Mai 2008

WDM

Wavelength Division and Multiplexing

Structura cursului

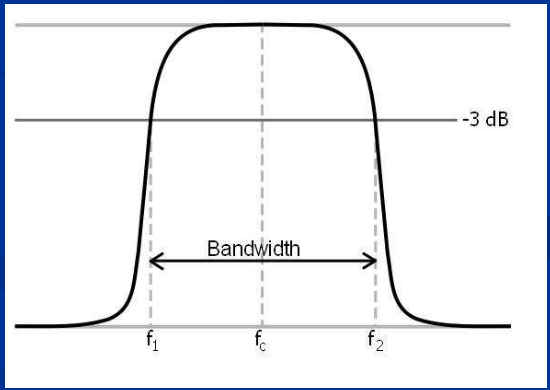
- Consideratii teoretice
- WDM design
- Configurare WDM (management echipamente) – Exemplu Aplicatie WDM pentru un centru de emisie audio/video

1. Consideratii teoretice

Domeniu de lungimi de unda	1260nm 1360nm	1360nm 1460nm	1460nm 1530nm	1530nm 1565nm	1565nm 1625nm	1625nm 1675nm
Numele conventional, ITU	O-band Original	E-band Extended	S-band Short	C-band Conventional	L-band Long	U-band sau L+ -band Ultralong band

-multiplexarea a mai multor λ, diferite, provenind din regiunea spectrala acoperita de benzile conventionale O pana la L, pe o singura fibra optica, simultan

-capacitatea fibrei este nelimitata, datorita pierderilor mici; capacitatea de transmisie este limitata de echipamentele electronice de emisie-receptie (tip raspuns pentru modularea semnalului = cel mult 8 biti pe sec -> limitare la aprox. 10 GHz sau 10Gbps) In consecinta fibra ar putea transmite de 10.000 ori mai multa informatie



Exemplu (IBM):

Expressed in terms of analogue bandwidth:

- a *1 nm* wide waveband at 1500 nm has a bandwidth of about *133 GHz*. X latimea benzii de 100nm = 13,3 x 10^{12} Hz
- a *1 nm* wide waveband at 1300 nm has a bandwidth of *177 GHz*. X latimea benzii de 150nm = 26,5x10^{12} Hz

In total, this gives a usable range of about *40 Tera Hertz* (4 × 10^{13} Hz) supported by optical fiber.

Limitare latime de banda (bandwidth) datorita fenomenului de dispersie cromatica

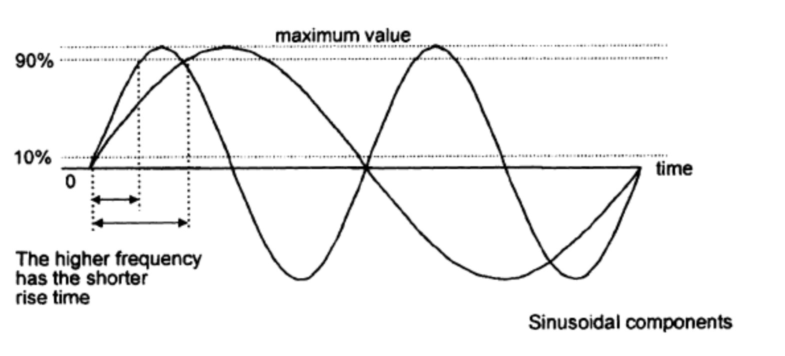
- Formule dimensionare
- **σ=D(λ) x Δ λ x L [ps],**
  - D(λ)<=3,5ps/nm/km pentru 1285 <λ<1330 nm
  - D(λ)<=17ps/nm/km pentru 1525 <λ<1575 nm
  - Δ λ – latimea spectrala a emitatorului
  - L-lungime fibra

  B (Latima de banda Bandwidth monomod) = 0.44/ σ

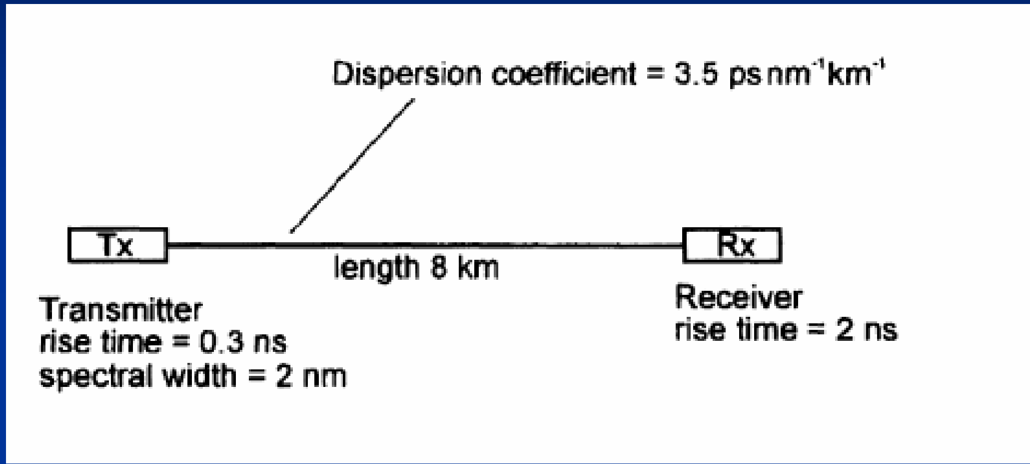
  t (Timp crestere fibra, 90% val impuls -Rise time) = 0.35/B

$$t_{total} = \sqrt{t^2_{emitator} + t^2_{fibra} + t^2_{receptor}}$$

  - **Tpuls>= 1.5 x t**
  - **NRZ (Gbps)=1/ Tpuls <= 0.67/T [ns]**



Exemplu



1. Dispersia fibrei : D=3.5ps/ nm/km x 2 x 8 km = 56 ps/ nm/km
2. LAtima banda B= 0.44/ D= 0.44/ (56 x 10 e -12) = 7.86 GHz
3. T fibra = 0.35 / B = 0.35/ 7.86 GHz = 0.35/ 7.86 x 10e9 = 44.53 ps
4. T total = $t_{total} = \sqrt{t^2{}_{emitator} + t^2_{fibra} + t^2_{receptor}}$

   t total= (0.3 ns ^ 2 + 44.53 ps ^2 + 2 ns ^2)^1/2 = 2.02 ns
5. B sistem=0.35/t total =0.35 / 2.02 ns = 173,3 MHz << 40 THz capacitate fibra

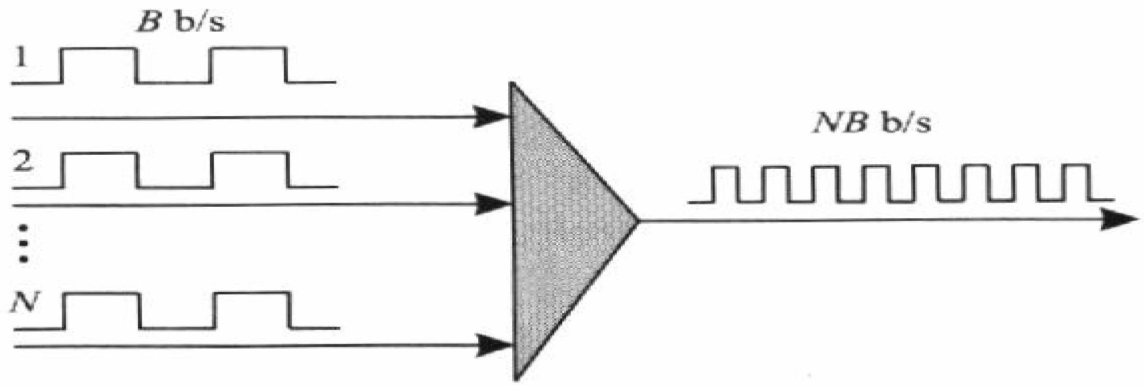
Caracteristici de baza ale WDM

- **Cresterea capacitatii** – daca o λ suporta o transmisie independenta de zeci Gbps, atunci fibra suporta o transmisie care creste cu fiecare λ aditional (crestere latime de banda)
- **Transparenta**- fiecare canal de transmisie suporta orice format de transmisie simultan si independent: informatie analogica, date digitale sincrone, asincrone- (Synchronous transmissions are synchronized by an external clock, while asynchronous transmissions are synchronized by special signals along the transmission medium.).
- **Rutare de lungimi de unda** – calea de transmisie a unui semnal poate fi routata (route/switch/cross-routing) prin conversia de λ la nodurile intermediare ale retelei (cap 17)
- **Scalabilitate** – adaugare usoara de echipamente, atunci cand e nevoie, pentru marirea capacitatii si extinderii retelei

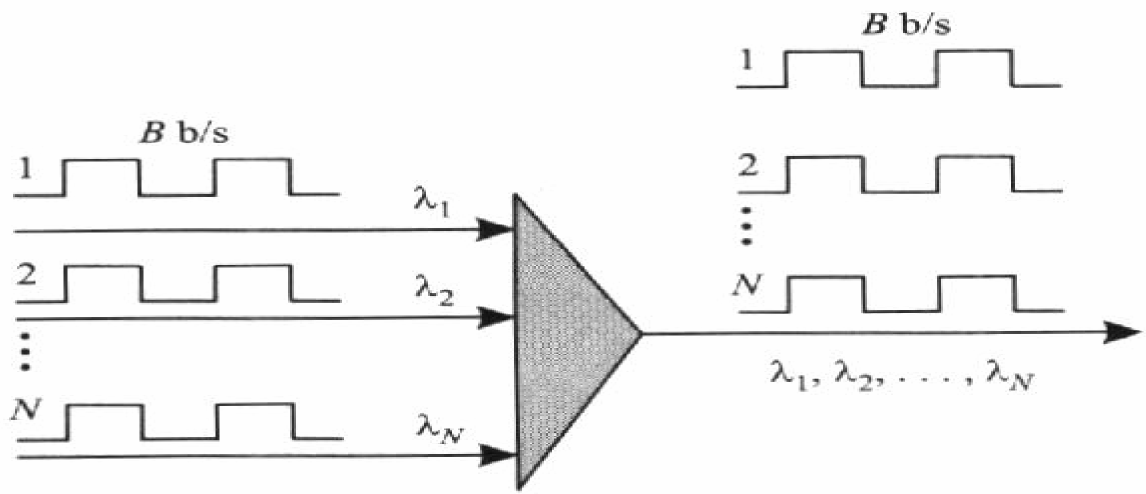
Tipuri retele WDM

- **TDM (Time Division Multiplexing) –** fiecare canal de comunicatie transmite cand ii vine randul (I se aloca o 'felie de timp'). Datele sunt multiplexate pe o singura fibra optica. Dezavantaj – timpi morti- alocare 'felie timp' pentru canale care pot sa nu aiba de transmis nimic.
- **CWDM (Coarse Wavelength Division Multiplexing)** –18 λ pe o singura fibra optica.
  - standardul ITU G.694.2 - distanta de 20nm intre λ consecutive, de la 1270nm la 1610nm. Transponderele nu sunt scumpe, datorita acestei distante mari intre canale.
  - Lungime retea: pana la 50km. Solutii LOW COST pentru short-haul (Metro Optical Network).
- **DWDM (Dense Wavelength Division Multiplexing)** - 64 λ pe o singura fibra optica.
  - technologia foloseste standardul ITU - distanta de 100GHz sau 200GHz – (0.8nm) - intre λ, aranjate in benzi intre ~1500-1600nm.
  - Transponderele sunt mai scumpe datorita densitatii canalelor, ceea ce face tehnologia lor mai complexa.
  - Avantajele: distanta mare (de la 200km la 600km) si densitatea mare
  - AZI: 16, 32,64,128,160 canale (lungimi de unda transmisa, fiecare la 10 Gbps, si spatii standard de 25, 50, 100, 200 and 1000 GHz (ITU) sau cu alte cuvinte 0.4-1.6 nm
- **Super-WDM** – NTT (**Nippon Telegraph and Telephone)-** prima retea cu 1000 λ pe o singura fibra. Este nevoie de dispozitive optice speciale, de mare precizie:

-emitator supercontinuu care genereaza 1000 λ la distanta fixa (6.25 GHz, adica de 8x mai dens decat orice retea existenta), mux/demux SDWDM, filtru super AWG



TDM or OTDM mux



WDM mux

Schema de principiu sistem WDM

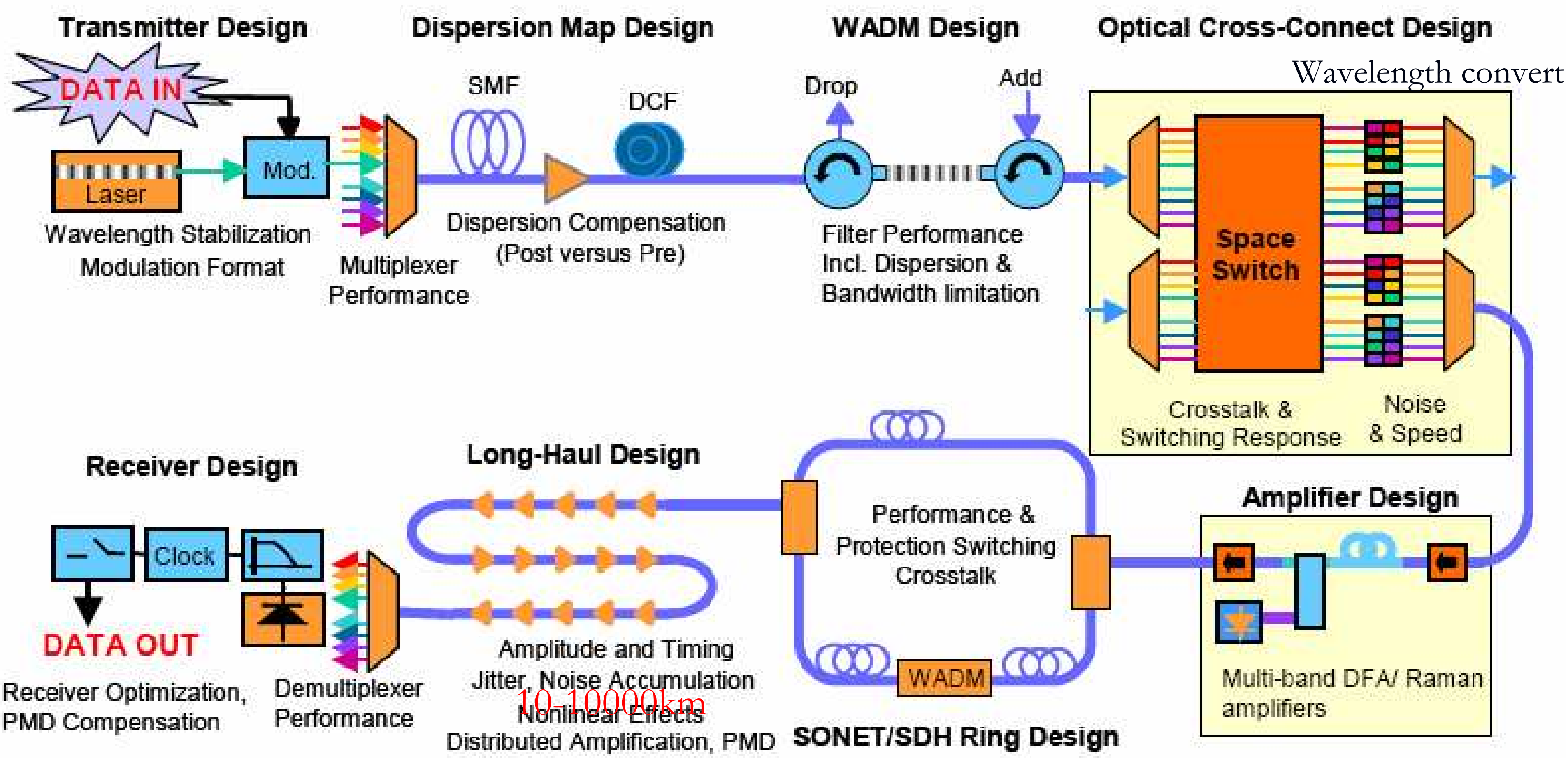
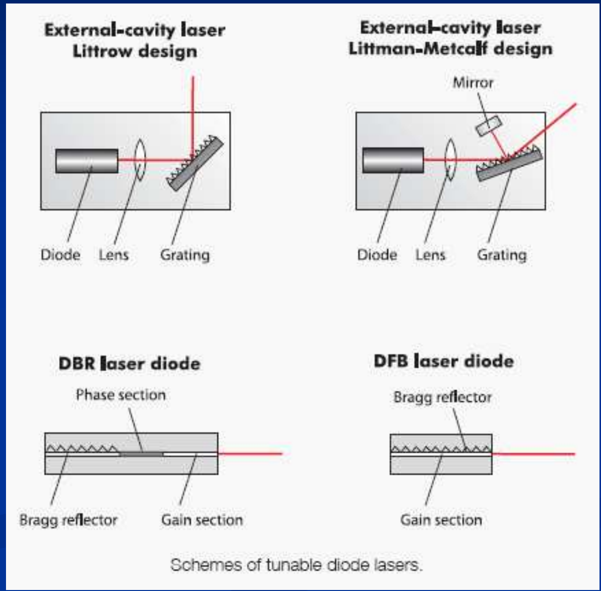


Figure 1-1 *Illustration of most potential design problems in a photonic system*

Principiul de functionare

1. **Emitatoare** – tunable lasers: utilizeaza retea de difractie Bragg in interiorul cavitatii pentru selectia unui spectru ingust de emisie.

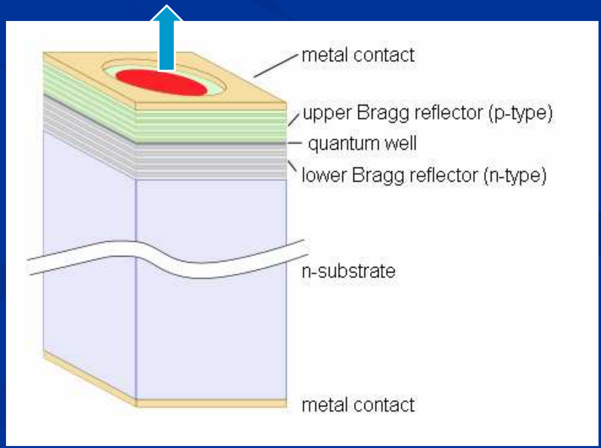
- pot emite la lungimi de unda (peak wavelength) la distanta de doar cativa nanometri, astfel incat sa nu existe interferenta intre canale (crosstalk) -chirped
- aceasta frecventa de emisie (peak wavelength) tb sa fie strict controlata pentru a nu se produce fenomenul de 'alunecare' (drift) peste teritoriul emisiei altui canal. Astfel se prevede o banda de 'garda' (empty guard band – conform ITU-T) intre canale -> receptia fidela a fiecarui semnal individual (eliminare efect SRS 'stimulated Raman scattering' si '4-wave mixing', cade in banda de garda)



Schemes of tunable diode lasers.

- **Distributed feedback (DFB) semiconductor lasers,**
- **vertical cavity surface emitting lasers** (VCSELs)
  - fosfat de indium (InP) la 1300 nm -> 2000 nm
  - Arseniura de galiu (GaAs) la 650 nm -> 1300 nm
- **Sample Grating Distributed Bragg Reflector lasers** (SGDBR)

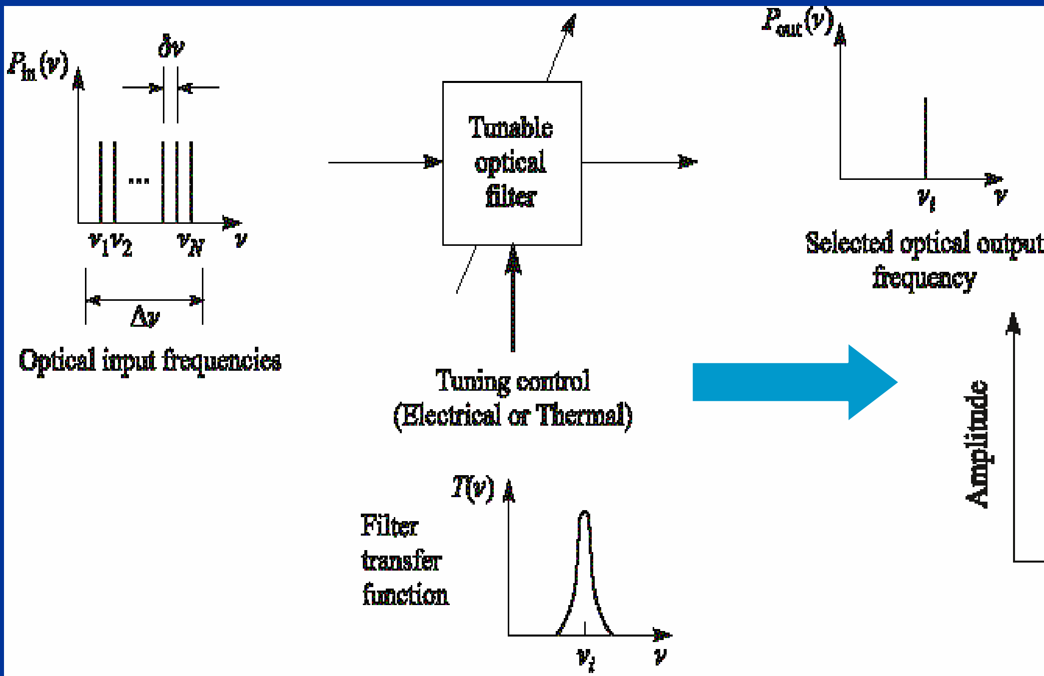
  ->1522 la 1573 nm , Putere: Aprox 30dB



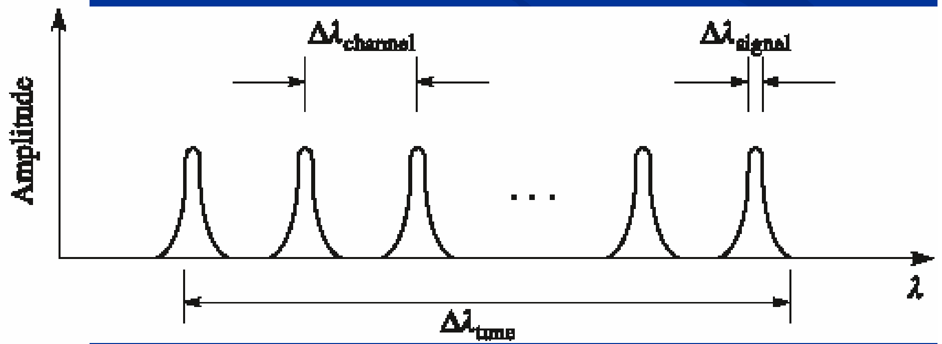
- **Fabry-Perrot (FP)** - Lasere multimodale utilizate in mod functionare imediat sub pragul de laserare, au o caracteristica spectrala cam cum ar fi utilza in cazul WDM (sub prag laserare apare fenomenul de fluorescenta), puterea de emisie a fiecarui lamda este aprox constanta - Se pot folosi multiplexoare selective (wavelength selective mux)
- **Lasere acordabile** (tuning lasers) - lasere uni-modale, cu latimea benzii spectrale de 1nm. Reglajul trebuie sa fie rapid, pentru selectia lungimii de unda dorite
  - Sunt sensibile la (vezi tuning control block):

    1. modificarile de temperatura (0.1 nm/^{O}C) –> cooler, si

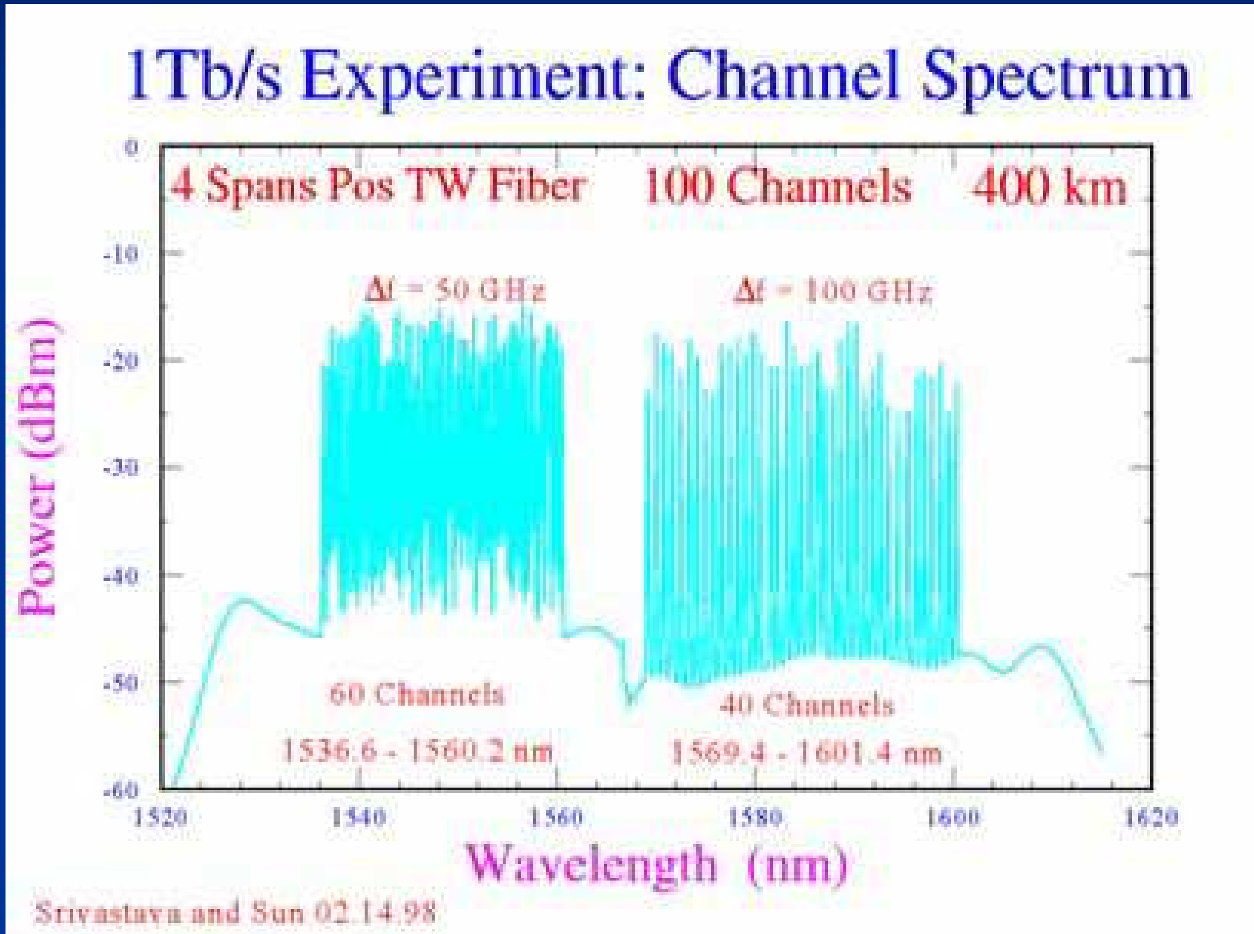
    2. modificarile curentului de injectie (0.006 nm/mA) daca controlul se realizeaza electric
  - Selectia trebuie sa se realizeze exact pentru a nu aparea fenomenul de ‘alunecare’ a unui canal peste celalalt (distanta de garda intre canale standardizata ITU-T)



$$|\Delta\nu| = \left(\frac{c}{\lambda^2}\right)|\Delta\lambda|$$



Exemplu emisie WDM



nivelul de putere al canalelor trebuie sa fie egal, altfel pe distante mari apar efecte nedorite datorita amplificarii inegale a semnalelor

2. Alte componente optice ale unui sistem WDM

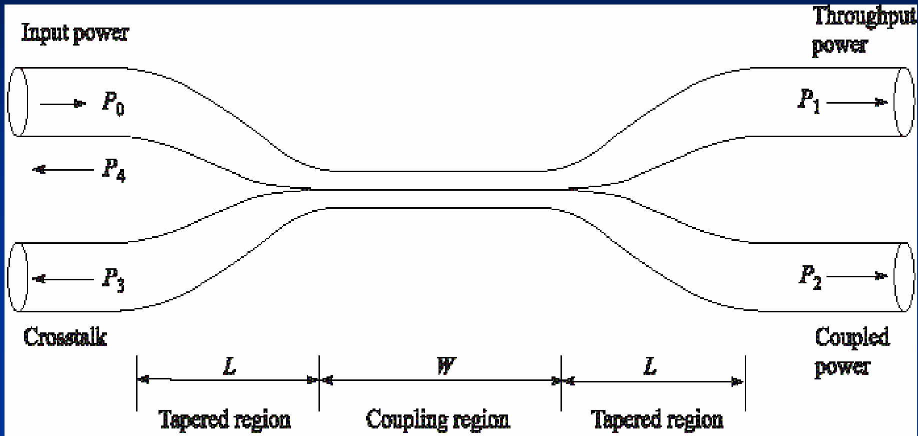
- Fibra optica: DOAR MONOMOD
- Amplificatoare – Dopate cu pamanturi rare – mediul activ= fibra optica dopata cu pamanturi rare (pamanturile rare introduc nivele intermediare intre nivelele Fermi ale mediului initial): EDFA (Erbium), YDFA (Ytterbium), TDFA (Thulium), PDFA (Praseodinium)
  - Exemplu: EDFA – pompaj la 890 sau 1480 nm in fereastra 1550, YDFA la 860 -> 1064 in fereastra 975-1150nm

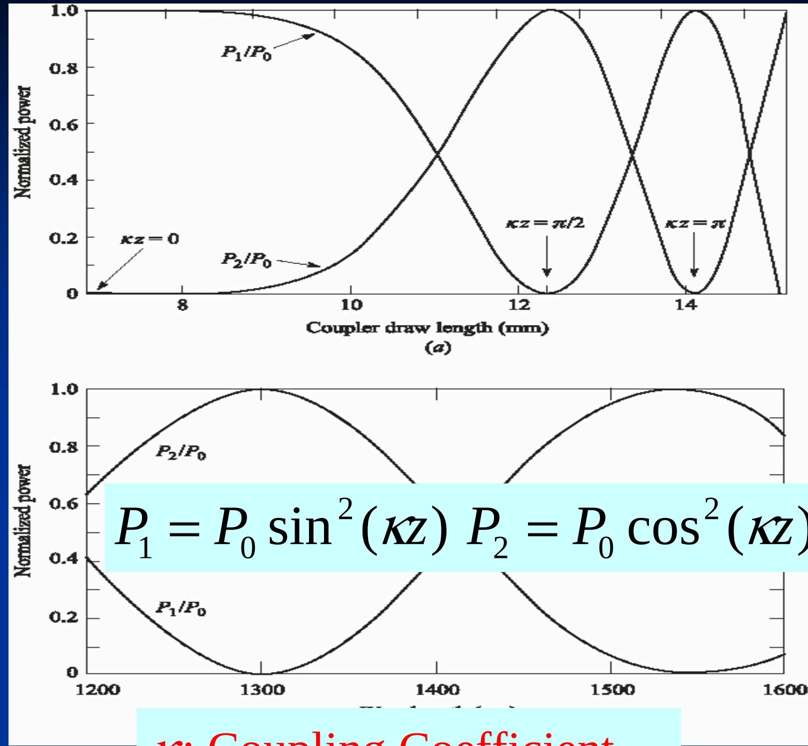
    - Raman – mediul activ este chiar fibra optica (folosite in config hibrida banda L) – pompa($\lambda 1$) la distanta de 13.5Thz(90nm) de semnal($\lambda 2$), $\lambda 1 < \lambda 2$. amplifica cel mai mult semnalul. (stoke shift) Semnalul amplificat pe un interval de 30nm (regiune de amplificare)

    - aceste tipuri de amplificatoare sunt utilizate in configuratie: codirectionala, contradirectionala, mixta

    - topologie: post amplificator, preamplificator (booster), in-line
- Retele de difractie, cuploare, splittere, interferometre, AWG
- Multiplexoare/Demultiplexoare (Wavelength Add/Drop Multiplexer –WADM sau OADM, OXC – Optical cross connect)
- optical interleaver and de-interleaver – componente optice de intretesere/combinare a canalelor DWDM
- DCF- fibre compensatoare de dispersie – Fibra standard ~ 17 ps/nm/km; DCF are (-100) ps/nm/km
  - Exenplu: fibra de 100 km standard urmata de o fibra DCF de 17 km → dispersie zero
- TRANSMISIE CU SOLITONI – unda electromagnetica care se propaga isi mentine forma si viteza (frecventa) pe distante mari, datorita compensarii dintre efectul neliniar Kerr (modificarea dupa o functie neliniara, a indicelui de refractie al miezului fibrei) si fenomenul de dispersie.

Componente optice elementare folosite in sisteme WDM



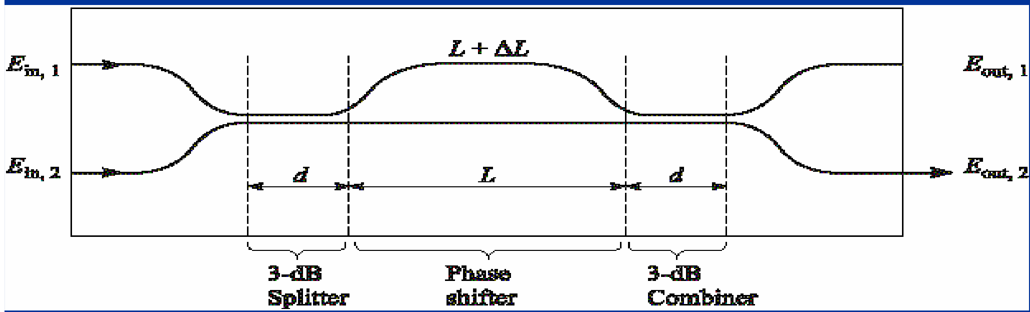


$$P_1 = P_0 \sin^2(\kappa z) \quad P_2 = P_0 \cos^2(\kappa z)$$

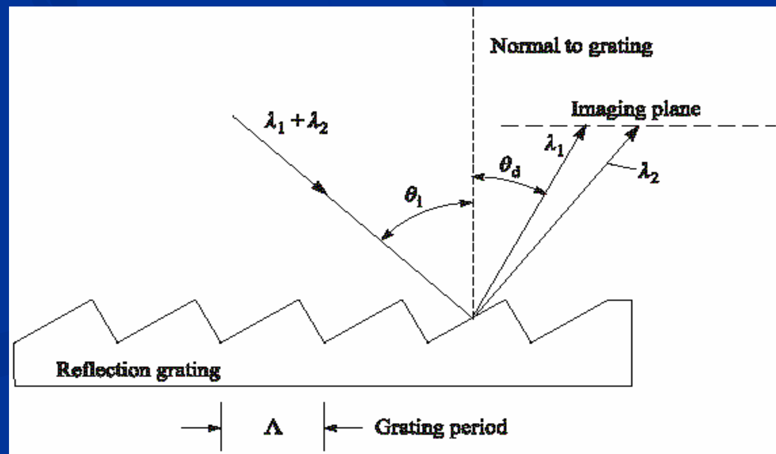
κ: Coupling Coefficient

1. Cuplor –> sisteme cu canale putine
   -> sist. Canale multe tb amplif

•Coupling / Splitting Ratio = *P2/(P1+P2)*



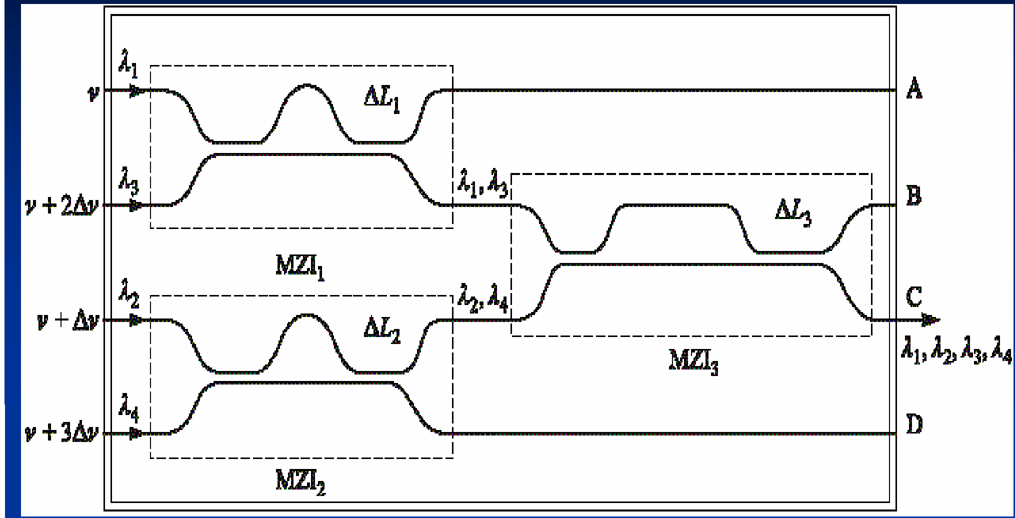
2. MZ – interferometrul Mach-Zehnder

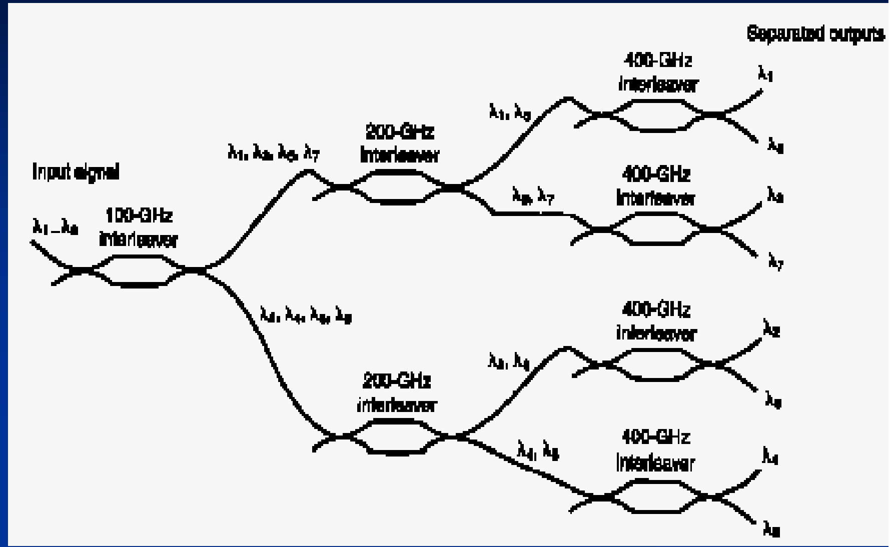


4. Circulator-1dB atenuare tipica

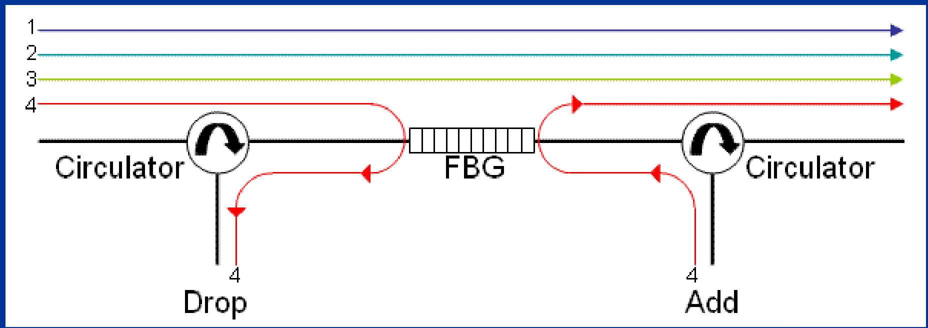
3. Retea de difractie –> canale multe

Exemple de componente optice complexe folosite in sisteme WDM

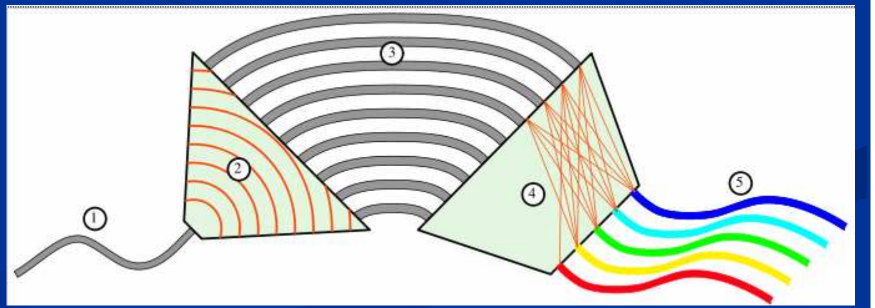




Multiplexor respectiv demultiplexor realizat cu MZI (Mach-Zehnder Interferometer)
8 iesiri a splitterelor 3dB - atenuare de 9dB



Add-and-Drop Multiplexer



AWG-arrayed waveguide grating
Power-loss – 5dB , 64 canale

Marimi specifice : BER- Eye Diagram – p235

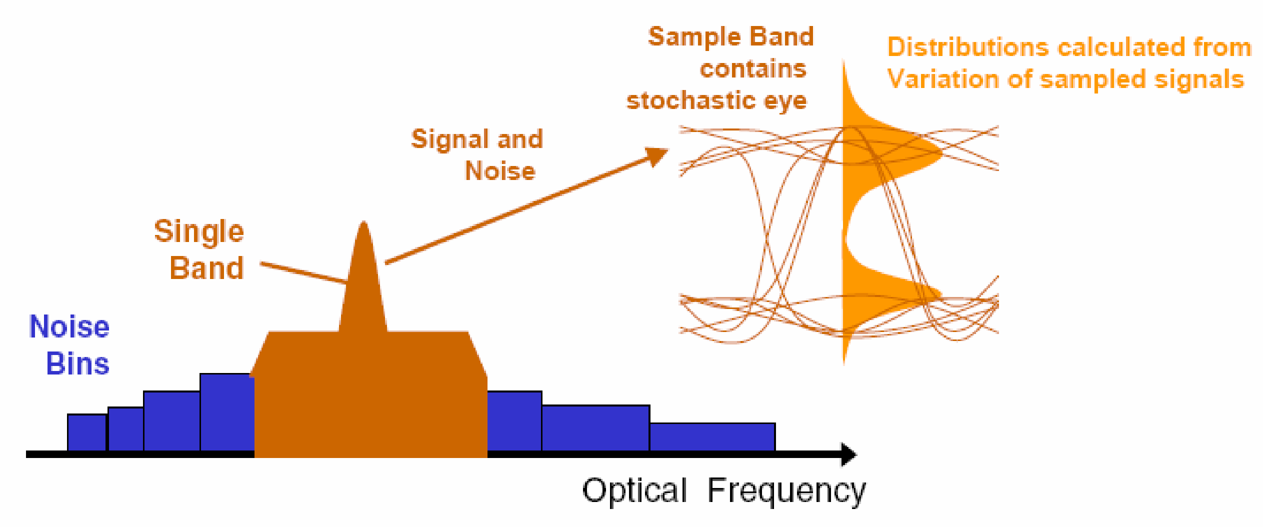
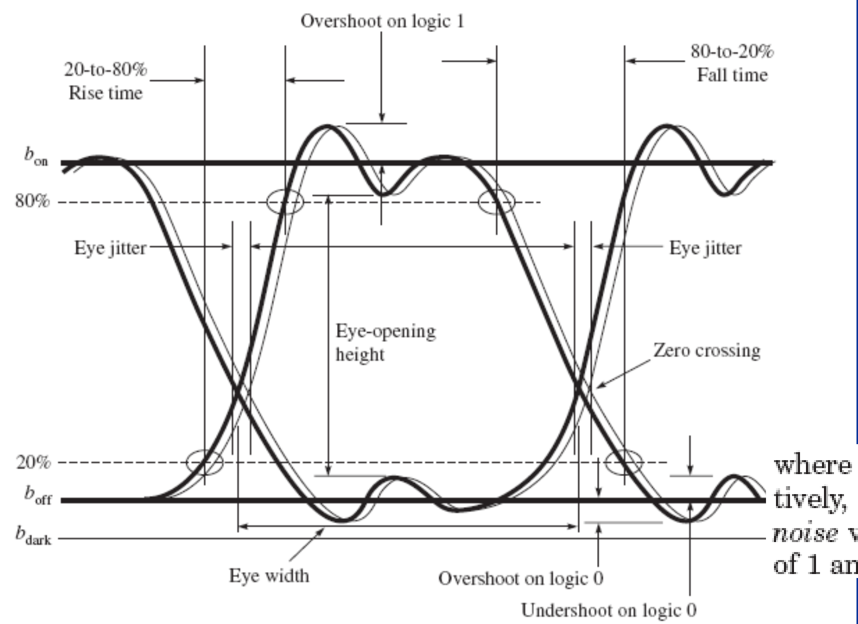


Figure 2-21 *Illustration of the stochastic BER calculation.*



$$\text{BER} = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} \exp\left(-\frac{x^2}{2}\right) dx \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-Q^2/2}}{Q}$$

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

BER=10^{-15}, Q=18dB

=10^{-12}, Q=16.1 dB

=10^{-9} Q=15.6 dB

where I_1 and I_0 are the average detected signal currents for 1 and 0 bits, respectively, and σ_1 and σ_0 are the corresponding detected *root-mean-square* (rms) *noise* values, assuming a non-return-to-zero (NRZ) code and an equal number of 1 and 0 pulses.

2. WDM design

- 2.1 - P 238, 271 – Keiser
- 2.2 - Cap 7 – VPI Photonics

2.1 Schema tipica DWDM

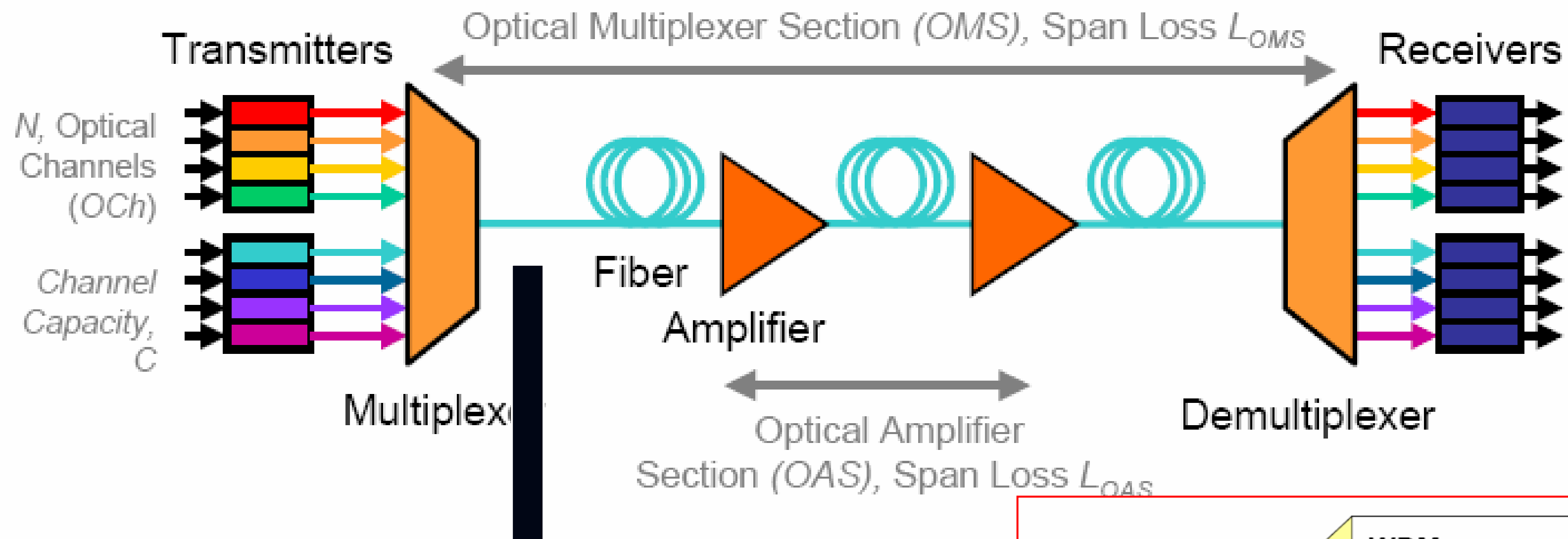
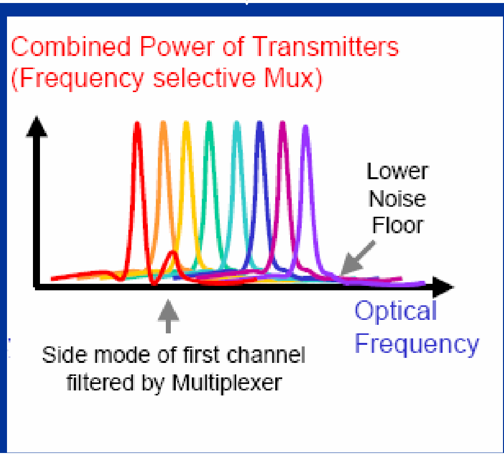


Figure 3-1 Ty... al WDM Optical Multiplex...



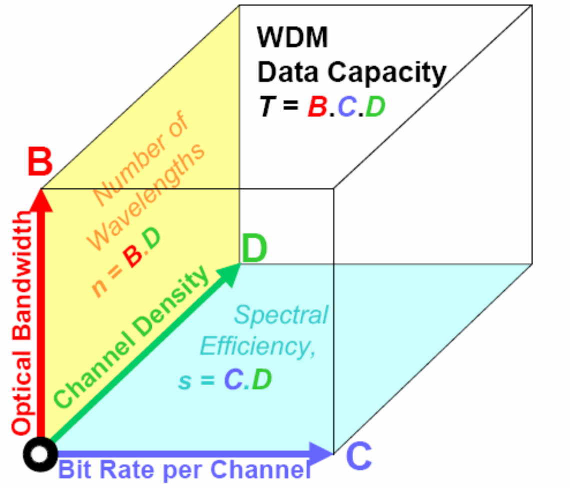
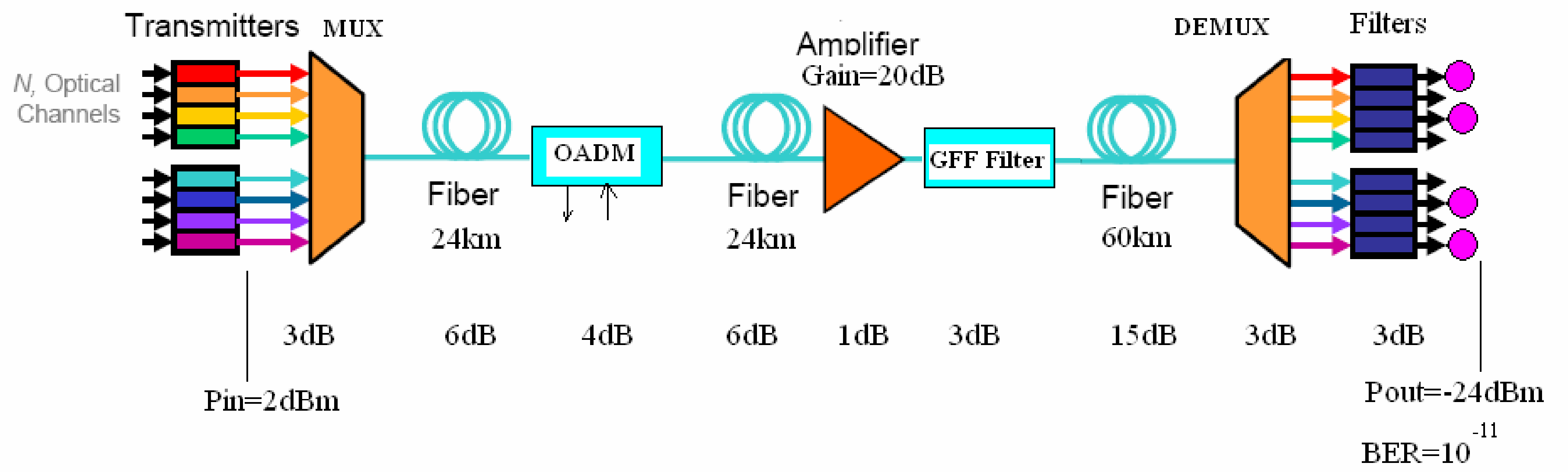


Figure 3-2 *WDM capacity can be related to the Volume (B.C.D) of a cube with sides: Optical Bandwidth, Bit Rate per Channel, and Channel Density*

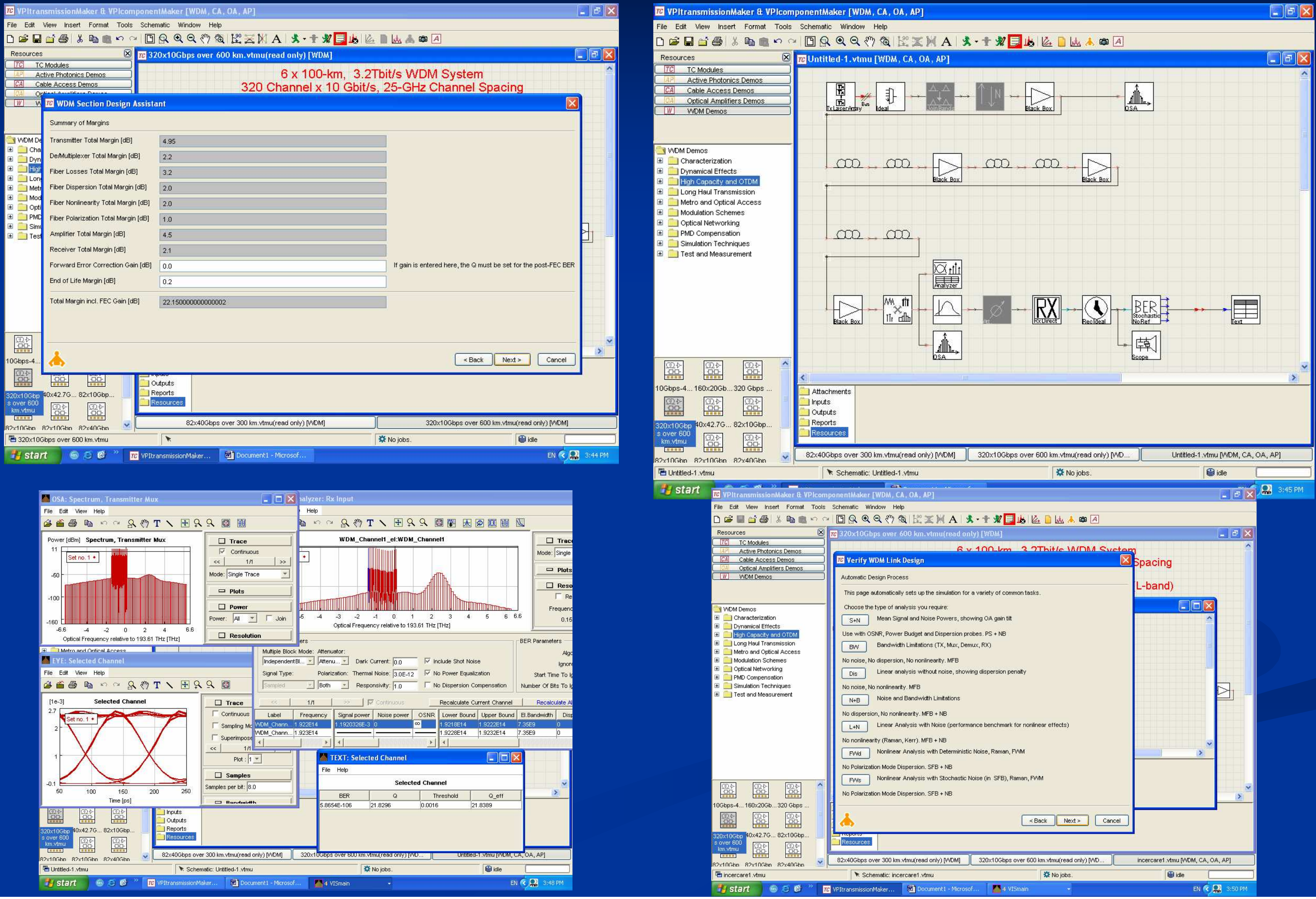


DWDM-
Exemplu proiectare

- Marginea de flux-

Component/loss parameter	Output/sensitivity/loss	Power margin, dB
Coupled laser diode output	+2 dBm	
APD sensitivity at 10 Gbps	−24 dBm	
Allowed loss [+2 − (−24)]		26.0
WDM mux loss	−3 dB	23.0
Cable attenuation (24 km)	−6 dB	17.0
OADM loss	−4 dB	13.0
Cable attenuation (24 km)	−6 dB	7.0
EDFA coupling loss	−1 dB	6.0
EDFA gain	+20 dB	26.0
GFF loss	−3 dB	23.0
Cable attenuation (60 km)	−15 dB	8.0
WDM demux loss	−3 dB	5.0
Optical filter loss	−3 dB	2.0 (final margin)

2.2 VPI Photonics - exemplu



WDM- margini de flux

ER linear = E(1)/E(0)

Table 7-1 *Margins used in the* Synthesize WDM Link *Design Assistant*

Margin	Comments	Typical Value
Transmitter Chirp Margin	Eye closure due to excess bandwidth of the transmitter compared with a chirpless modulator.	0.5 dB
Transmitter Extinction-Ratio Margin	Eye closure due to imperfect extinction ratio of the transmitter. Closure is worst for amplified systems. Typical margin is for a 10-dB extinction ratio.	1.0 dB (unamplified systems) 3.7 dB (amplified systems)
Transmitter Electrical Response Margin	Eye closure due to imperfect (i.e., not flat amplitude, not linear phase) response of the transmitter drive circuitry and laser parasitics.	0.5 dB upwards
Transmitter Aging Margin	Eye closure due to degradation of transmitter from beginning of life to end of life.	0.25 dB
WDM Multiplexer Bandwidth and Phase Margin	Eye closure due to imperfect (not flat) amplitude and phase (non-linear) response of optical multiplexer on desired channel.	0.5 dB (depends on channel density)
WDM Multiplexer Polarization Margin	Eye closure due to polarization dependence of multiplexer.	0.1 dB (depends on technology)
WDM Multiplexer Crosstalk Margin	Eye closure due to crosstalk from adjacent channels in an imperfect multiplexer.	0.3 dB (depends on channel density)
WDM Multiplexer Aging Margin	Eye closure due to degradation of multiplexer from beginning of life to end of life.	0.2 dB

Exemplu: Retea WDM de distributie semnale Video/audio (Fuji Television - Broadcast Center)

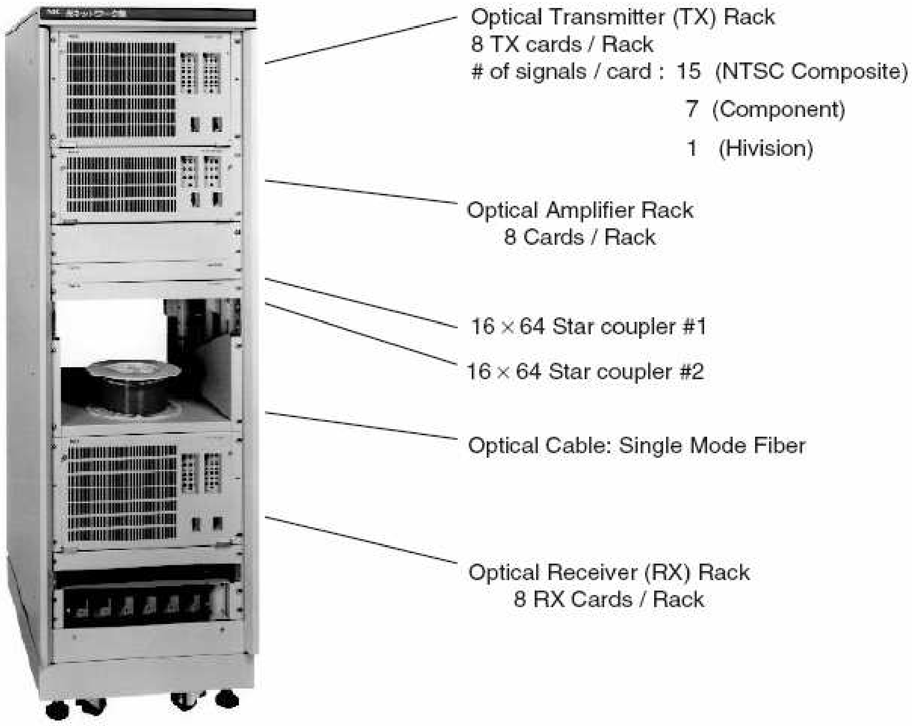
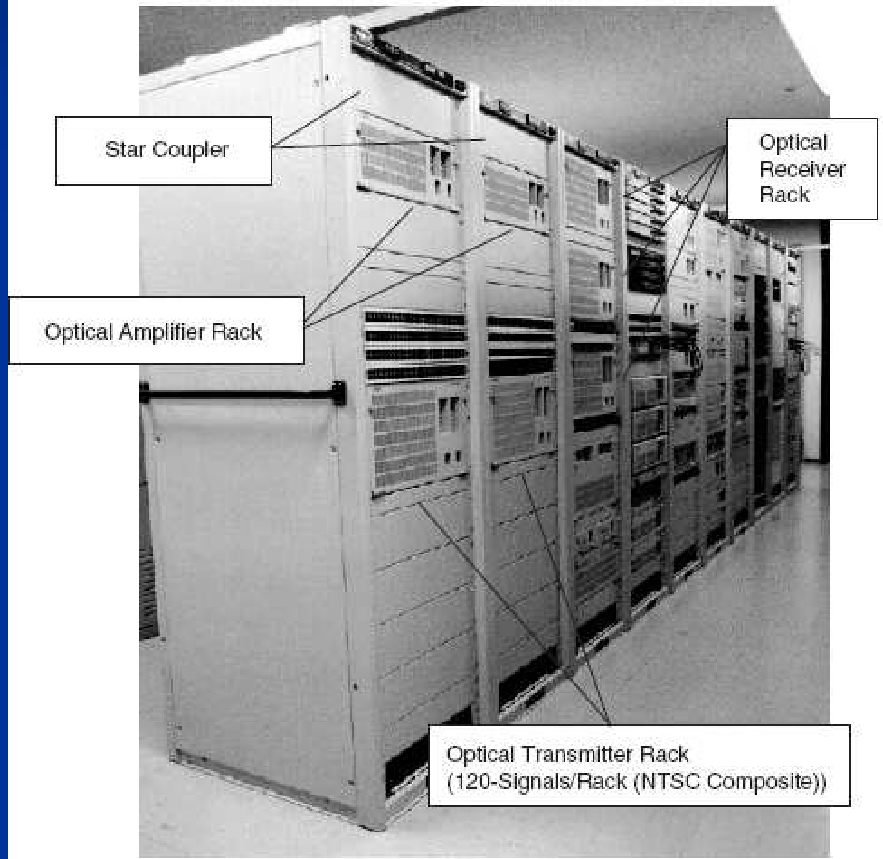


Fig. 7.22 Photograph of network equipment.

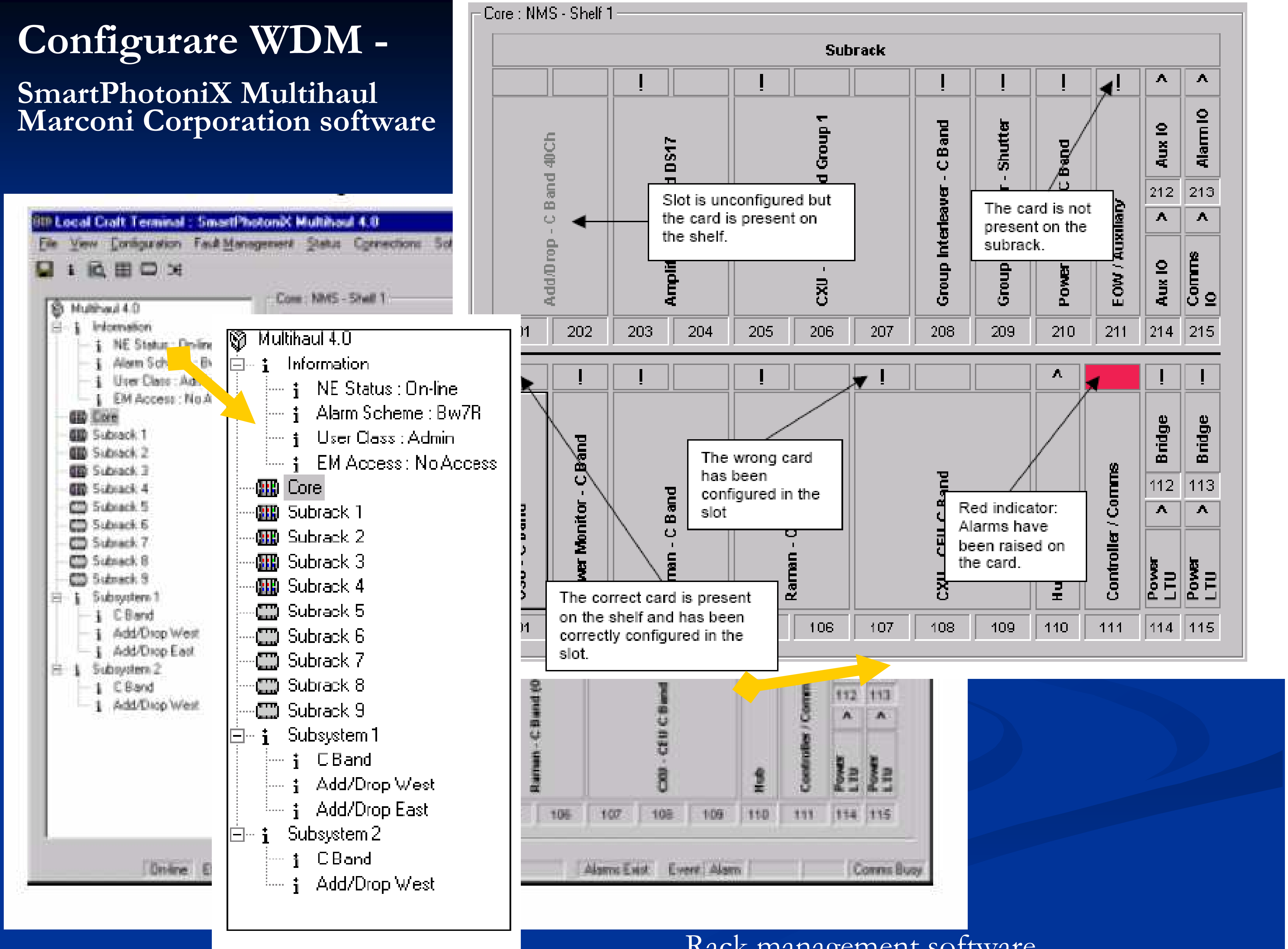
Format Rack



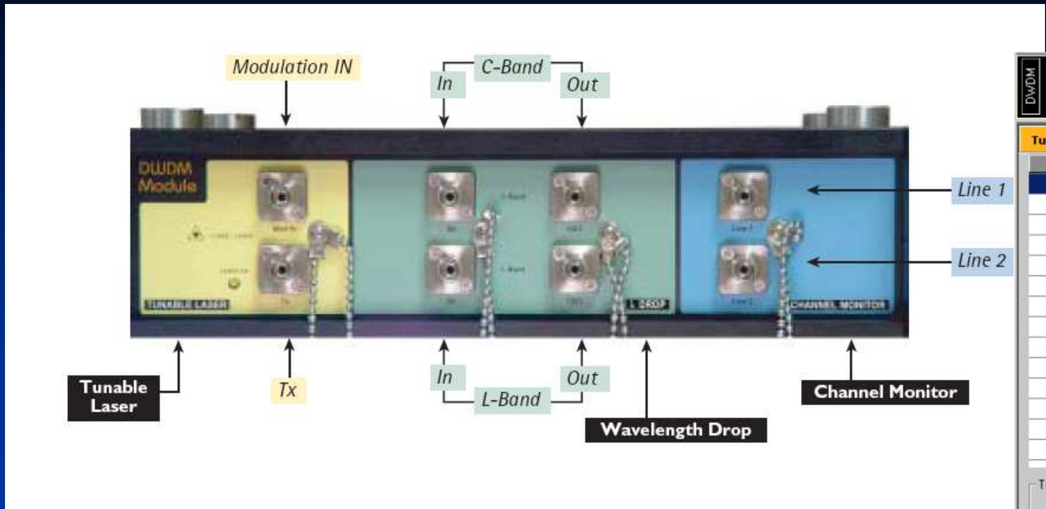
ig. 7.24 Racks for optical transmitter, amplifier, star coupler, and optical receiver units n the signal-distribution center.

Configurare WDM -

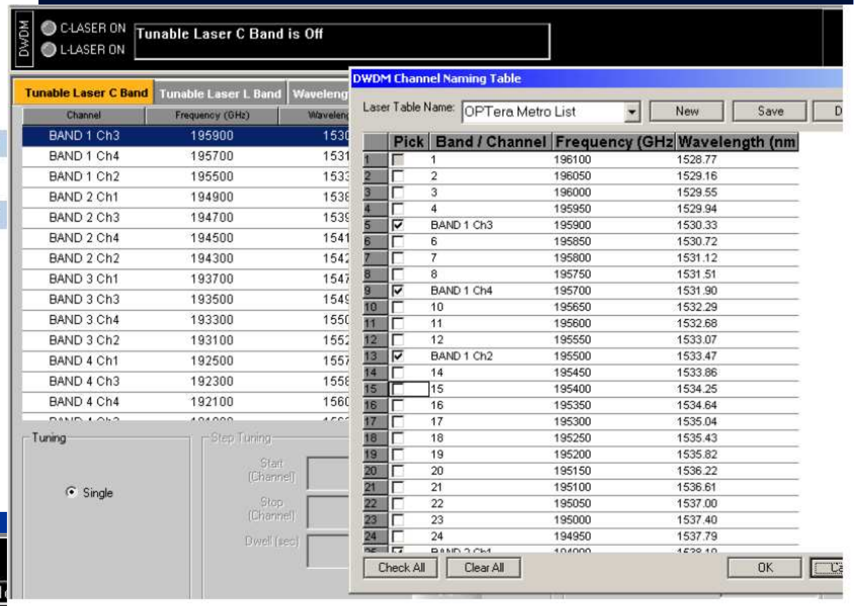
SmartPhotoniX Multihaul
Marconi Corporation software



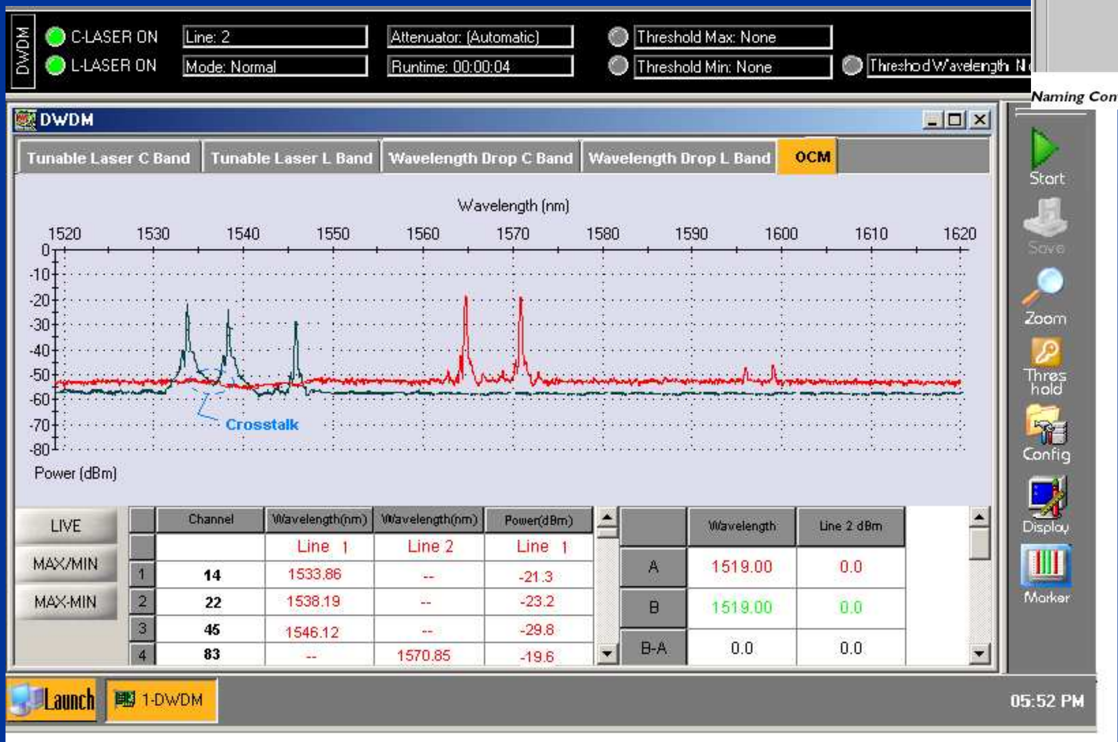
Rack management software



DWDM Module Connector Panel



Naming Conversion Screen



Standardul ITU- T G.694 (2002)

Table 1-1: C-Band Wavelength Allocation

Group C1				Group C2			
Frequency Groups	Channel No.	Frequency THz	Wavelength nm	Frequency Group	Channel No.	Frequency THz	Wavelength nm
	1	192.1	1560.61		41	192.05	1561.01
	2	192.2	1559.79		42	192.15	1560.20
	3	192.3	1558.98		43	192.25	1559.39
	4	192.4	1558.17		44	192.35	1558.58
1	5	192.5	1557.36	6	45	192.45	1557.77
	6	192.6	1556.55		46	192.55	1556.96
	7	192.7	1555.75		47	192.65	1556.15
	8	192.8	1554.94		48	192.75	1555.34
	9	192.9	1554.13		49	192.85	1554.54
	10	193.0	1553.33		50	192.95	1553.73
	11	193.1	1552.52		51	193.05	1552.93
2	12	193.2	1551.72	7	52	193.15	1552.12
	13	193.3	1550.92		53	193.25	1551.32
	14	193.4	1550.12		54	193.35	1550.52
	15	193.5	1549.32		55	193.45	1549.72
	16	193.6	1548.51		56	193.55	1548.91
3	17	193.7	1547.72	8	57	193.65	1548.11
	18	193.8	1546.92		58	193.75	1547.32
	19	193.9	1546.12		59	193.85	1546.52
	20	194.0	1545.32		60	193.95	1545.72
3	21	194.1	1544.53	8	61	194.05	1544.92
	22	194.2	1543.73		62	194.15	1544.13
	23	194.3	1542.94		63	194.25	1543.33
	[illegible]	[illegible]	1542.14		64	194.35	1542.54
	[illegible]	[illegible]	1541.35		65	194.45	1541.75
	[illegible]	[illegible]	1540.56		66	194.55	1540.95
	[illegible]	[illegible]	1539.77		67	194.65	1540.16
	[illegible]	[illegible]	1538.98		68	194.75	1539.37
	[illegible]	[illegible]	1538.19	9	69	194.85	1538.58
	[illegible]	[illegible]	1537.40		70	194.95	1537.79
	[illegible]	[illegible]	1536.61		71	195.05	1537.00
	[illegible]	[illegible]	1535.82		72	195.15	1536.22
	[illegible]	[illegible]	1535.04		73	195.25	1535,43
	[illegible]	[illegible]	1534.25		74	195.35	1534,64
	[illegible]	[illegible]	1533.47		75	195.45	1533,86
	[illegible]	[illegible]	1532.68		76	195.55	1533,07
	[illegible]	[illegible]	1531.9	10	77	195.65	1532,29
	[illegible]	[illegible]	1531.12		78	195.75	1531,51
	[illegible]	[illegible]	1530.33		79	195.85	1530,72
	[illegible]	[illegible]	1529.55		80	195.95	1529,94

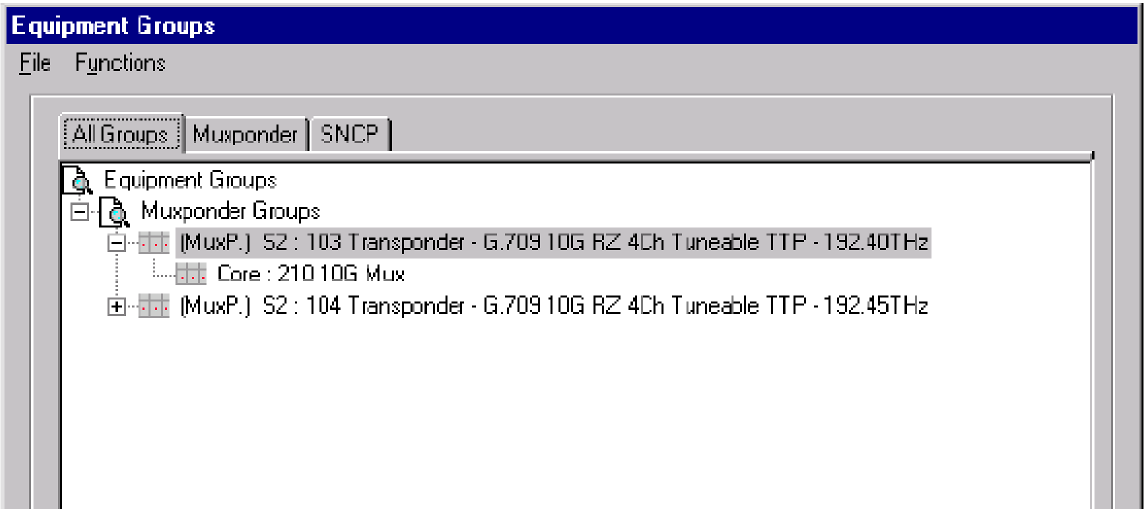


Table 7.1 Specifications of the Video/Audio-Signal Distribution Network Installed in Fuji Television's New Broadcast Center.

		Requirements	
		Present	*Future*
Transmission Format		NTSC Composite (143 Mb/s) HDTV (1.5 Gb/s)	
Number of Signals	NTSC	150	>200
	HDTV	15	20
Number of Destinations		20	>50
Number of Outputs		150	>200

-16 canale WDM x 2= 32 canale WDM, cu echipament la 2.4 Gbps -> >200 semnale digitale video (480 NTSC se pot transmite si 32 HDTV)

- pentru NTSC – 143 sau 270 Mbps (16 semnale pentru NTSC composite signal format (200/16=12) si 8 semnale pentru NTCS component format)

-Pentru HDTV – 1 485 Gbps -> 1 canal WDM la un semnal HDTV (sunt 32, mai raman 12 canale neutilizate)

--compress video format – 10Mbps

Table 7.2 Optical Power Budget of Network.

EO Output (dBm)	0.0
EDFA Output (dBm)	14.5
Receiver Sensitivity (@10^{-9} BER, dBm)	−32.0
Allowable Loss (dB)	46.5
Worst case Optical Loss (dB)	
16 × 64 Star coupler	20.0
1 km Optical fiber cable (including connectors)	2.0
1 × 8 Optical coupler	11.0
1 × 2 Photonic switch	1.0
Tunable wavelength filter	4.0
10:90 Optical coupler	1.0
Power Penalty (dB)	
EDFA noise	negligible
Interchannel crosstalk	0.5
Total (loss + penalty, dB)	39.5
System Margin (dB)	7.0

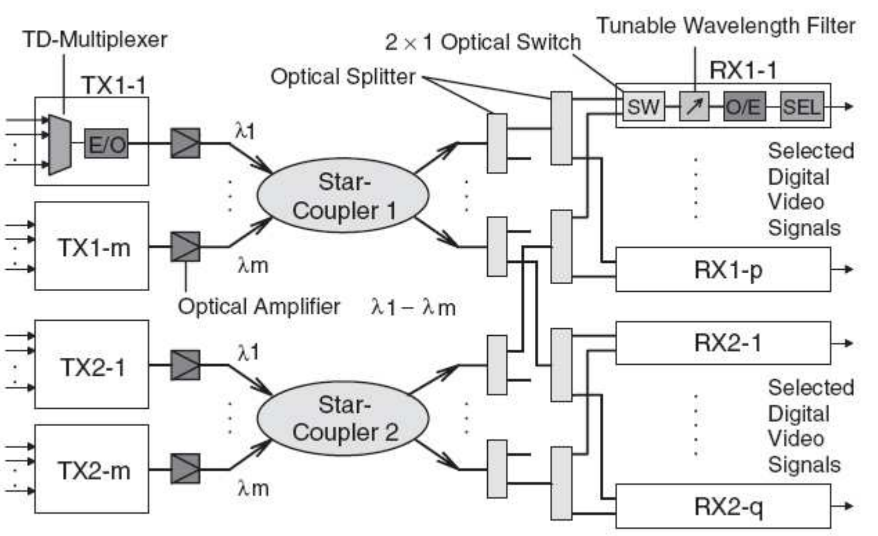


Fig. 7.4 Network structure using two sets of WD/TD optical network with 2 × 1 photonic switches.

Bibliografie recomandata

- Keiser
- Erricson
- VPI Photonics – WDM Module
- Kaminow
- ITU-T Standard
- IBM – Dutton
- Marconi Corporation site

Multumesc pentru atentie