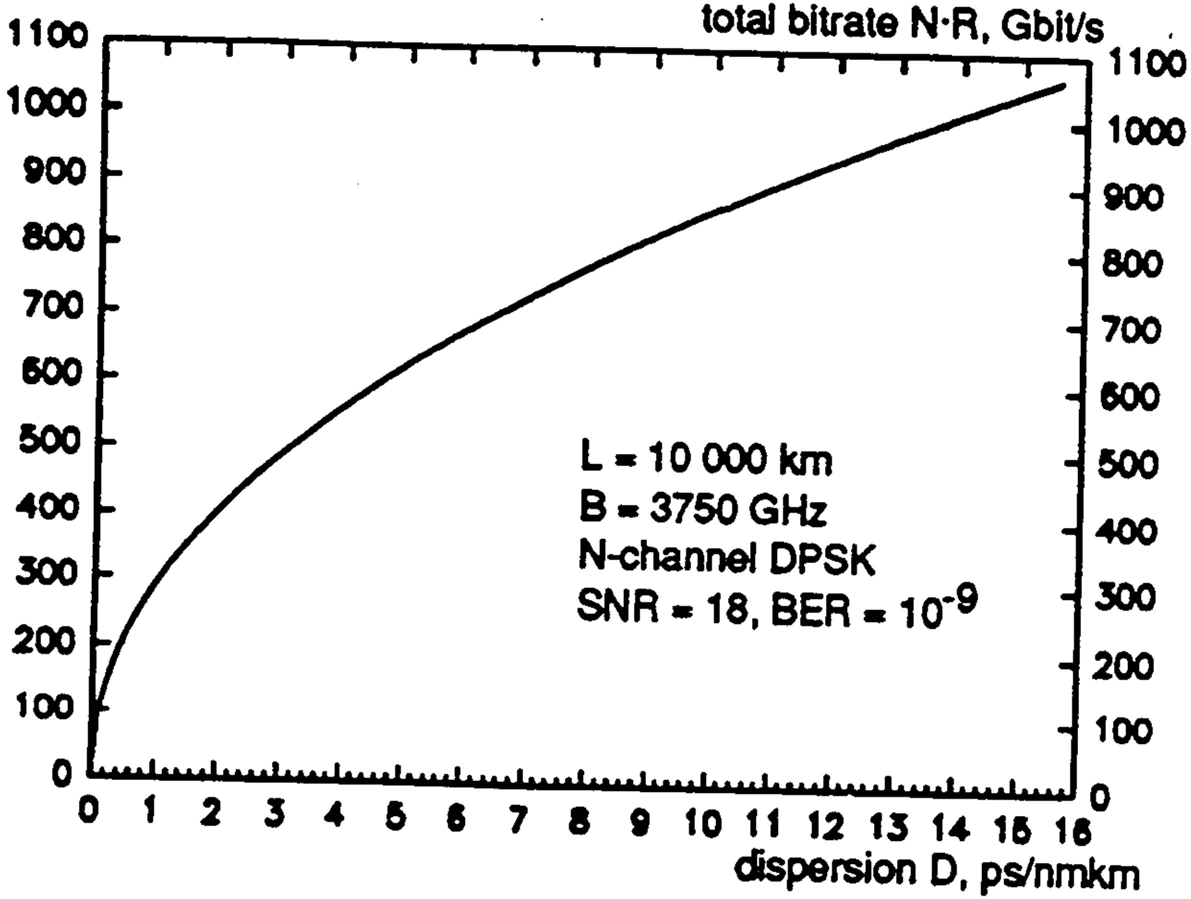
- Only one compensator required at link mid-point
- Compensates TX chirp <u>and</u> (first-order) fibre dispersion
- Tolerates some link non-linearity
- Very powerful technique (to 100 Tbit/s.km?)

ADVANTAGES

- Standard fibre ➡ *cheaper*
- Lower loss ➡ *longer repeater spacings*
- High dispersion ➡ *increased non-linear threshold*
- Phase conjugation ➡ *minimises dispersion at all λ's*
- Phase conjugation ➡ *compensates fibre nonlinearity (Kikuchi & Lorattanasane, OAA)*

Do we need solitons?

ULTIMATE TRANSMISSION CAPACITY OF OPTICALLY AMPLIFIED FIBRE SYSTEMS



A. Splett et al, ECOC '93

STANDARD FIBRE NETWORK UPGRADE; SUMMARY

- 1.3μm
  - *Semiconductor amplifiers* - *crosstalk?*
  - *Fibre amplifiers* - *inefficient at present*
  - *Solitons*

- 1.5μm
  - *Solitons* - *possible, but not easy*
  - *Dispersion compensation* - *fibre, gratings, MPSI*
    - *allows maximum fibre bandwidth*

Do we need solitons?