Optical networks and equipment

www.ces.net

czechlight.cesnet.cz

Jan Radil

CESNET z.s.p.o.

- CESNET (Czech Educational and Scientific NETwork) - NREN in the Czech Republic
- Established as a legal entity – not for profit
- Association of Legal Entities (z.s.p.o.) in 1996
    - 27 Universities
    - Czech Academy of Sciences
- 52 staff members in Praha
- More than 150 part-time universities and Academy of Sciences staff working on projects

Participation on International Projects

- (GÉANT), GN2
- 6NET
- EGEE
- (SCAMPI), LOBSTER
- SEEFIRE
- PORTA OPTICA
- LUCIFER

CESNET z.s.p.o. - Funding

- Research plan: „Optical High Speed National Research Network and its New Applications“
- 2004 – 2010
- Funded by Ministry of Education, Youth and Sports of the Czech republic and Association Members - budged approx. 12 MEuro/year
- Research activity annual report is available www.ces.net/doc/2005/

CzechLight

- An experimental and breakable optical network
- For disruptive tests, not 24/7 NOC (Network Operation Centre)
- CzechLight optical equipment
- Parallel infrastructure together with a production network CESNET2

Motivations

- Utilization of dark fibres – Customer Empowered Fibre networks (the first DF line lighted in 1999, 2.5 Gb/s PoS, 327 km with 3 OEO regenerators)
- Now CESNET has 4200 km of leased dark fibres
- Cost effective deployment of multigigabit DF lines (N x 1 GE, N x 10 GE) with pluggable DWDM transceivers – GBIC, SFP, XENPAK, XFP
- Lack of optical equipment suitable for NRENs
- Development of our own optical amplifiers (and other equipment)
- Repeaterless or Nothing-in-line (NIL) approach, where possible and practicable

A little bit of History (1)

- Back to Antiquity (mirrors, fire beacons, smoke signals) [Agr]
- The end 18th century with lamps, flags
- 1792, Claude Chappe with mechanical „optical“ telegraph
- 1830 – the advent of telegraphy
- 1866 – the first transatlantic cable went into operation
- 1876 – the invention of telephone (A.G.Bell, U.S. Patent No. 174 465)
- 1940 – 3 MHz coax-cable system (repeater spacing 1 km)
- 1948 – 4 GHz microwave system
- 1960 – the invention of laser (suitable transmission medium?)
- 1960s – optical fibre (1000 dB/km)

A little bit of History (2)

- 1970 – fibres with losses 20 dB/km
- Evolution of optical communication systems
- 850 nm, 1310 nm, 1550 nm, TDM, WDM, CWDM, DWDM
- 1980 – 45 Mb/s (1st generation)
- 1980s – 1310 nm, 1 dB/km, 100 Mb/s, multi-mode fibres
- Late 1980s – 2 Gb/s, single mode fibres, repeater spacing 50 km (2nd generation)
- 1990s – 1550 nm (problem with lasers, dispersion of fibres), 2.5 Gb/s or 10 Gb/s (3rd generation)
- 1990s - DWDM, optical amplification (4th generation)
- Today – 10 and 40 G waves, 160 channels ie x Tb/s, thousands of kilometers

A little bit of Theory (1)

- All electromagnetic phenomena are described by Maxwell‘s equations
- An optical fibre (silica or non-silica) is a nonconducting medium without free charges

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{D} = 0$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \qquad \nabla \cdot \mathbf{B} = 0$$

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$

$$\mathbf{B} = \mu_0 \mathbf{H}$$

- E, H: electric/magnetic fields vectors
- D, B: electric/magnetic flux densities
- P: induced electric polarization
- M: induced magnetic polarization = 0
- ε_0: the vacuum permittivity
- μ_0: the vacuum permeability

A little bit of Theory (2)

- Div, grad, rot, Nabla, Laplace

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \quad \nabla \cdot \nabla = \Delta \quad \Delta = \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

$$\nabla \cdot f = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) = \mathrm{grad}\ f$$

$$\nabla \cdot \mathbf{F} = \left(\frac{\partial f_1}{\partial x}, \frac{\partial f_2}{\partial y}, \frac{\partial f_3}{\partial z}\right) = \mathrm{div}\ \mathbf{F}$$

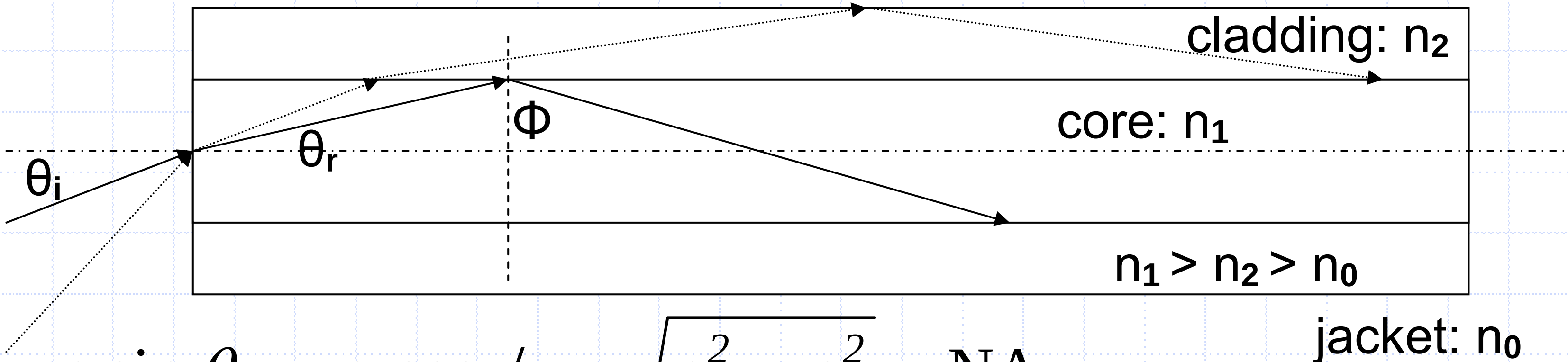
$$\nabla \times \mathbf{F} = \mathrm{rot}\ \mathbf{F}$$

Optical fibres

- Total internal reflection (discovered 1854)
- 1970: 20 dB/km (Kapron, Keck, Maurer), silica fibres
- Multimode (MM) and singlemode (SM) fibres
- Multimode: step-index (SI) or graded index (GI)
- MM SI: modal dispersion: different rays disperse in time because of the shortest (L) and longest ($L/\sin\Phi_c$) paths
- MM SI: 10 Mb/s, up to 10 km
- MM GI: parabolic index, lower modal dispersion, higher bit rates
- MM GI: 100 Mb/s, up to 100 km
- Plastic MM GI, for 1 GE (or even 10 Gb/s)
- Attenuation: 1 – 4 dB/km, <10 dB/km for plastic

Optical fibres

$$\sin \phi_c = \frac{n_2}{n_1}$$



$$n_0 \sin \theta_i = n_1 \cos \phi_c = \sqrt{n_1^2 - n_2^2} = \mathrm{NA}$$

- Numerical aperture NA, the maximum angle of the incident ray to remain inside the core
- Core: MM: 50 μm/62,5 μm, SM: 8,6 μm – 9,5 μm
- Cladding: 125 μm

Optical fibres

- Single mode (SM, Standard SMF, G.652) fibres
- Supports only one so called „the fundamental mode of the fibre" HE_{11} (TE_{11}), all higher modes are cut off @ the operating wavelength
- An optical mode refers to a specific solution of the wave equation (satisfies boundary conditions, spatial distribution is constant as light travels along a fibre)
- TE_{MN} or TM_{MN} , magnitude of the transverse electric field or the transverse magnetic field at the surface of the fibre core
- The cutoff wavelength is specified in ITU G.650, the V parameter (or normalized frequency), $V < 2{,}405$
- SM@1310 nm and 1550 nm, cutoff approx. 1200 nm
- 0,2 dB/km@1550 nm, 0,4 dB/km@1310 nm

Optical fibres – Dispersion (1)

- MM: Intermodal dispersion (pulse broadening, the most important limiting factor)
- SM: Intermodal dispersion is absent, pulse broadening is present still because of Intramodal dispersion (or Group-velocity dispersion GVD), even laser pulses have *finite* spectral width and pulses are *modulated*
- GVD: different spectral components of the pulse travel at different speeds
- Increases as the square of the bit rate
- $v_g = (d\beta(\omega)/d\omega)^{-1}$, β – the propagation constant
- Intramodal dispersion has two components:
  - Material dispersion
  - Waveguide (or wavelength) dispersion

Optical fibres – Dispersion (2)

- D – the dispersion parameter [ps/(nm*km)]

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2$$

- β_2 - the GVD parameter

$$\beta_2 = \frac{d^2\beta}{d\omega^2}$$

- $D = D_M + D_W$
- Material dispersion: dependence of the refractive index *n* on frequency ω, positive D
- Waveguide dispersion: nonlinear dependence of the propagation constant β on frequency ω, negative D

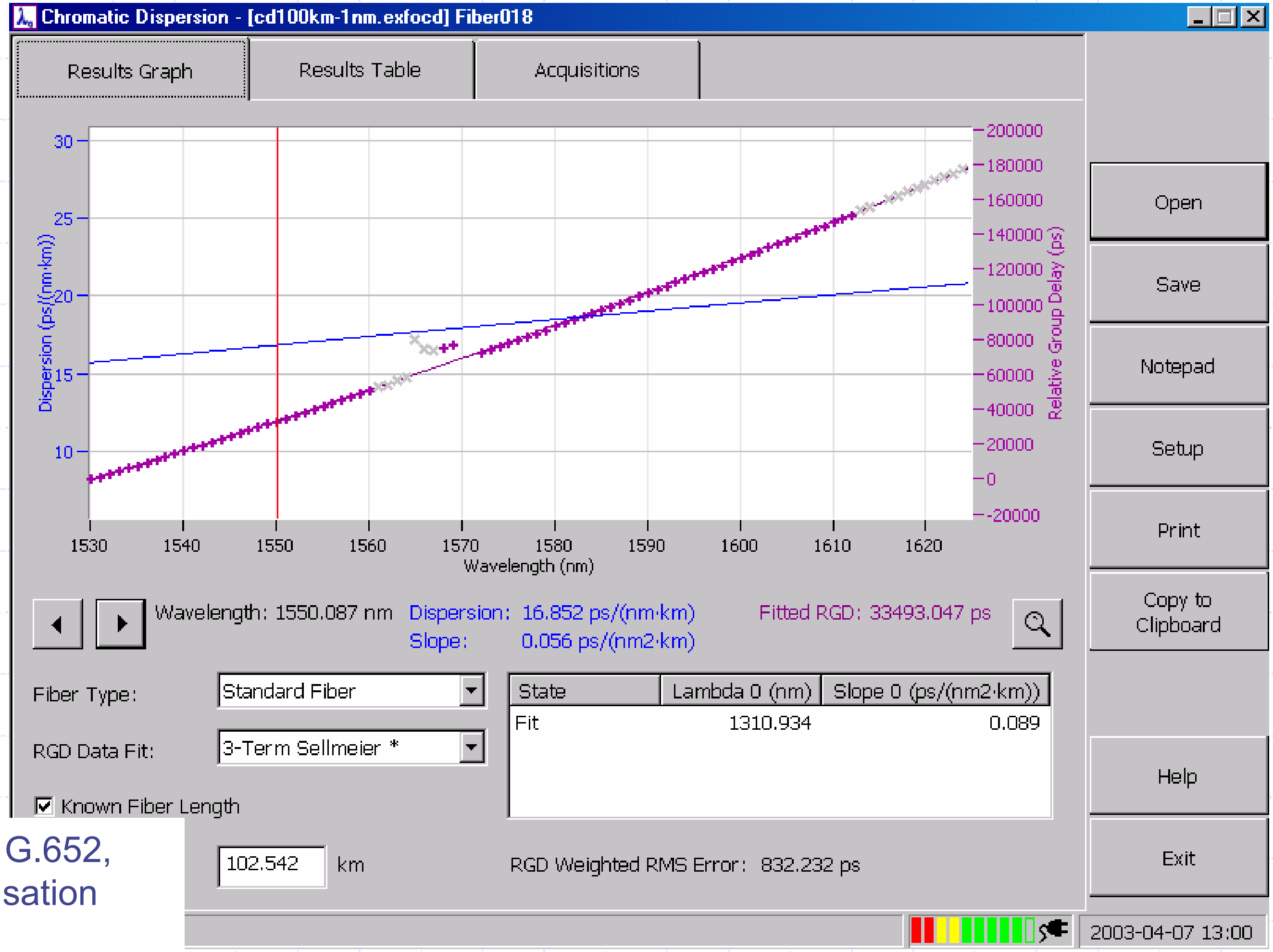
Optical fibres – Dispersion (3)

- ITU – Limits of Chromatic dispersion
- Maximum CDC and D(λ), specified in G.652, G.653, G.655
- G.652 (SSMF): Zero dispersion at 1310 nm
- G.653 (DSF): Zero dispersion at 1550 nm
- G.655 (NZDSF): Small dispersion at 1550 nm, positive/negative
- Dispersion-flattened fibre (DFF), positive/negative
- Dispersion Compensating fibres (DCF)

Optical fibres – Dispersion (4)

- Higher-Order Dispersion(s)
- Governed by the dispersion slope $S = dD/d\lambda$
- β_3 - the third order dispersion parameter

Optical fibres – Cromatic Dispersion (1)



Chromatic Dispersion - [cd100km-1nm.exfocd] Fiber018

Wavelength: 1550.087 nm Dispersion: 16.852 ps/(nm·km) Fitted RGD: 33493.047 ps
Slope: 0.056 ps/(nm2·km)

Fiber Type: Standard Fiber

RGD Data Fit: 3-Term Sellmeier *

☑ Known Fiber Length

102.542 km

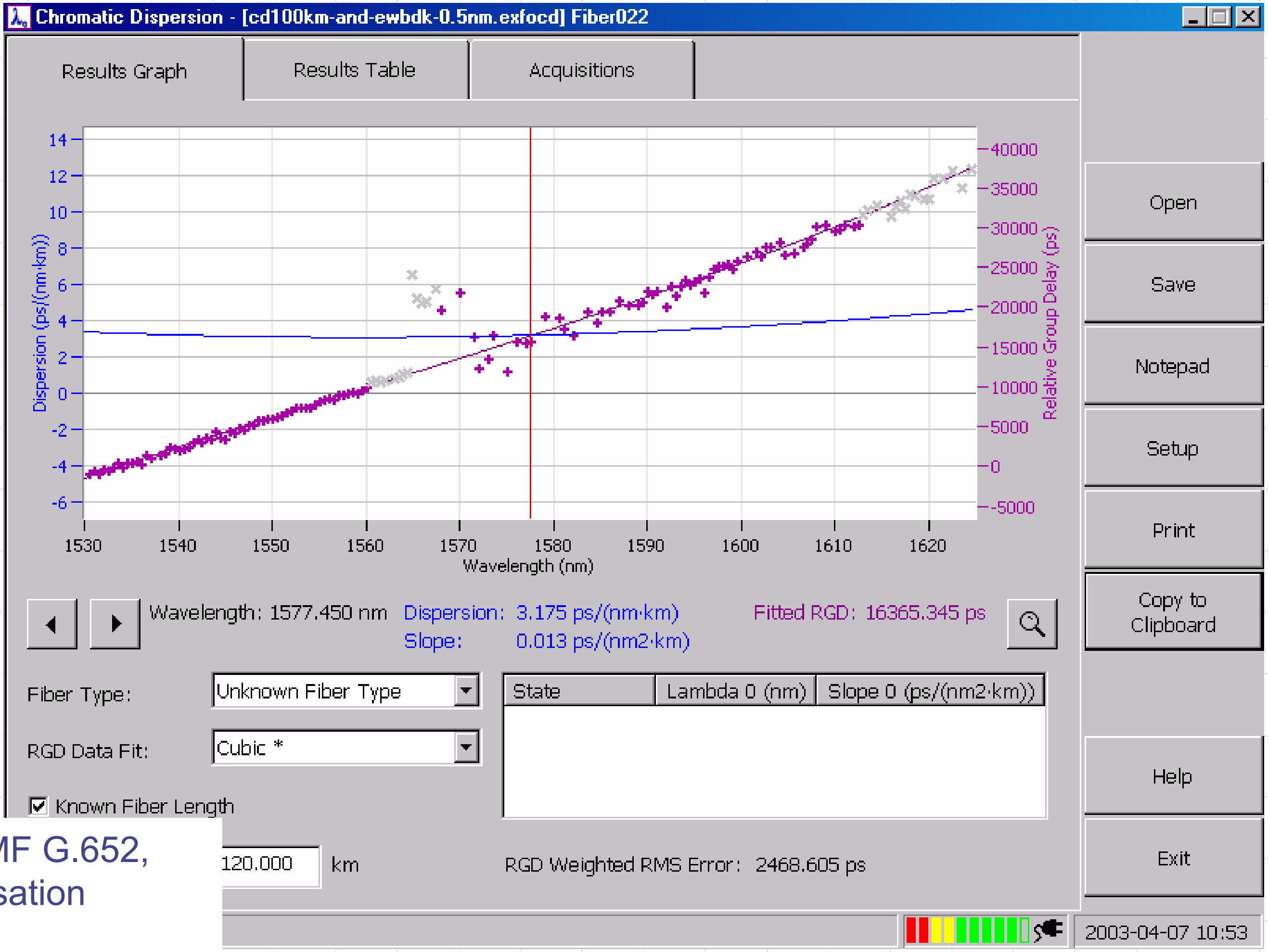
State	Lambda 0 (nm)	Slope 0 (ps/(nm2·km))
Fit	1310.934	0.089

RGD Weighted RMS Error: 832.232 ps

2003-04-07 13:00

100 km of SMF G.652,
without compensation

Optical fibres – Cromatic Dispersion (2)



Chromatic Dispersion - [cd100km-and-ewbdk-0.5nm.exfocd] Fiber022

Wavelength: 1577.450 nm
Dispersion: 3.175 ps/(nm·km)
Slope: 0.013 ps/(nm2·km)
Fitted RGD: 16365.345 ps

Fiber Type: Unknown Fiber Type

RGD Data Fit: Cubic *

☑ Known Fiber Length

120.000 km

State	Lambda 0 (nm)	Slope 0 (ps/(nm2·km))

RGD Weighted RMS Error: 2468.605 ps

2003-04-07 10:53

100 km of SMF G.652,
with compensation

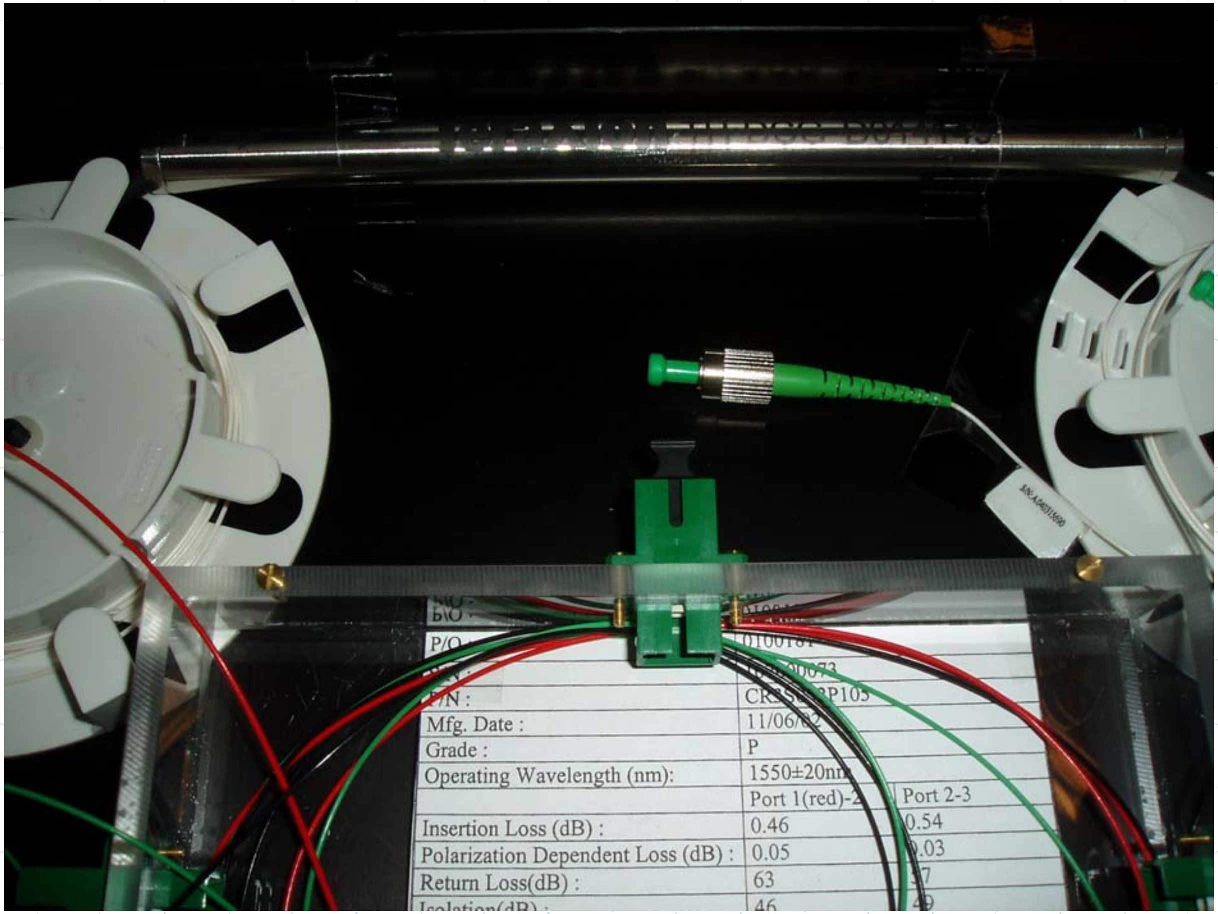
Cromatic Dispersion Compensation

- Dispersion compensating fibres (DCF)
  - A special kind of fibre, compensates all wavelengths (the only solution for „grey‟ transmitters)
  - Adds link loss (and money), especially for long-haul applications
  - Stronger non-linear effects (due to a smaller core diameter)
- Fibre Bragg gratings (FBG)
  - Narrow-band elements – a stabilized DWDM laser is a must
  - „Wide-band‟ FBGs available today (for 50 ITU DWDM channels)
  - Signal filtering, spectrum shaping, tuneable compensators
  - Cost effective solution

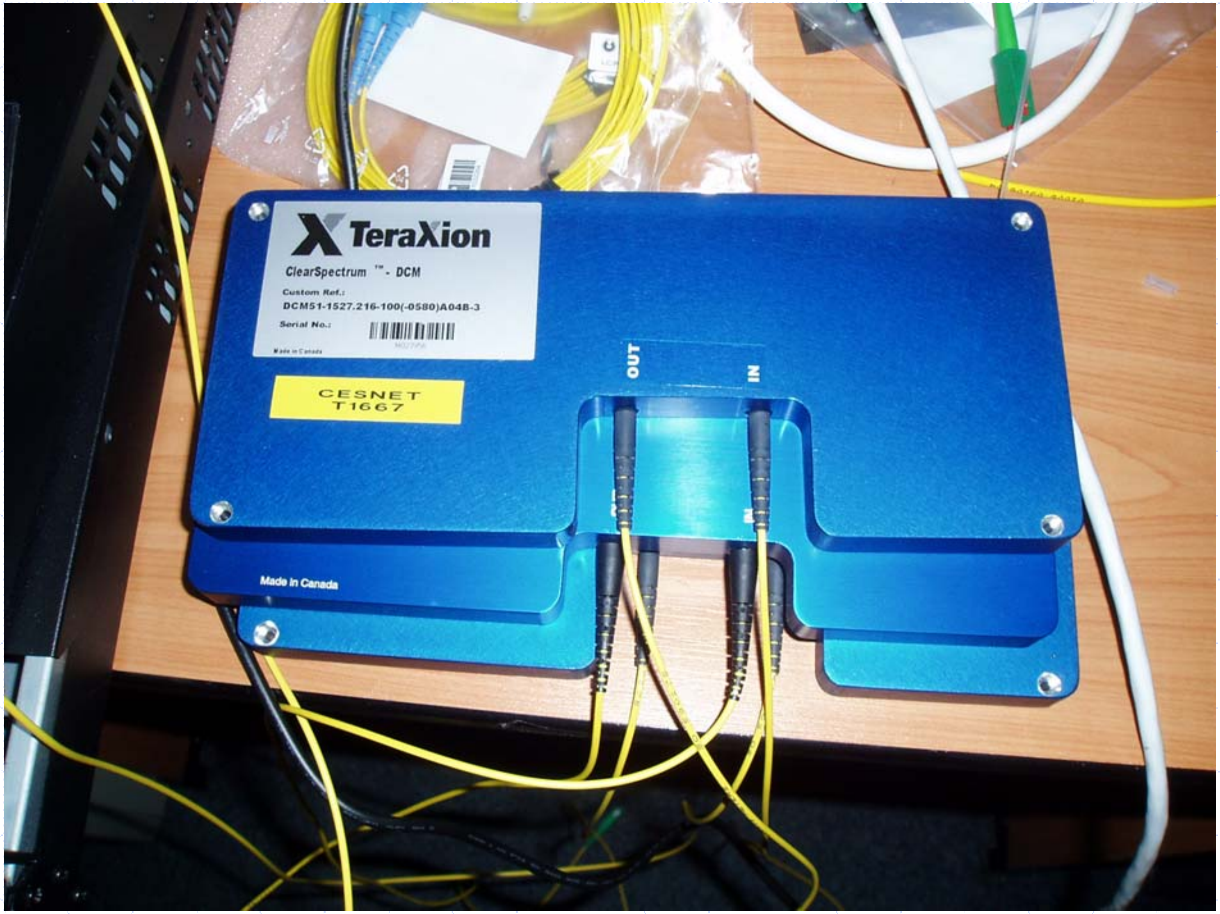
Cromatic Dispersion Compensation

- Optical Phase Conjugation (OPC)
  - A nonlinear optical technique (midspan spectral inversion)
  - The complex conjugate of a pulse-propagation equation
  - Four-wave mixing in a nonlinear medium (phase conjugators)
- Electronic pre-compensation
  - A relatively new technique
  - An electrical signal is pre-distorted before converting into an optical domain
  - Dispersion can be tuned for up to thousands kilometers of G.652 fibre

Cromatic Dispersion Compensation (FBG)



Cromatic Dispersion Compensation (FBG)



Cromatic Dispersion Compensation

- Typical values (receivers can have different tolerance to CD!)

Bit rate (Gbit/s)	Maximum length of G.652 link (km)
2,5	1000
10	80
40	4

Cromatic Dispersion Measurements

- Modulated Phase-Shift Method (FOTP 169)
- Differential Phase-Shift Method (FOTP 175)
  - Both phase-shift methods are accurate, measurement throught optical amplifiers, expensive
- Spectral Group Delay Measurement in the Time Domain (FOTP 168)
  - Still accurate enough, no measurement through optical amplifiers
  - Relative group delay is measured and the dispersion coefficient D is calculated
- TIA/EIA

Optical fibres – PMD (1)

- Polarization Mode Dispersion (PMD)
- Fibre birefringence (stress, temperature, imperfections)
- The stochastic phenomenon
- The fundamental mode HE_{11} (TE_{11}) has two orthogonally polarized modes
- The two components with different propagating speeds disperse along the fiber
- The difference between the two propagation times is known as the Differential Group Delay (DGD)
- PMD is a wavelength averaged value of DGD

Optical fibres – PMD (2)

- PMD is measured and quoted in ps for a particular span and discrete components but its coefficient is in ps/(km)$^{1/2}$
- PMD accumulates as the square root of distance of a link
- A single span with high PMD dominates the total PMD for the whole network
- A big issue for older fibres (late 1980s, 80 000 000 km) and higher bit rates (10 Gb/s)
- Moder fibres have PMD of less than 0,5 ps/(km)$^{1/2}$
- Difficult to compensate (electronic)

Optical fibres – PMD (3)

- Second-order PMD
- For long-haul links, together with CD and laser chirping

ITU proposed PMD values

Bit rate (Gb/s)	Maximum PMD (ps)	PMD coefficient for 400 km fibre (ps/(km)$^{1/2}$)
2,5	40	2,0
10	10	0,5
20	5	0,25
40	2,5	0,125

PMD Measurements

- The Fixed Analyzer Method (FOTP 113)
    - Well known, low price, problem with accuracy
- The Interferometric Method (FOTP 124)
    - Well known, average PMD
- The Jones Matrix Method (FOTP 122)
    - „Golden Standard"
    - Measures DGD per wavelength
- TIA/EIA

Nonlinear Optical Effects

- When an intesity of elektromagnetic fields becomes too high, the response of materials becomes nonlinear
- For optical systems, nonlinear effects can be both advantageous (Raman amplification) and degrading (Four Wave Mixing, Self Phase Modulation)

Nonlinear Optical Effects

- Stimulated Raman Scattering (SRS)
- A signal is scattered by molecular vibrations of fibre – optical phonons
- Can occur both in forward and backward directions
- Shifted to longer wavelengths (lower energy) by 10 to 15 THz in the 1550 nm window
- Wide bandwidth of about 7 THz (55 nm)
- Maybe used for amplification (Raman fibre lasers), so called counter directionally pumping schemes
- In DWDM systems: transfer of power from shorter wavelengths to longer ones

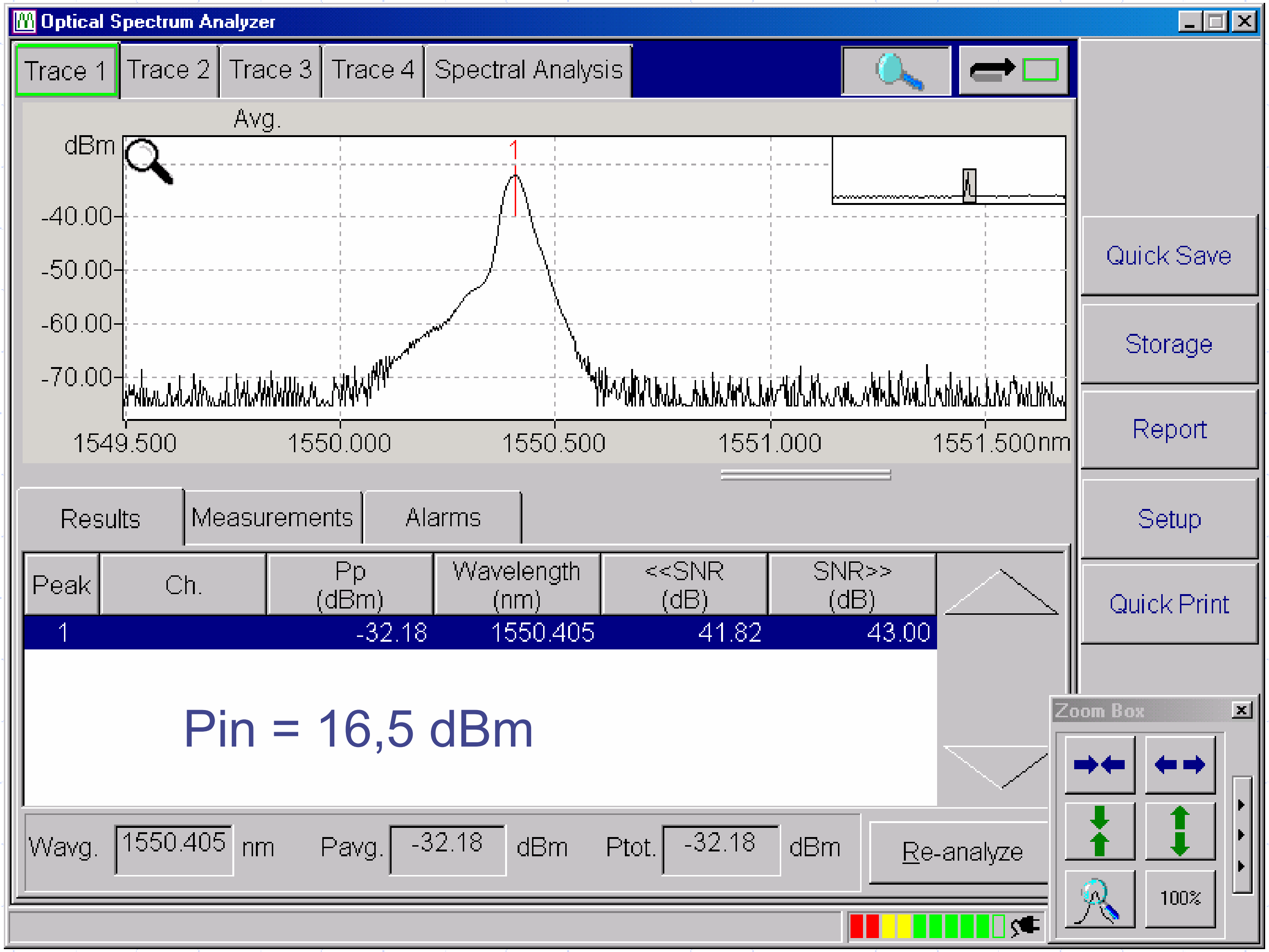
Nonlinear Optical Effects

- Stimulated Brillouin Scattering (SBS)
- A signal is scattered by sound waves – acoustic phonons
- Shifted to longer wavelengths (lower energy) by 11 GHz in the 1550 nm window
- Narrow bandwidth of about 30 MHz
- A problem for monochromatic unmodulated signals

Nonlinear Optical Effects

- Self-Phase Modulation (SPM)
- When the intensity of the signal becomes too high, the signal can modulate its own phase
- The refractive index is no longer a constant
- Spectral broadening (positive chromatic dispersion) or spectral compression (negative CD)
- Significant for fibres with small effective areas (G.655, DCF)
- Higher bit rates (10 Gb/s)

Nonlinear Optical Effects (SPM1)



Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-32.18	1550.405	41.82	43.00

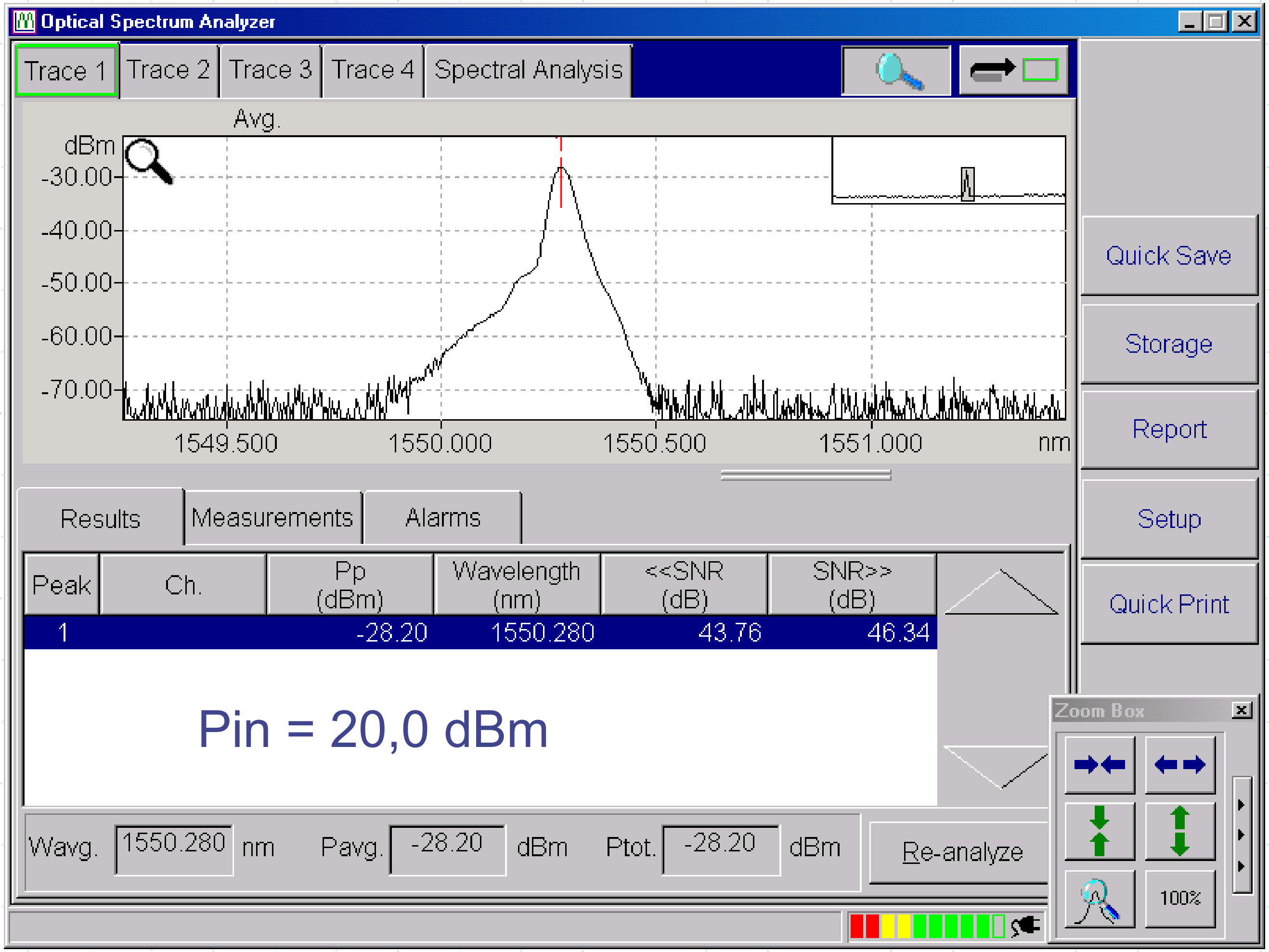
Pin = 16,5 dBm

Wavg. 1550.405 nm

Pavg. -32.18 dBm

Ptot. -32.18 dBm

Nonlinear Optical Effects (SPM2)

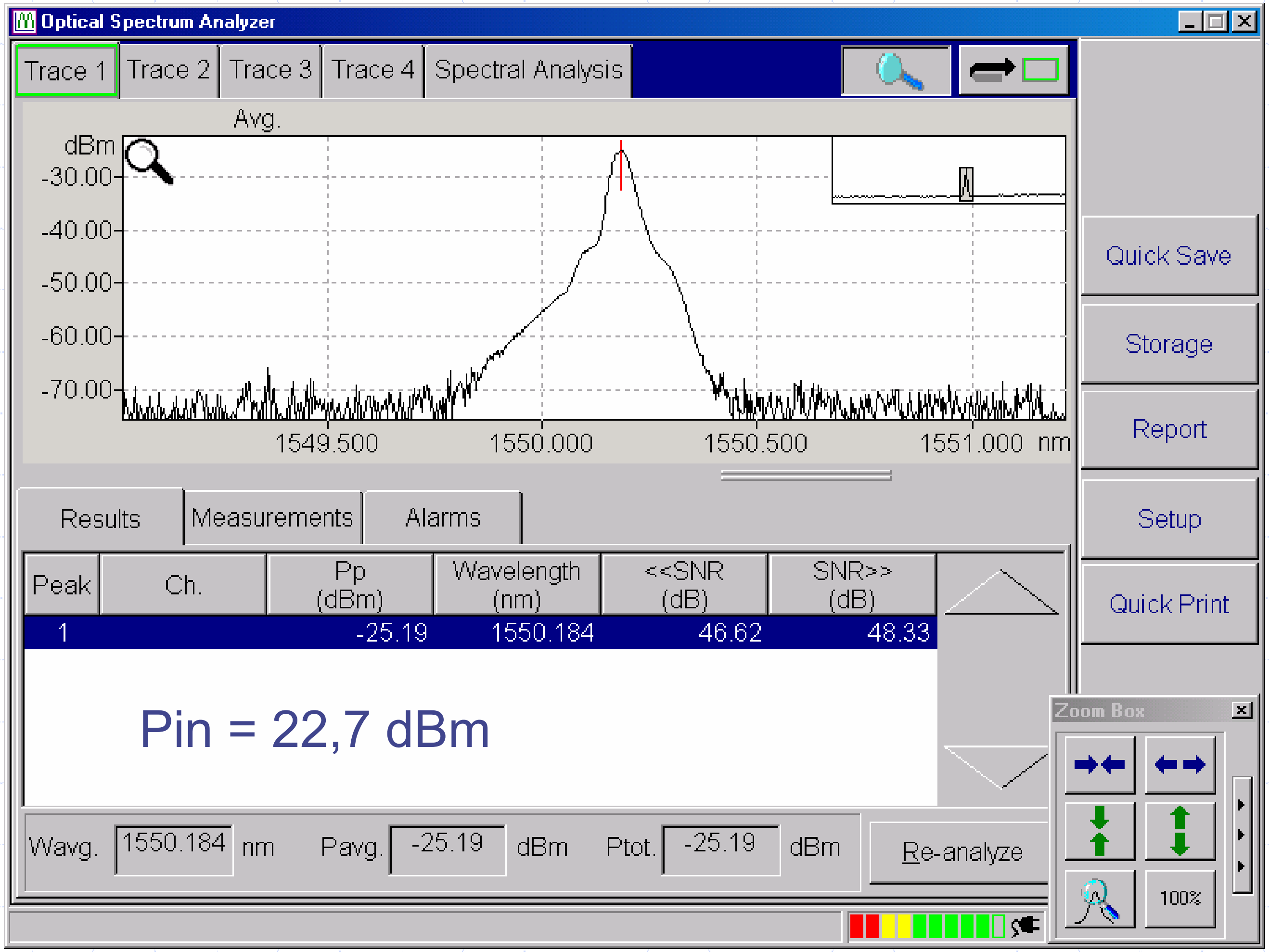


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-28.20	1550.280	43.76	46.34

Pin = 20,0 dBm

Wavg. 1550.280 nm Pavg. -28.20 dBm Ptot. -28.20 dBm

Nonlinear Optical Effects (SPM3)

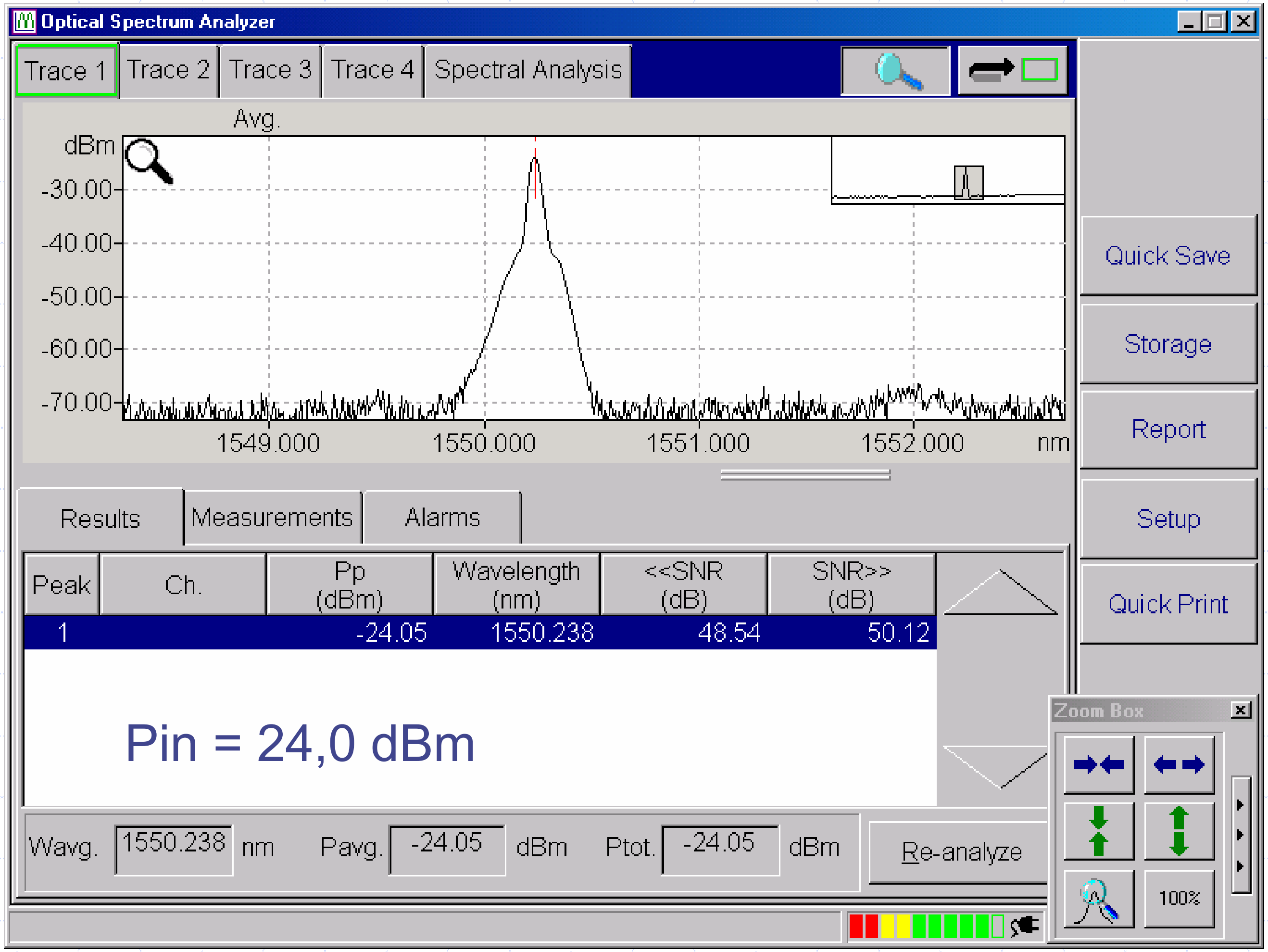


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-25.19	1550.184	46.62	48.33

Pin = 22,7 dBm

Wavg. 1550.184 nm Pavg. -25.19 dBm Ptot. -25.19 dBm

Nonlinear Optical Effects (SPM4)

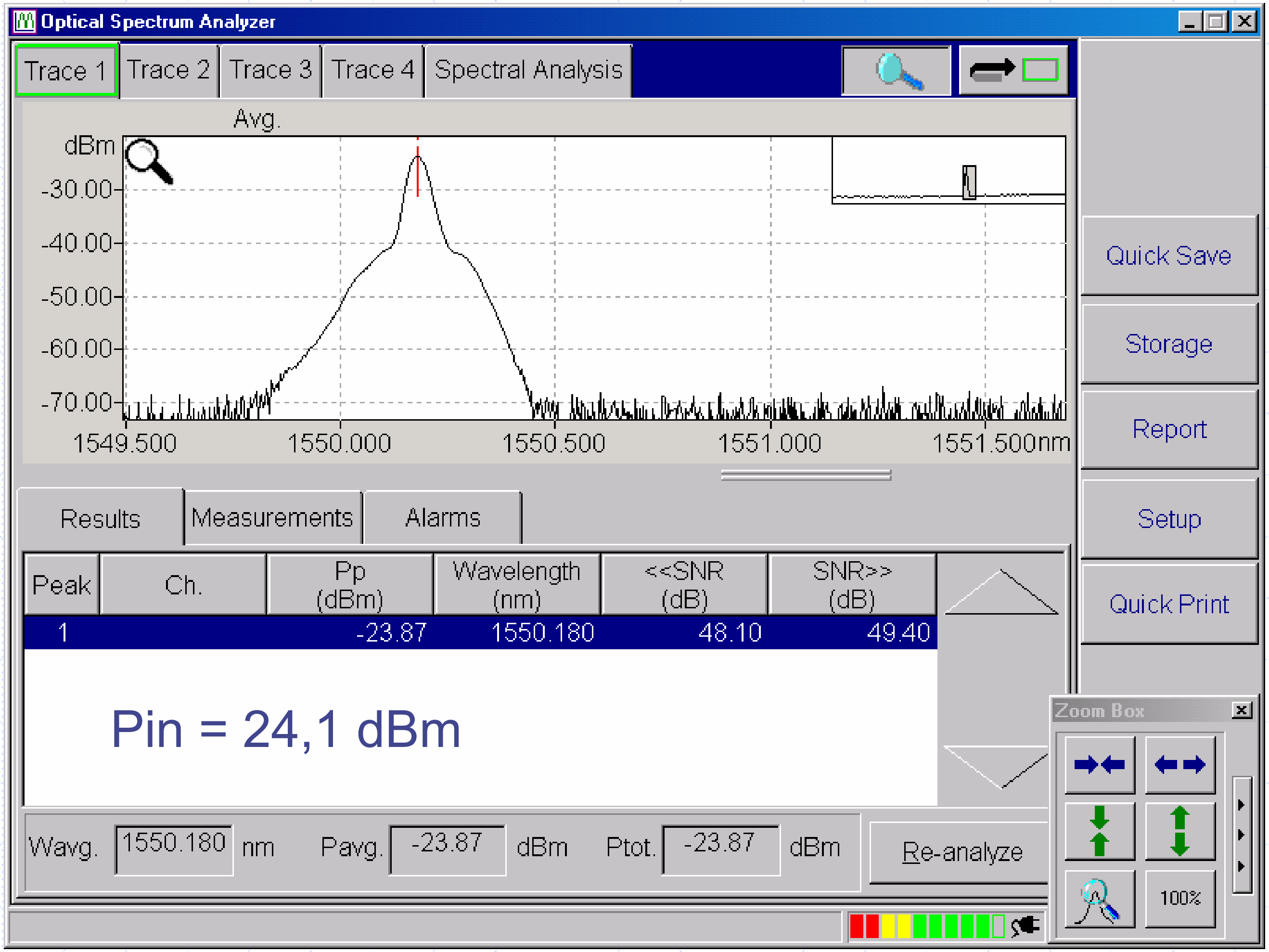


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-24.05	1550.238	48.54	50.12

Pin = 24,0 dBm

Wavg. 1550.238 nm Pavg. -24.05 dBm Ptot. -24.05 dBm

Nonlinear Optical Effects (SPM5)

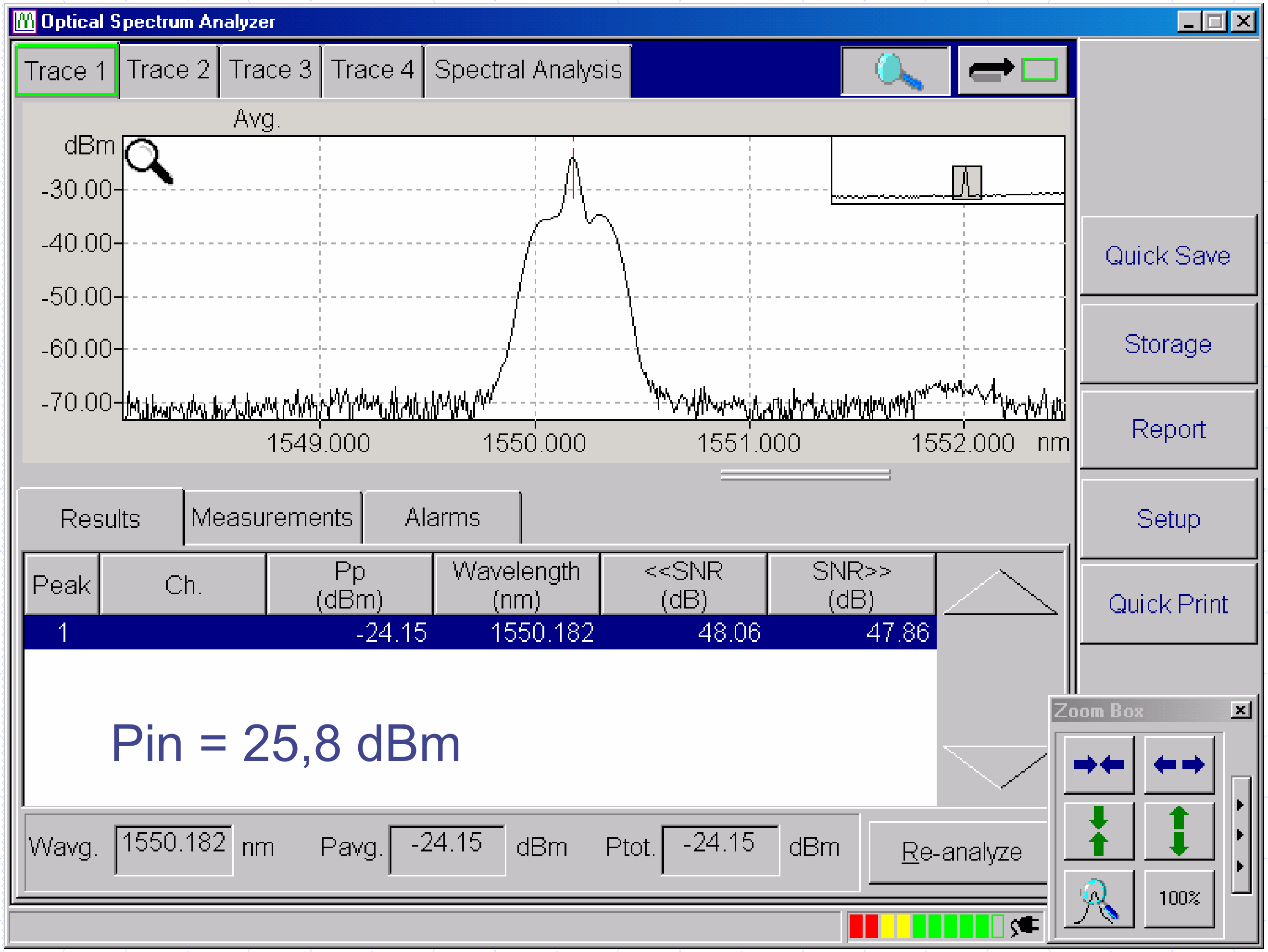


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-23.87	1550.180	48.10	49.40

Pin = 24,1 dBm

Wavg. 1550.180 nm Pavg. -23.87 dBm Ptot. -23.87 dBm

Nonlinear Optical Effects (SPM6)

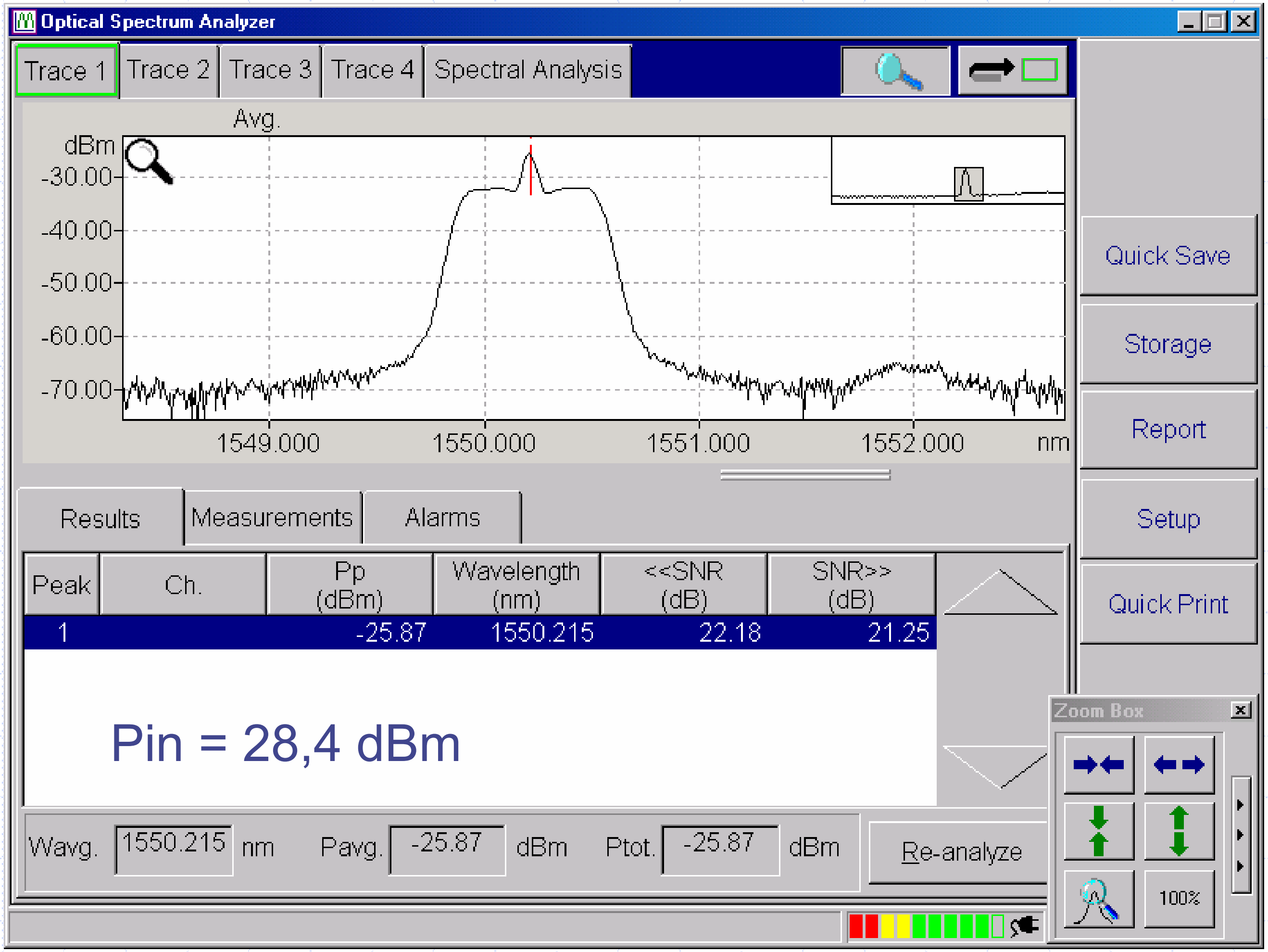


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-24.15	1550.182	48.06	47.86

Pin = 25,8 dBm

Wavg. 1550.182 nm
Pavg. -24.15 dBm
Ptot. -24.15 dBm

Nonlinear Optical Effects (SPM7)

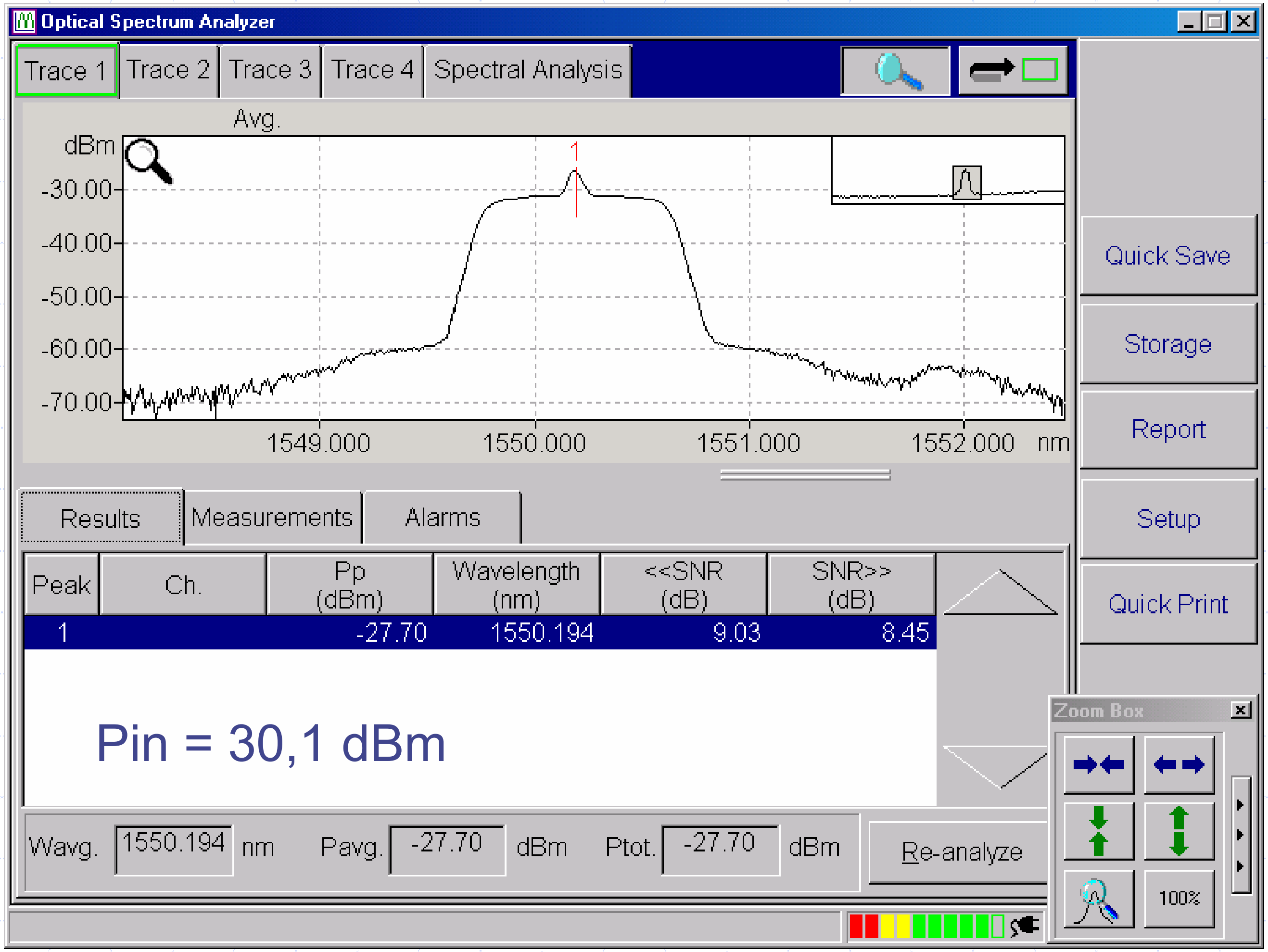


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-25.87	1550.215	22.18	21.25

Pin = 28,4 dBm

Wavg. 1550.215 nm Pavg. -25.87 dBm Ptot. -25.87 dBm

Nonlinear Optical Effects (SPM8)



Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-27.70	1550.194	9.03	8.45

Pin = 30,1 dBm

Wavg. 1550.194 nm Pavg. -27.70 dBm Ptot. -27.70 dBm

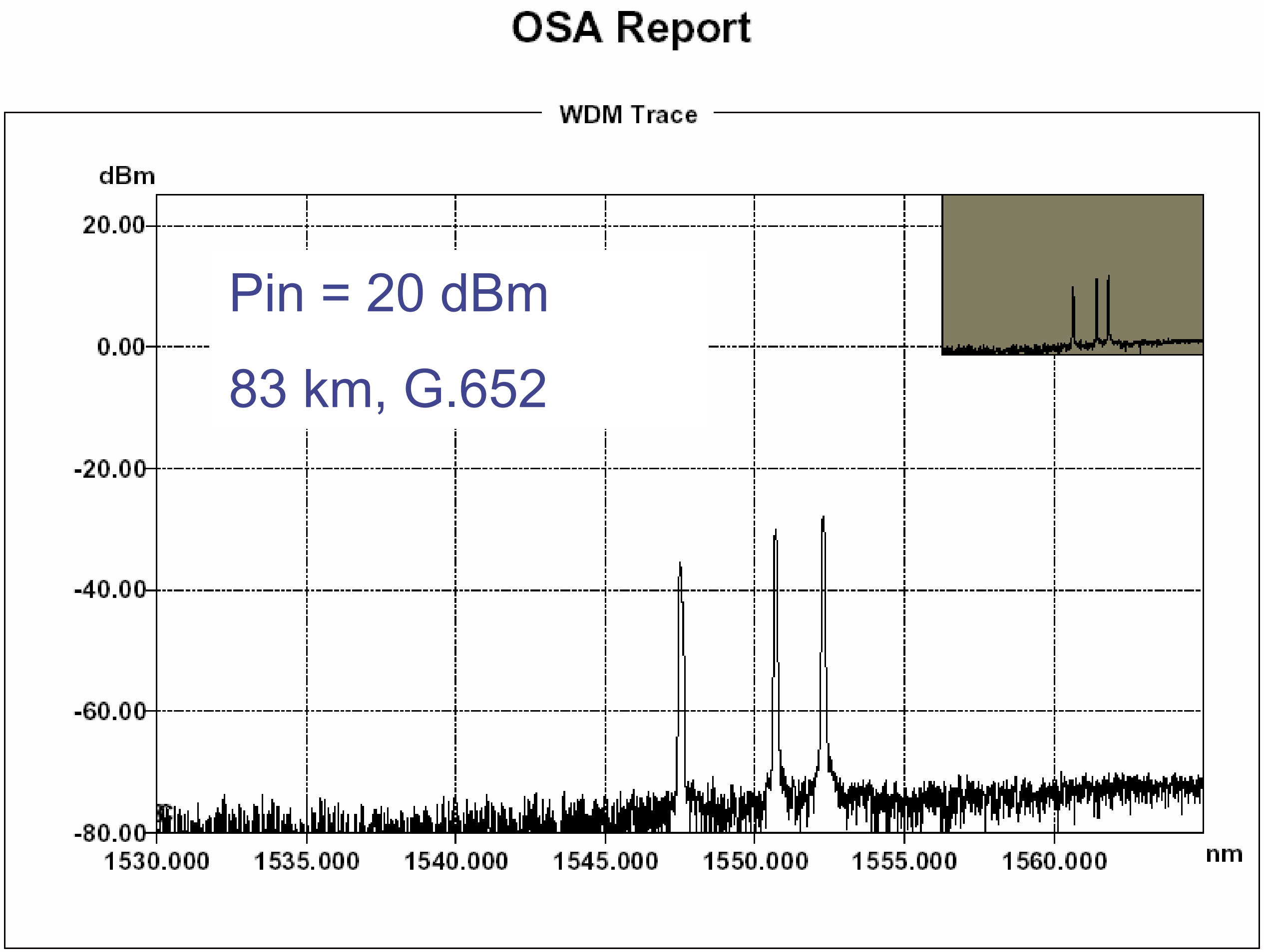
Nonlinear Optical Effects

- Cross-Phase Modulation (CPM)
- A signal modulates the phases of adjacent channels

Nonlinear Optical Effects

- Four Wave Mixing (FWM)
- New „ghost“ signals appear in the transmission spectral range
- Depends on several factors like launched powers, the CD, the refractive index, the fibre length
- Severe limitations for G.653 fibres and DWDM transmissions in the 1550 nm window (C band)
- Solution to this problem is to deploy L band DWDM systems (1565 nm – 1625 nm), where CD is high enough

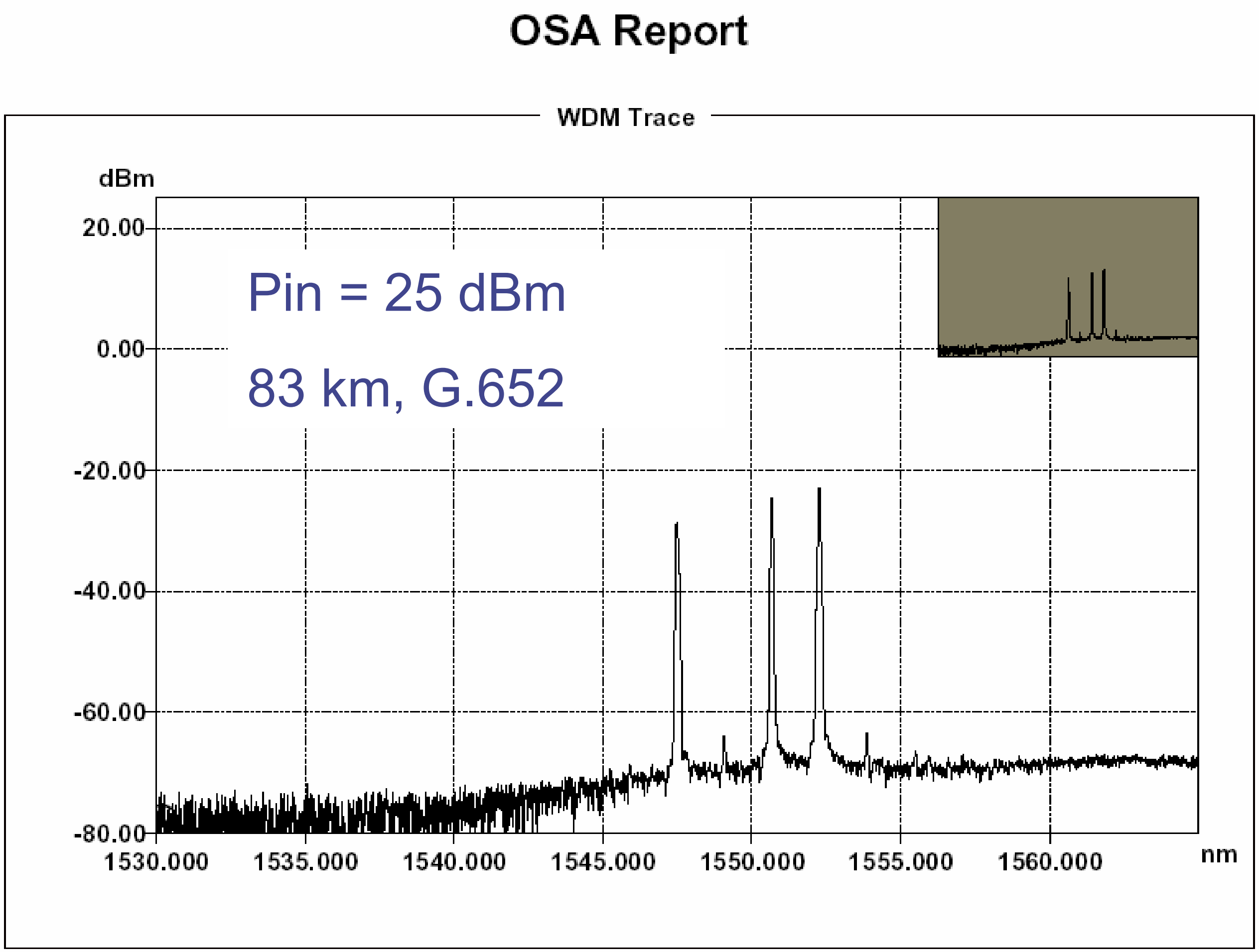
Nonlinear Optical Effects (FWM1)



Pin = 20 dBm

83 km, G.652

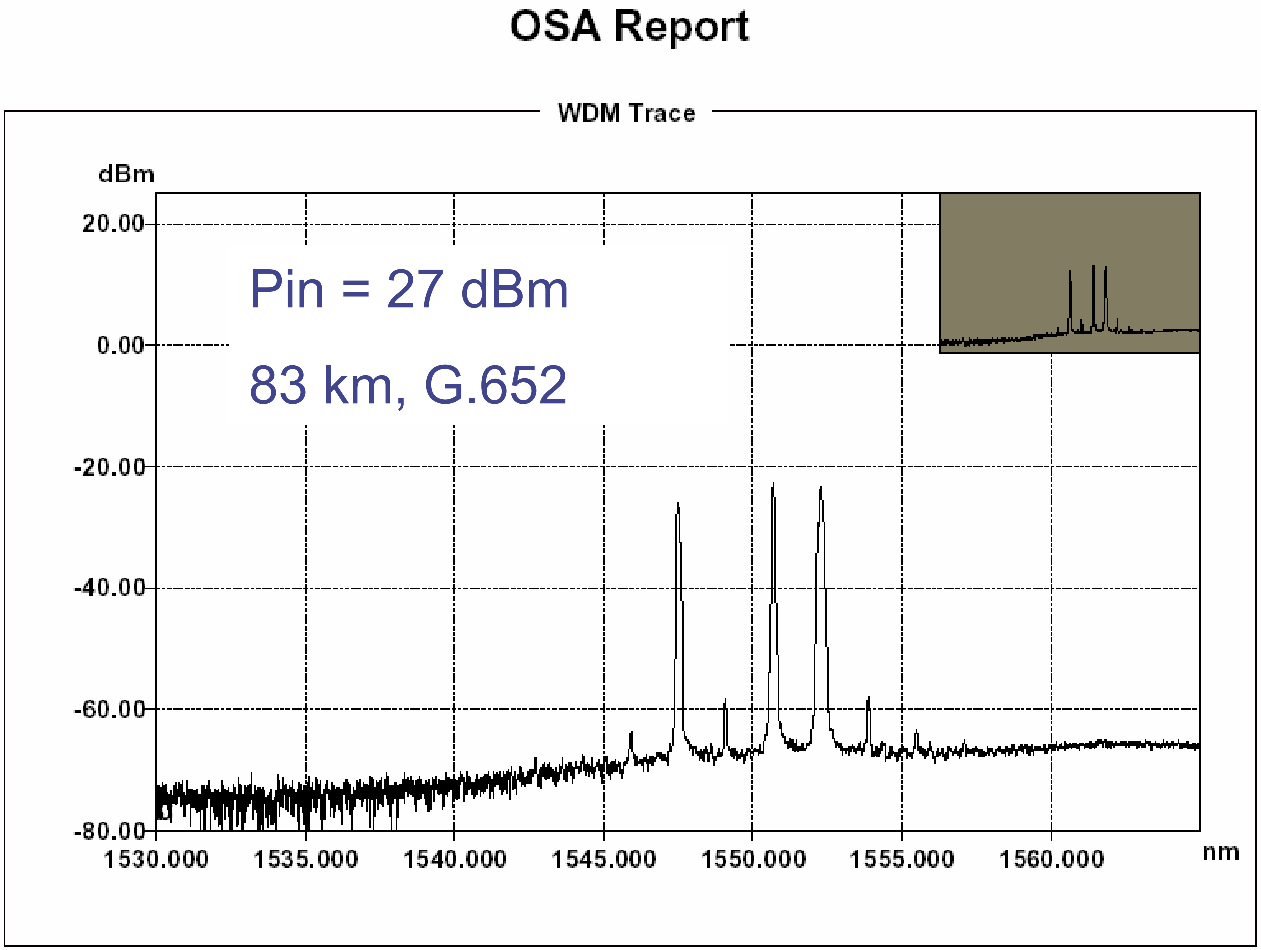
Nonlinear Optical Effects (FWM2)



Pin = 25 dBm

83 km, G.652

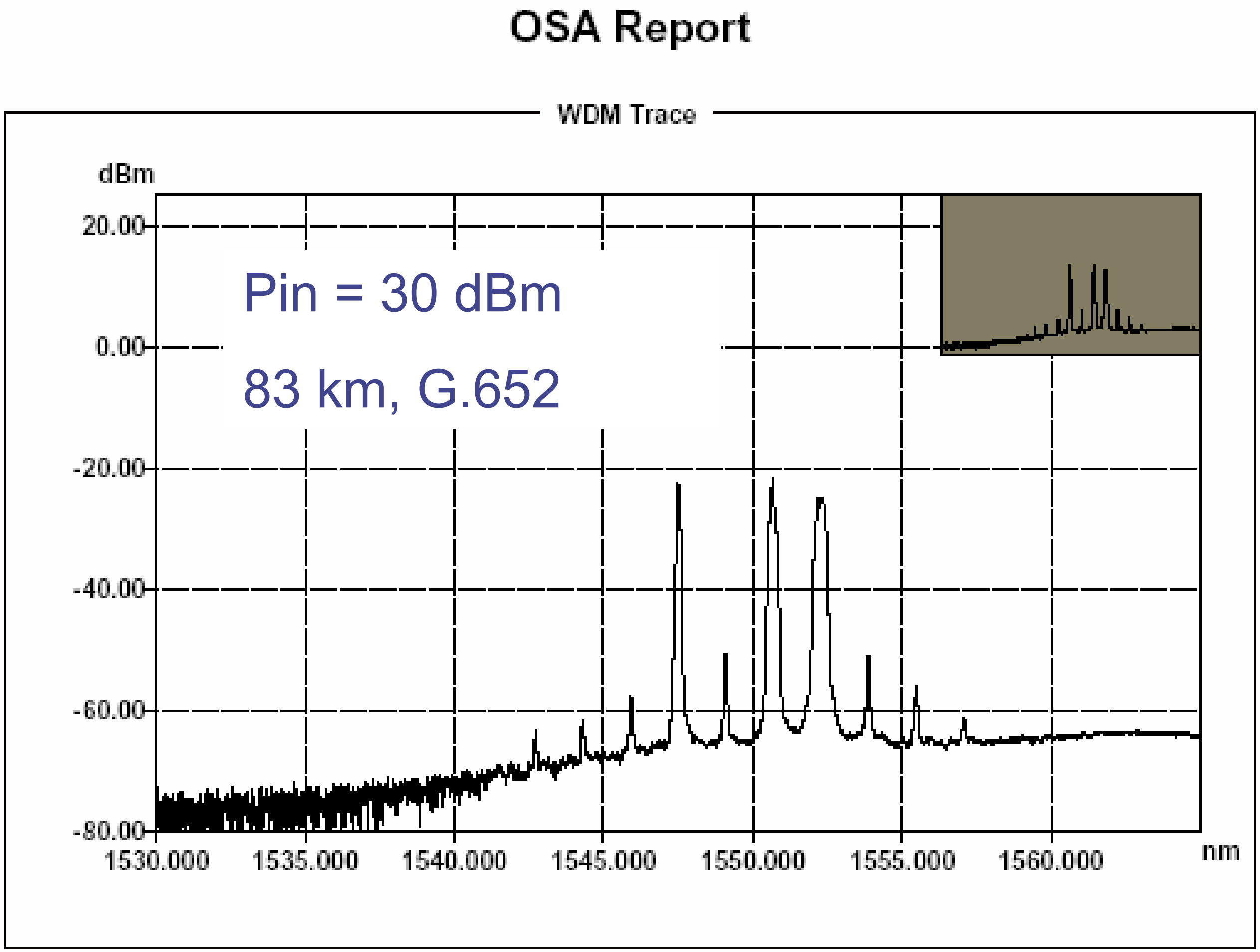
Nonlinear Optical Effects (FWM3)



Pin = 27 dBm

83 km, G.652

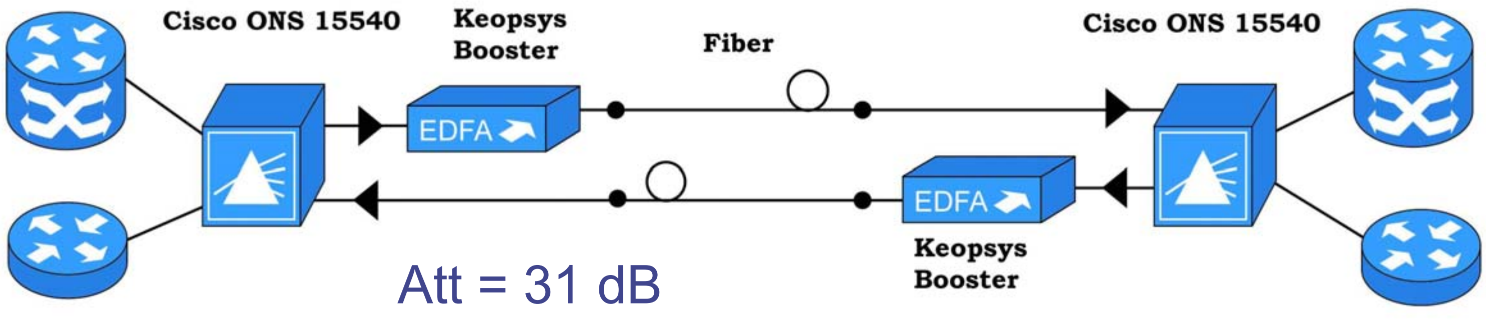
Nonlinear Optical Effects (FWM4)



Pin = 30 dBm

83 km, G.652

Nonlinear Optical Effects (FWM5), TNC03

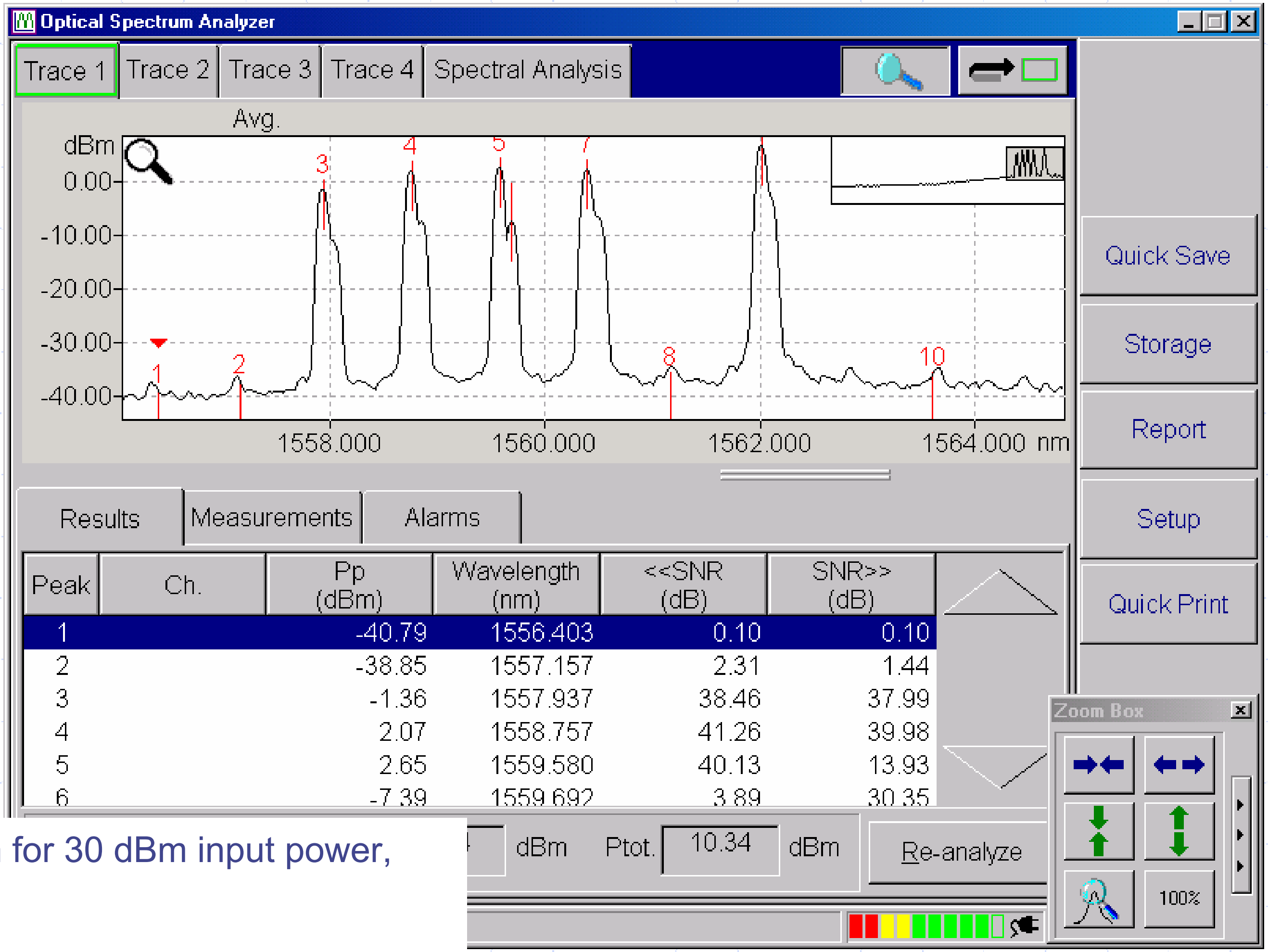


Att = 31 dB

124 km, G.652

- Strong effects of SPM, CPM and FWM
- OSC mostly affected
- Single-channel EDFAs are OK for 5 channels
- For 16/32 channels you need really powerful booster (17 dBm for 1 channel corresponds to 2 dBm for 32 channels)

Nonlinear Optical Effects (FWM6)

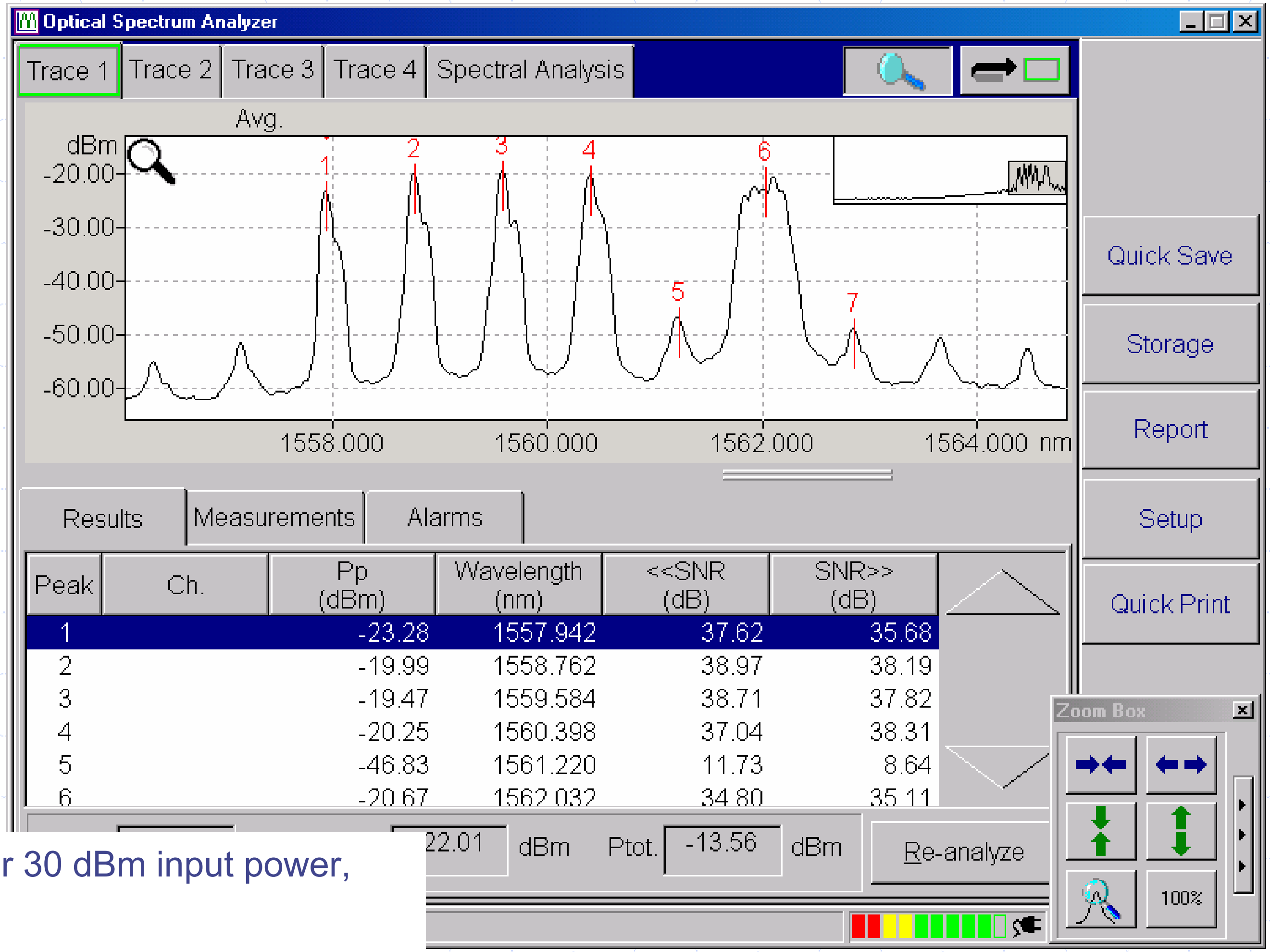


Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-40.79	1556.403	0.10	0.10
2		-38.85	1557.157	2.31	1.44
3		-1.36	1557.937	38.46	37.99
4		2.07	1558.757	41.26	39.98
5		2.65	1559.580	40.13	13.93
6		-7.39	1559.692	3.89	30.35

dBm Ptot. 10.34 dBm

Spectral diagram for 30 dBm input power, after EDFA.

Nonlinear Optical Effects (FWM7)



Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-23.28	1557.942	37.62	35.68
2		-19.99	1558.762	38.97	38.19
3		-19.47	1559.584	38.71	37.82
4		-20.25	1560.398	37.04	38.31
5		-46.83	1561.220	11.73	8.64
6		-20.67	1562.032	34.80	35.11

22.01 dBm Ptot. -13.56 dBm

Spectral diagram for 30 dBm input power, before reciever.

Transmitters

- Laser and modulator
- Conversion of electrical signals into optical streams
- Laser: LED, Fabry-Perot (FP), Distributed Feedback (DFB)
- Direct or external (10 Gb/s) modulation
- Output powers: 0 dBm – 5 dBm
- Pluggable, DWDM ITU wavelengths (193,1 THz)
- GBIC (1 Gb/s), SFP (1 Gb/s – 2,5 Gb/s)
- Xenpak, XFP, Xpak, X2 (10 Gb/s)

Transmitters

- Price comparison
- GBIC 1550 nm: USD 6 000 (2002) from big vendors
- SFP DWDM: USD 2 000 (2005)
- Xenpak 1550 nm: USD 12 000 (2005)
- Xenpak DWDM: USD 31 000 (2005) from big vendors
- Xenpak DWDM: USD 5 500 (2005) from manufacturers
- XFP 1550 nm: USD 2 500 (2005)
- XFP DWDM: USD 4500 (2006)

Transmitters

Transmitters – Modulations 1

- Different modulation formats, signal formats
- How to convert an electrical signal into an optical stream?
- On-Off Keying (OOK)
- A simple digital modulation scheme, easy to implement
- Intensity modulation with direct detection (IM/DD)
- Incoherent (the intensity only, no phase coherence)
- Two basic choices for the signal formats – return-to-zero (RZ) and nonreturn-to-zero (NRZ)
- Carrier suppressed (CS), Single side band (SSB), Vestigial sideband (VSB), Chirped (C) both for RZ and NRZ (CS-RZ, C-RZ,…)

Transmitters – Modulations 2

- Coherent - well known from radio and microwave systems and literature
- Improvement of receiver sensitivity (up to 20 dB) when compared to IM/DD systems [Agrawal]
- More efficient use of bandwidth by increasing the spectral efficiency (higher tolerance to nonlinear effects, chromatic dispersion CD, polarization mode dispersion PMD)
- More complicated and more expensive

Advanced Modulation Formats

Amplitude-shift keying	(ASK)
Phase-shift keying	(PSK)
Frequency-shift keying	(FSK)
Differential phase-shift keying	(DPSK)
Differential quadrature phase-shift keying	(DQPSK) – Wi-Fi

- Optical Duo Binary ODB (also known as phase shaped binary modulation)

Advanced Modulation Formats

- Signal formats can be RZ, NRZ, CS-, etc. again
- DQPSK, ODB are *multilevel* modulations
- Multilevel – more amplitude levels (to achieve spectral efficiency better than 1 bit/s/Hz), 40 Gb/s is 10 Gbaud for a 16 level modulation
- DQPSK (information is encoded in the 4 differential optical phase between successive bits)
- ODB (in simplest scheme - two consecutive bits are summed -> a three level code is created, AM-PSK)
- RZ-DPSK, NRZ-DPSK, CS-RZ OOK, RZ-ODB have been studied extensively (better tolerance to different impairments)

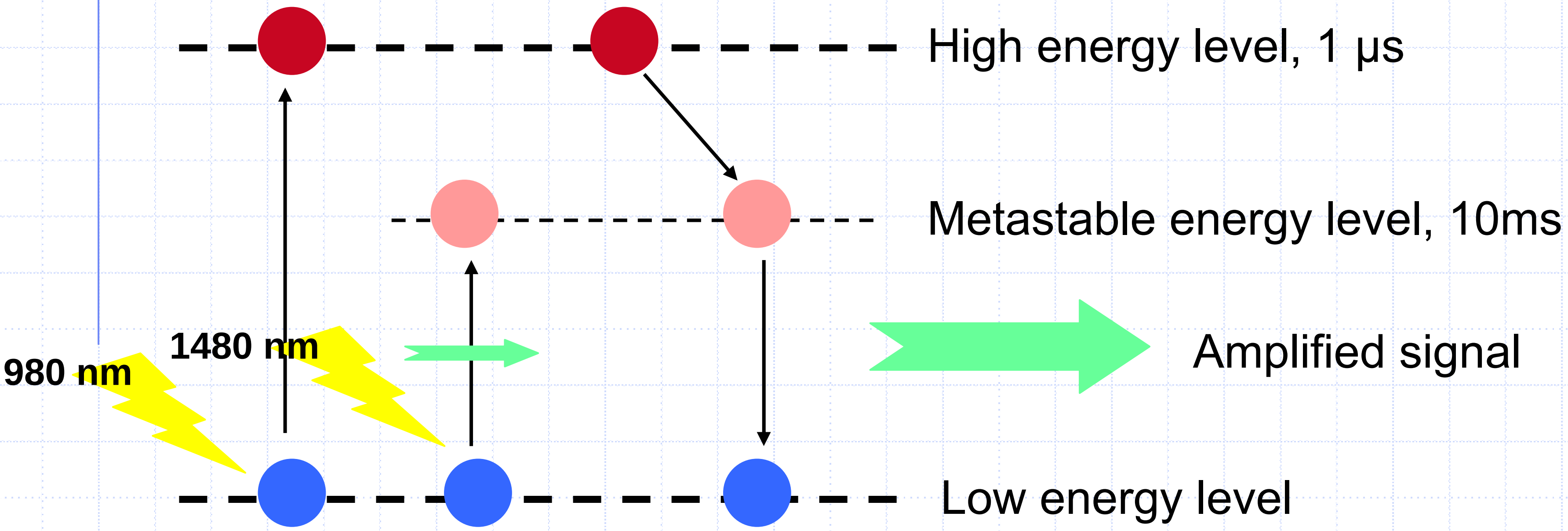
Receivers

- Photodetector and demodulator
- PIN
- APD (better performance)
- Receiver sensitivity for certain BER
- 1 GE: - 34 dBm
- 10 GE: - 15 dBm/- 24 dBm
- BER: 10^{-9}, 10^{-12} ,10^{-15}
- Coherent (transmitted signal plus local oscillator) and incoherent (OOK) receivers

Optical Amplifiers

- Fibre, Semiconductor (SOA), Raman
- Erbium Doped Fibre Amplifiers (EDFA)
- Really began a revolution in the telecommunications industry
- Late 1980s, Payne and Kaming (University of Southampton)
- OAs can directly amplify many optical signals
- Protocol, bit-rate transparent
- EDFAs working in the 1550 nm window (C band and later L band)

Optical Amplifiers EDFA



High energy level, 1 µs

Metastable energy level, 10ms

1480 nm

980 nm

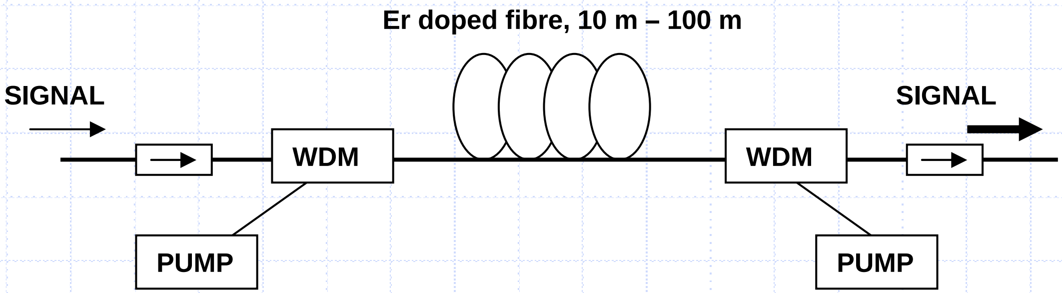
Amplified signal

Low energy level

● Er atoms

- Light Amplification by Stimulated Emission

Optical Amplifiers EDFA

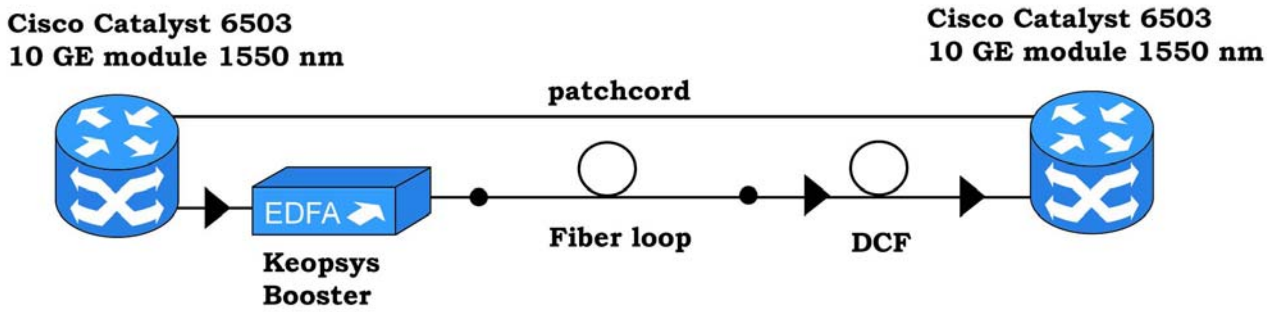


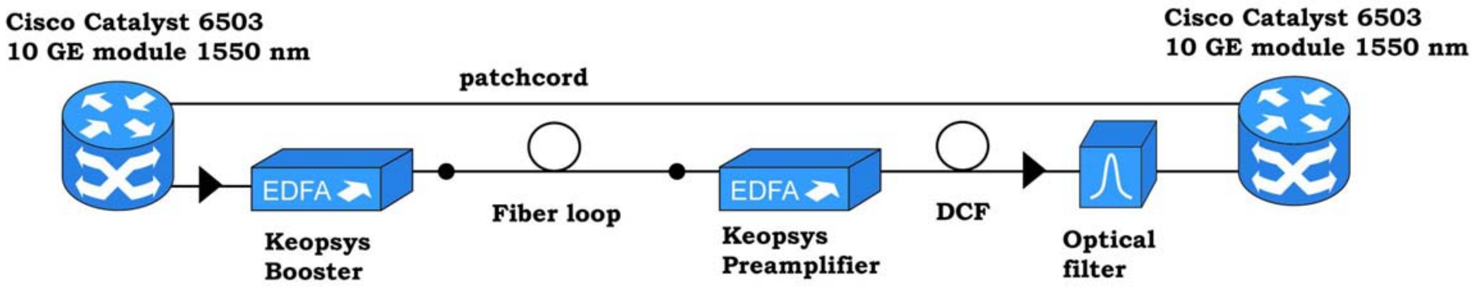
- Forward, backward pumping
- Forward: lowest noise
- Backward: highest output power
- 980 nm: low noise
- 1480 nm: stronger pump sources (req. longer Er fibres)
- 1480 nm & backward; 980 nm & forward
- Single or dual stage (for DCF)

Optical Amplifiers EDFA

- Output powers (5 Watts or more)
- Gain (30 dB), is not uniform across C (L) band
- Input power (- 35 dBm)
- Noise Figure (NF): theoretical minimum 3 dB
- ASE
- For L band: long Er fibres (> 100 m)
- Booster, in-line, preamplifiers

Optical Amplifiers





Other Optical Fibre Amplifiers

- Praseodymium Doped Fluoride Fibre Amplifier (PDFFA)
  - 1310 nm, not as energy efficient compared to EDFA
  - Problems with fluoride fibres, not very widespread
- Thulium DFFA (TDFFA)
  - 1460 nm, 1650 nm
  - the lifetime problems
- Neodymium DFA
  - 1310 nm, fluoride fibre

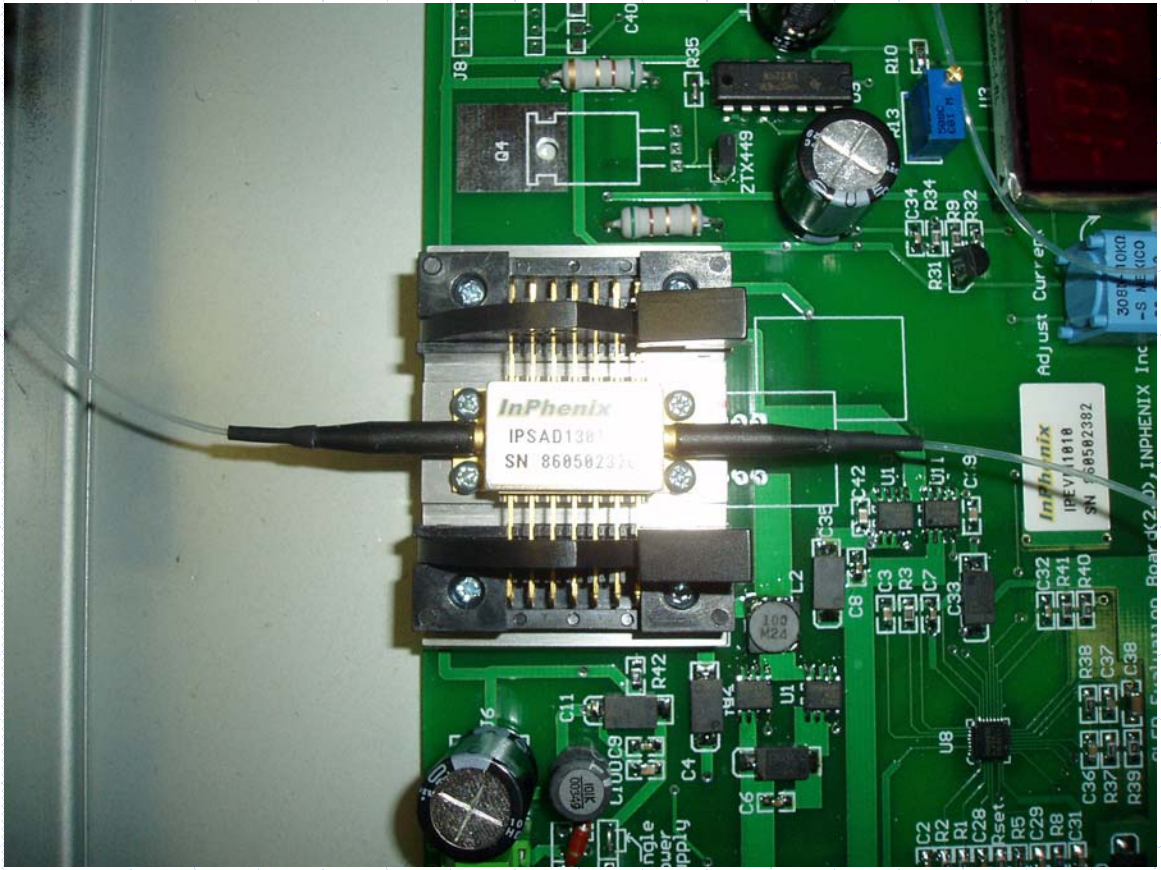
Semiconductor Optical Amplifiers

- Cost effective solutions, especially for 1310 nm window
- Based on conventional laser principles
- Active medium (waveguide) between N and P regions
- High gain (up to 25 dB)
- Low output powers (15 dBm)
- Wide bandwidth
- High noise figure (8 dBm)
- InGaAsP – small and compact components

Semiconductor Optical Amplifiers

- Can be used as wavelength convertors, regenerators, time demultiplexors (OTDM), clock recovery devices
- EDFAs are more powerful and less noisy (but more expensive)
- But PDFAs are not so widespread and common, optical parameters (output powers and noise figures are not comparable with EDFAs) – SOAs can present an interesting solution
- 10 GE line cards for PC (PCI-X, PCI-E) S2io (Neterion), Chelsio, Intel with fixed 1310 nm transceivers only
- The only way to extend a reach is to deploy amplifiers (10 km is not enough, even for MANs in the Czech Republic) or use wavelength convertors (OEO – L2 Ethernet switches)

Semiconductor Optical Amplifiers



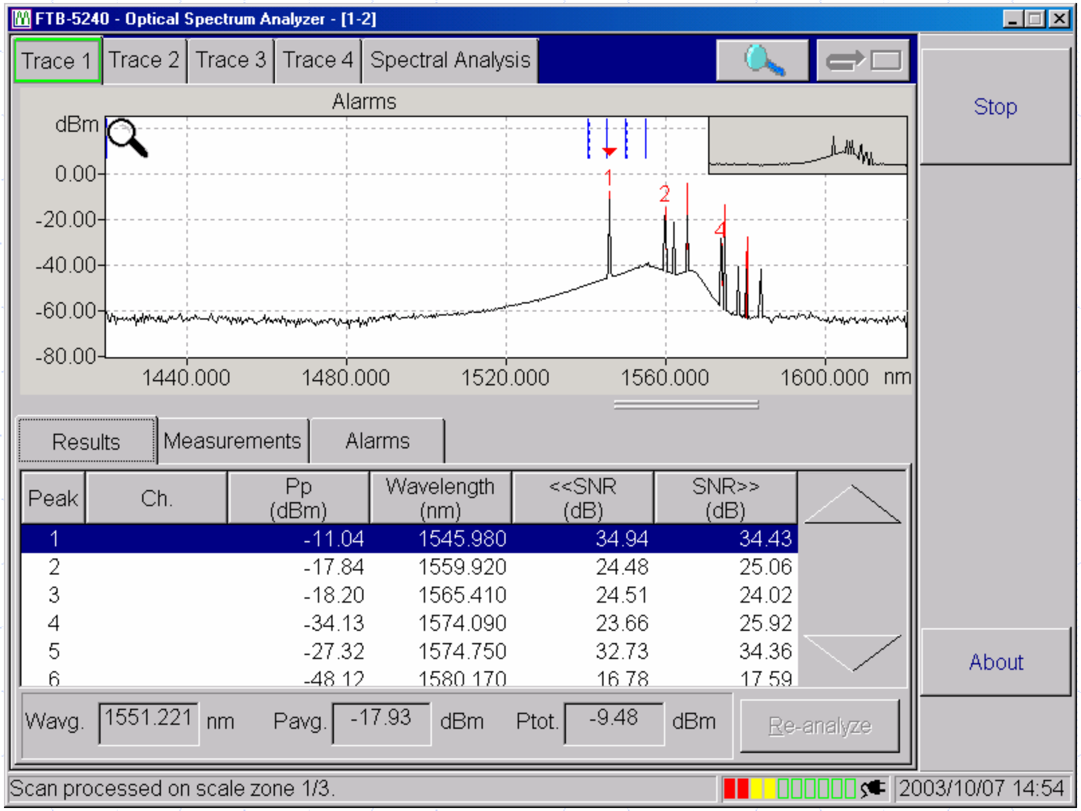
SOAs versus FOAs

Raman Amplification

- Not a discrete amplifier
- Stimulated Raman scattering effect
- Distributed amplification, a communication fibre itself is a gain medium
- Can add 40 km to increase a maximum transmitter-receiver distance
- Upgrading of existing links to add more channels
- A quite weak effect in silica fibre – very high powers have to be used
- Safety problems (automatic laser shutdown - ALS)

Raman Amplification

- Double Rayleigh scattering (DRS)
- Fibre acts like mirrors ie limits launch powers



Peak	Ch.	Pp (dBm)	Wavelength (nm)	<<SNR (dB)	SNR>> (dB)
1		-11.04	1545.980	34.94	34.43
2		-17.84	1559.920	24.48	25.06
3		-18.20	1565.410	24.51	24.02
4		-34.13	1574.090	23.66	25.92
5		-27.32	1574.750	32.73	34.36
6		-48.12	1580.170	16.78	17.59

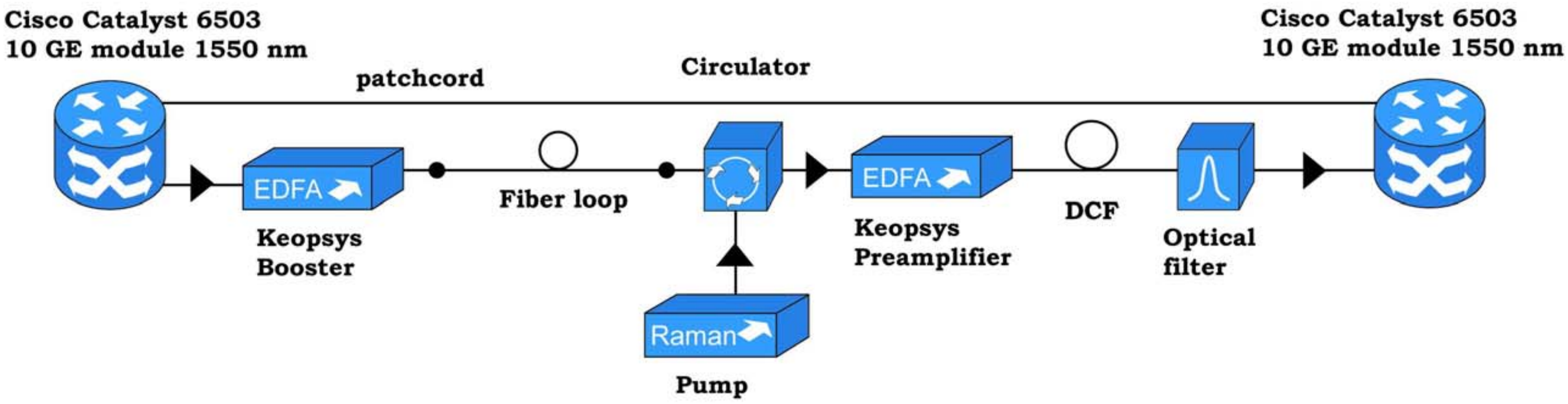
Wavg. 1551.221 nm Pavg. -17.93 dBm Ptot. -9.48 dBm

Scan processed on scale zone 1/3.

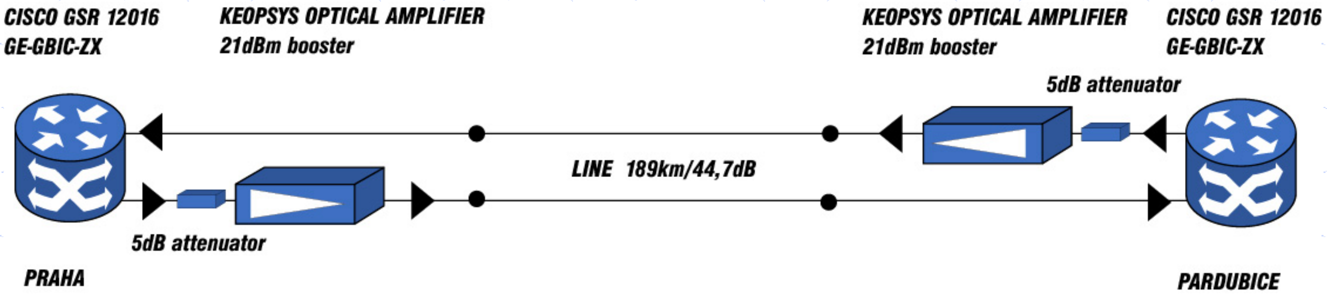
2003/10/07 14:54

Raman Amplification

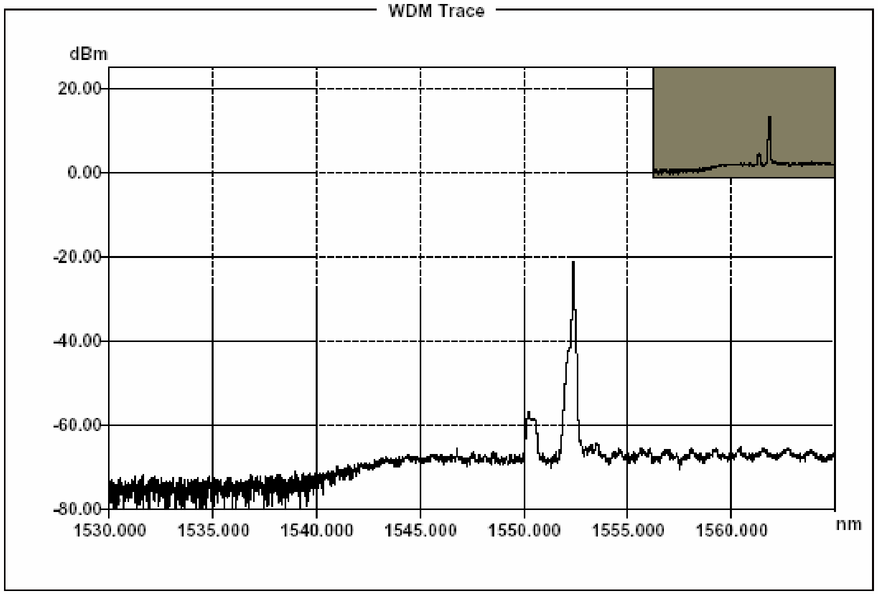
- Counter-directionally pumping schemes



OAs and Practical Deployment



OSA Report

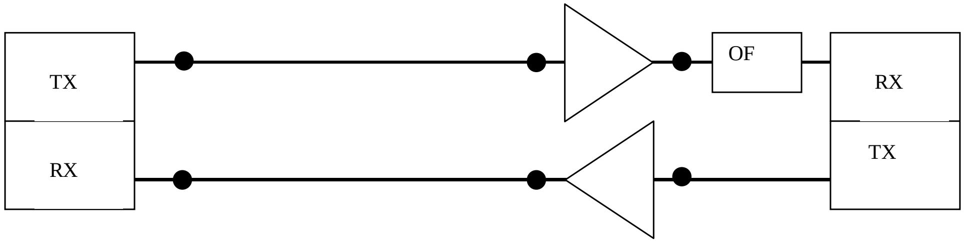


Praha - Pardubice

Since May 17, 2002

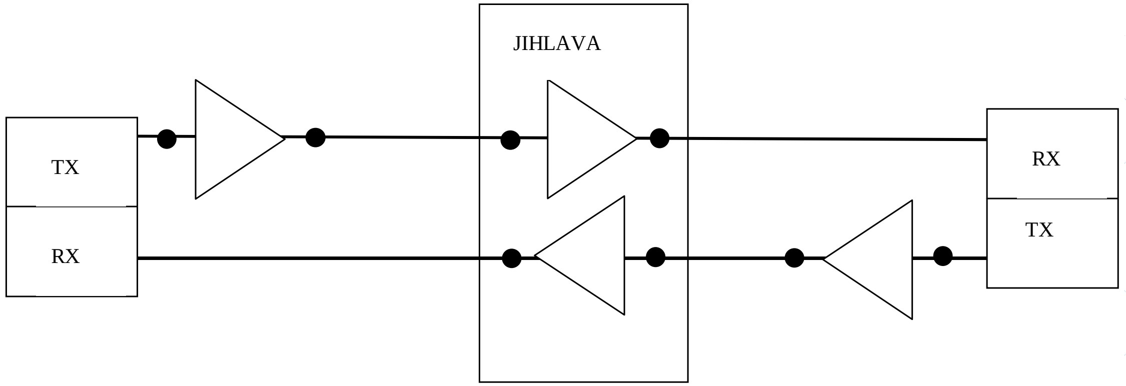
OAs and Practical Deployment

- Praha – Pardubice, 189 km, 44 dB, 1 GE
- Praha – Plzeň (One Side Amplification), 123 km, 34 dB, 1 GE



OAs and Practical Deployment

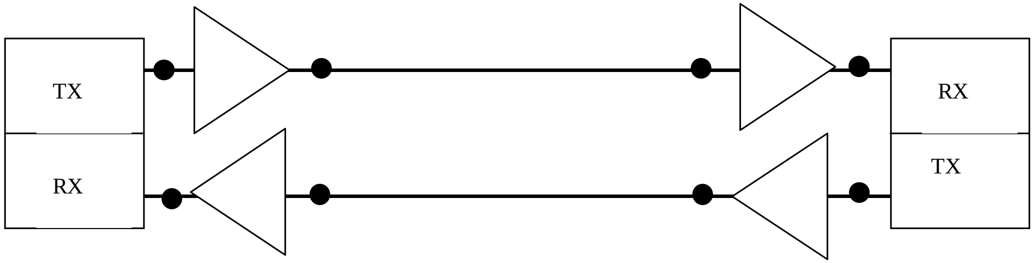
- Brno – České Budějovice, 308 km, 70 dB, 2,5 Gb/s, PoS, without optical filters



Optical networks and equipment

OAs and Practical Deployment

- Brno – Ostrava, 235 km, 51 dB, 1 GE (tested for 2,5 G PoS), without optical filters



PDFAs/SOAs and Ramans for 1310 nm

- Development of high-speed customer empowered fibre networks and availability of 10 GE LAN cards with 1310 nm transceivers stimulates the need for interconnection of stand-alone or hardware accelerated PCs at 10 Gbit/s rate
- Advantage – zero chromatic dispersion of standard single mode fibres (SSMF) at 1310 nm in, the 1310 nm transceivers are much cheaper than the 1550 nm ones
- Disadvantage – loss of SSMF at 1310 nm is almost twice as high as at 1550 nm

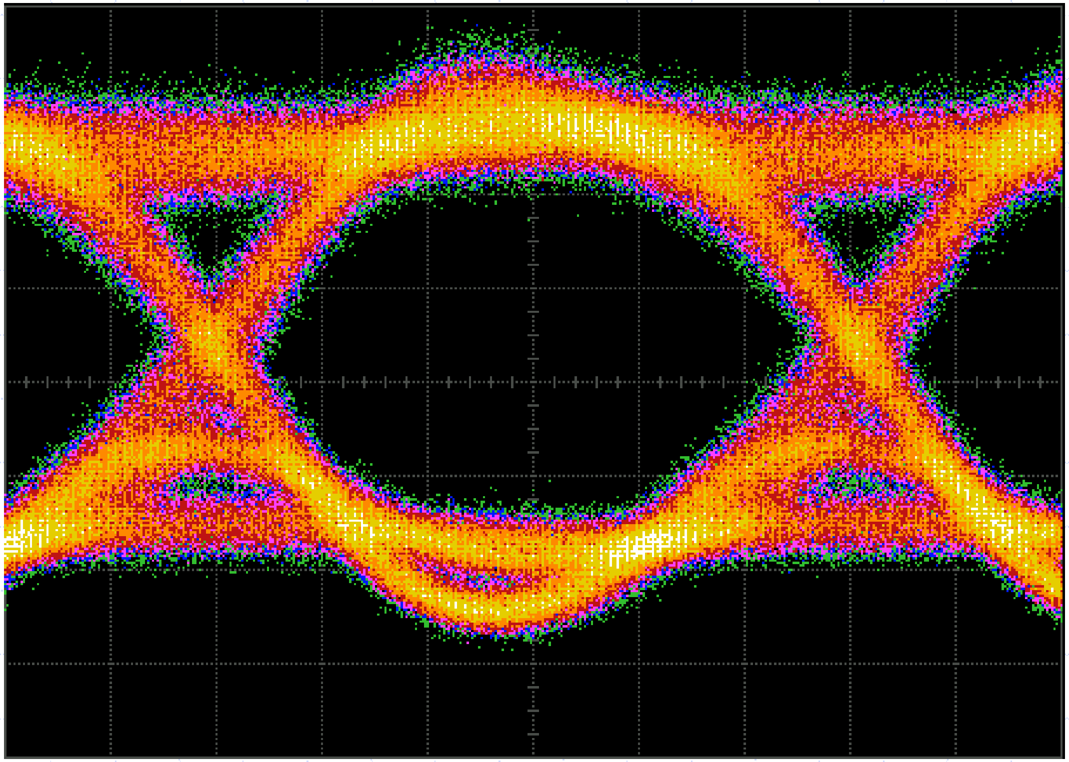
PDFAs/SOAs and Ramans for 1310 nm

- Praseodymium-doped fluoride fibre amplifiers (limited number of manufacturers, low saturated output power in comparison with EDFA, FiberLabs, FL8610-OB, Psat=16dBm, NF=5.5dB)
- Distributed amplification in the transmission fibre utilizing stimulated Raman scattering (Raman fibre amplifier (RFA), no pump LDs at 1250 nm, Raman fibre laser, IPG, Poutmax =2 W at 1250nm)
- Semiconductor optical amplifiers (InPhenix, IPSAD1301, Psat=10dBm, NF=7.5dB)
- Experiments with 10 GE

PDFAs/SOAs and Ramans for 1310 nm

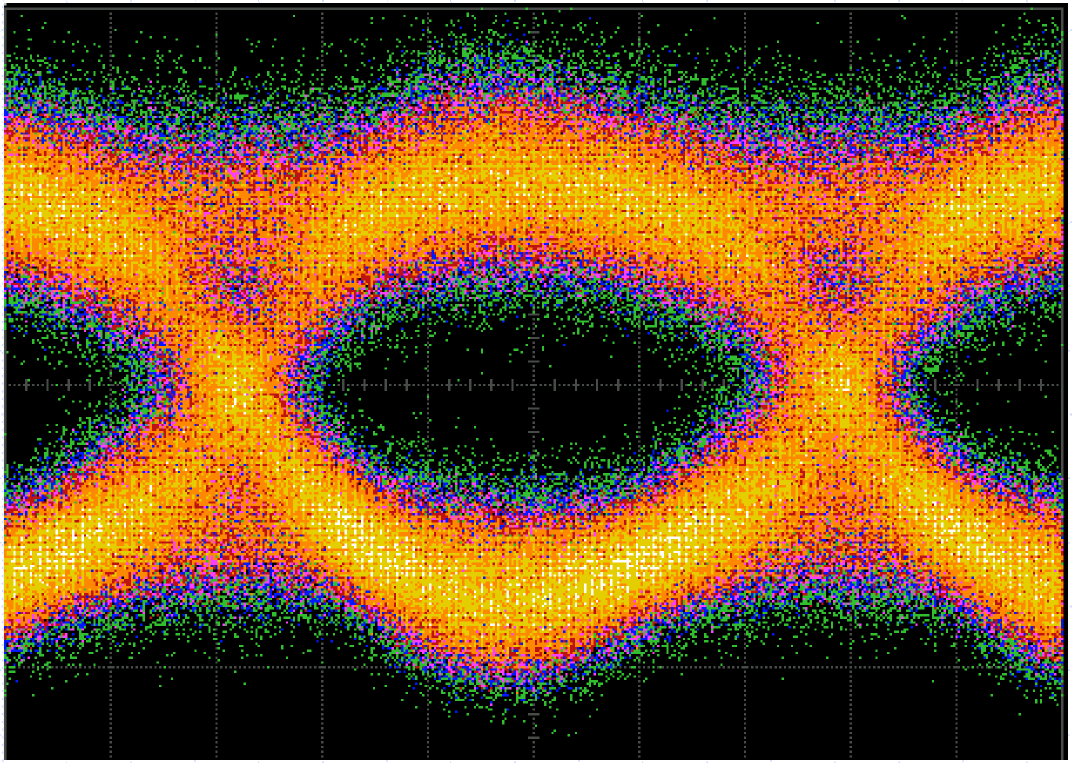
- Similar configuration as for EDFAs plus Ramans
- Booster or preamplifier only
- Booster and preamplifier
- Booster and in-line amplifier
- Booster, preamp and Raman amplifier
- Dual booster (to increase the output power) and Raman
- Booster, inline and Raman

PDFAs/SOAs and Ramans for 1310 nm



Eye diagram after preamp, l = 100 km

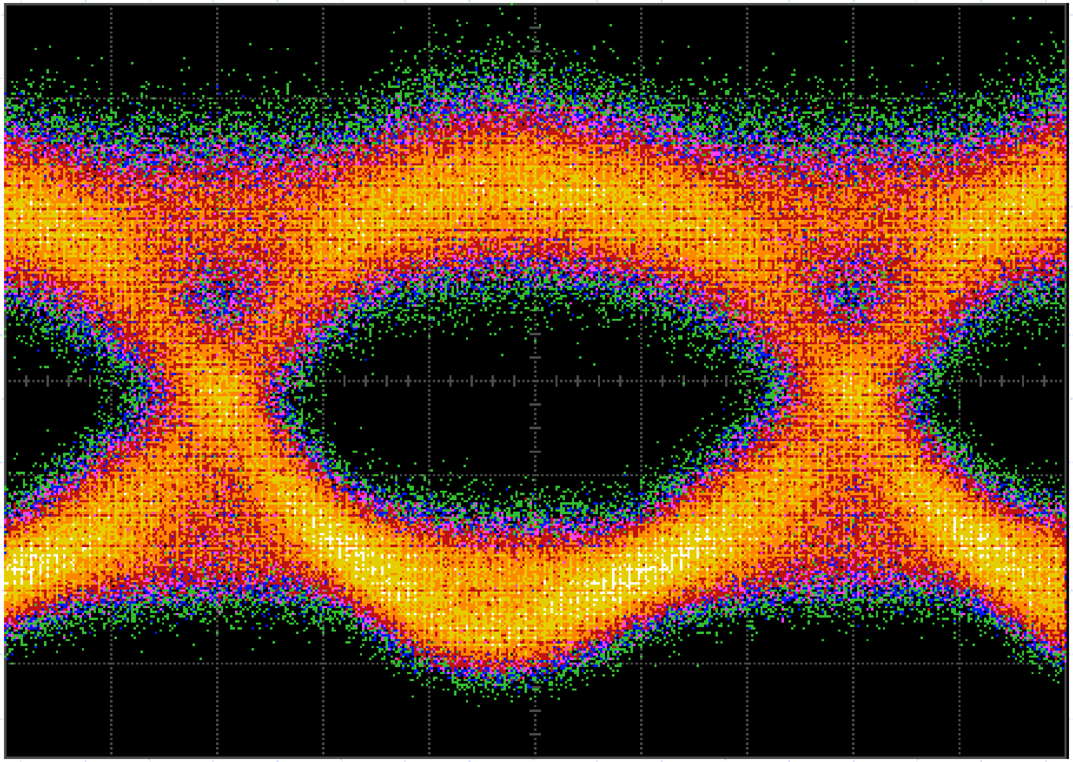
PDFAs/SOAs and Ramans for 1310 nm



Eye diagram after preamp, l = 120 km

Optical networks and equipment

PDFAs/SOAs and Ramans for 1310 nm



Eye diagram after preamp and optical filter, l = 120 km

PDFAs/SOAs and Ramans for 1310 nm

Configuration	Reach (km)
Guaranteed	10
In lab, no amps	30
Booster	85
Booster and preamp	120
Dual booster and Raman	135

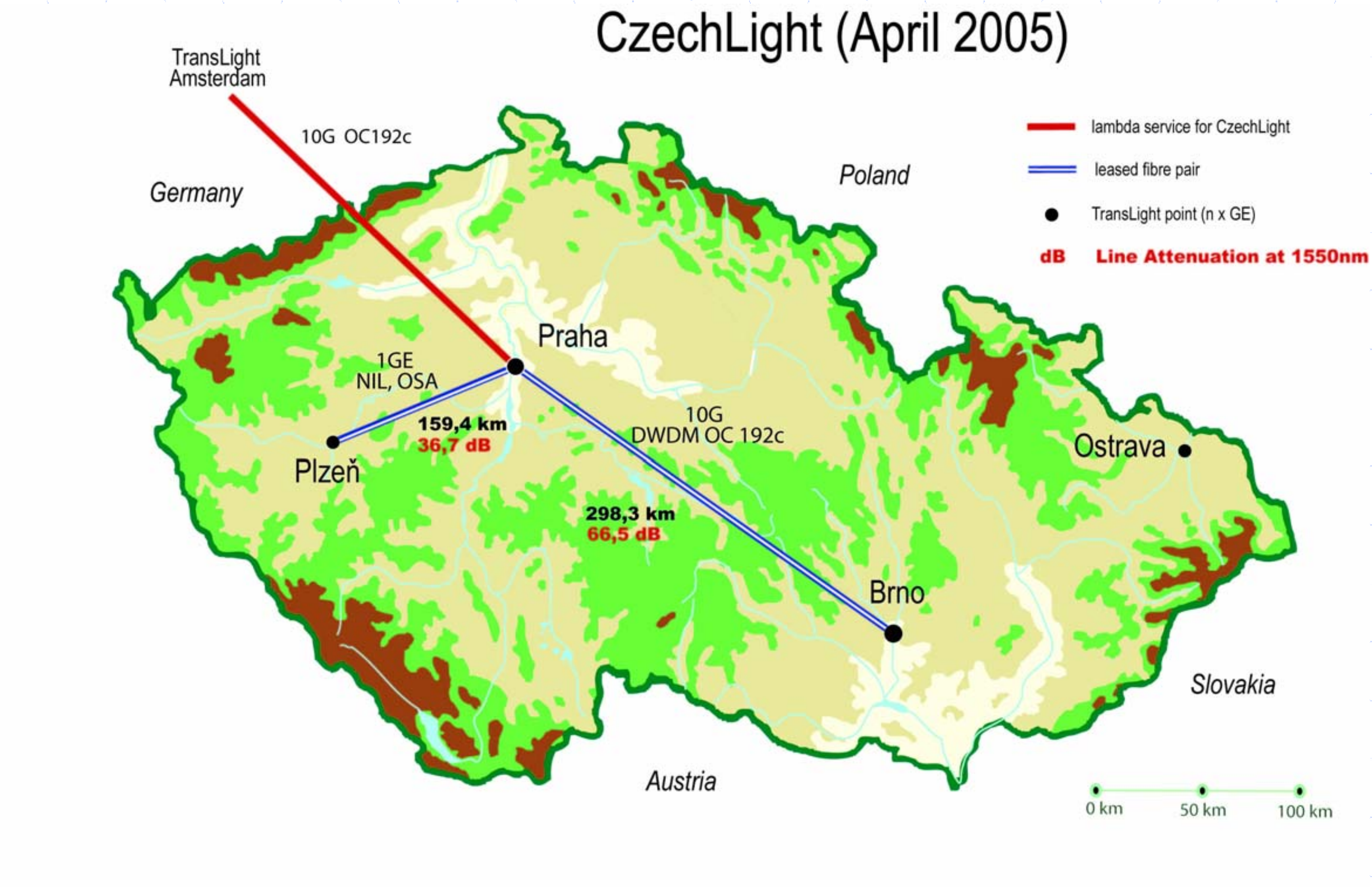
CzechLight Amplifiers

- An optical kit composed from commercially available elements
- Cost effectivity & reliability
- Possibilities of future development
- Customer based OFA modules – EDFA for 1550 nm, PDFA for 1310 nm (*10 GE line cards for PC*), Raman modules
- High power boosters, low-noise preamps, in-line amps…
- The result is: CzechLight amplifiers (CLAs)
- Why? What is CzechLight?

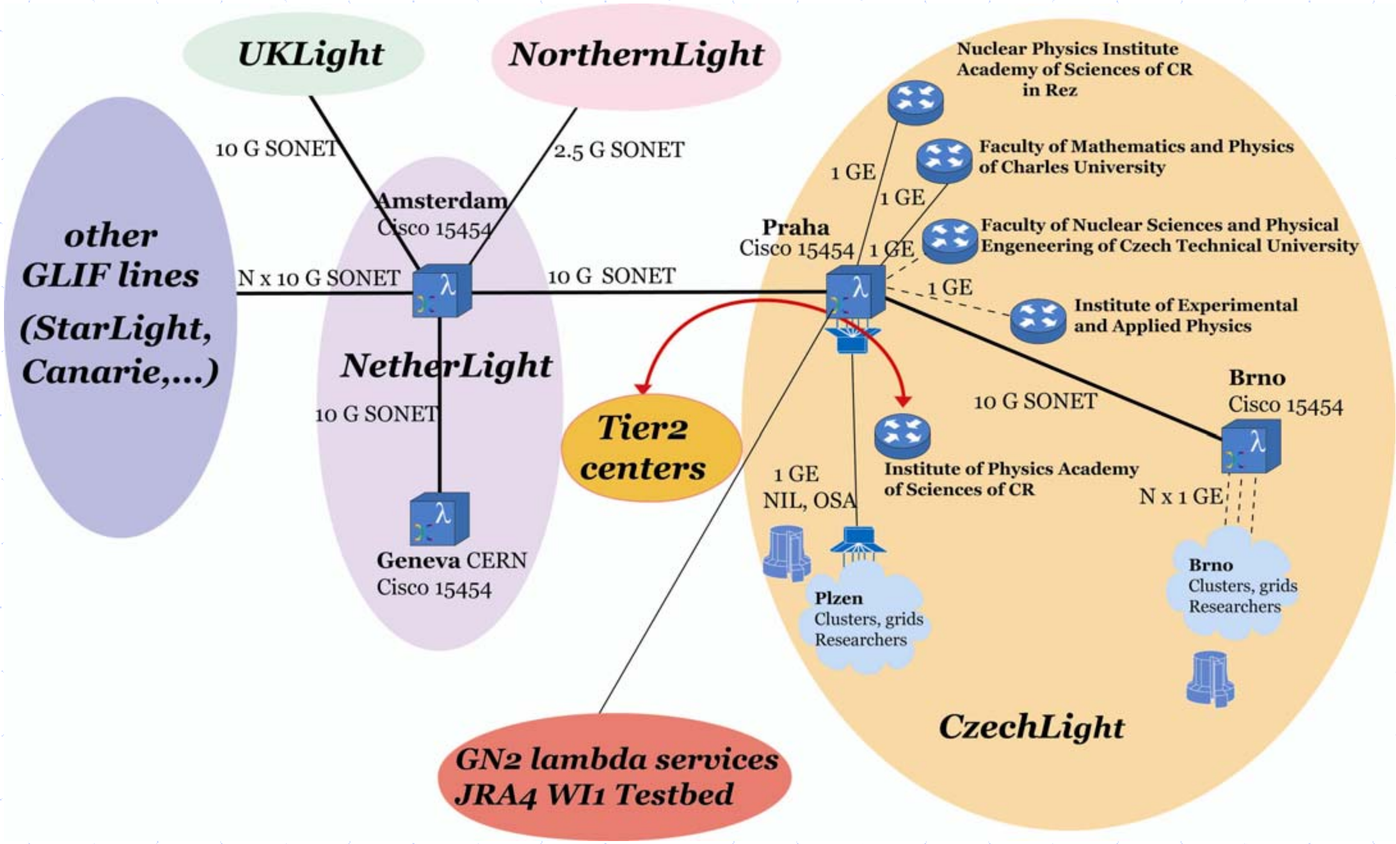
CzechLight

- An experimental and breakable optical network, testbed
- 10 G lambda to NetherLight (Amsterdam), a part of GLIF
- Started as 2,G G lambda, back in January 2003
- To test new components before deployment (lab -> CzechLight -> CESNET2)
- Experimental traffic for Institute of Physics and other researchers
- Praha – FermiLab (1 GE)
- Praha – Taipei (1 GE)
- For high speed experiments like iGrid2005, SC2005 (full 10 G)
- http://www.ces.net/doc/press/2005/pr051219.html

CzechLight


CzechLight (April 2005)
TransLight Amsterdam
10G OC192c
Germany
Poland
lambda service for CzechLight
leased fibre pair
TransLight point (n x GE)
dB Line Attenuation at 1550nm
Praha
1GE
NIL, OSA
159,4 km
36,7 dB
Plzeň
10G
DWDM OC 192c
298,3 km
66,5 dB
Ostrava
Brno
Slovakia
Austria
0 km
50 km
100 km

CzechLight, GLIF



CzechLight Amplifiers Features

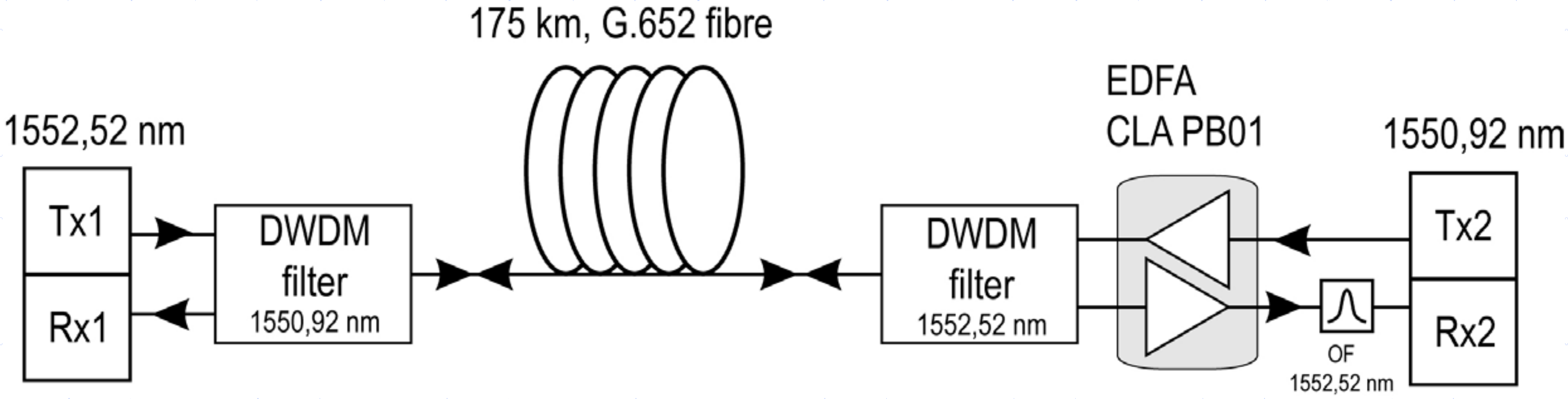
- Redundant PSUs from industry leading vendor
- DC voltages, fan speeds, temperatures are monitored
- Runs on flash disc (no vibration sensitive rotational parts), Linux based
- Interfaces: RS232, FastEthernet, USB, I^{2}C
- Extensive management capabilities – console, LAN, GSM/GPRS, Wi-Fi, BlueTooth, SSH, SNMP

CzechLight Amplifiers

- CLA PB01 – preamplifier and booster, applicable as: DF link terminating OAs, inline OAs with CD compensation and for one side amplified (OSA) DF links
  - OSA – all components are located at one place, star topologies
- CLA DI01 - dual inline OA, used during iGrid2005 and SC2005 experiments
- Now looking for manufacturers/partners

CzechLight Amplifiers

- OSA (One Side Amplification) – all components are located at one place, for star topologies



CzechLight Compensators

- To eliminate effects of Chromatic Dispersion
- A big issue for 10 G speeds (and beyond) in 1550 nm
- Dispersion compensation fibres – lossy, bulky and expensive
- Fibre Bragg gratings – a relatively new element, DWDM laser is a must (narrow band), today FBGs can compensate for 51 DWDM channels
  - Signal filtering, spectrum shaping
- Cost effective solution
- Tuneable FBGs, not possible with DCFs (for e2e lightpaths, lambdas on demand)
- CLCs (an FBG plus management capabilities)

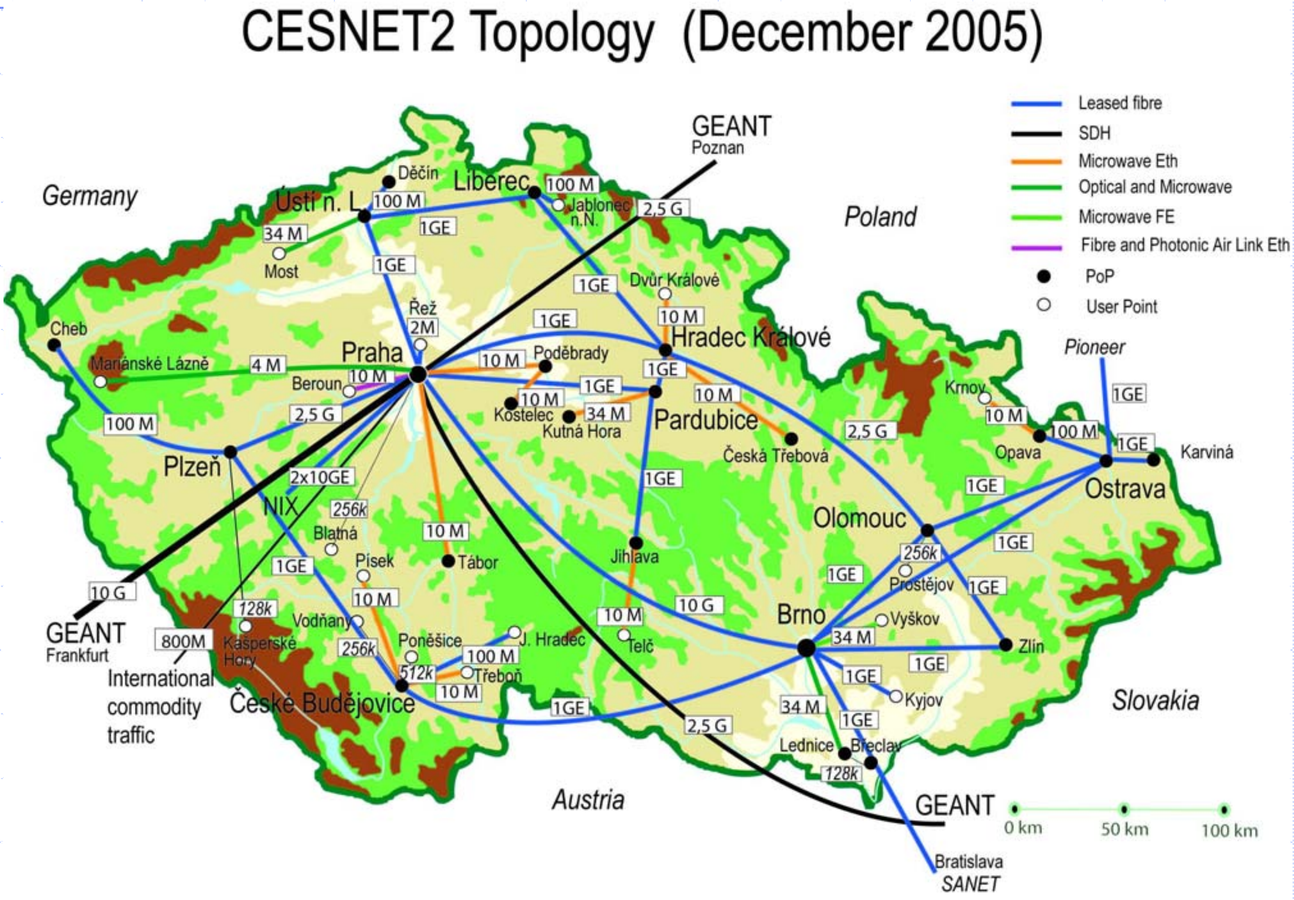
CzechLight OOO switches

- The last component for a transparent optical network
- ROADM vs. OOO switches
- 8 x 8 switching nonblocking matrix (16 x 16 in future)
- RS232 for configuring
- Management dtto CLAs

CLAs Deployment

- Both in CESNET2 (production) and CzechLight (experimental and breakable) networks
- Praha – Hradec Králové (CESNET2)
  - 150.4 km of G.652, 35.7 dB@1550nm
  - NIL, OSA (one side amplification) w/ CLA, 1 GE
  - From Dec 2004 till Dec 2005, working without any problem
  - CLA now moved to other edge link
- New 10 G Cross Border Fibre links to Poland and Austria are being prepared
- 10 G CBF to Slovakia operational (4 x 10 Gb/s)

CESNET2


CESNET2 Topology (December 2005)

CLAs Deployment

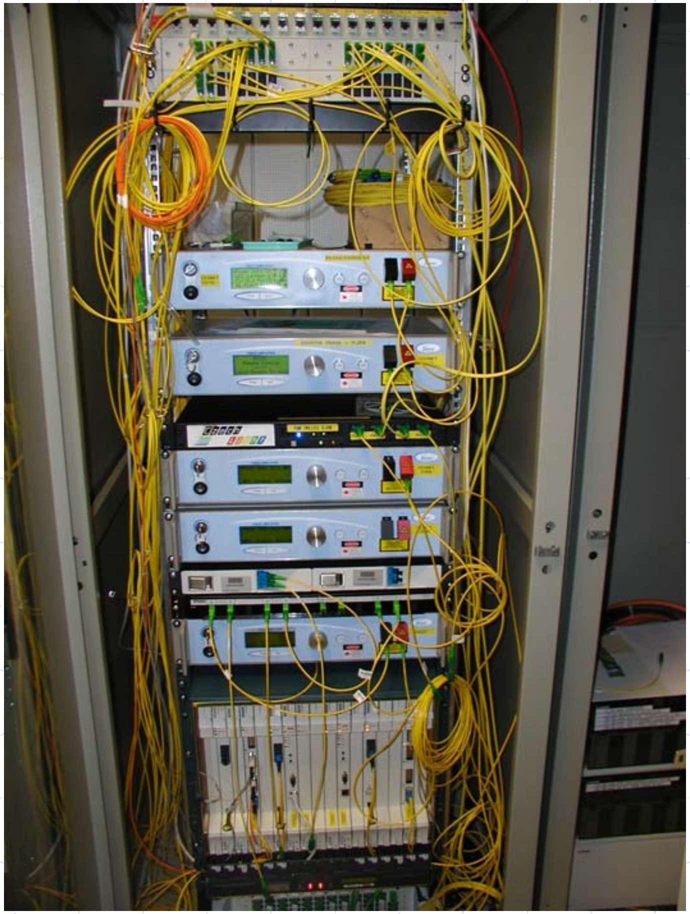
- Praha – Brno (CzechLight)
    - 298 km, mixture of G.652/G.655+/G.655-, 67 dB@1550nm
    - Not NIL solution, without Ramans but with one inline CzechLight amplifier (DI01)
    - Today 1 channel, 10 G SONET, DWDM transceivers, ready for up to 8 (16 with high power boosters and inline amps) 10 G DWDM SONET/SDH/Ethernet channels
    - Deployment of (tuneable) FBGs and ROADMs/OOO switches is already planned

CLAs Deployment

- A bit of History :-)
  - Started with 302 km of mixture of G.652/G.655+ fibre spools, EDFAs and Ramans, 65 dB@1550nm - working fine
  - 297 km testing fibre loops, in the ground, mixture of G.652/G.655+/G.655-, 66 dB@1550nm - working fine
  - The „true“ 298 km/67 dB line Praha – Brno was (and still is) sort of bewitched, the BER was too high for our NIL configuration with Ramans :- (

CLAs Deployment

- Praha – Hradec Králové (CESNET2)
- The rest of a rack is for CzechLight



CzechLight Equipment and NIL

- 302 km, 1 x 10 G DWDM channel, in lab on fibre reels
  - With Raman amplifiers and dispersion compensating fibres
- 250 km, 4 x 10 G DWDM channel, in lab on fibre reels
  - Without Ramans, with Fibre Bragg gratings
- 135 km, 1 x 10 GE, 1310 nm!, in lab on fibre reels
  - No CD compensation at all, PDFA and Ramans for 1310 nm
- One historic footnote from February 2003 (TF - NGN, Rome)
  - **10 Gigabit Ethernet**
  - **In my opinion, we can go over 40 km :-)**
  - **Again, our goal is Nothing-In-Line solution**
  - **The latest result: 252 km, 2 x 10 GE grey 155O nm channels**

Conclusions

- Development and deployment of new components
- Especially important (in our opinion) for academic and research community
- The results will (may) be used in a successor of SEEFIRE, GN2 (Joint Research Activities), Porta Optica
- Cross Border Fibre solutions
- Metropolitan Area Networks, Regional Optical Networks

Acknowledgement

- Lada Altmanová, Miroslav Karásek, Václav Novák, Martin Míchal, Stanislav Šíma, Karel Slavíček, Josef Vojtěch and Jan Gruntorád

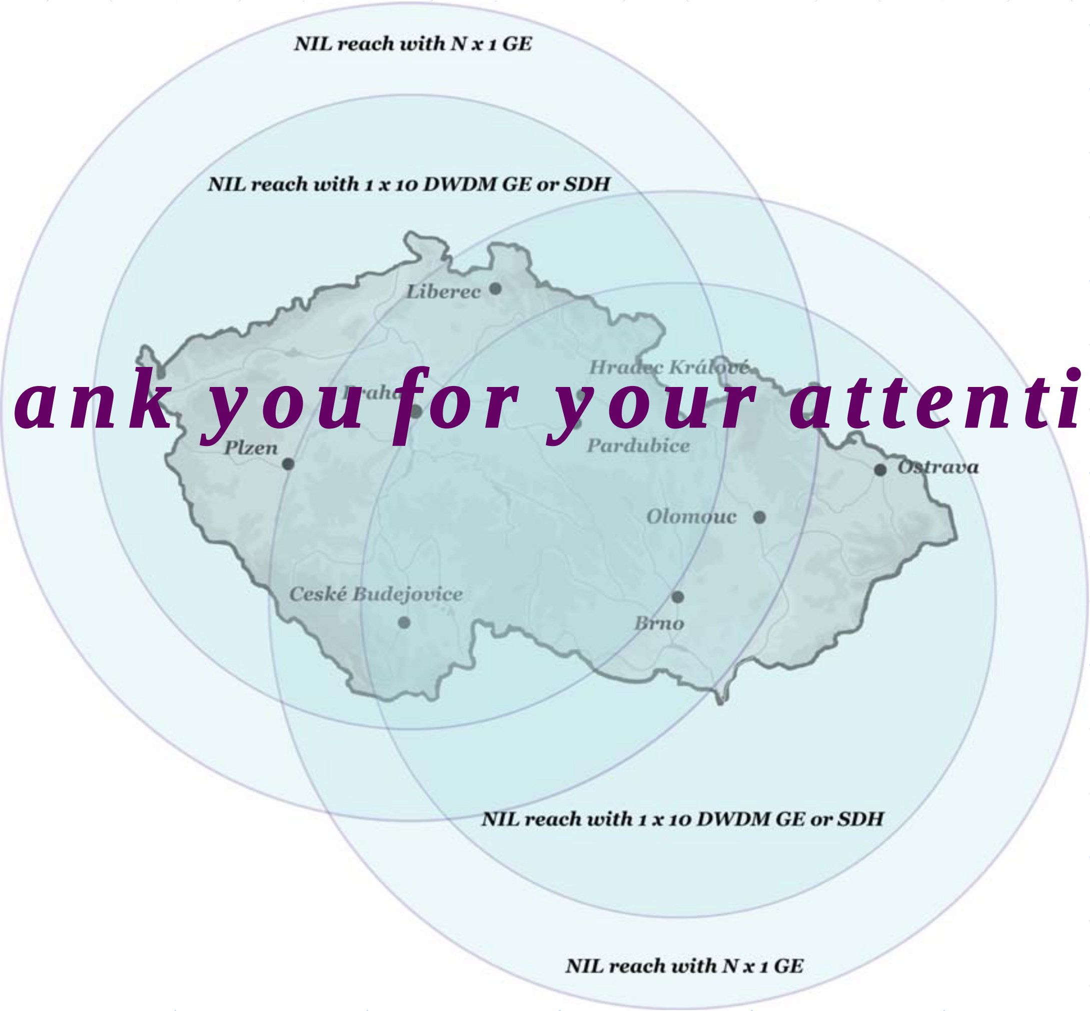
References 1

- [1] Agrawal G.P., „Fiber-Optic Communications Systems‟, 2002.
- [2] Kartalopoulos S.V., „DWDM Networks, Devices and Technology‟, 2003.
- [3] Ramaswami R., Sivarijan K.N., „Optical Networks‟, 2nd edition, 2002.
- [4] Radil, J. - Karásek, M., „Experiments with 10 GE long-haul transmissions in academic and research networks.‟, In: I2 member meeting, Arlington, VA, 2004.
- [5] Vojtěch J., „CzechLight and CzechLight amplifiers‟. In: 17th TF-NGN meeting, Zurych, Switzerland, April 2005.
- [6] Vojtěch J., Karásek M., Radil J., „Extending the Reach of 10GE at 1310 nm ‟. In: ICTON 2005 meeting, Barcelona, Spain, 2005.

References 2

- [7] www.seefire.org, Deliverables
- [8] czechlight.cesnet.cz, Publications
- [9] ECOC 2004 , 2005 proceedings
- [10] OFC 2004 , 2005 proceedings

Optical networks and equipment



Thank you for your attention!