Some repetition

- Regeneration (3R) is needed to scale a network
- Scaling of all optical networks: No digital optics (so far)
- Optical network elements: Today in essence analog ones (1R or 2R)

Network elements:

- –Optical cross connects (OXCs)
- –Optical add drop multiplexers (OADMs)
- –Optical line amplifiers (OLAs)
- –Optical line terminals (OLTs)
- –………..

OXC

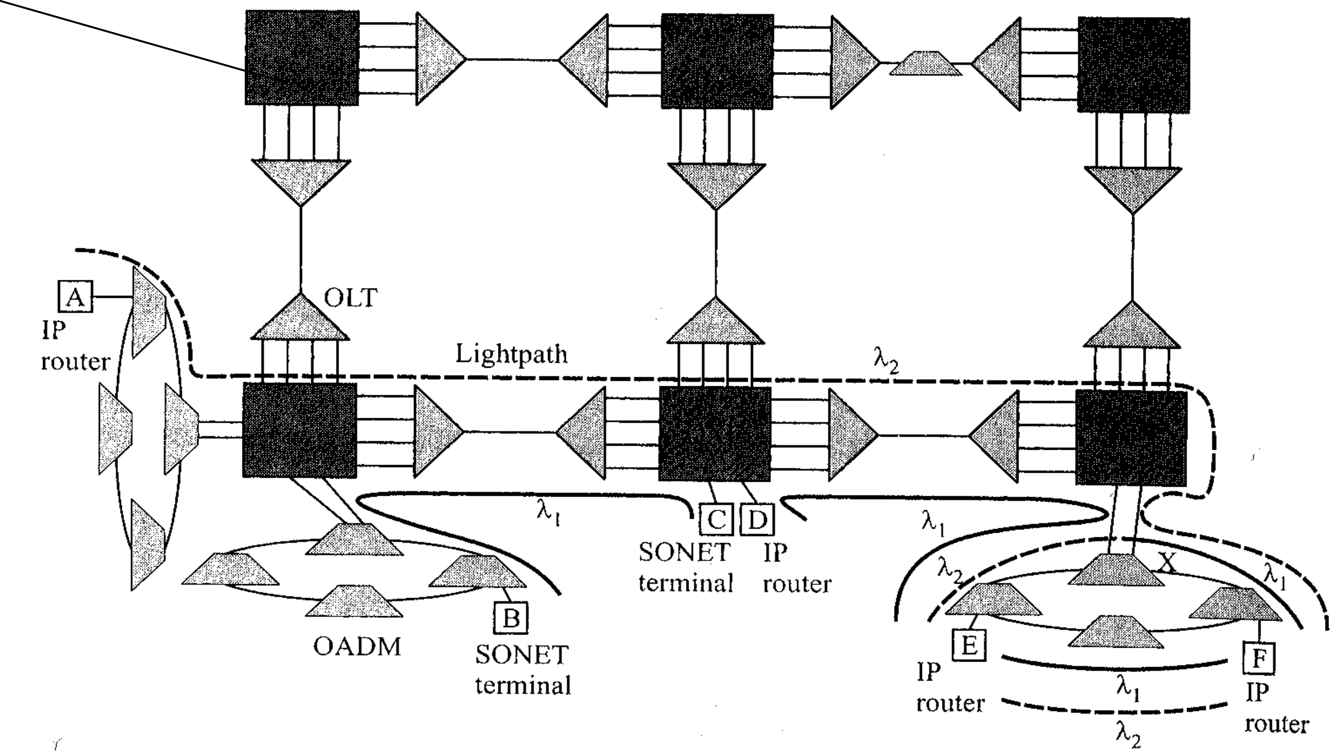


Figure 7.1 A wavelength-routing mesh network showing optical line terminals (OLTs), optical add/drop multiplexers (OADMs), and optical crossconnects (OXCs). The network provides lightpaths to its users, such as SONET boxes and IP routers. A lightpath is carried on a wavelength between its source and destination but may get converted from one wavelength to another along the way.

Need for wavelength conversion

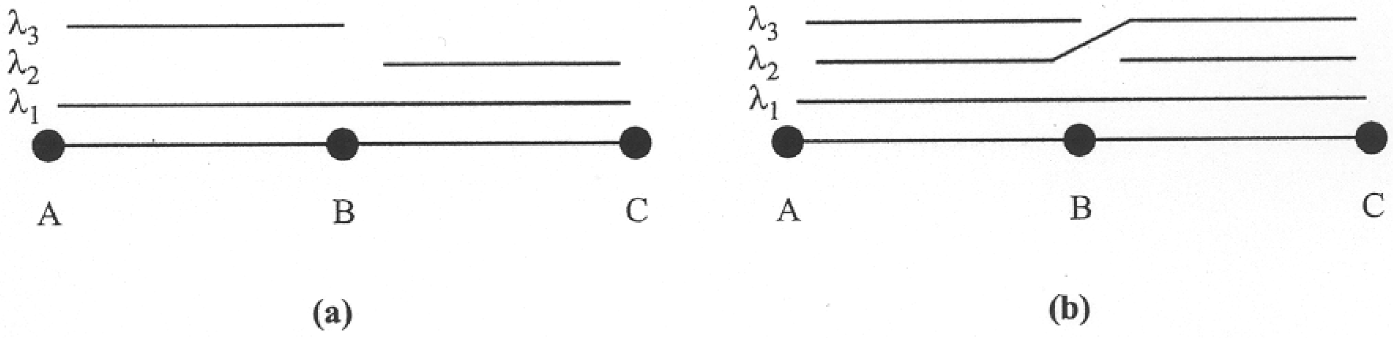


Figure 7.10 Illustrating the need for wavelength conversion. (a) Node B does not convert wavelengths. (b) Node B can convert wavelengths.

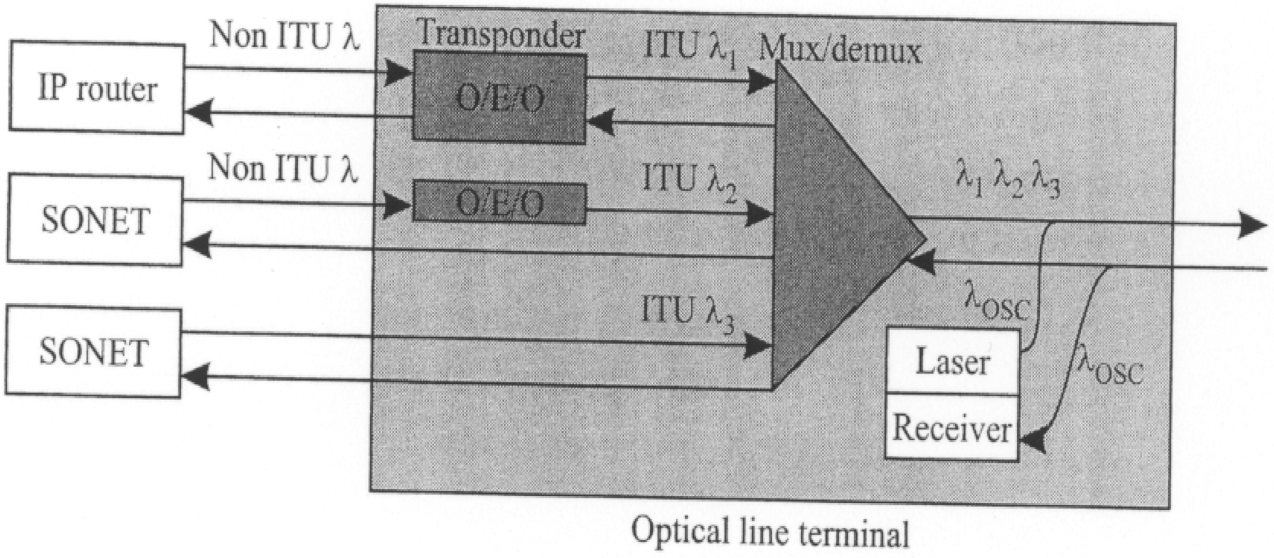


Figure 7.2 Block diagram of an optical line terminal. The OLT has wavelength multiplexers and demultiplexers and adaptation devices called transponders. The transponders convert the incoming signal from the client to a signal suitable for transmission over the WDM link and an incoming signal from the WDM link to a suitable signal toward the client. Transponders are not needed if the client equipment can directly send and receive signals compatible with the WDM link. The OLT also terminates a separate optical supervisory channel (OSC) used on the fiber link.

OADM

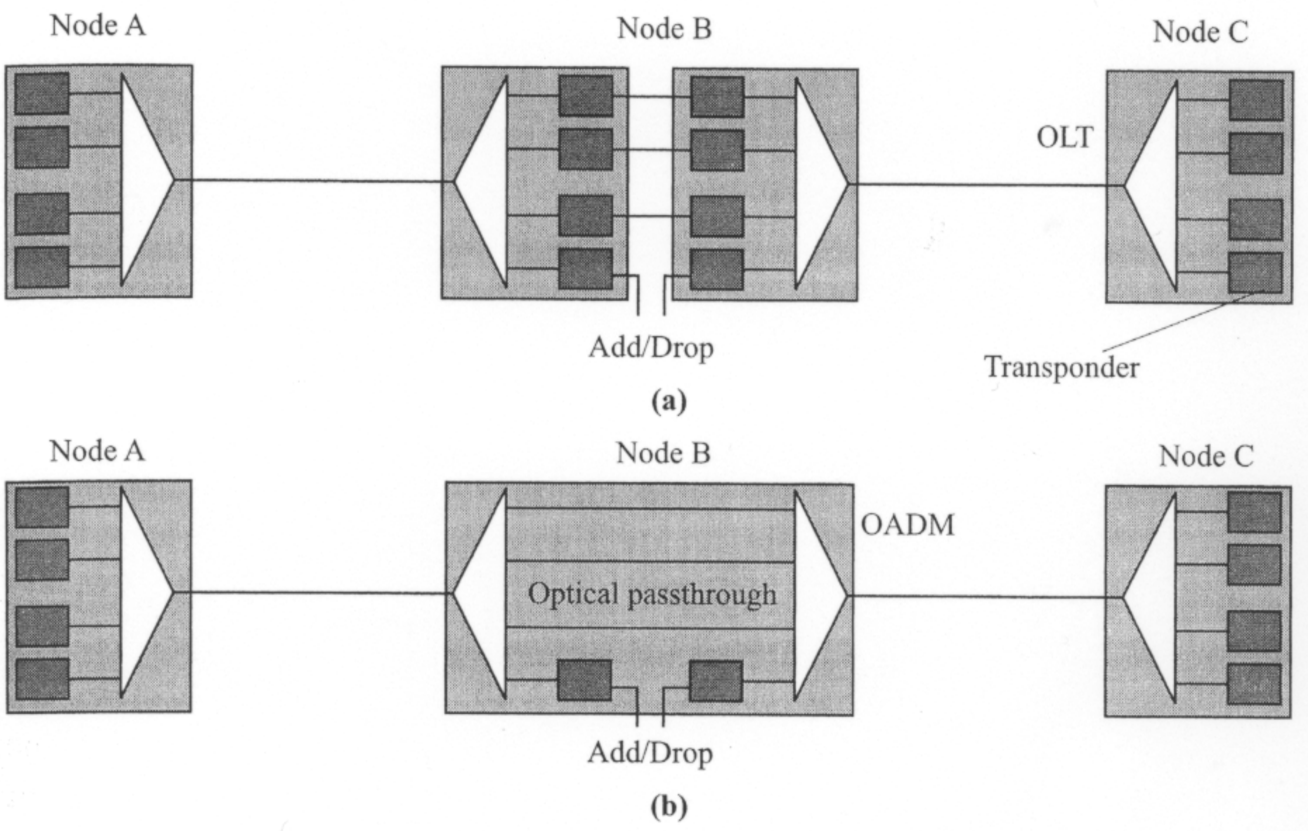


Figure 7.4 A three-node linear network example to illustrate the role of optical add/drop multiplexers. Three wavelengths are needed between nodes A and C, and one wavelength each between nodes A and B and between nodes B and C. (a) A solution using point-to-point WDM systems. (b) A solution using an optical add/drop multiplexer at node B.

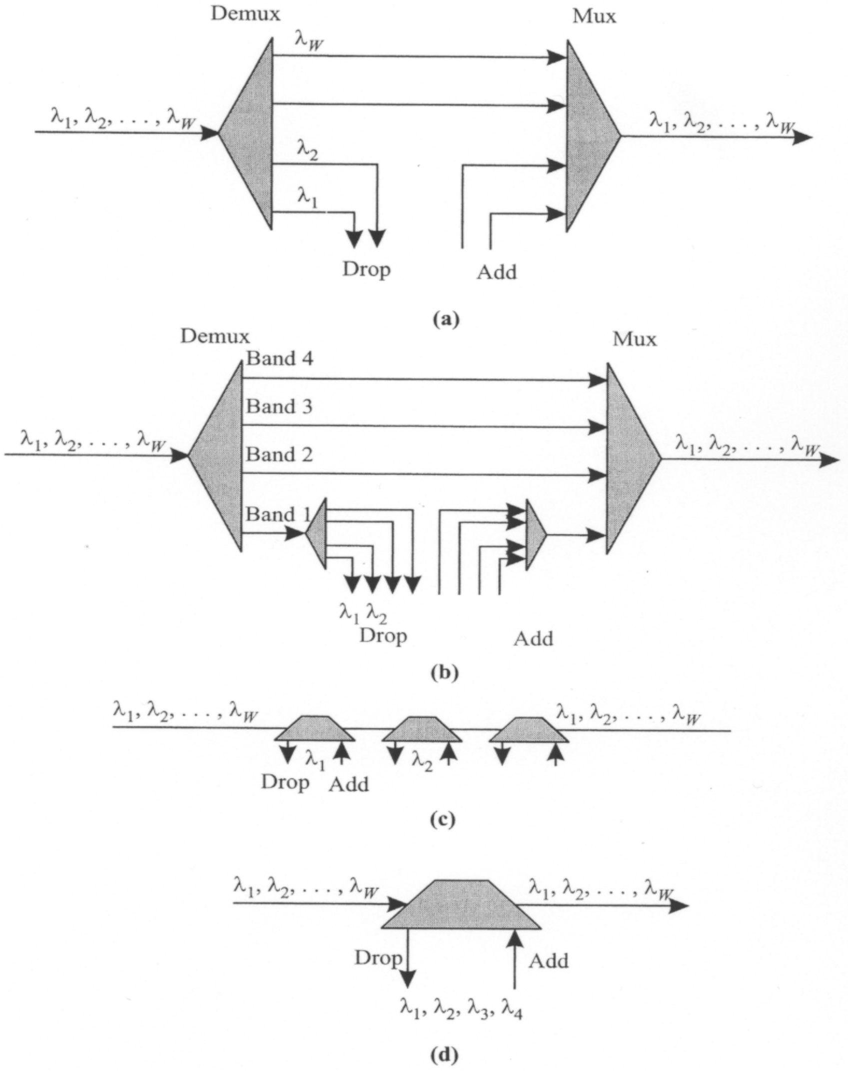


Figure 7.5 Different OADM architectures. (a) Parallel, where all the wavelengths are separated and multiplexed back; (b) modular version of the parallel architecture; (c) serial, where wavelengths are dropped and added one at a time; and (d) band drop, where a band of wavelengths are dropped and added together. *W* denotes the total number of wavelengths.

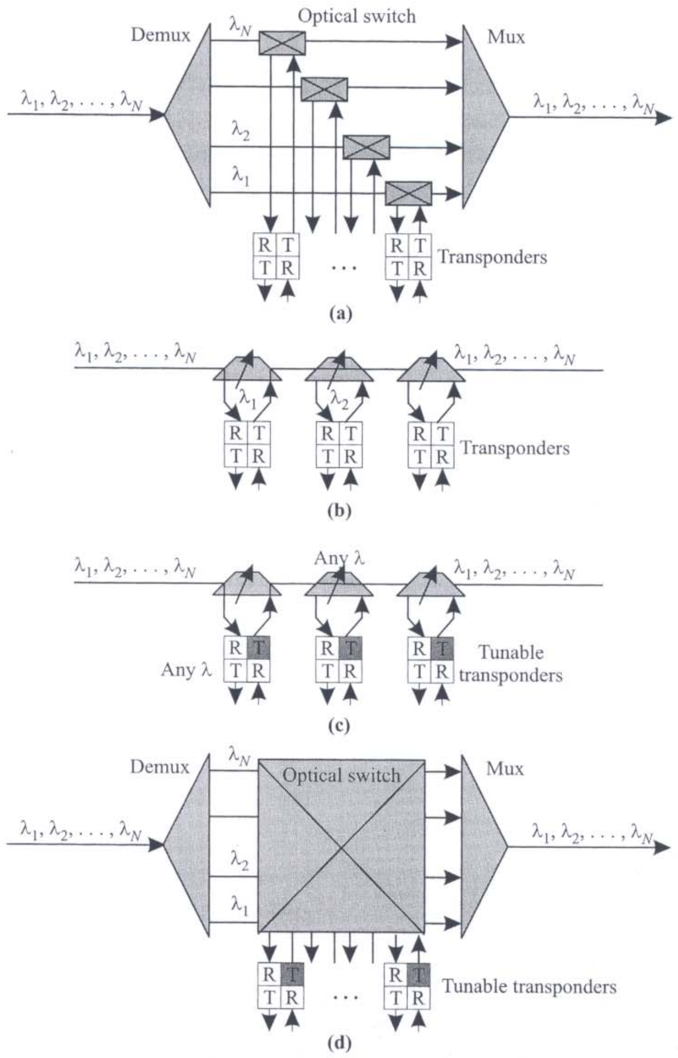


Figure 7.7 Reconfigurable OADM architectures. (a) A partially tunable OADM using a parallel architecture with optical add/drop switches and fixed-wavelength transponders. T indicates a transmitter and R indicates a receiver. (b) A partially tunable OADM using a serial architecture with fixed-wavelength transponders. (c) A fully tunable OADM using a serial architecture with tunable transponders. This transponder uses a tunable laser (marked T in the shaded box) and a broadband receiver. (d) A fully tunable OADM using a parallel architecture with tunable transponders.

Fig 7.6

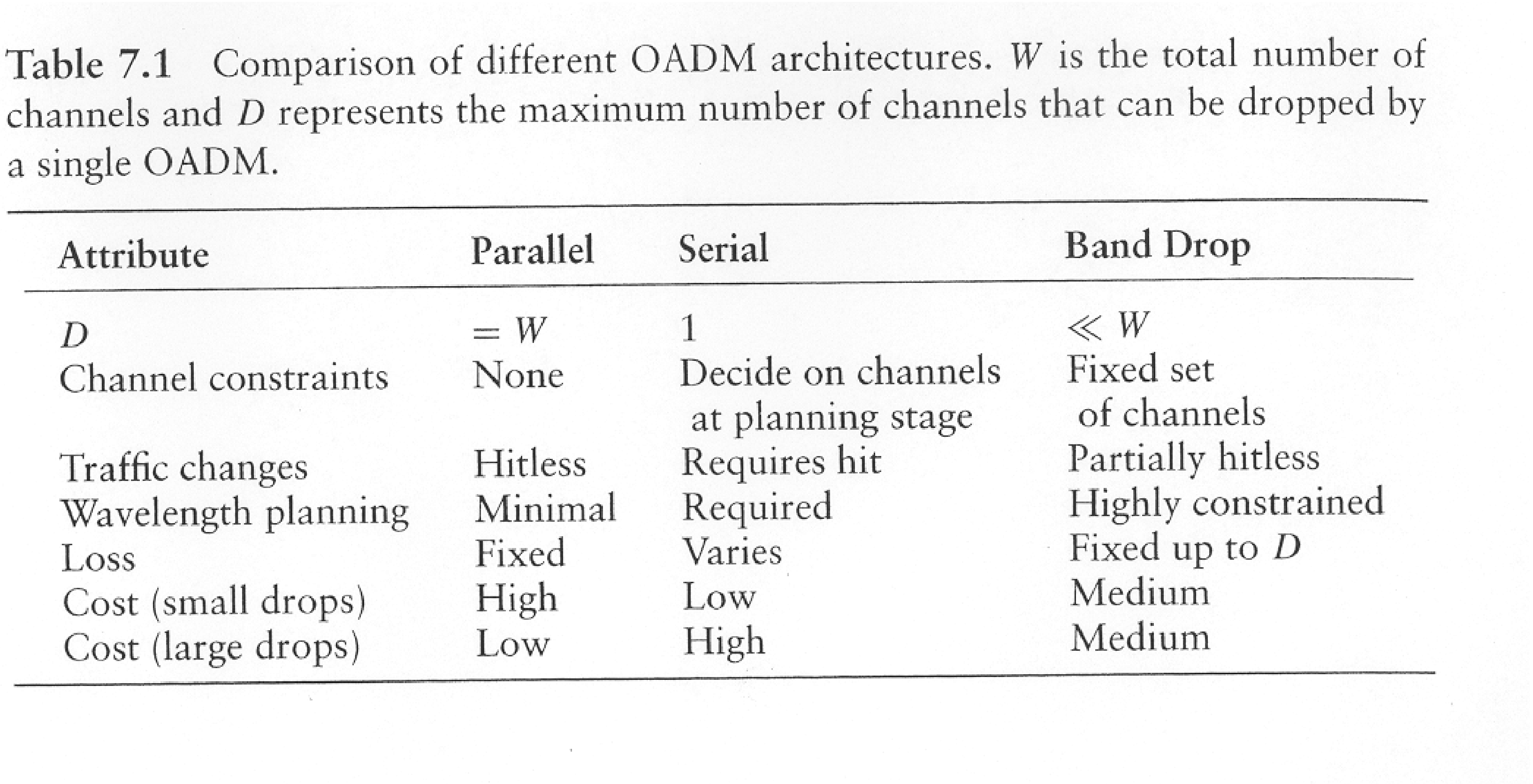


Table 7.1 Comparison of different OADM architectures. *W* is the total number of channels and *D* represents the maximum number of channels that can be dropped by a single OADM.

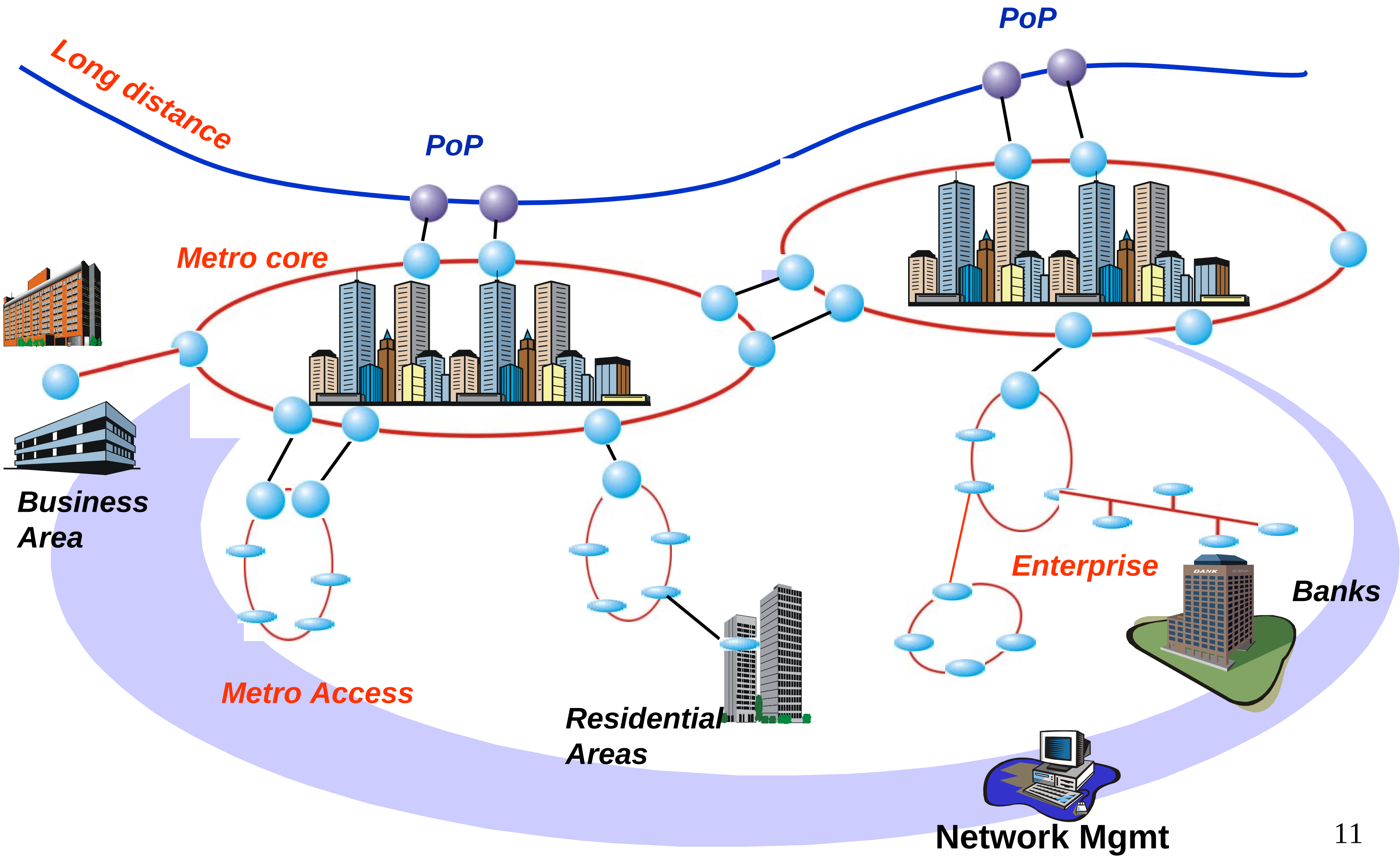
Attribute	Parallel	Serial	Band Drop
D	$= W$	1	$\ll W$
Channel constraints	None	Decide on channels at planning stage	Fixed set of channels
Traffic changes	Hitless	Requires hit	Partially hitless
Wavelength planning	Minimal	Required	Highly constrained
Loss	Fixed	Varies	Fixed up to D
Cost (small drops)	High	Low	Medium
Cost (large drops)	Low	High	Medium

Issues for OADMs

- Should be capable of dropping a certain number of wavelengths
- Should allow an operator to drop/add channels under computer control, without affecting other channels
- Should have fixed loss, regardless of OADM configuration (i e how many channels are dropped/passed through)

2nd generation networks

Metro DWDM Network



Optical cross connects

- Needed for complex mesh topologies and large number of wavelengths
- Functions:
  - Service provisioning
  - Protection switching
  - Bit rate transparency (if it is all optical)
  - Performance monitoring
  - Wavelength conversion
  - Multiplexing and grooming

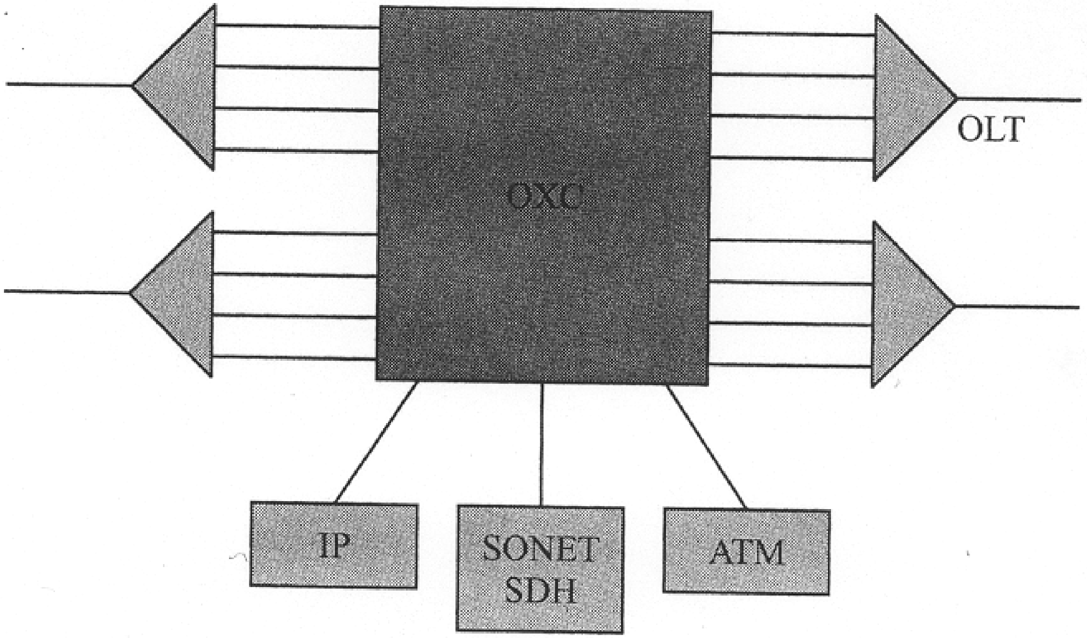


Figure 7.8 Using an OXC in the network. The OXC sits between the client equipment of the optical layer and the optical layer OLTs.

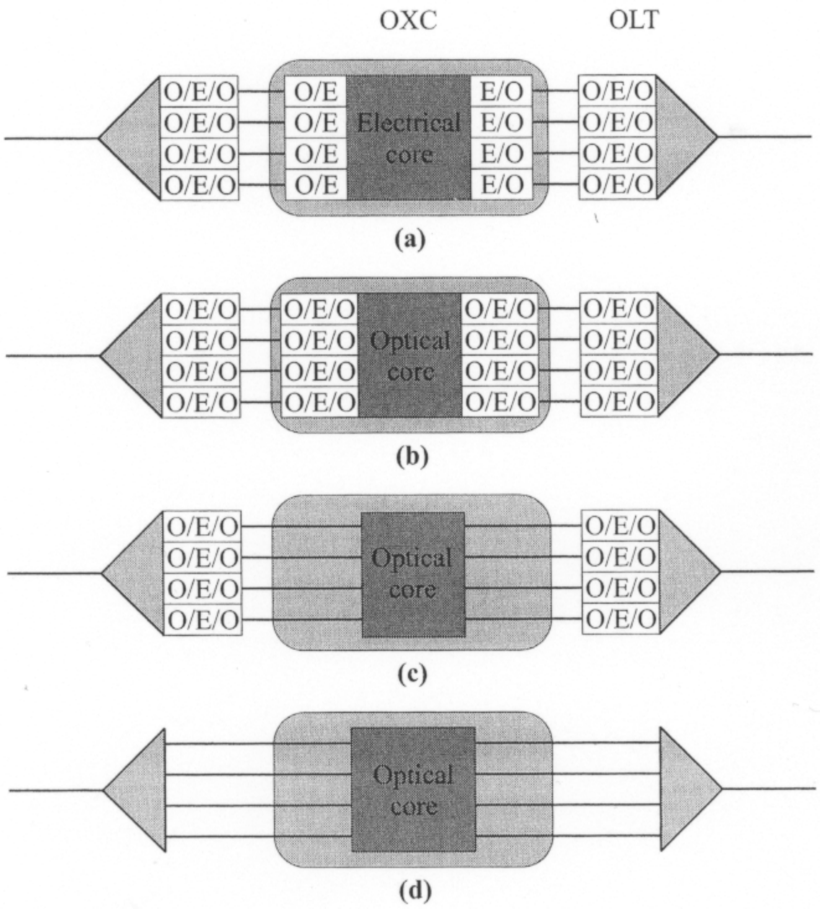


Figure 7.9 Different scenarios for OXC deployment. (a) Electrical switch core; (b) optical switch core surrounded by O/E/O converters; (c) optical switch core directly connected to transponders in WDM equipment; and (d) optical switch core directly connected to the multiplexer/demultiplexer in the OLT. Only one OLT is shown on either side in the figure, although in reality an OXC will be connected to several OLTs.

Grooming, regeneration, wavelength conversion

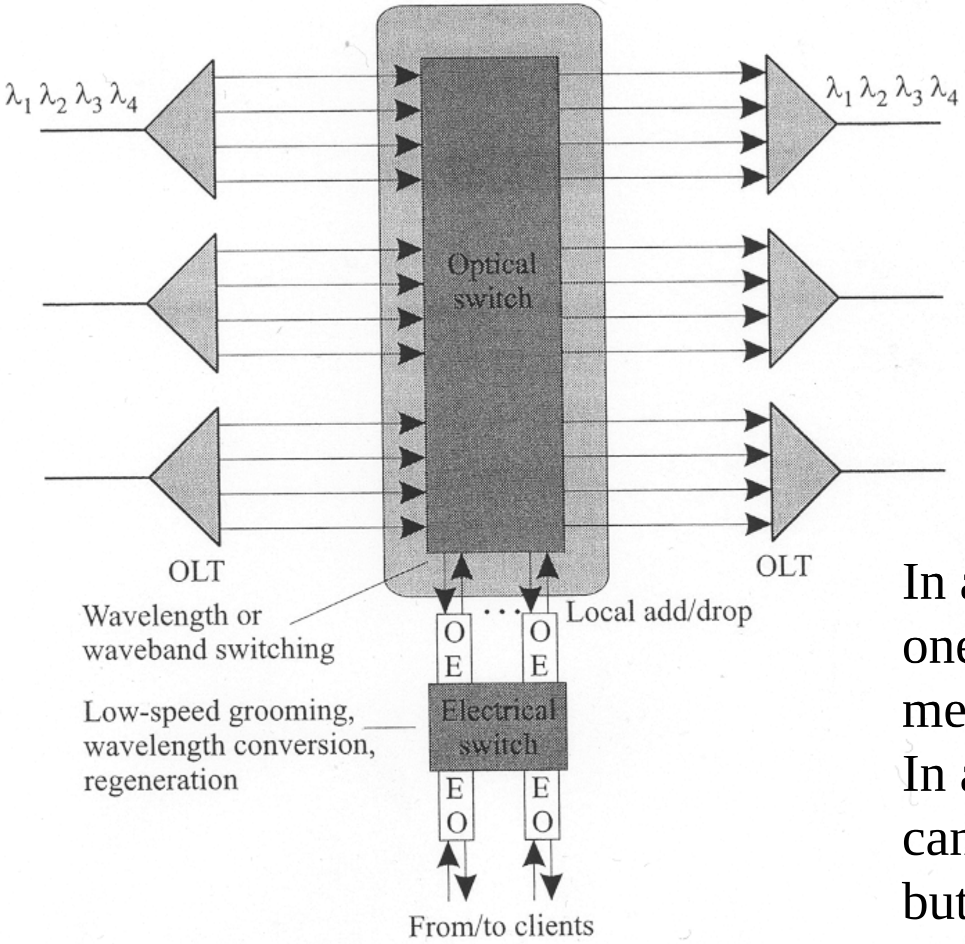


Figure 7.11 A realistic "all-optical" network node combining optical core crossconnects with electrical core crossconnects. Signals are switched in the optical domain whenever possible but routed down to the electrical domain whenever they need to be groomed, regenerated, or converted from one wavelength to another.

In an electronic switch
one can monitor signals,
measure BER, groom, etc
In an optical one, optical power
can conveniently be measured,
but not much more

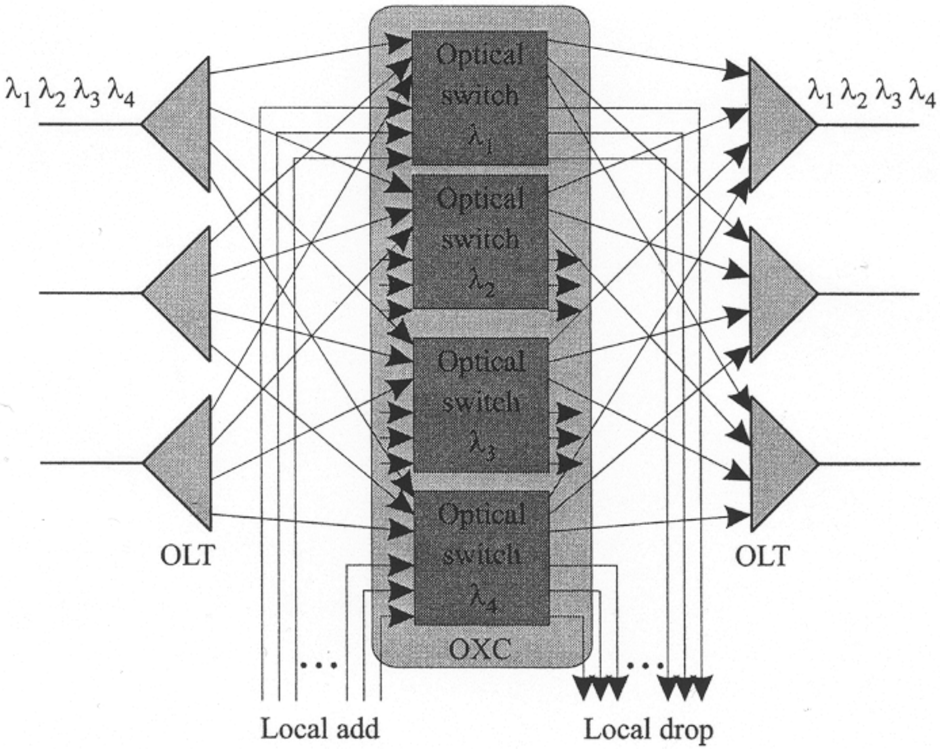


Figure 7.12 An optical core wavelength plane OXC, consisting of a plane of optical switches, one for each wavelength. With F fibers and W wavelengths on each fiber, each switch is a $2F \times 2F$ switch, if we want the flexibility to drop and add any wavelength at the node.

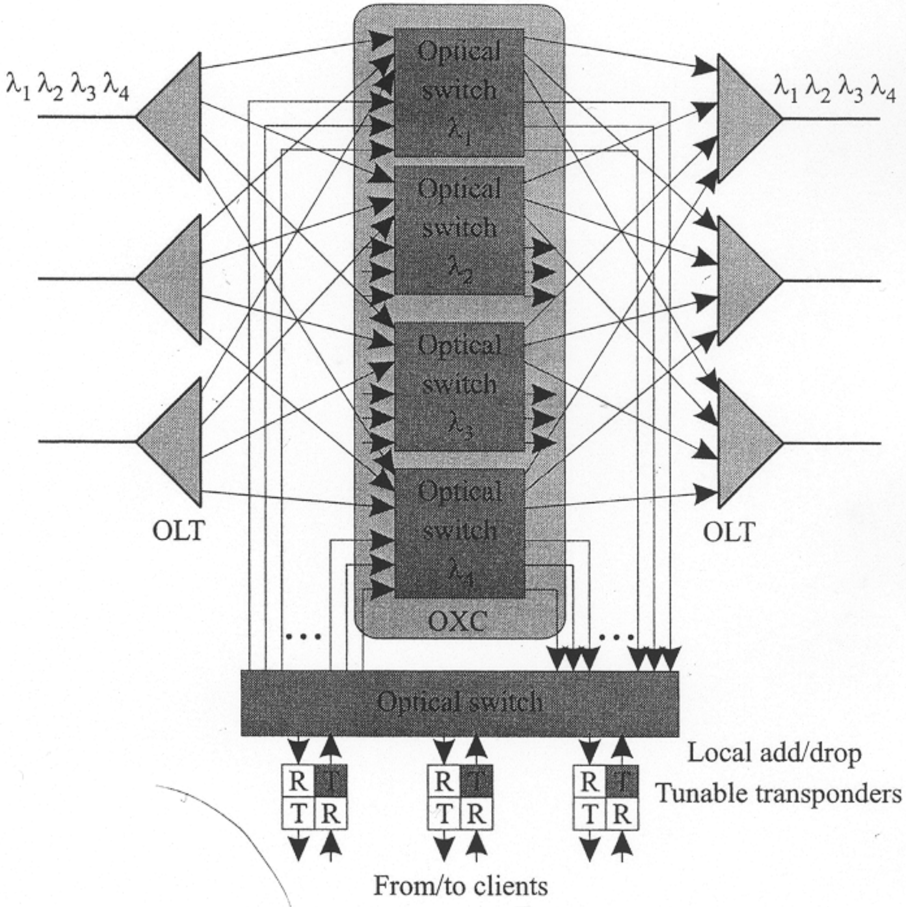


Figure 7.13 Dealing with add/drop terminations in a wavelength plane approach. An additional optical switch is required between the tunable transponders and the wavelength plane switches. Here, T denotes a transmitter, assumed to be a tunable transmitter on the WDM side, and R denotes a receiver.

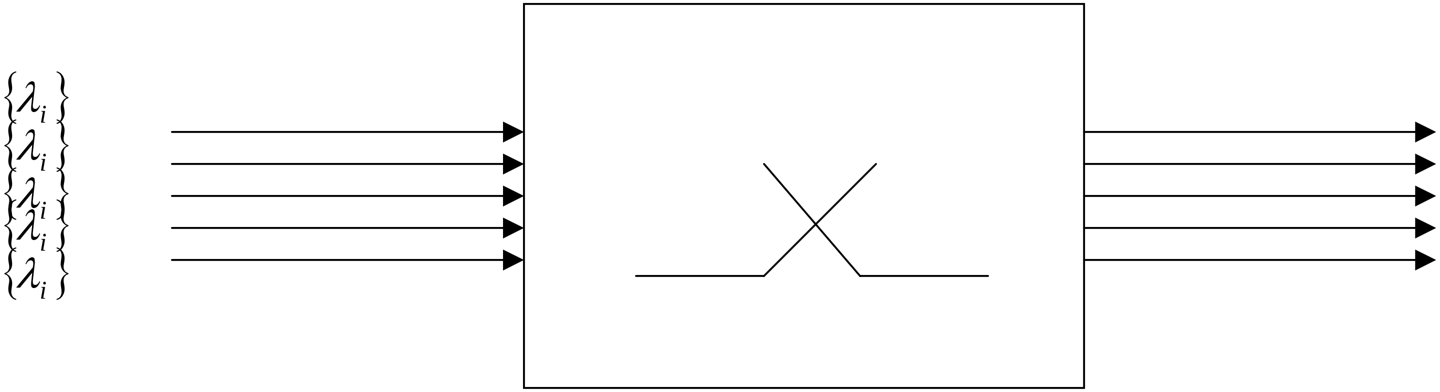
Table 7.2 Comparison of different OXC configurations. Some configurations use optical to electrical converters as part of the crossconnect, in which case, they are able to measure electrical layer parameters such as the bit error rate (BER) and invoke network restoration based on this measurement. For the first two configurations, the interface on the OLTs is typically a SONET short-reach (SR), or very-short-reach (VSR) interface. For the opaque photonic configuration, it is an intermediate-reach (IR) or a special VSR interface. The cost, power, and footprint comparisons are made based on characteristics of commercially available equipment at OC-192 line rates.

Attribute	Opaque Electrical	Opaque Optical with O/E/Os	Opaque Optical	All-Optical
	Figure 7.9(a)	Figure 7.9(b)	Figure 7.9(c)	Figure 7.9(d)
Low-speed grooming	Yes	No	No	No
Switch capacity	Low	High	High	Highest
Wavelength conversion	Yes	Yes	Yes	No ?
Switching triggers	BER	BER	Optical power	Optical power
Interface on OLT	SR/VSR	SR/VSR	IR/serial VSR	Proprietary
Cost per port	Medium	High	Medium	Low ?
Power consumption	High	High	Medium	Low ?
Footprint	High	High	Medium	Low ?

Wavelength crossconnect

General strictly non-blocking wavelength switch:
Paths in the wavelength
and space domains

Any input (space,lambda) port can be connected
to any output (space, lambda) port by a control signal
(normally electronic signal) => Wavelength conversion



Devices in optical networks

Photonics in information transfer and in general

- Functionality
  - –Photonics lacks, *currently*, RAM type memory and signal processing capability
- Physical size (”footprint”)
  - – 100s to 1000s of wavelengths in length, order of wavelength in transverse dimension
  - – Compare electronics (FET gate lengths < 100 nm), but interconnects important for photonics as well as electronics
- Cost
  - –Too expensive (too much handcraft..)
- *But there are ways to resolve this*

Devices in optical networks

- Bulk photonics
  - Dominating today, but has in most cases all the drawbacks listed above
- Integrated photonics
  - The most interesting candidate for solving these problems, is increasing being deployed in the network (e g arrayed waveguide gratings)
- But do not forget MOEMS…

Integrated photonics

Integrated optics is a single mode technology!

Laser

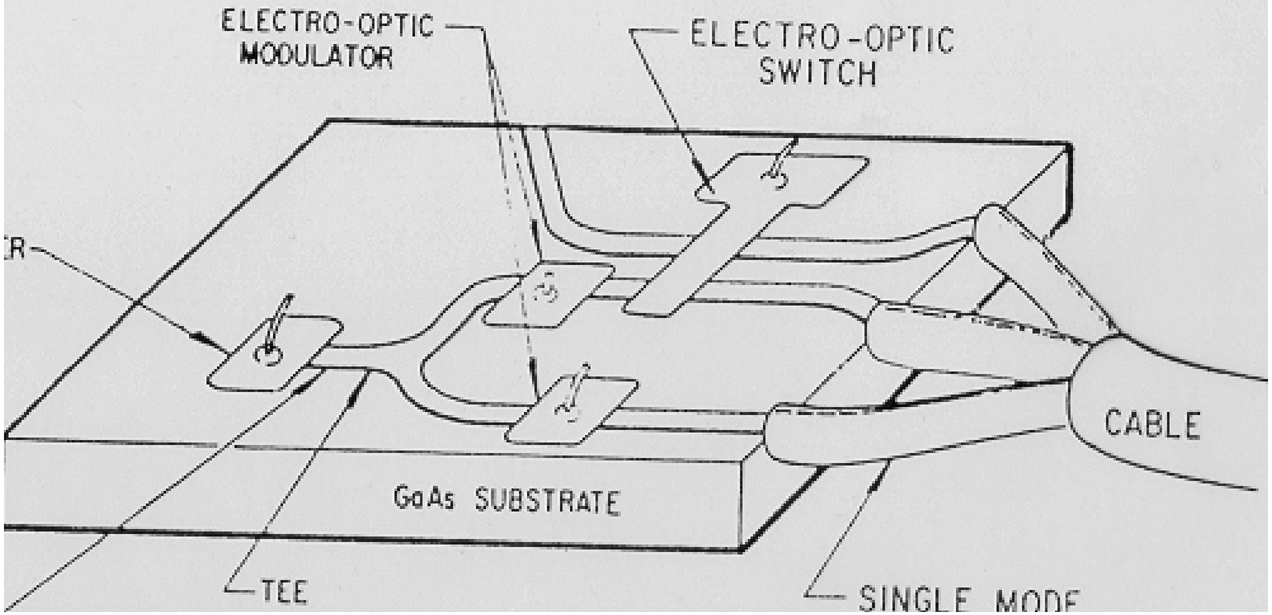


Fig. 1.2 Artist’s sketch of a monolithic integrated GaAs transmitter. (After Blum et al. (1.54)

Photonic Integrated Circuits (PICs)

Integrated photonics has been conditioned on the development of ***single mode*** fiber networks, since the most efficient use of PICs requires a single mode system. *Why?* Most PICs are based on some sort of modal interference, this effect is washed out in multimode structures…

Why guided wave optics?

- Flexible interconnect with low crosstalk and with no diffraction spreading due to propogation
- The small transverse interaction areas and the selectable interaction lengths decrease the energy required to control the devices by orders or magnitude, and ensures compatibility with electron confinement volumes.

But there are also drawbacks:

- Guided wave optics is(at least today) a planar technology, i e the inherent 3 D parallelism of optics is not utilized. *But this is changing!*
- The polarization sensitivity is in general aggravated in guided wave optics, since modal confinement factors and propagation constants are mode dependent (gratings)

Example

Drive or switch energy reduction in guided wave modulators in relation to bulk devices

Energy stored in interaction volume, L=length

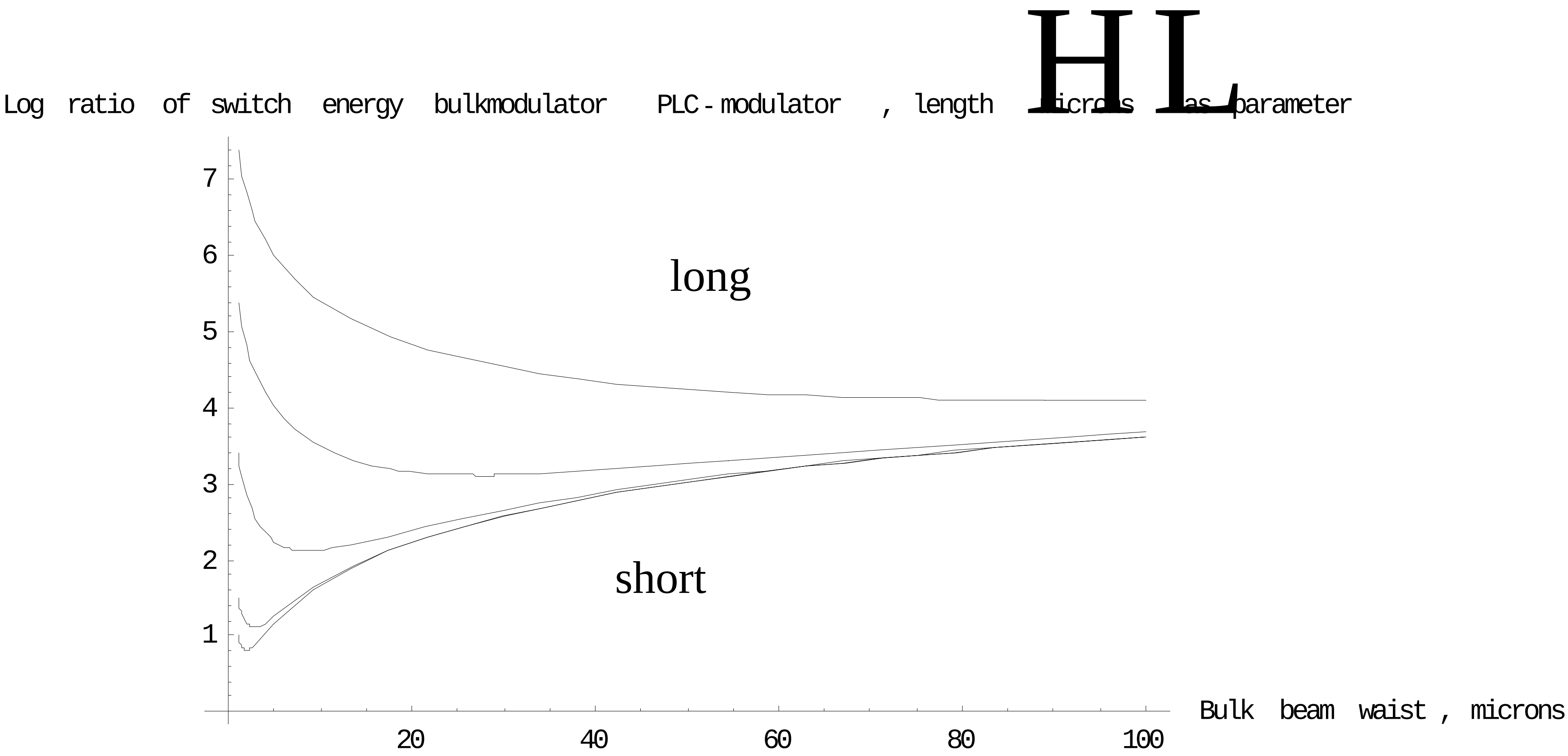
w=beam waist

$$Volume_{Bulk\,\mathrm{mod}\,ulator} = L\left(w + \frac{\lambda}{w}\frac{L}{2}\right)^2$$

$$Volume_{Channelwaveguide\,\mathrm{mod}\,ulator} = L(\lambda)^2$$

Equal lengths => Switch energy ratio=

$$\left(w + \frac{\lambda}{w}\frac{L}{2}\right)^2 / \lambda^2$$


Log ratio of switch energy bulkmodulator PLC - modulator , length H microns L as parameter
7
6
5
4
3
2
1
long
short
20
40
60
80
100
Bulk beam waist , microns

Classical PIC problems

- ***Insertion loss (due to propagation, elements in the cct, coupling to the surrounding world /fiber/)***
  - ***Typical values: 0.5-3 dB PIC/fiber, 0.1-1dB/cm, ?/cct element***
- ***Polarization***

Polarization

The ordinary standard single mode fiber does not preserve a defined state of polarization

Solutions:

- *Strictly polarization independent devices: Devices independent of the state and degree of polarization, i.e. rapid polarization fluctuations are allowed.*
- Polarization control, i.e. feedback stabilization, which requires an assessment of the state of polarization (performed in coherent systems at the time)
- *Polarization diversity, i.e. separating the polarizations and processing them separately (probably only solution for photonic crystal devices)*
- Polarization holding (PH) fibers: Expensive, nonstandard fibers, *but* new photonic crystal fibers emerging??
- Polarization scrambling, i.e. the polarization is randomized before entering the device in question

Photonic integrated circuits (PICs)

- ”Active”: Manipulation of the real and imaginary parts of the refractive index
- Passive

The Kramers Krönig relations

$$\chi'(\omega) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{\chi''(\omega')}{\omega' - \omega} d\omega'$$

$$\chi''(\omega) = -\frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{\chi'(\omega')}{\omega' - \omega} d\omega'$$

Physical Mechanism	Operation mode	Characteristics	Materials
Index change through Pockel effect (linear EO effect).	Voltage applied over dielectric or reverse-blased pn-junction	Speed usually limited by Walk-off or RC-constants. Small nonresonant effect. Dn/n ~0.0001 typically, no associated absorption.	All materials lacking inversion symmetry: LN, III-V semiconductors
Index change through nonresonant Kerr effect (quadratic EO effect)	See above	See above. Usually very small	All materials
Free carrier, intra-band transitions ("plasma" effect). Index and absorption change	Carrier injection or depletion through injection and reverse blasing, respectively	Usually smaller than other carrier-induced effects. Nonresonant effect, increases with the square of the wavelength	All semiconductors and other materials in which free carriers can be induced
Absorption/gain change through bandfilling	Unipolar through reverse blasing of pin-junction (depletion), bipolar	Unipolar operation is fast (RC-limited) but cannot give gain, bipolar operation limited by carrier recombination. Strong λ dependence.	III-V (and other SC)
Index change through bandfilling	See above	See above. Large index changes achievable, of the order An/n ~0.001-0.01 Strong λ dependence.	See above
Absorption change by Quantum Confined Stark Effect (QCSE)	Reverse blased pin-junctions	RC – or transport – time limited response (fast, depends on number of wells and barrier heights etc). Strong λ dependence.	Quantum Well SC
Index change through QCSE	See above	RC-limited response. An/n 0.001-0.01 Strong λ dependence.	See above
Absorption change by Franz-Keldysh (FK) effect	See above	RC – or transport time limited response. Strong λ dependence.	All SC
Temperature induced absorption and index changes	Change of external temperature, and heat dissipation associated with carrier recombination	Large effect that partially counteracts the index and absorption changes induced by electronic effect. Depends on heat sinking and the ratio between radiative and non-radiative recombination channels inSCs	All materials

However, MOEMs!

- Microoptoelectromechanical systems
- Huge ”index changes” (material-air, i e 0.5 to 2!)
- Electronically controlled but SLOW (> 1 μs)

Materials for integrated photonics

	Ferroelectrics	*Semiconductors (III-V)*	*Dielectrics*	*Polymers*	*Si*
Detector		Yes			Yes
Amplifier/Laser					
- El pumped		Yes			??
- Opt pumped	Yes	Yes	Yes	Yes	Yes
Index change [1]	Yes	Yes	(Yes)	Yes	Yes (plasma)
Abs change [1]		Yes			??
Opt nonlinearity	Yes	Yes	Yes	Yes	
Electronics integrate		Yes			Yes

[1] *Electronically controlled*

Ferro electrics: $LiNbO_3$, $LiTaO_3$, strontium barium niobate (SBN)…

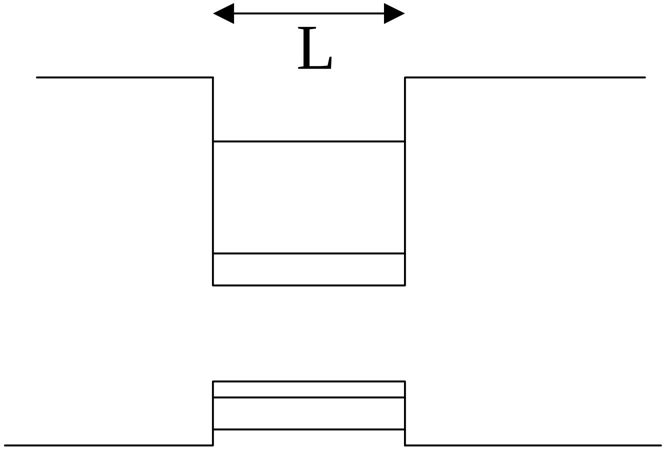
Semiconductors: GaAs, InP, GaN … …

Dielectrics: Glass, SiO_2/Si…

Why $LiNbO_3$?

- Easy fabrication of low loss waveguides
- Large electrooptic effect
- Good RF properties

Semiconductor PICs:
Bulk, quantum wells, quantum wires, quantum boxes: material engineering: manipulation of energy levels, density of states, matrix elements…



$$\frac{\sqrt{E2m^*}}{\hbar}L = n\pi; n = 1,2,3...$$

Requirements on semiconductor materials for photonic integrated circuits

- Control of composition, doping and dimensions over areas > 1cm^2 （ at least currently)

- Mixing of ”active” and ”passive” elements on one chip

- Mixing of forward and reversed biased pn-junctions on one chip => semiinsulating materials

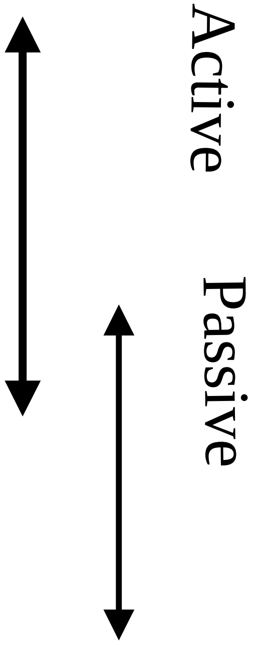
- Integration of electronic and photonic elements on one chip?? (immature technology and maybe questionable approach)

Devices in optical network elements

- ***Couplers***
- *Isolators and circulators*
- ***Multiplexers and filters***
- *Optical amplifiers (covered in the photonics course, only network issues treated here)*
- ***Switches***
- ***Wavelength converters***
- ***Tunable devices***
- *Transmitters and receivers*
    - *Boldface: Covered in this course*

Types of photonic integrated circuits (PICs)

- **Switches**
- **Modulators**
- **Amplifiers**
- **Filters**
- **(De)Multiplexers**
- **Splitters, couplers**
- **Isolators, circulators**
- …
- ….
- **(Optically) Nonlinear devices**
-



Couplers

B

Couplers

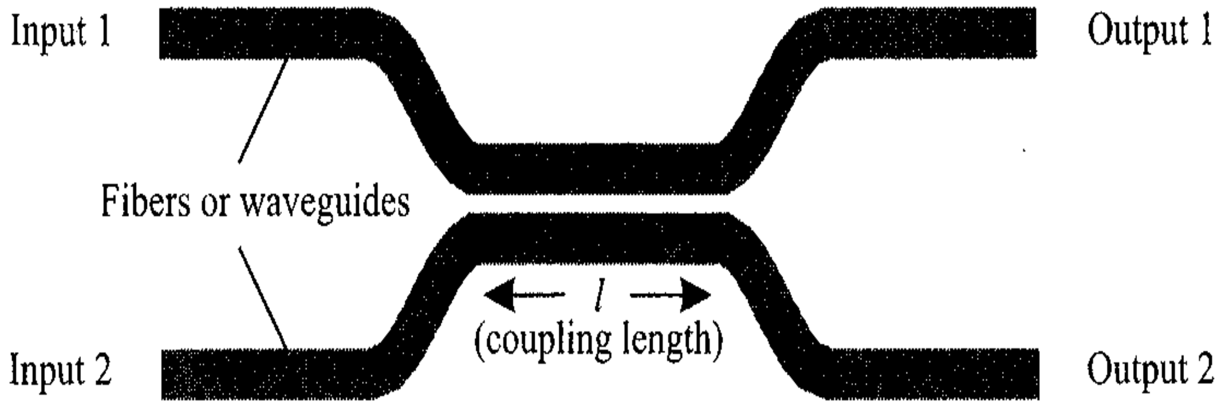


Figure 3.1 A directional coupler. The coupler is typically built by fusing two fiber together. It can also be built using waveguides in integrated optics.

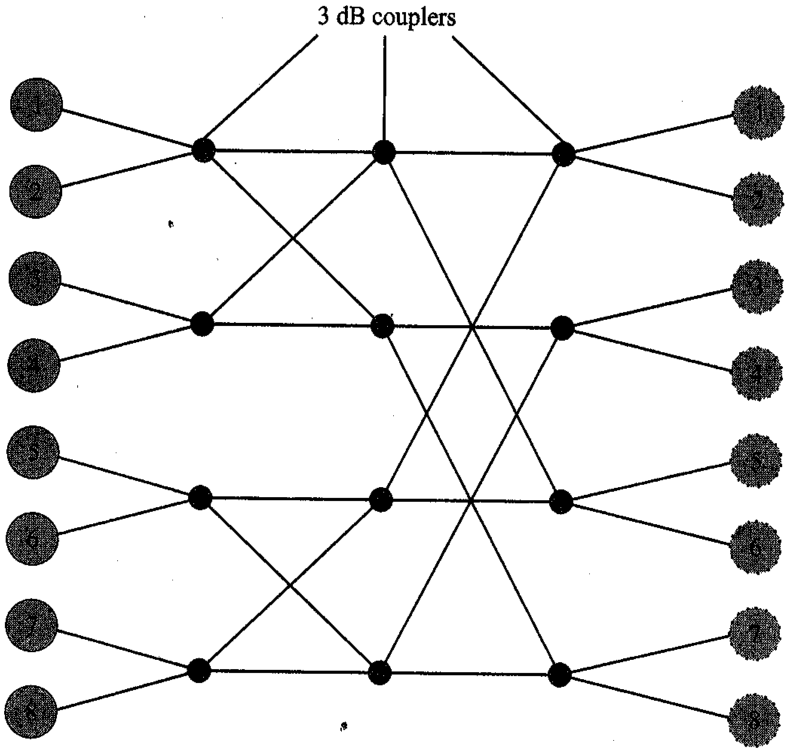


Figure 3.2 A star coupler with eight inputs and eight outputs made by combining 3 dB couplers. The power from each input is split equally among all the outputs.

Power question

Equations for directional coupler

(codirectional coupling)

Example of use of coupled mode equations

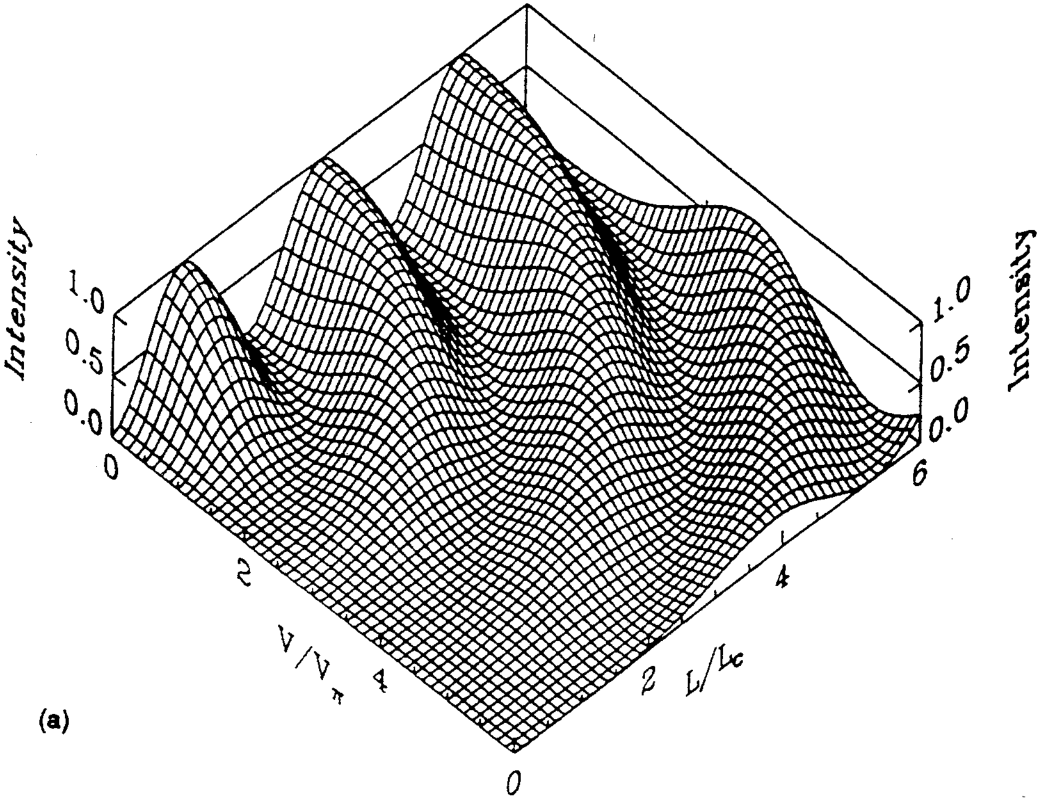
(see eg T Tamir (ed), Integrated optics, Springer, 1975)

$$A' = -j\kappa B \exp(-2j\delta z)$$
$$B' = -j\kappa A \exp(2j\delta z)$$

κ is coupling coefficient, $2\delta = \beta_1 - \beta_2$, z is propagation direction

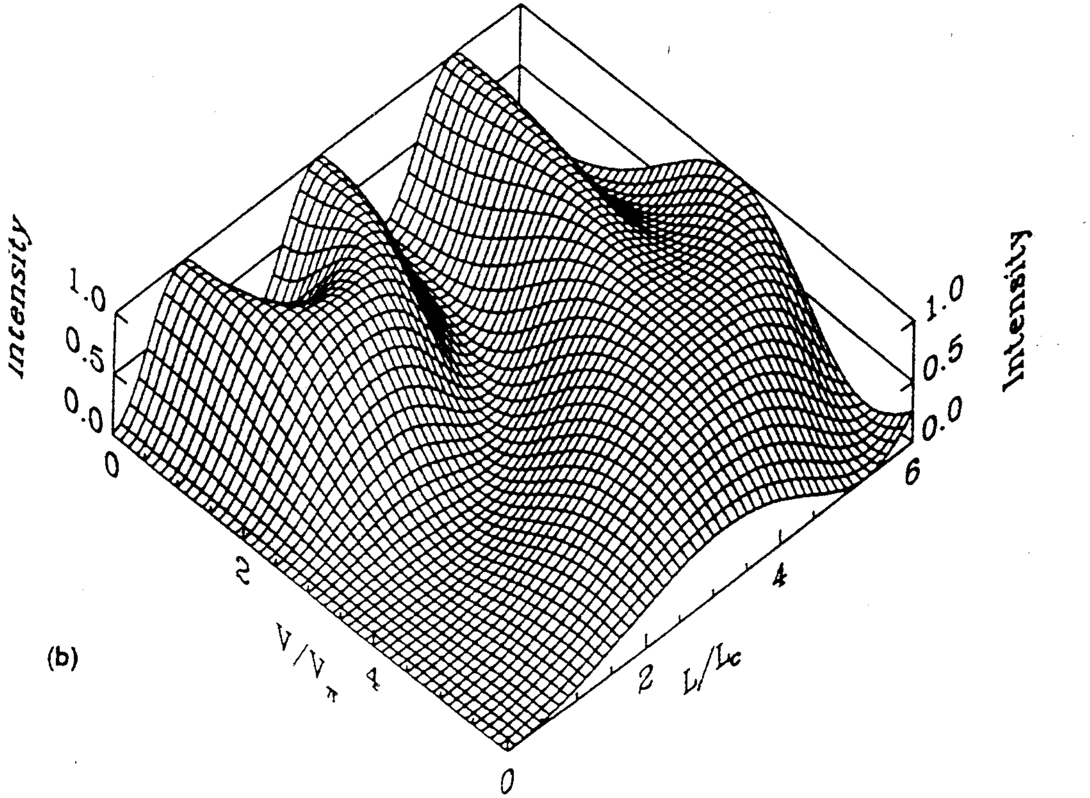
Set
$$A = \mathrm{Re}\,xp(-j\delta z),\quad B = S\exp(j\delta z)$$

Solutions :
$$S(z) = -j\kappa \sin(z\sqrt{\kappa^2+\delta^2})/\sqrt{\kappa^2+\delta^2}$$
$$\mathrm{R(z)} = \cos\left(z\sqrt{\kappa^2+\delta^2}\right) + j\delta \sin(z\sqrt{\kappa^2+\delta^2})/\sqrt{\kappa^2+\delta^2}$$



(a)

•Stepped Δβ coupler



H. Kogelnik and R. V. Schmidt, IEEE

J. Quantum Electron. **QE-12**, 395 (1976).

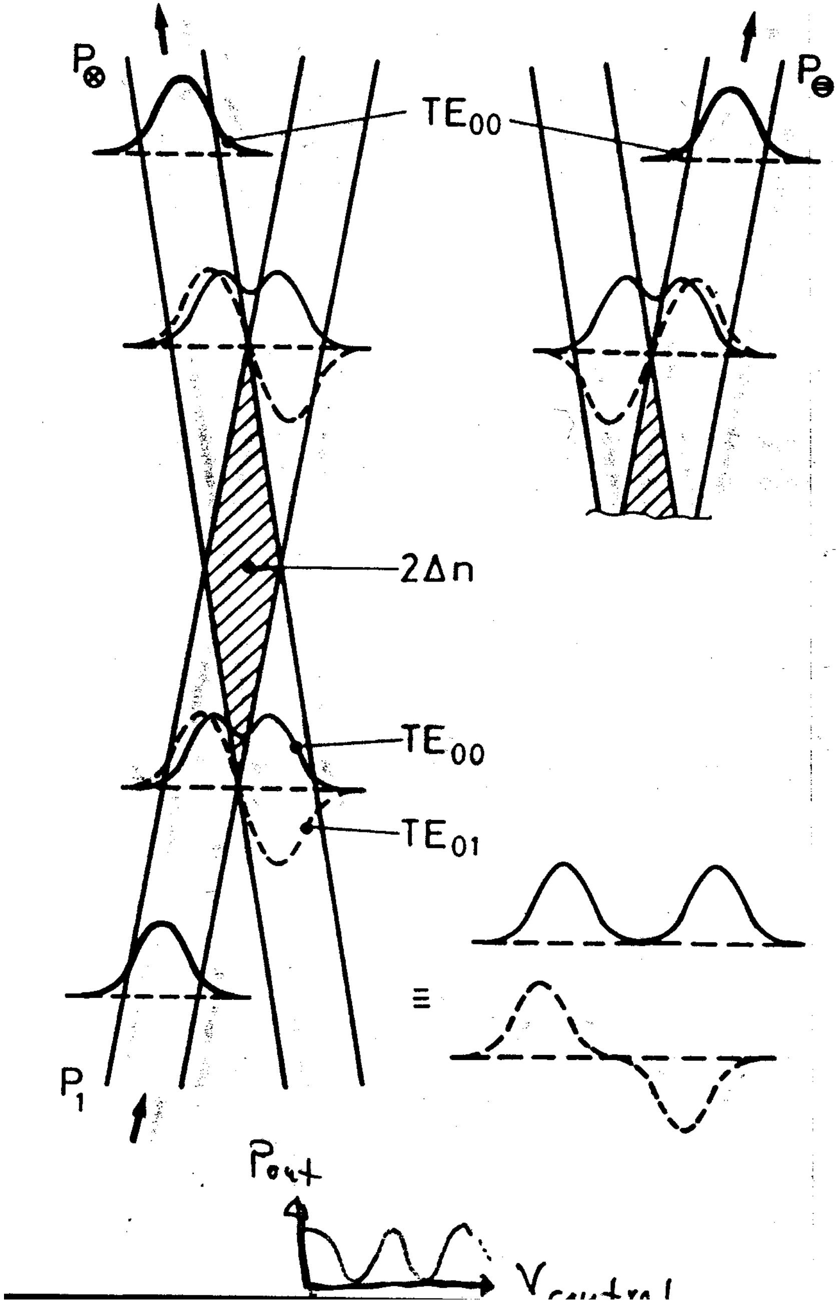
Modes of the composite structure (”supermodes”)

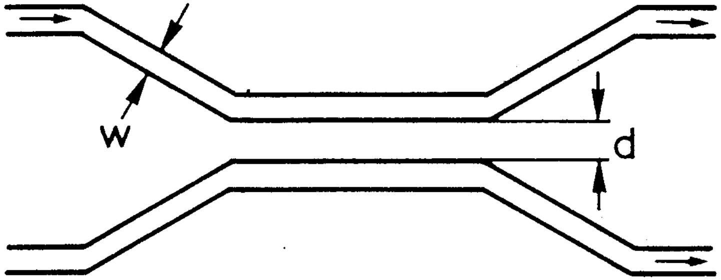
$$\begin{pmatrix} R \\ S \end{pmatrix}' = \begin{pmatrix} i\delta & -i\kappa \\ -i\kappa & -i\delta \end{pmatrix} \bullet \begin{pmatrix} R \\ S \end{pmatrix} \equiv \underline{M} \begin{pmatrix} R \\ S \end{pmatrix}$$

$$\underline{M} \begin{pmatrix} R \\ S \end{pmatrix} = k \begin{pmatrix} R \\ S \end{pmatrix}$$

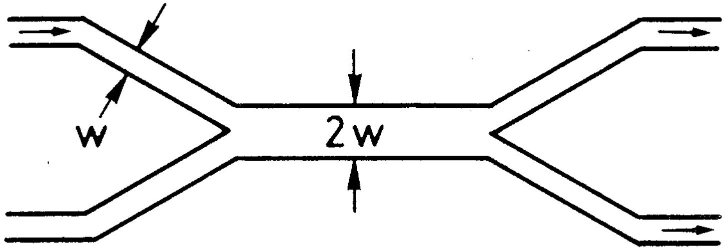
$$\text{Eigenvalues} : \pm i\sqrt{\delta^2 + \kappa^2}$$

$$\text{Eigenvectors} : \begin{pmatrix} -\dfrac{\delta \pm \sqrt{\delta^2 + \kappa^2}}{\kappa} \\ 1 \end{pmatrix}$$

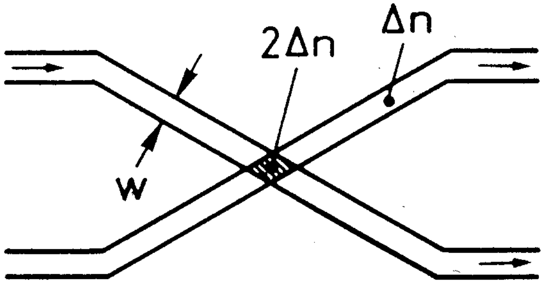

P⊗
TE00
P⊖
2Δn
TE00
TE01
≡
P1
Pout
Vcontrol



a) DIRECTIONAL COUPLER



b) BOA - COUPLER



c) X-SWITCH