Optical Physical Layer Issues in Wavelength-Division Multiplexed Networks

C. R. Doerr and G. Wilfong

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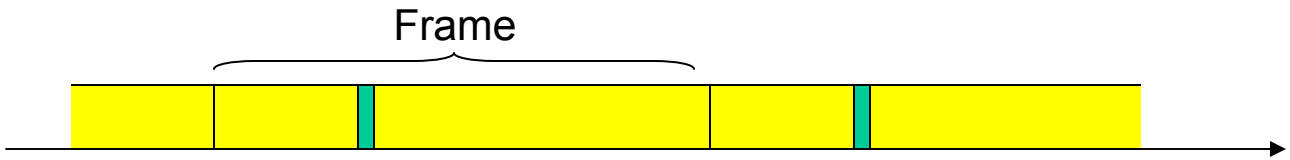
Outline

- WDM network basics
- Passive WDM routing devices
- Active WDM routing devices
- Conventional WDM mesh nodes
- Novel WDM mesh nodes
- Electronic switching vs. optical switching
- Conclusion

WDM network basics

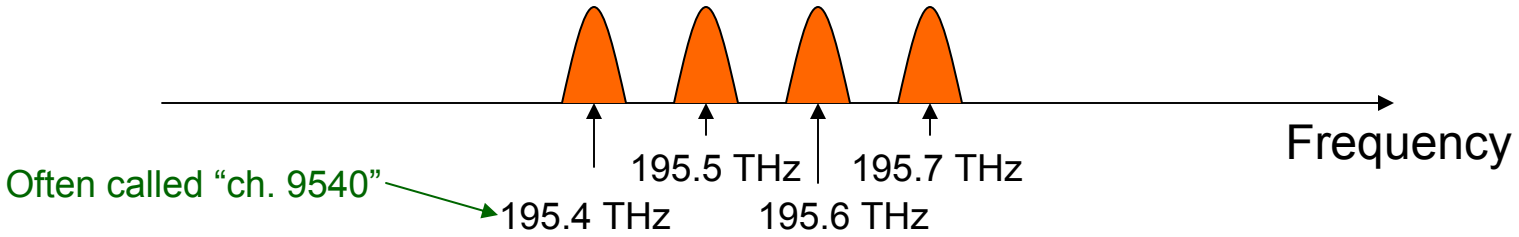
Two main types of optical transport

TDM



Examples: SONET, SDH

WDM

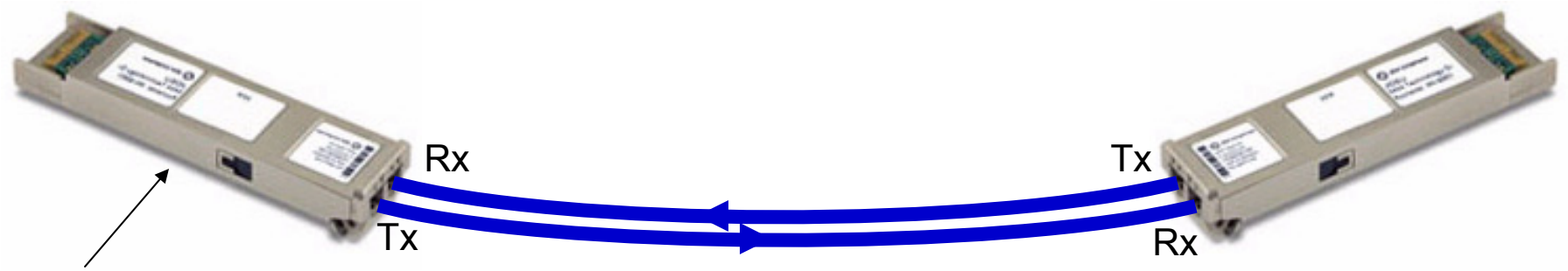


Examples: DWDM, CWDM

There is also packet-based transport, such as Ethernet, but it is usually put into TDM frames.

Basic optical network

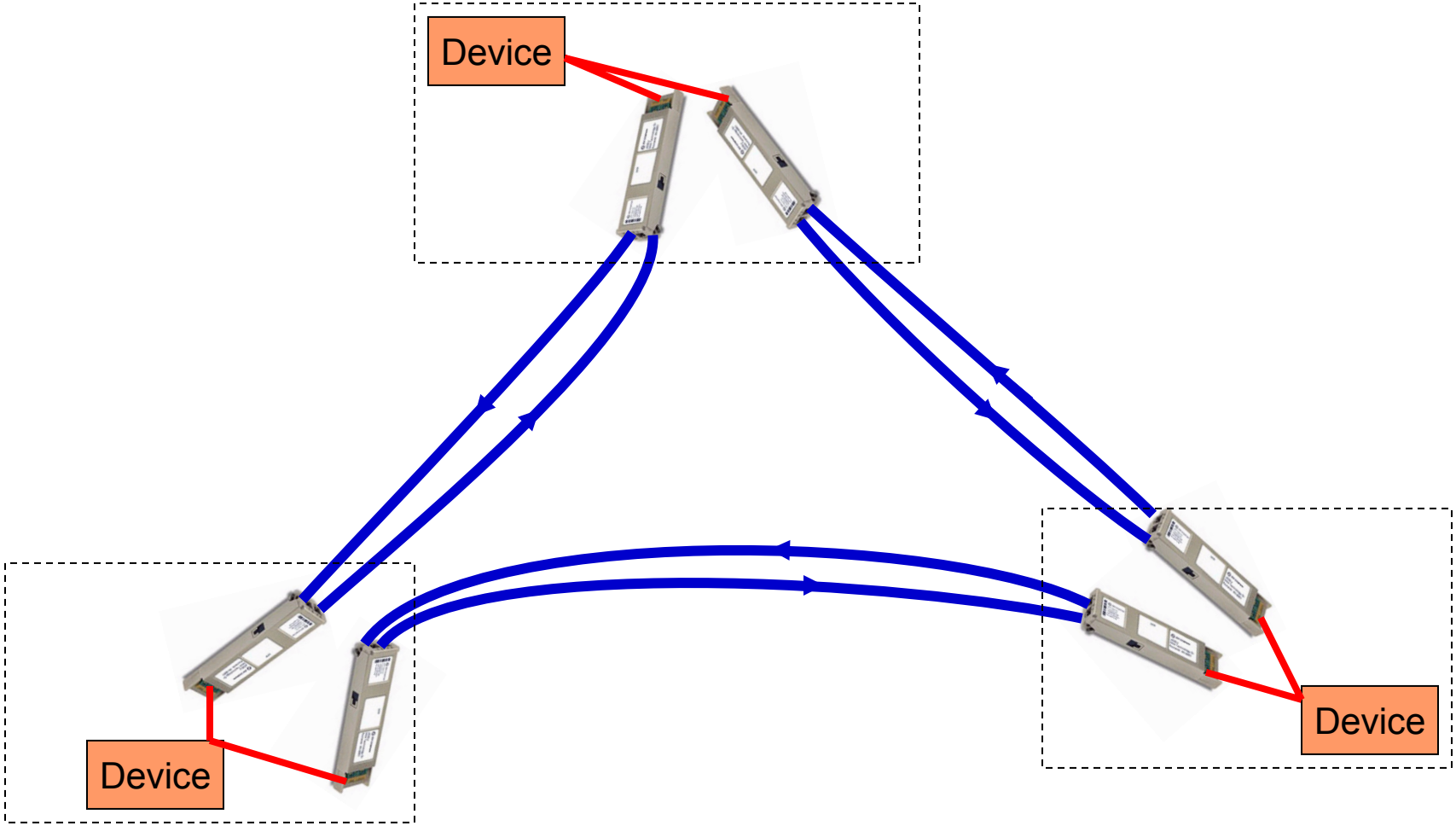
Optical networks are traditionally based on *transceivers*



"XFP"
(10-Gb/s small form-factor pluggable)

One transceiver traditionally talks to one other transceiver, i.e., transceivers *connect in pairs*.

Ring



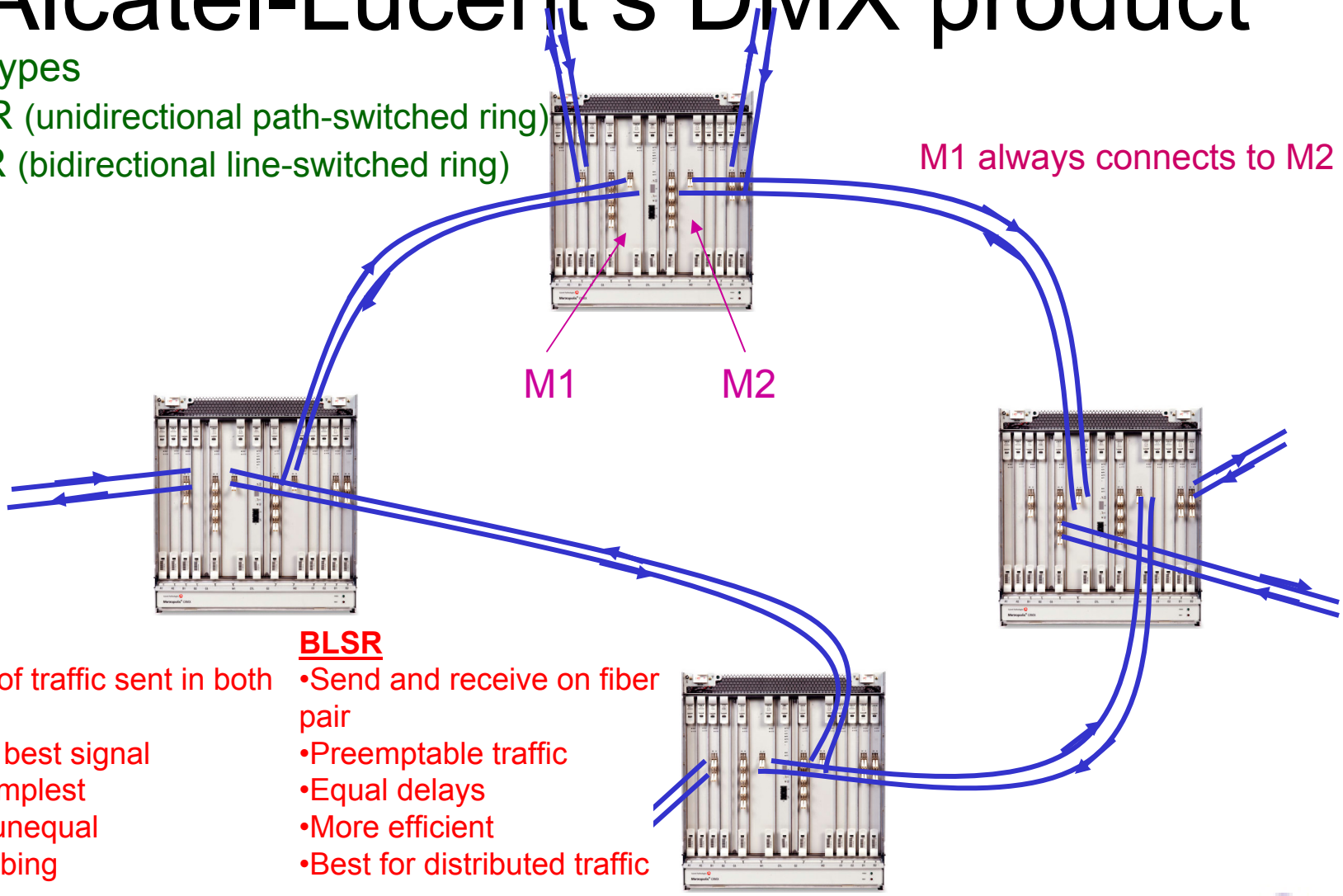
All devices can still communicate *if one transceiver fails or if one span is broken*.

The physical layout may not look much like a ring. For example, as long as two routes are on different sides of a road, they can be different parts of a ring.

Example SONET ring using Alcatel-Lucent's DMX product

Two ring types

1. UPSR (unidirectional path-switched ring)
2. BLSR (bidirectional line-switched ring)



UPSR

- Same copy of traffic sent in both directions
- Rx chooses best signal
- Control is simplest
- Delays are unequal
- Best for hubbing

BLSR

- Send and receive on fiber pair
- Preemptable traffic
- Equal delays
- More efficient
- Best for distributed traffic

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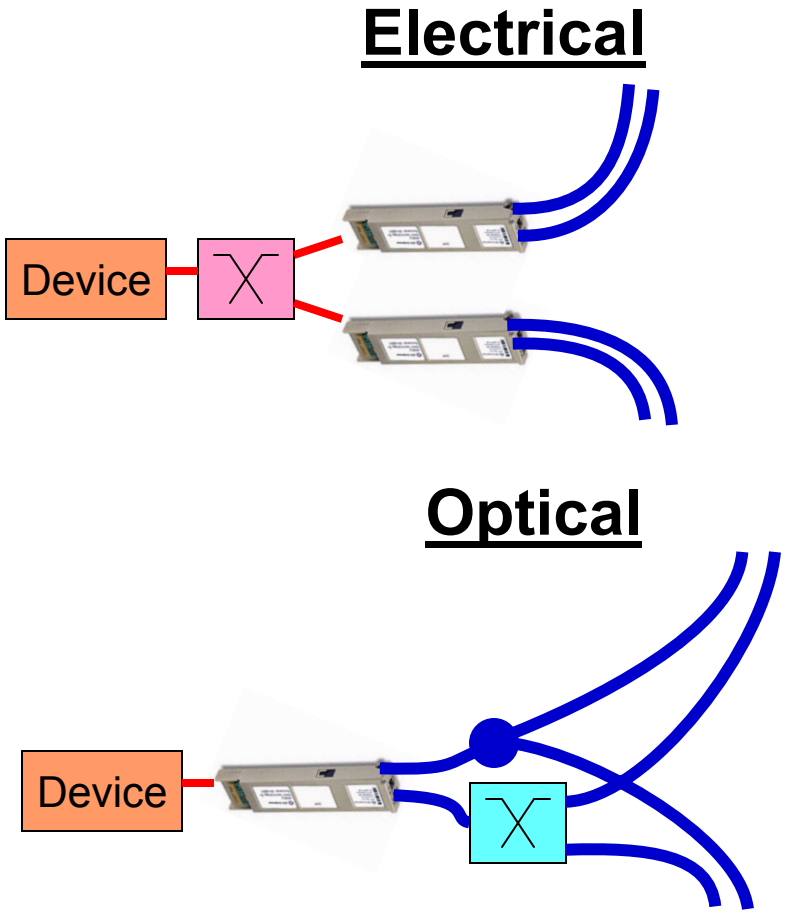
Two main categories of protection



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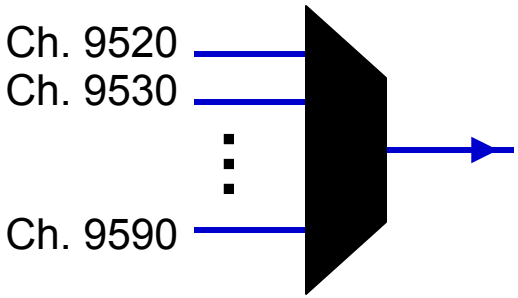
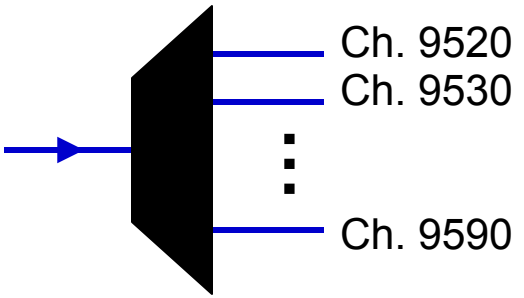
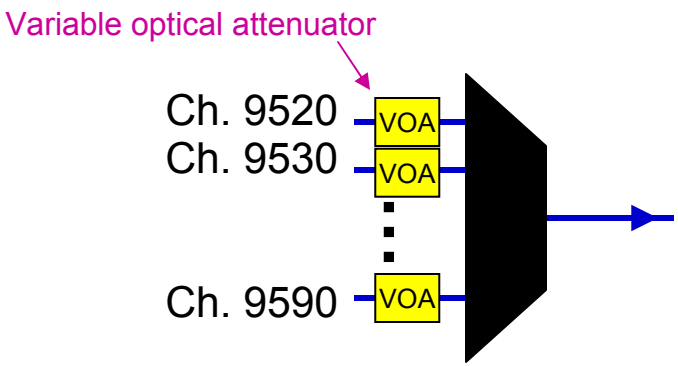
Very basic WDM components



Multiplexer (Mux)



Demultiplexer (Dmux)



VOA multiplexer (Vmux)

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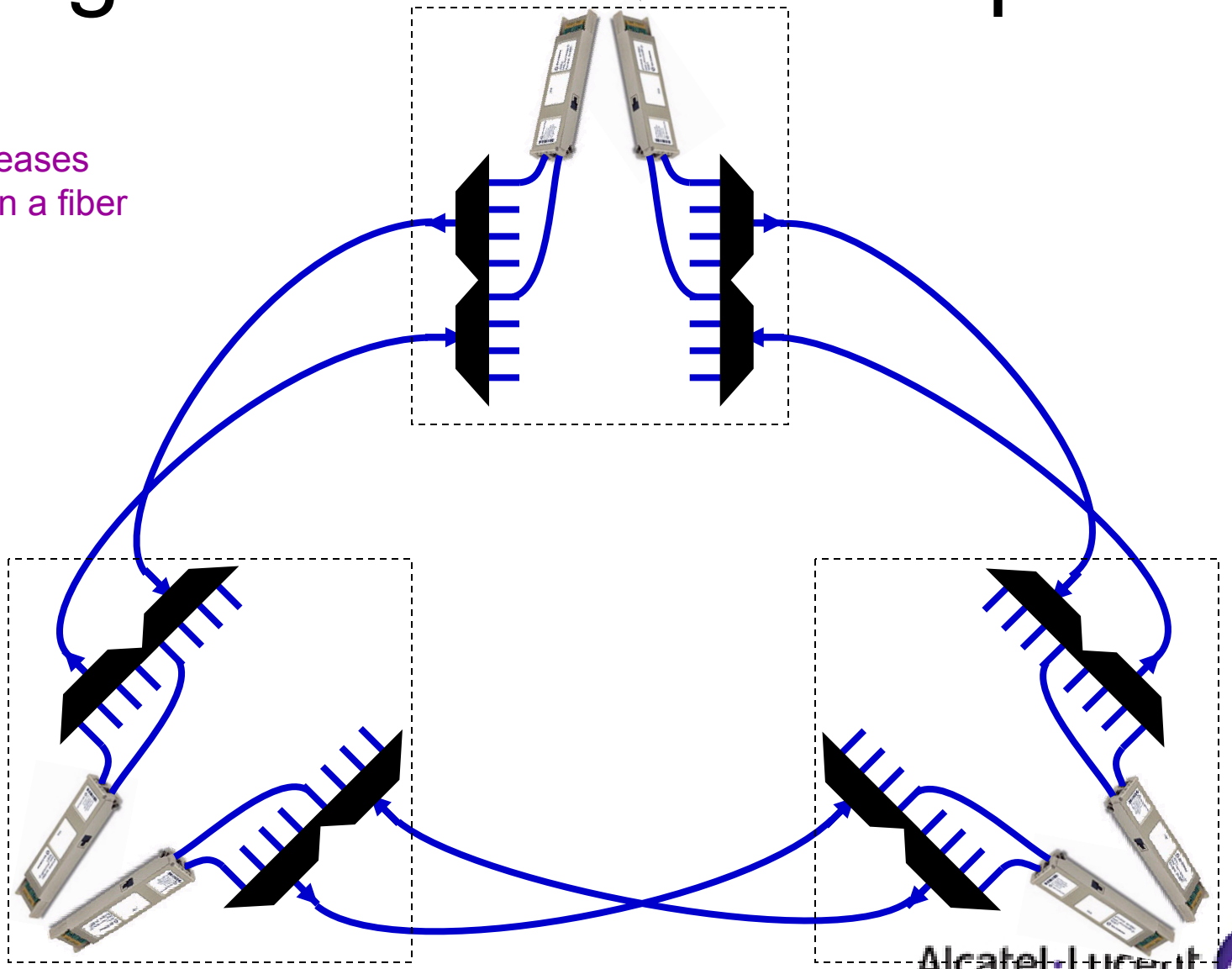
Ring with WDM point-to-point

WDM increases capacity on a fiber



Recent proponent for WDM point-to-point

Original use of WDM was just point-to-point, with all switching done in the electronic domain. Now, one company claims that networks should go back to such an architecture, because of integration.

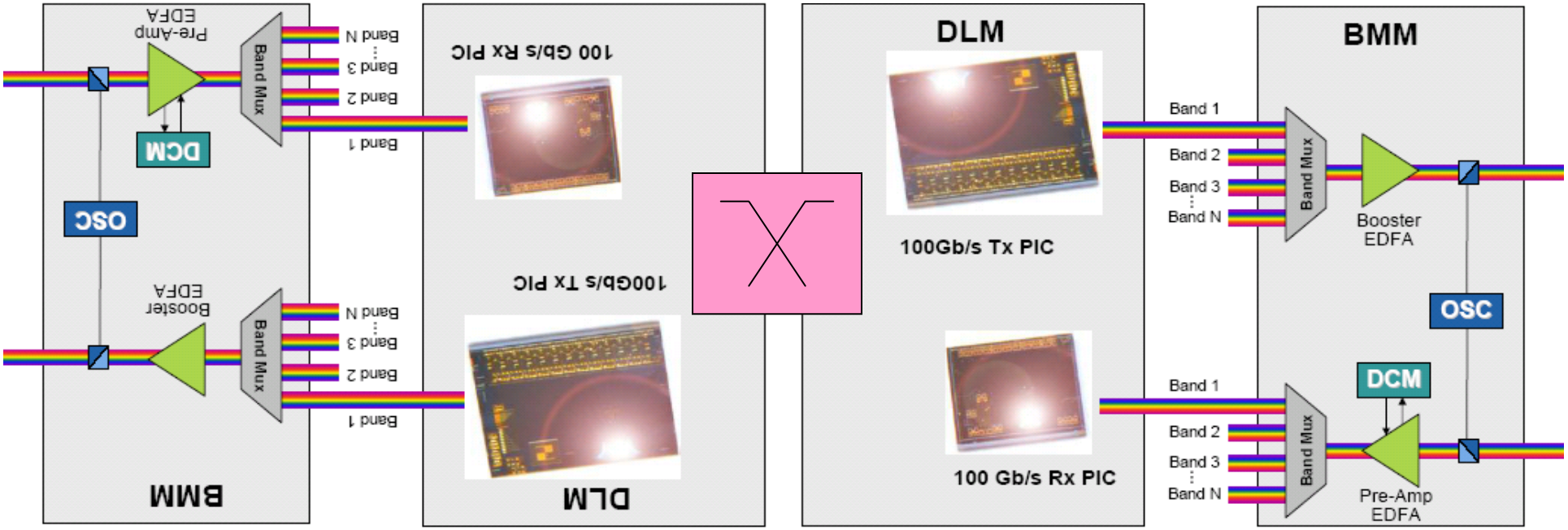


Image from Infinera

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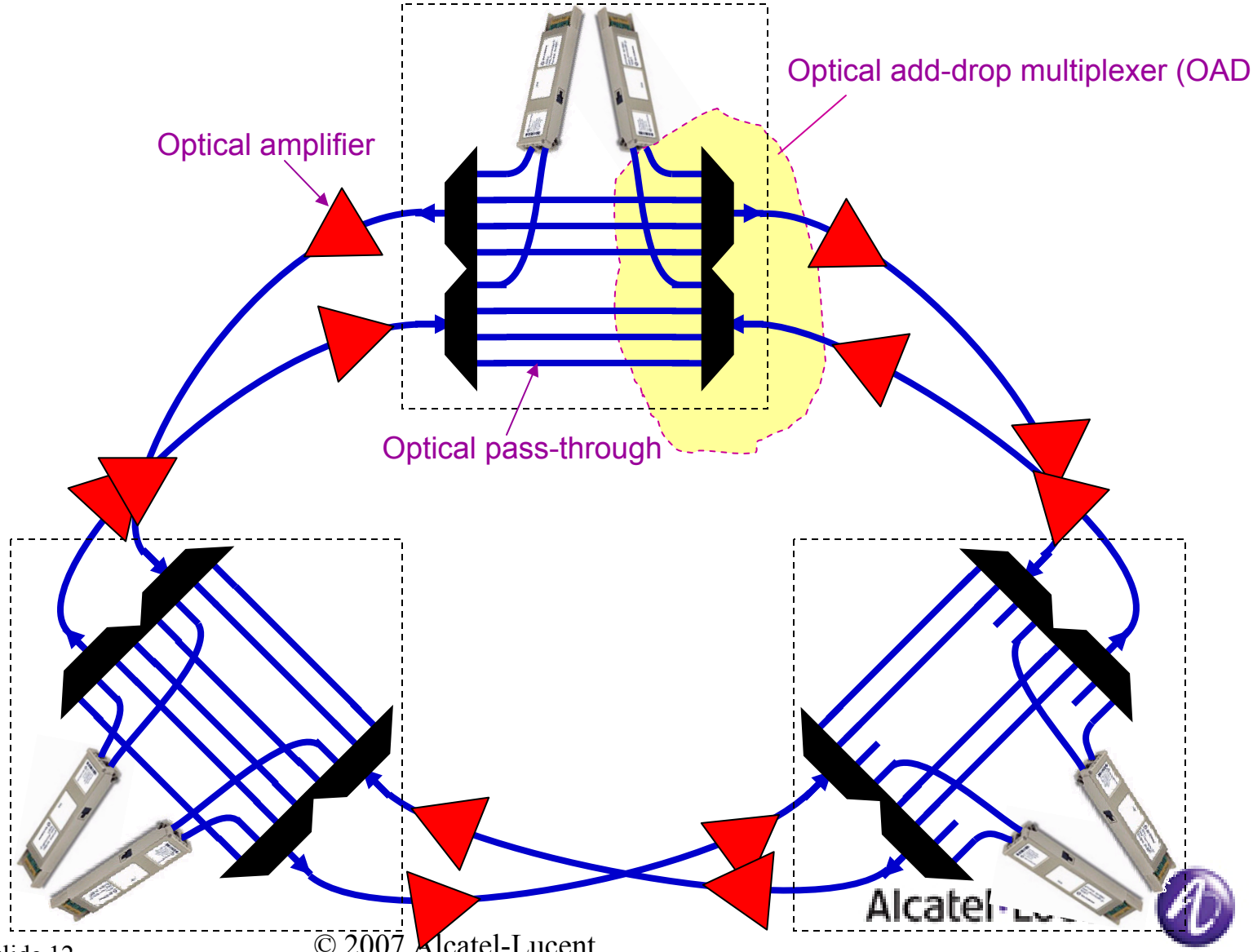
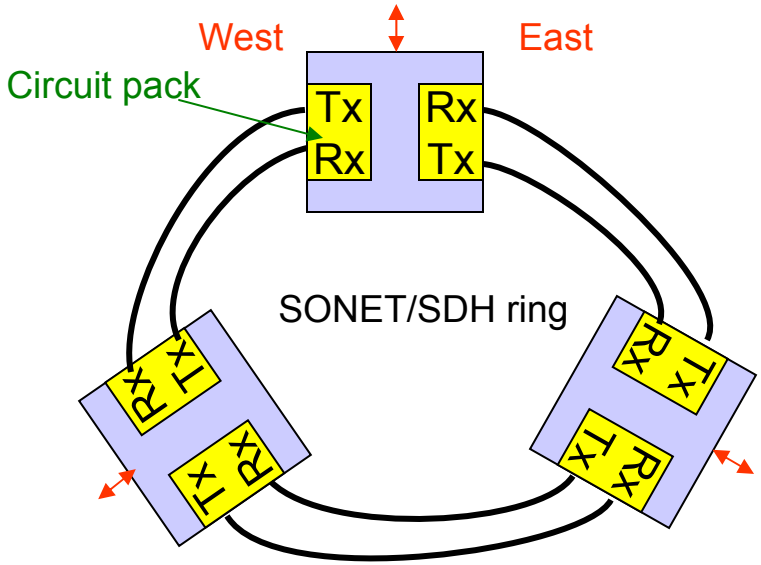
Ring with WDM add-drop



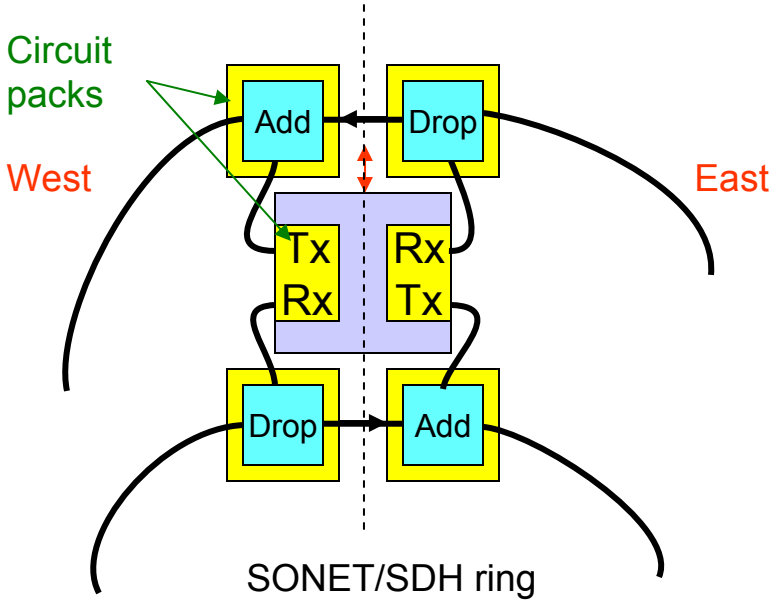
“East-west” separability requirement for WDM add-drop

Pure TDM case



If any one circuit pack is removed, all nodes can still communicate.

WDM case with add-drop



If any one circuit pack is removed, all nodes can *still* communicate.

The OADM *must* have the drop and add for each direction at each node on separate circuit packs

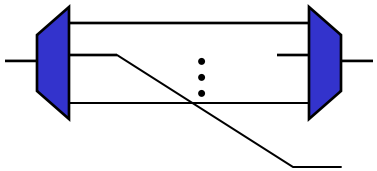
Types of WDM drops

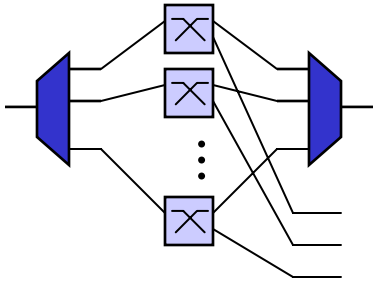
- Static OADM
- Fixed-port ROADM
- Port-selectable ROADM
- Full WSS

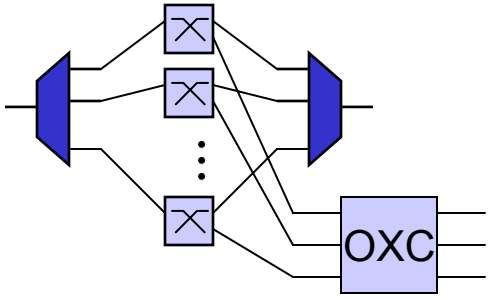
Less blocking

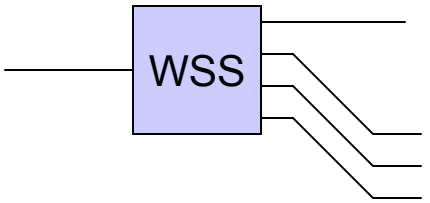
Also called “colorless” ROADM

Wavelength-selective switch









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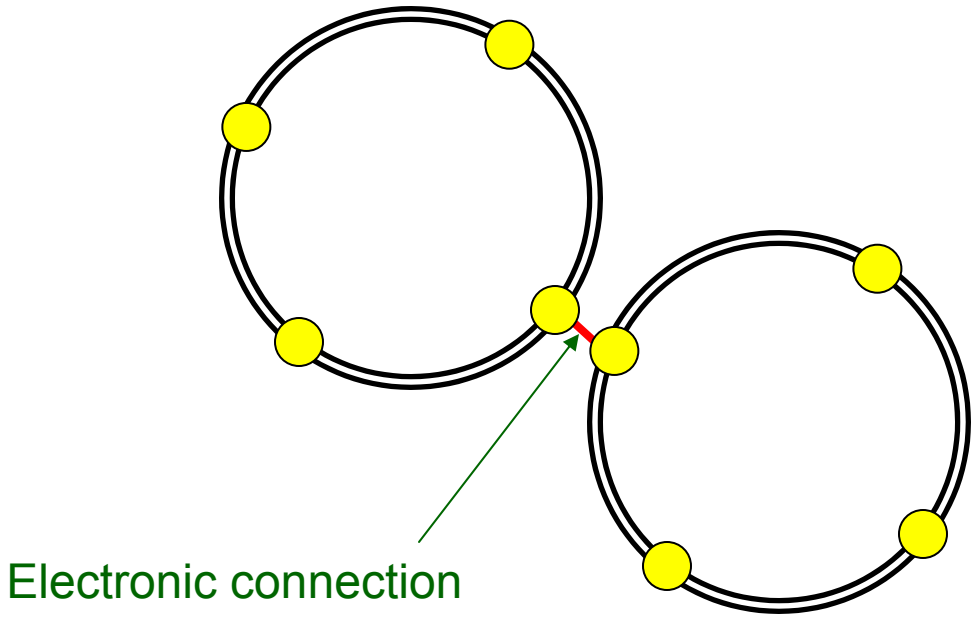
Interconnecting rings



If it is an optical connection, then it becomes…

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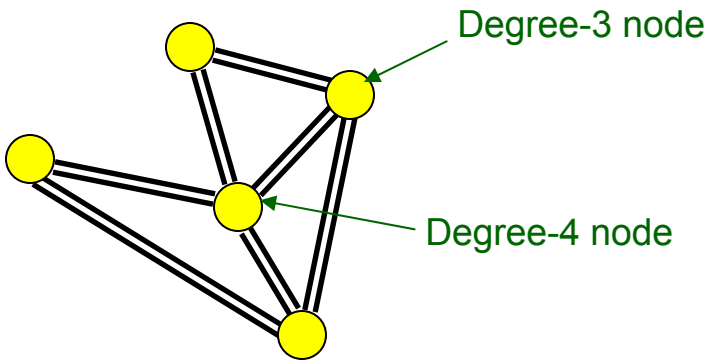
Optical mesh



Mesh provides greater flexibility and protection

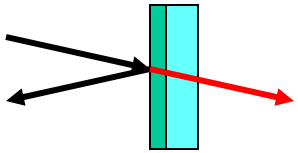
Degree is the number of main line pairs connected to the node.
Confusing point: sometimes the degree number includes local add-drop and sometimes it doesn't.

Passive WDM routing devices

Mux/Dmux

Thin-film filter (TFF)

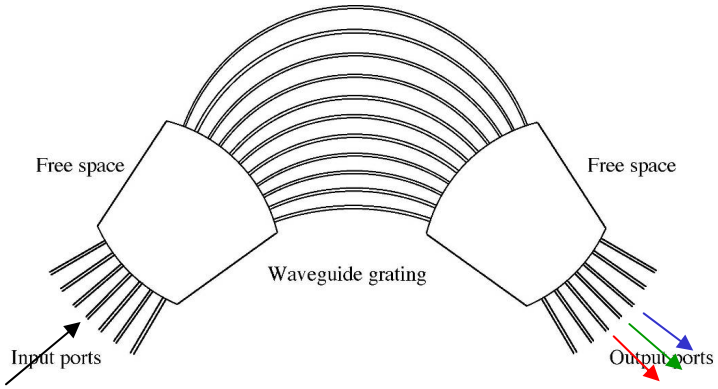
For ≤ 8 chs



"Bulk" optics

Arrayed waveguide grating (AWG)

For > 8 chs



"Integrated" optics

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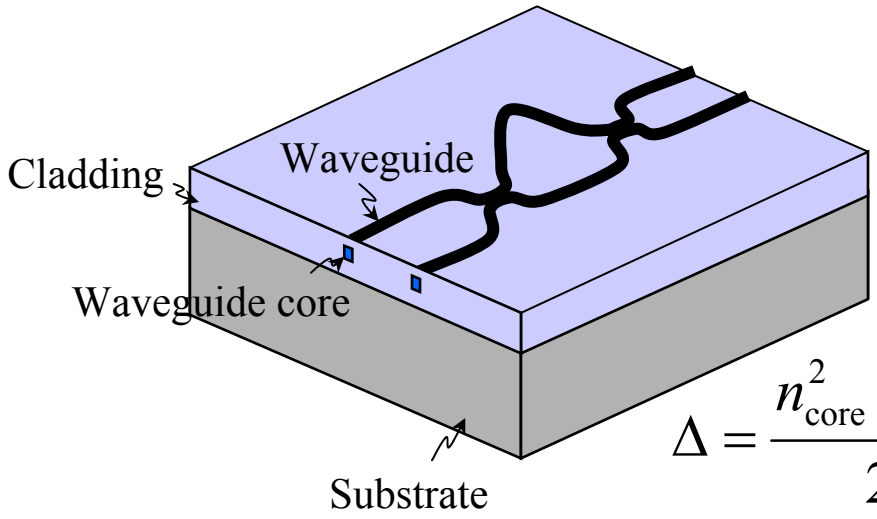
Planar lightwave circuit (PLC)

A planar arrangement of waveguides on a substrate



Normalized index contrast

$$\Delta = \frac{n_{\text{core}}^2 - n_{\text{cladding}}^2}{2n_{\text{core}}^2} \approx \frac{n_{\text{core}} - n_{\text{cladding}}}{n_{\text{core}}}$$

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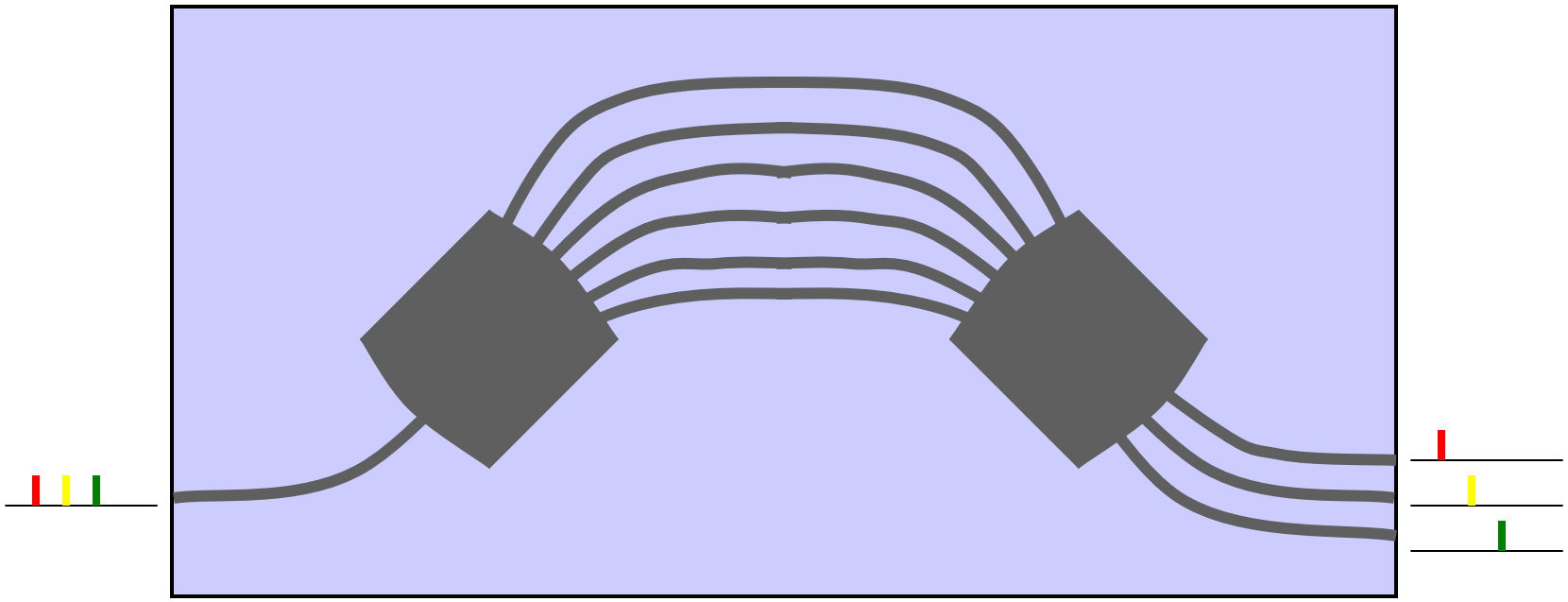
Arrayed waveguide grating (AWG)



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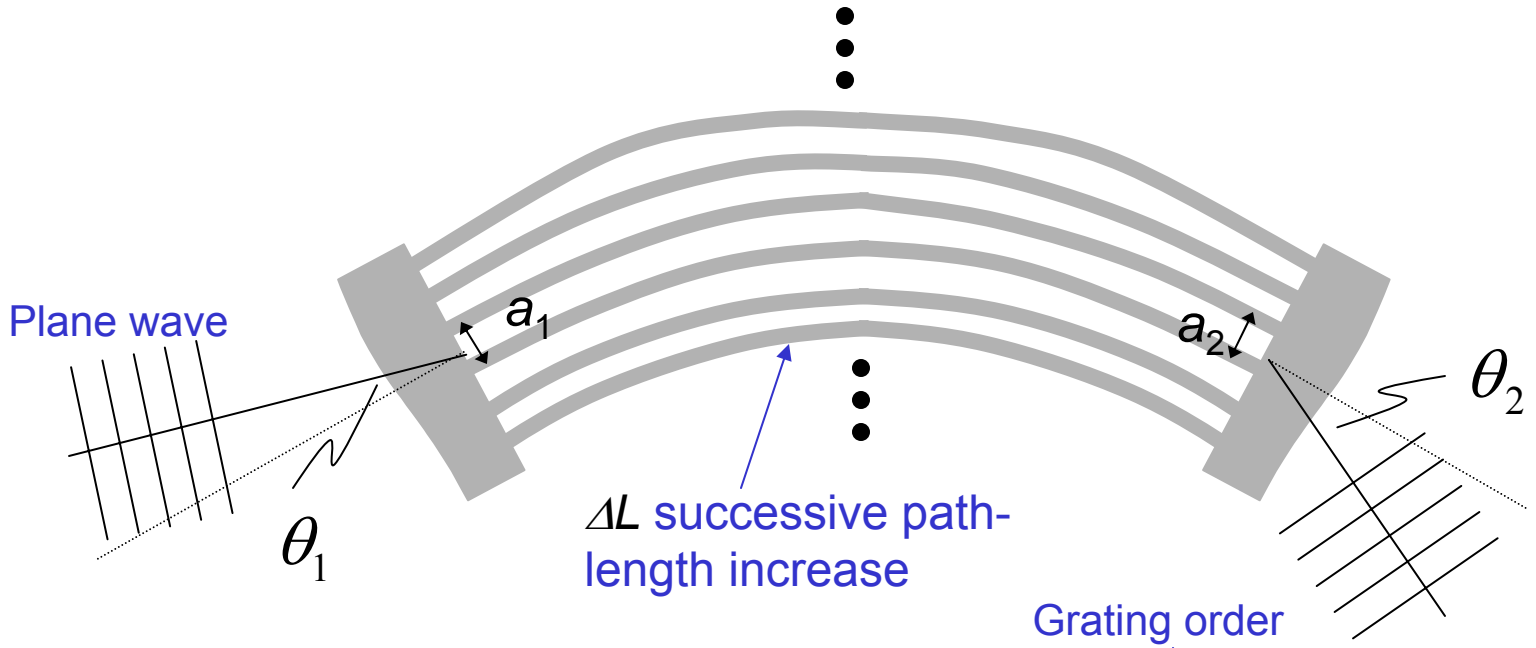
AWG principle of operation



Grating order

Effective index of channel waveguides

$$n_{\mathrm{wg}}\Delta L + n_{\mathrm{fs}}\left(a_1\theta_1 + a_2\theta_2\right) \approx A\lambda$$

Effective index of slab waveguides

M. K. Smit, Electron. Lett., vol. 24, pp. 385-386, 1988.

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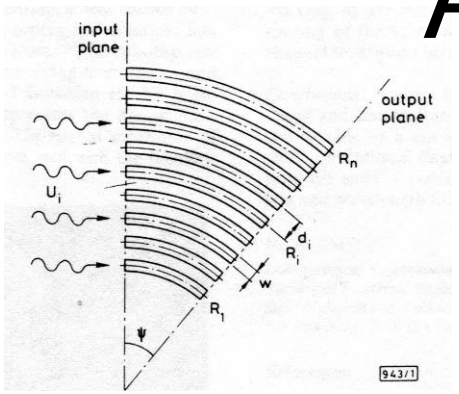
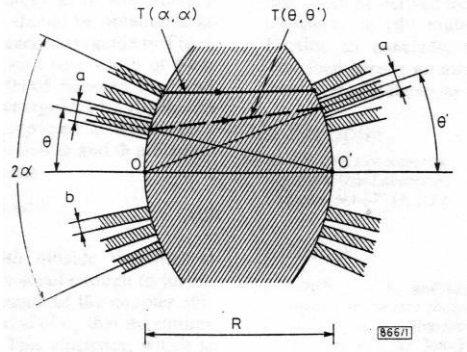
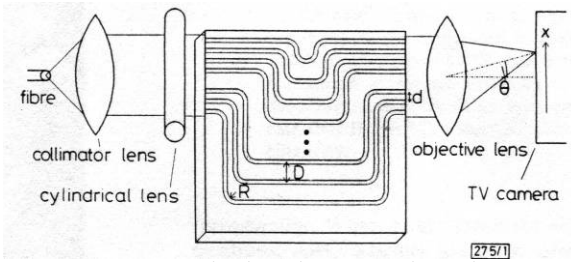
AWG history



M. Smit, Electron. Lett., p. 385, 1988.

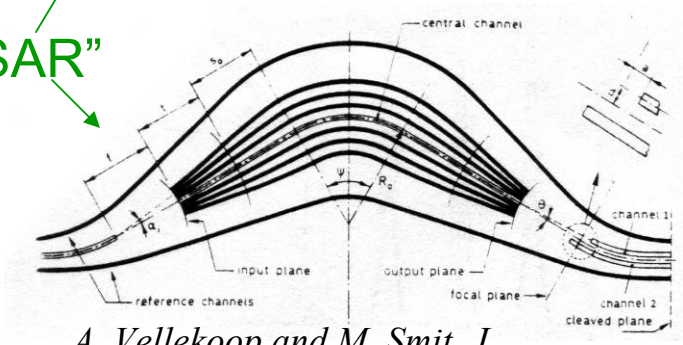


C. Dragone, Electron. Lett., p. 942, 1988.



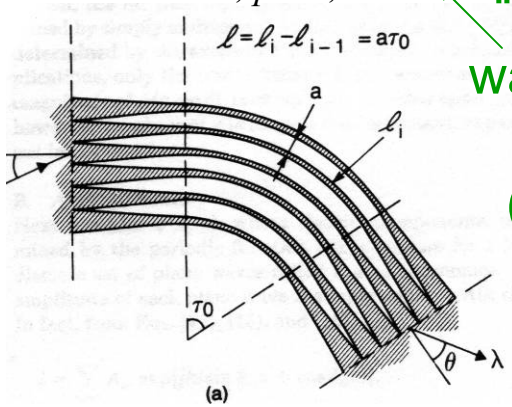
H. Takahashi, et. al., Electron. Lett., p. 87, 1990.

"PHASAR"



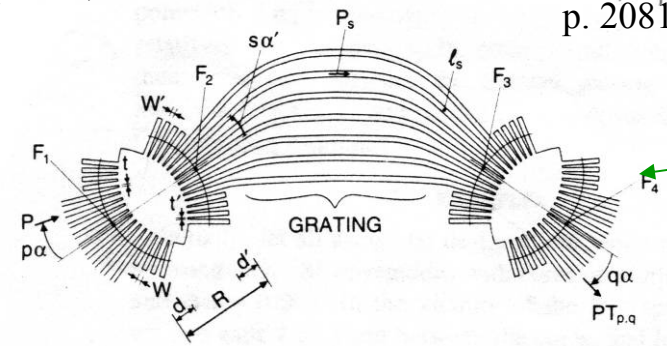
A. Vellekoop and M. Smit, J. Lightwave Technol., p. 310, 1991.

"Arrayed waveguide grating (AWG)"



C. Dragone, *J. Opt. Soc. Am. A*, p. 2081, 1990.

"Waveguide grating router (WGR)"



C. Dragone, IEEE Photon. Technol. Lett., p. 812, 1991.

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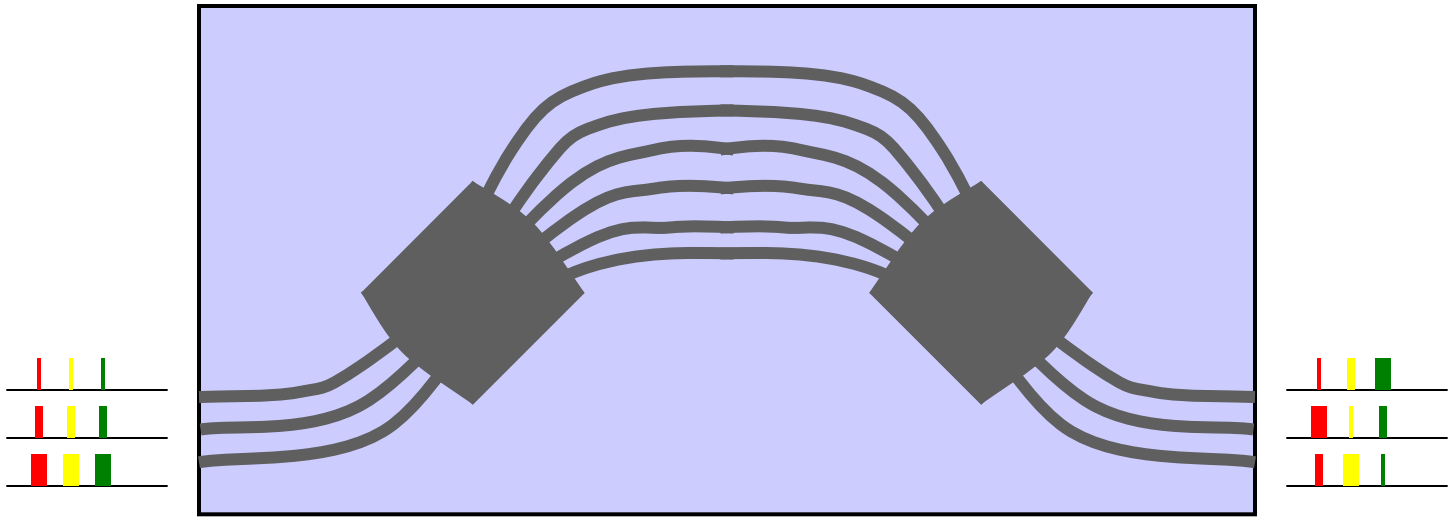
N x *N* AWG



Gives passive cyclic wavelength routing.
Not used in today's networks.

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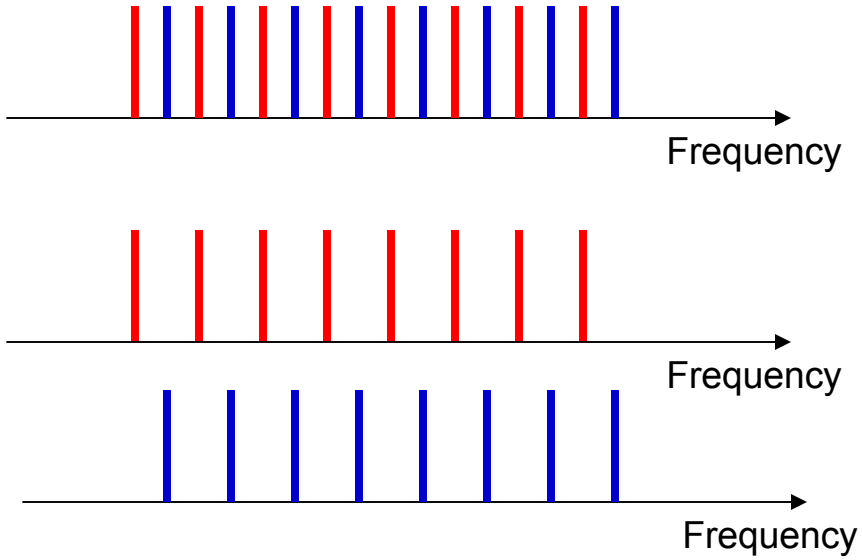
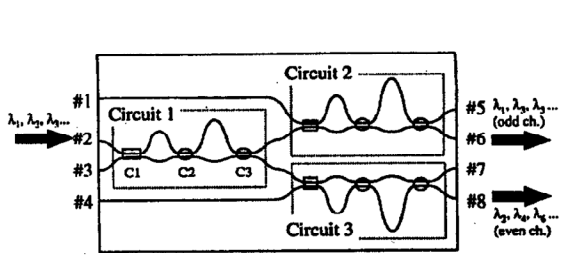
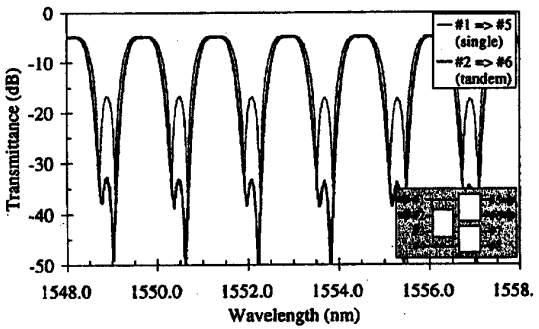
Interleaving

Divides channels into combs







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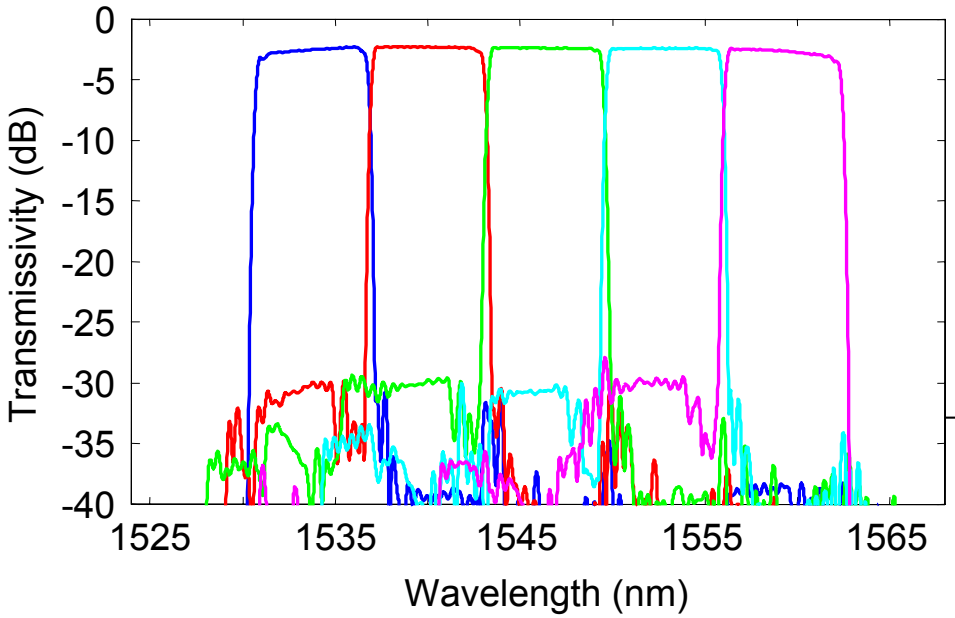
Banding

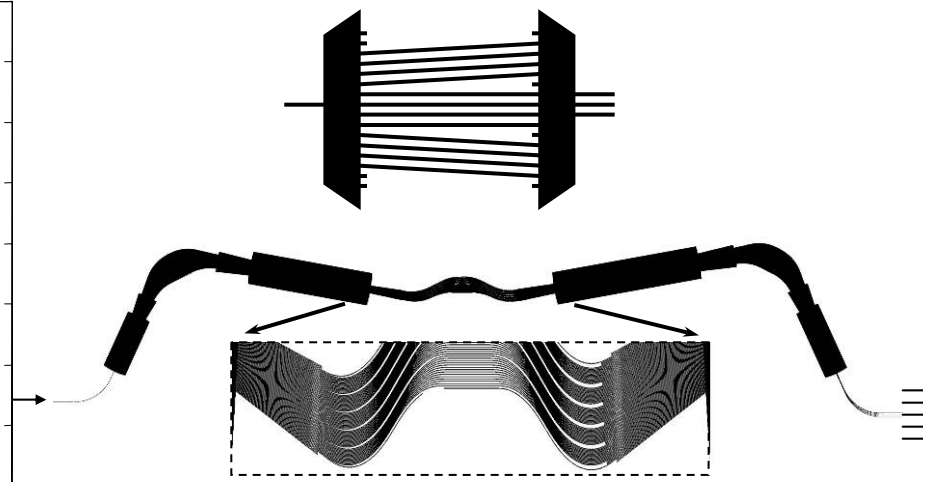
Divides channels into contiguous bands

M-skip-*N*

Number of channels in band (usually on 100-GHz grid)

Number of dead channels between bands





C. Doerr et al. " Integrated band demultiplexer using waveguide grating routers", PTL, 15, 1088-1090, 2003

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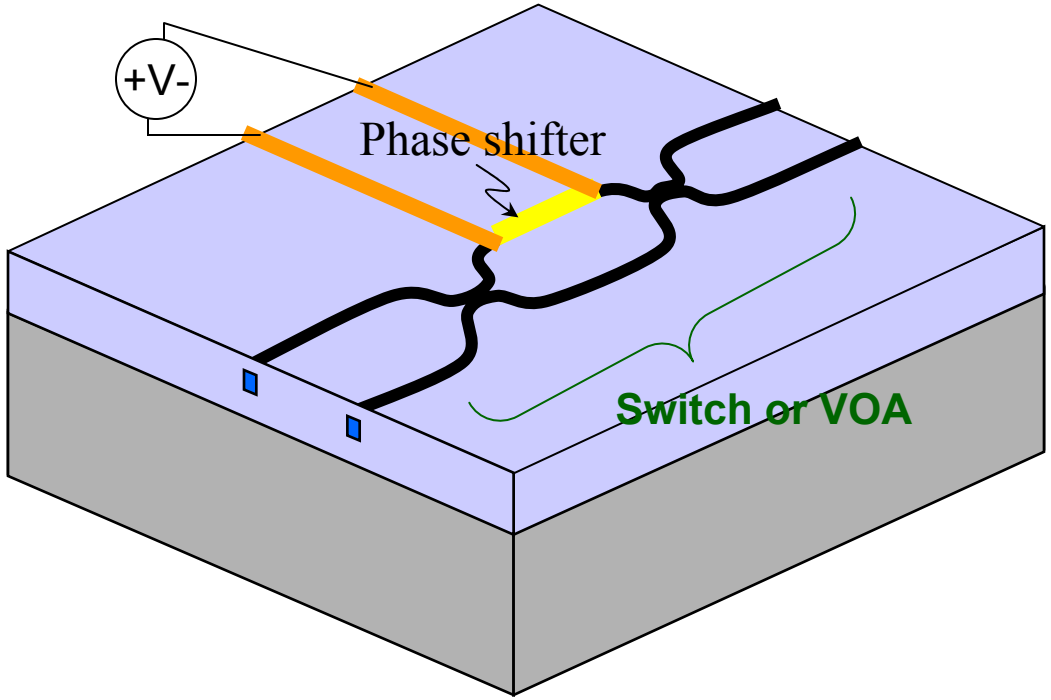
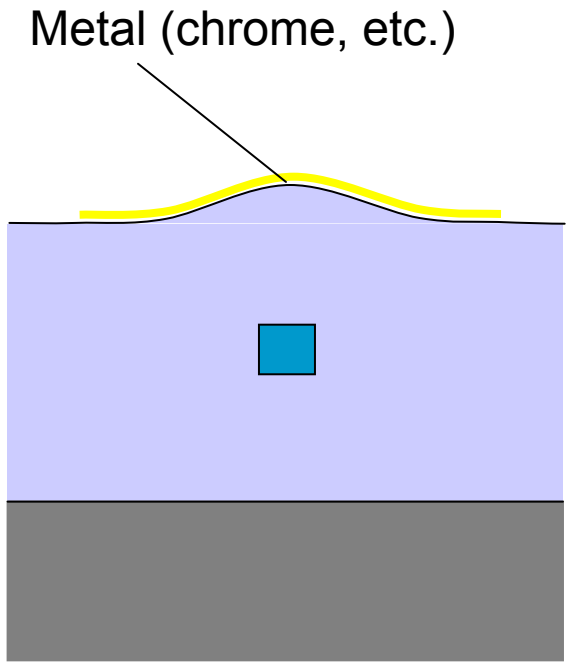
Active WDM routing devices

Thermooptic phase shifter in silica





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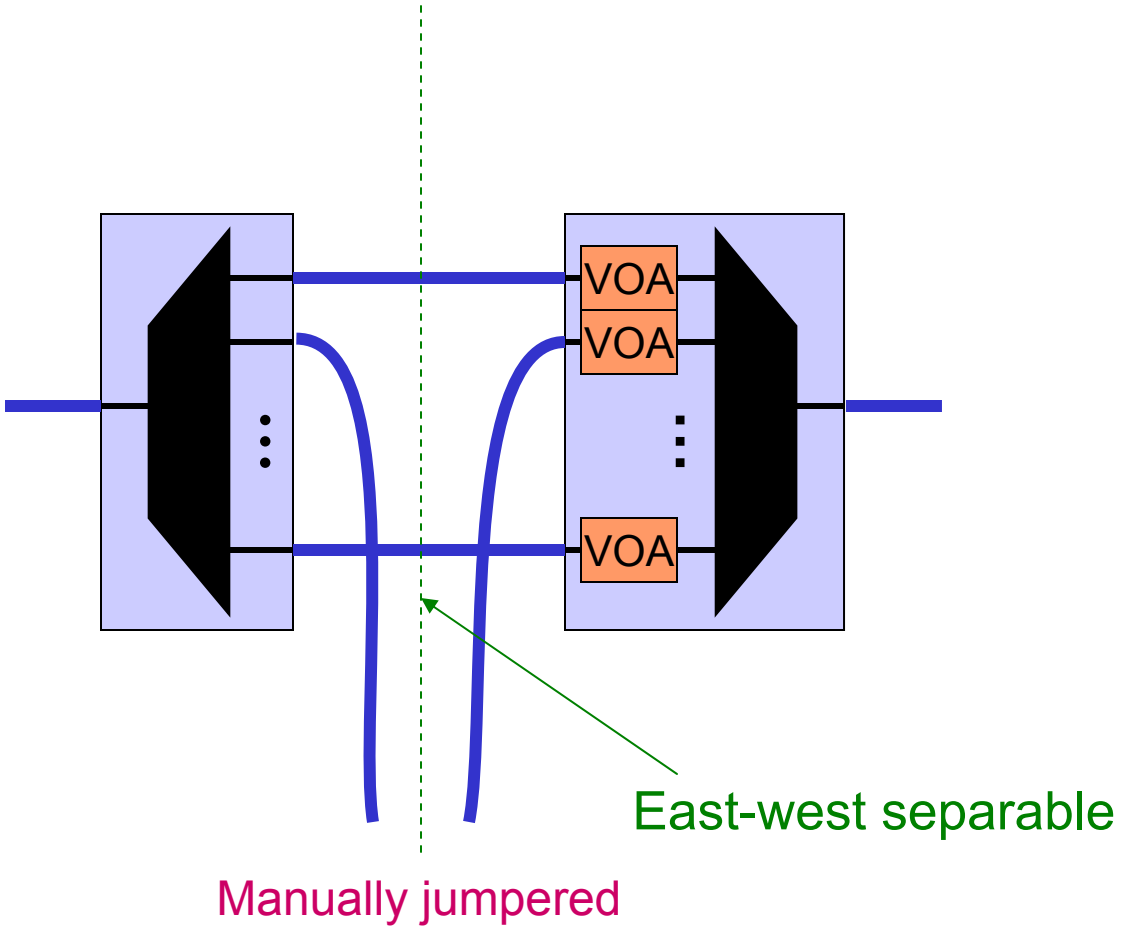
Active WDM routing devices for deg-2 nodes

OADM



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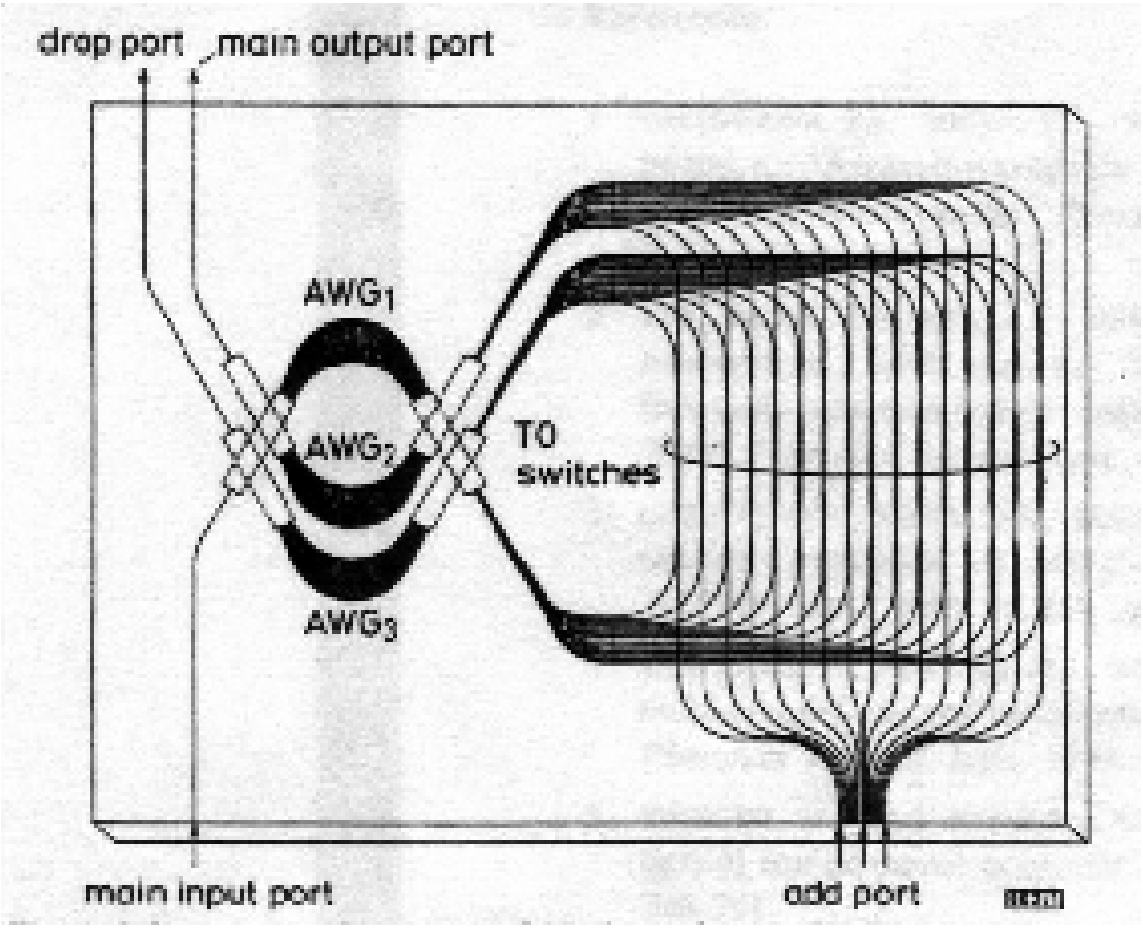
First integrated ROADM



Silica

K. Okamoto, K. Takiguchi, and Y. Ohmori, Electron. Lett., pp. 723-724, 1995.

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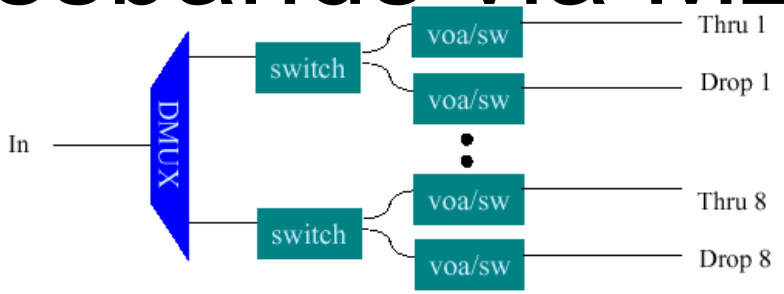
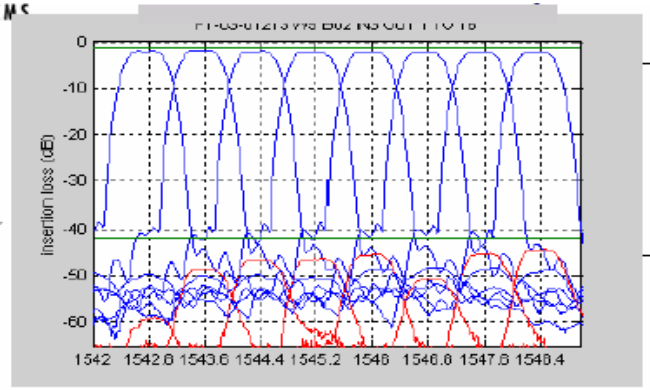
8-channel ROADM with flat-top passbands via MZI-AWG



MICROSYSTEMS

All Thru

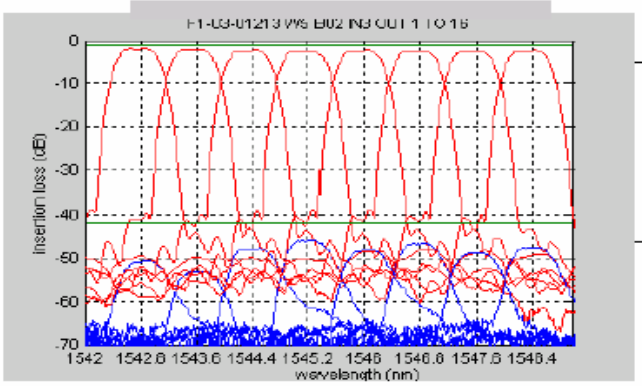


Thru-Loss ~ 2.5 dB

(Loss Includes AWG, Switch VOA)

Drop-Thru extinction>40dB

All Drop



Drop-loss ~2.5 dB

(Loss Includes AWG, Switch VOA)

Thru-Drop extinction>40dB

Blue: thru channels
Red: drop channels

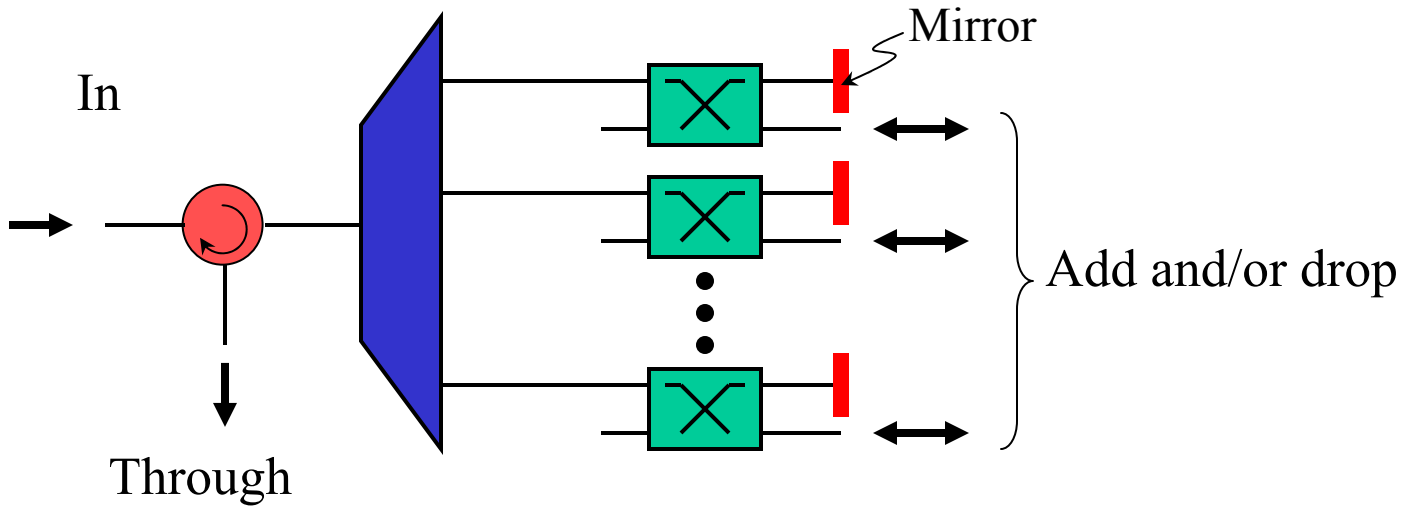
Test Data From 8 Channel ROADM Drop

Low loss achieved through DMUX design and integration

NeoPhotonics

cent

ROADM design without waveguide crossings



Avoidance of waveguide crossings allows for lower loss and smaller size.

For study of waveguide crossings see *H. G. Bukkems, et. al., IEEE Photon. Technol. Lett., pp. 1420-1422, 1999.*

C. R. Doerr, et al., IEEE Photon. Technol. Lett., vol. 11, pp. 1437-1439, 1999.

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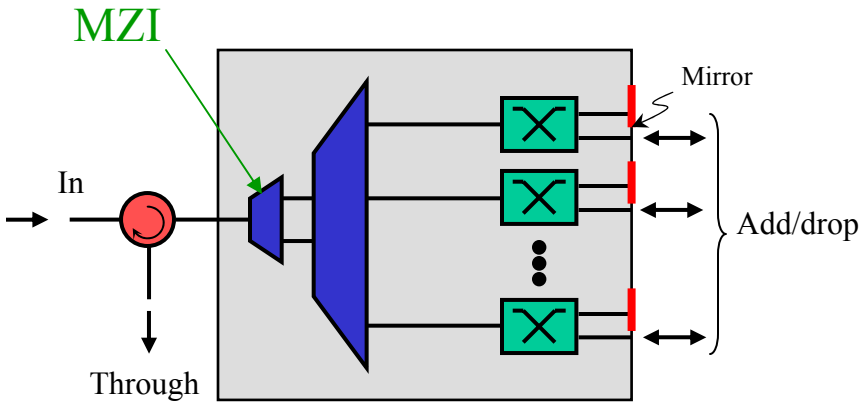
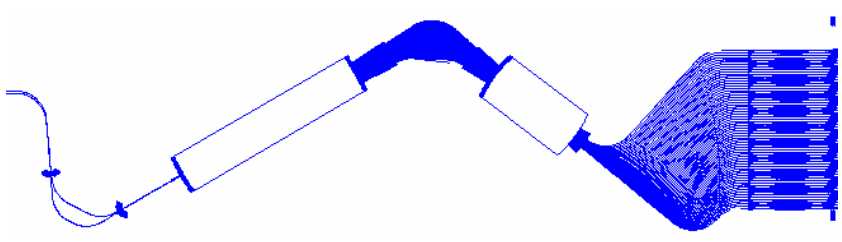
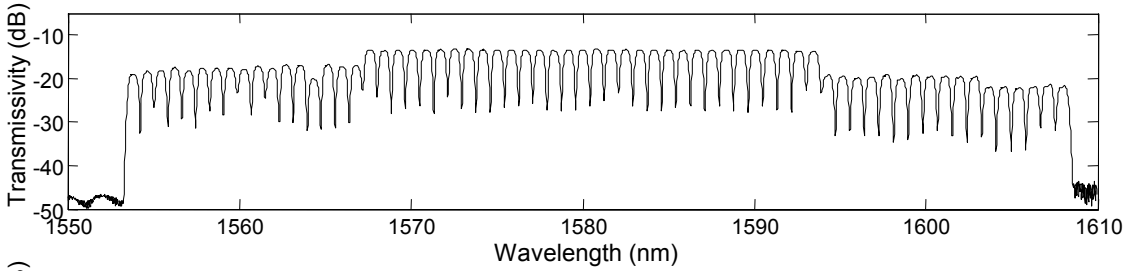
64-ch ROADM



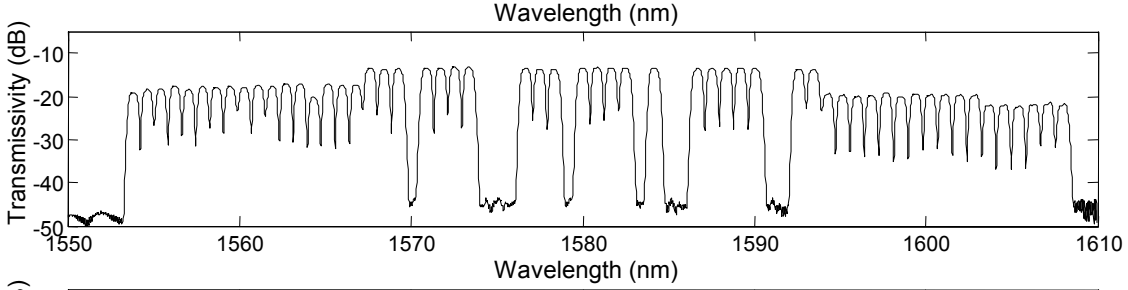
Silica



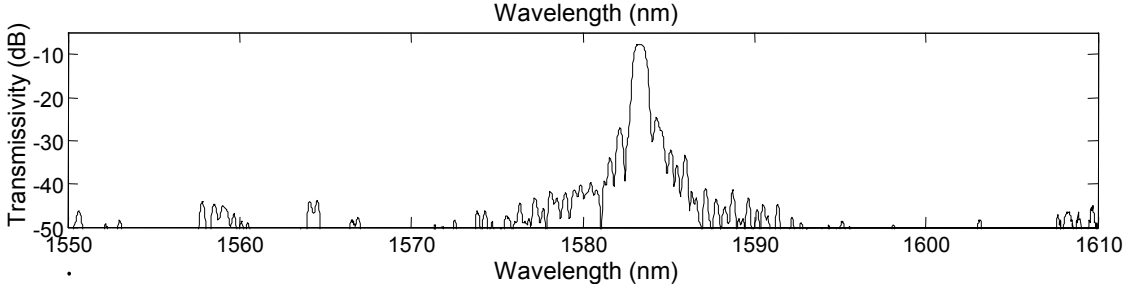
In-through



In-through



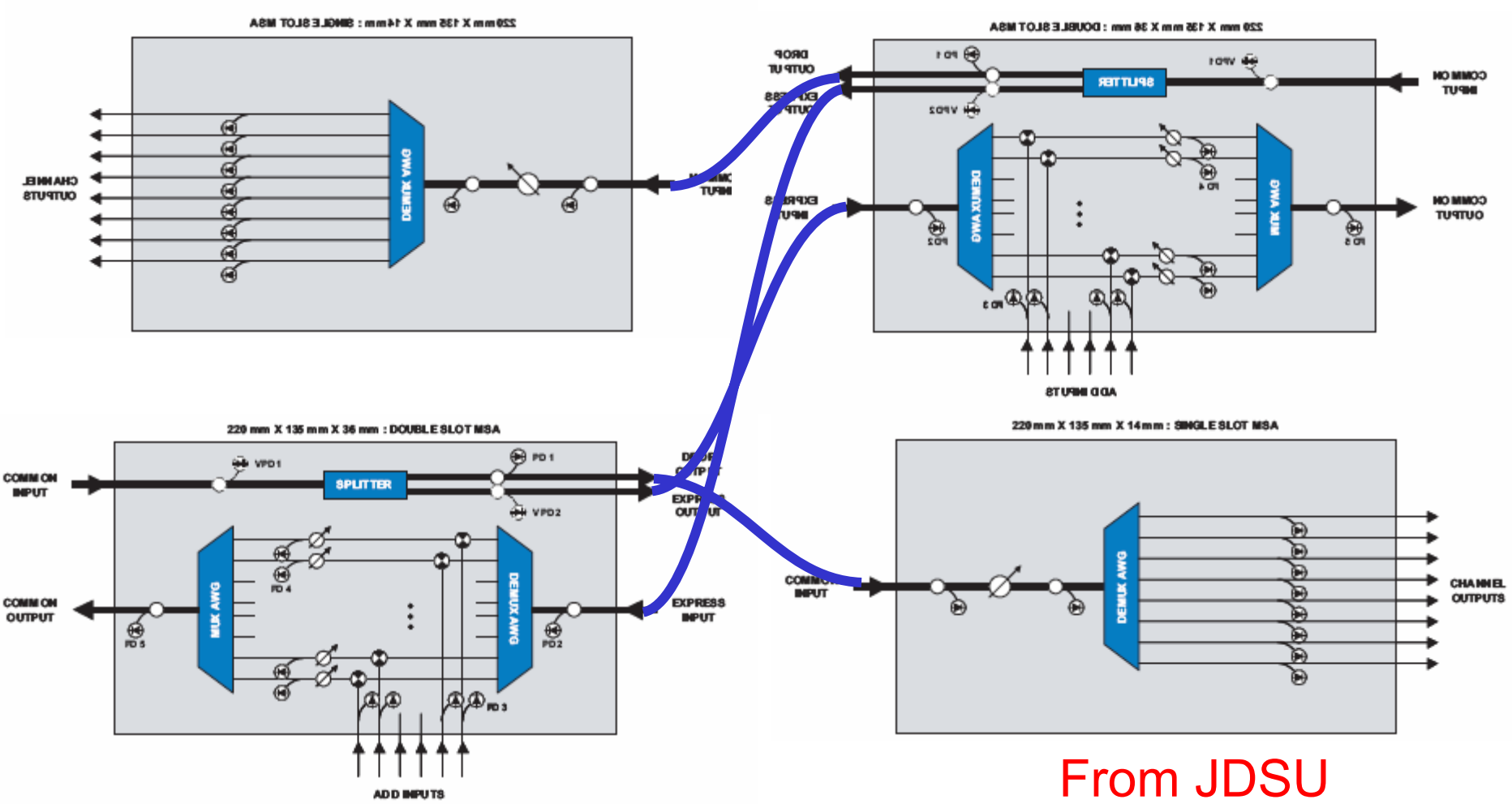
Add-through



Activated only central 32 channels

C. R. Doerr, et. al., IEEE Photon. Technol. Lett., pp. 56-58, 2002.

32-channel commercially available ROADM



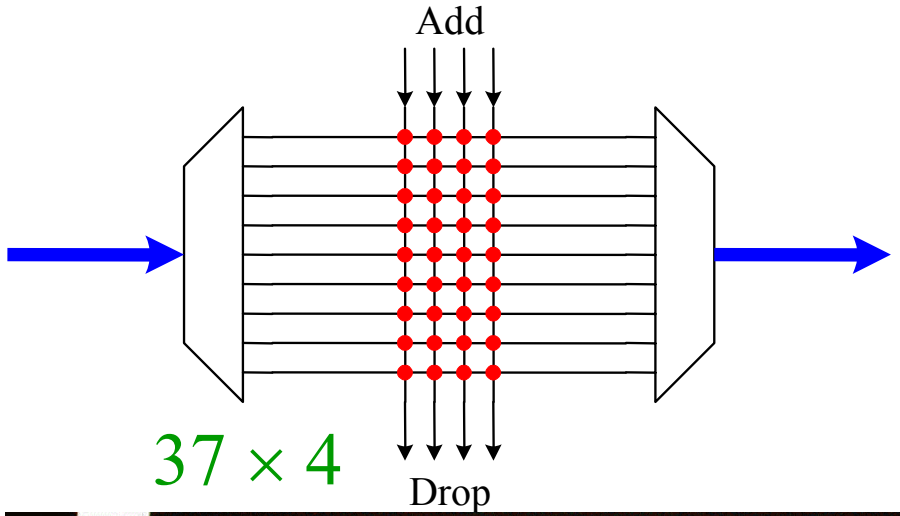
From JDSU

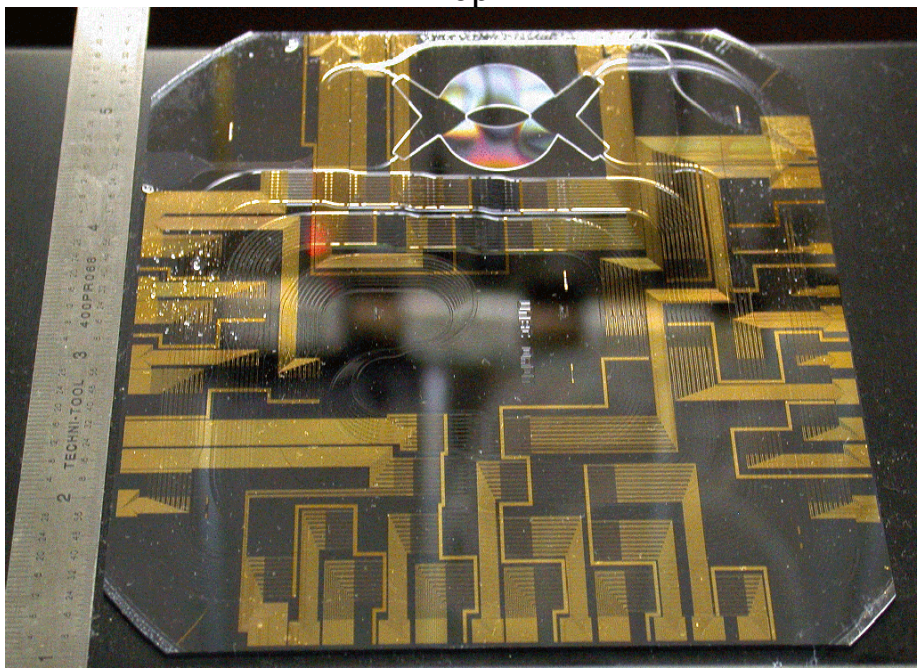
All silica PLC

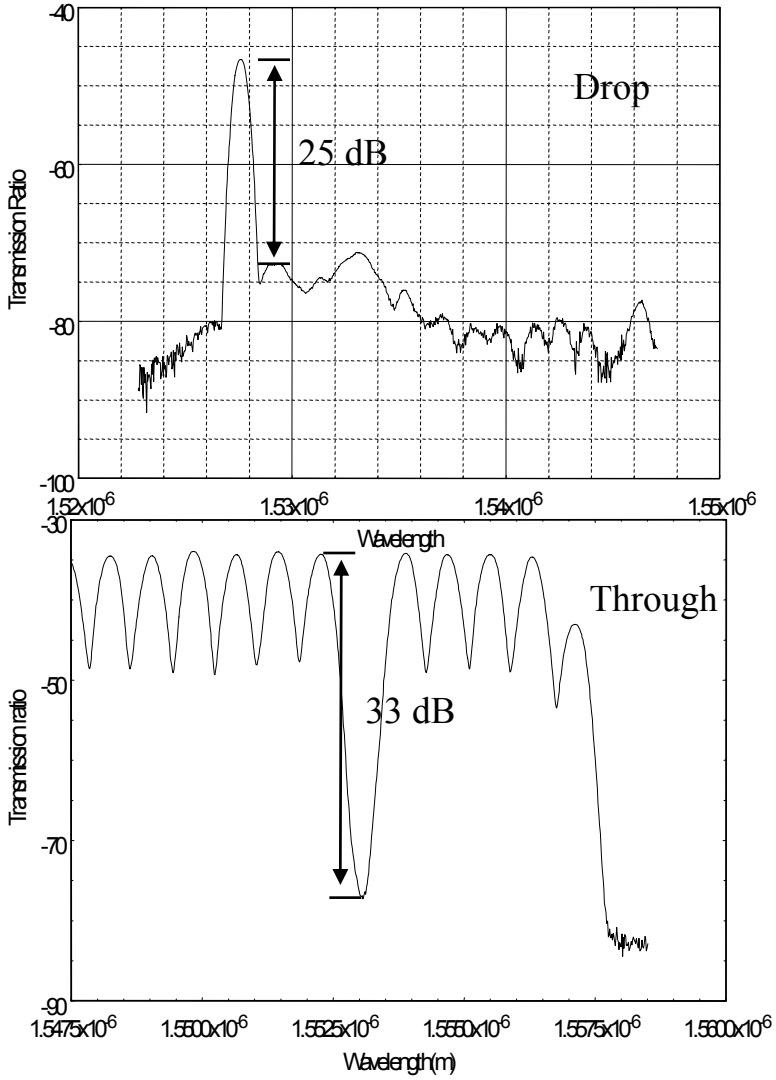
Alcatel·Lucent

Port-selectable ROADM—cross-bar type

Silica



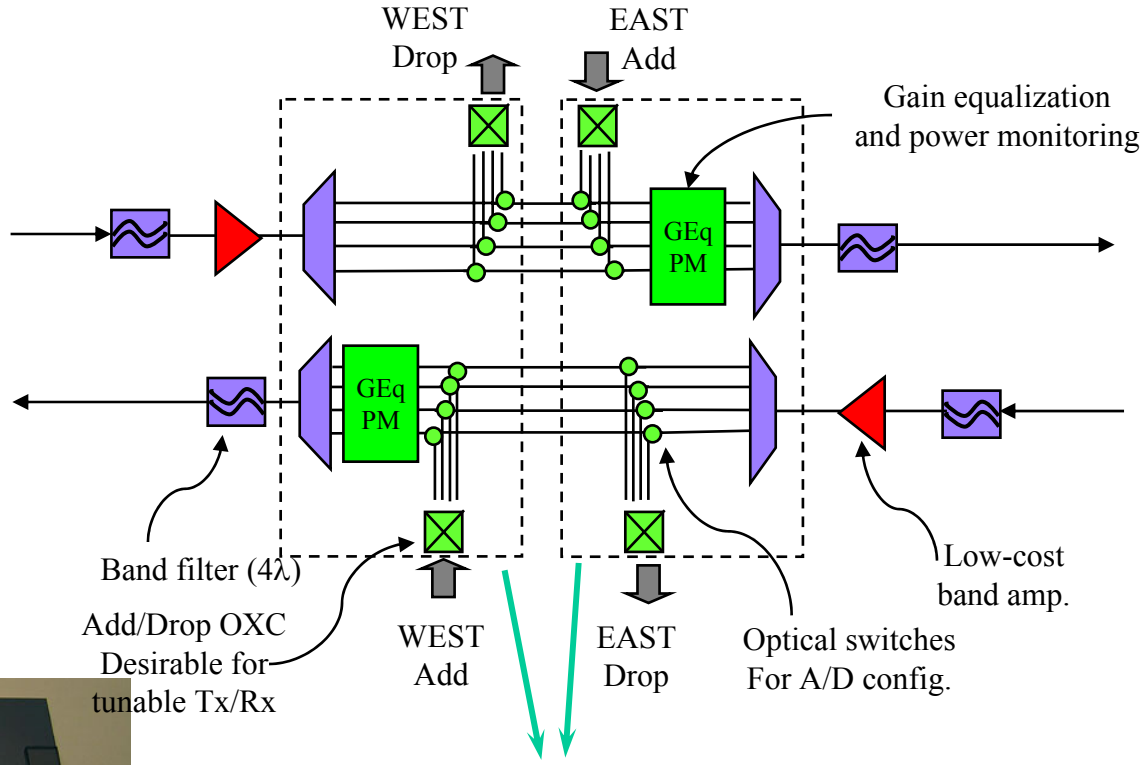


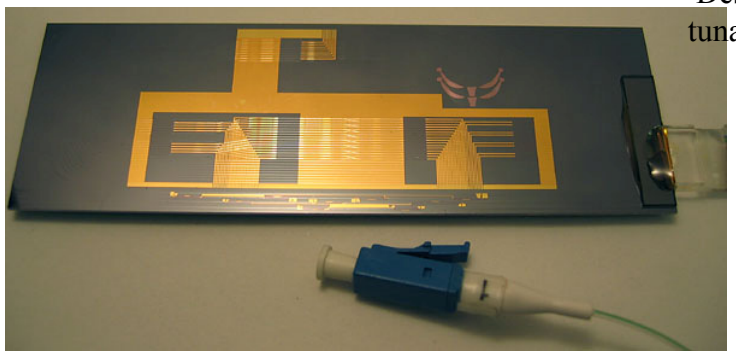


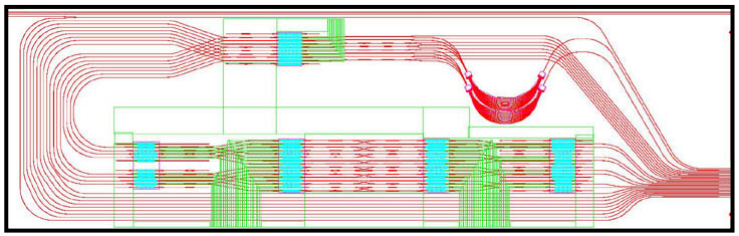
Courtesy of R. Chen from Univ. of Maryland

Alcatel·Lucent

Port-selectable ROADM—post OXC type







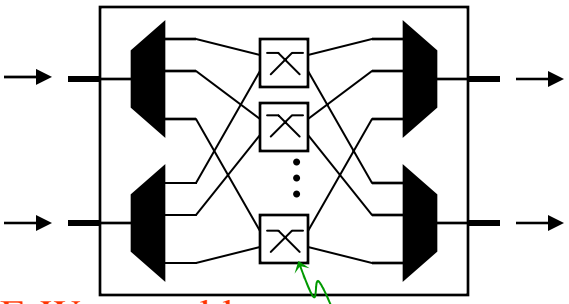
Die layout - 72x31mm

Courtesy of M. Earnshaw from Lucent

M. Earnshaw, et. al., IPR 2004.

Active WDM routing devices for deg >2 nodes

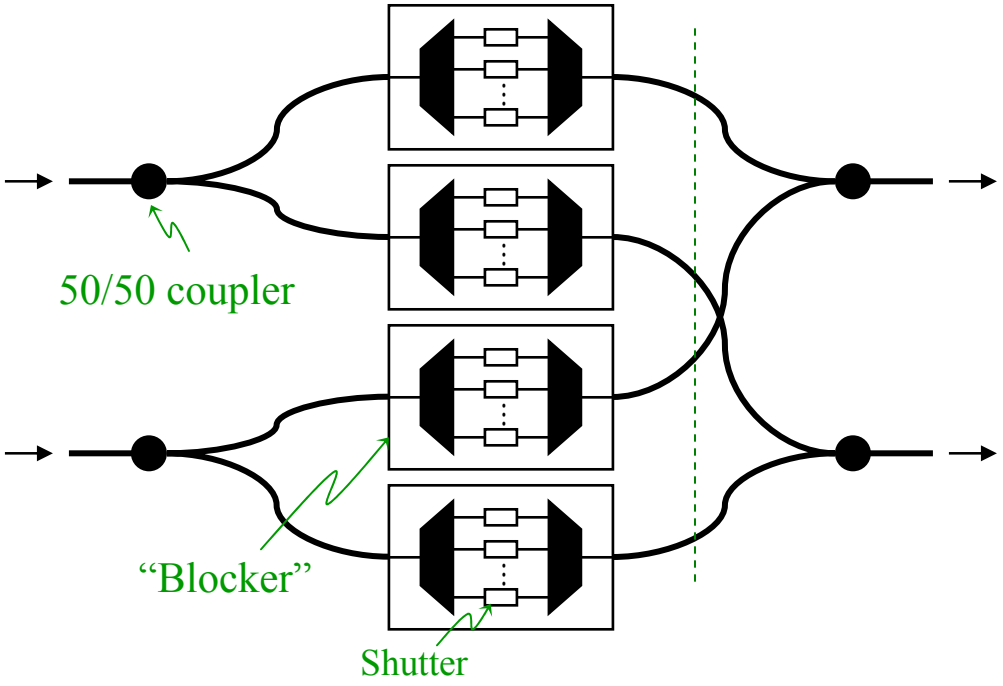
“Directional” deg-4 nodes



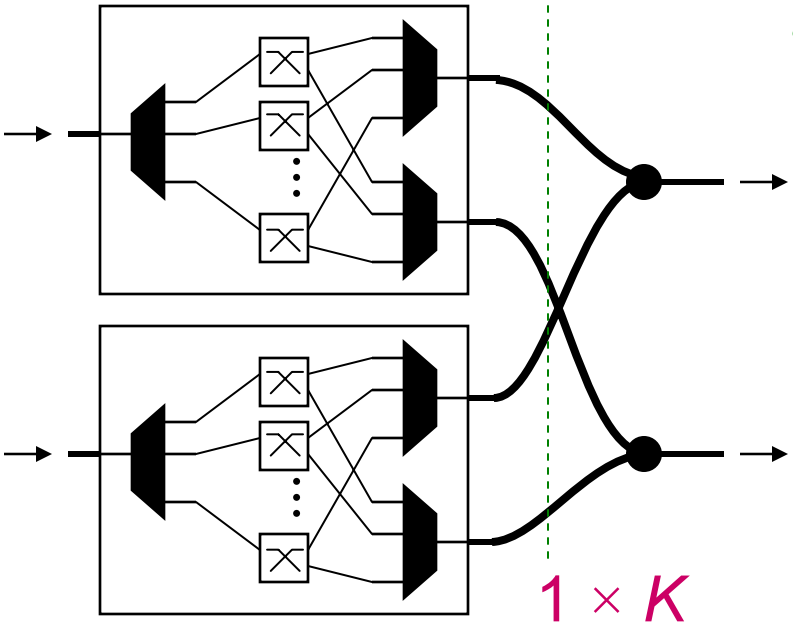
Not E-W separable

2 × 2 switch

Conventional



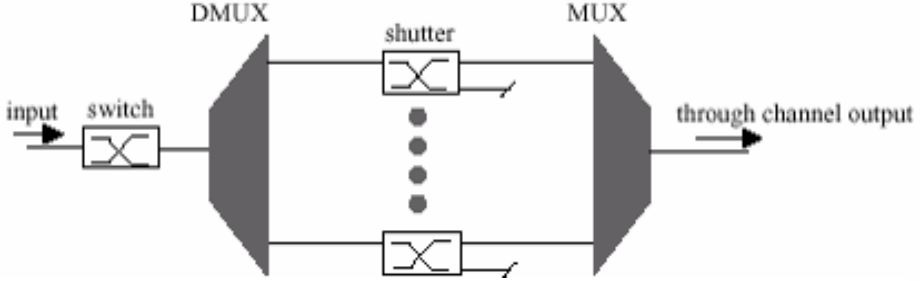
Broadcast-and-select (also called “blocker-type”)

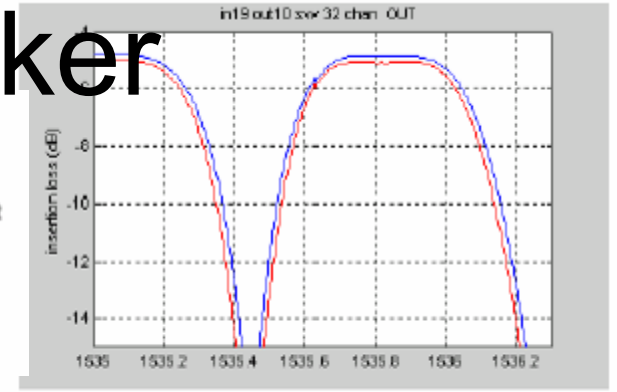


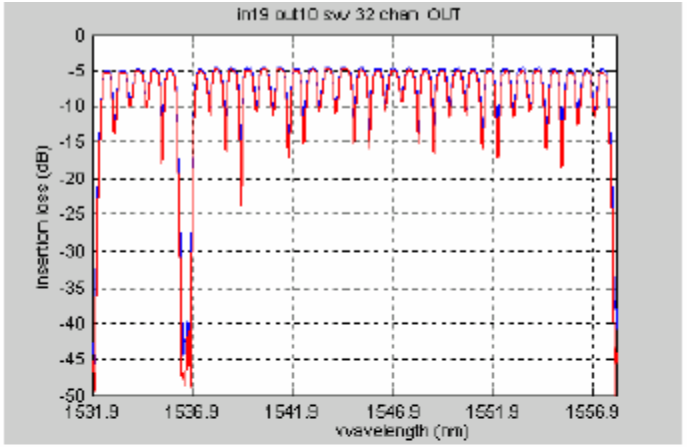
1 × *K*

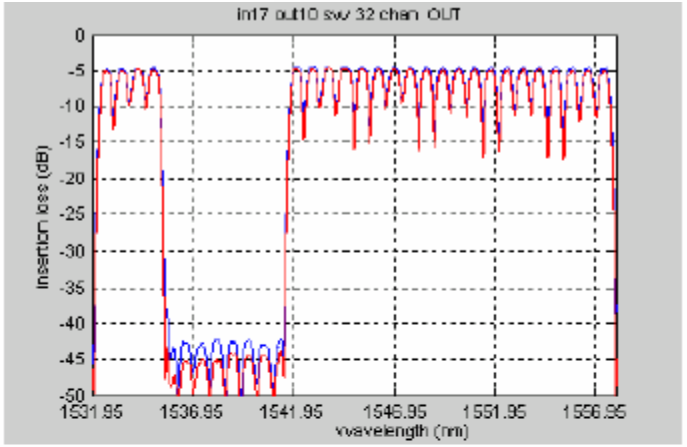
Alcatel·Lucent

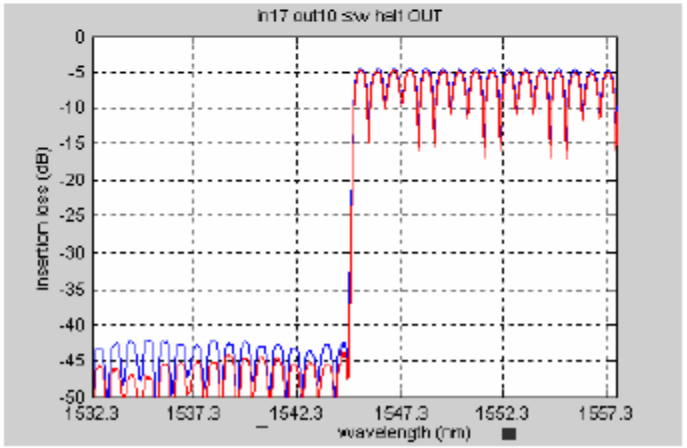
32-ch PLC blocker

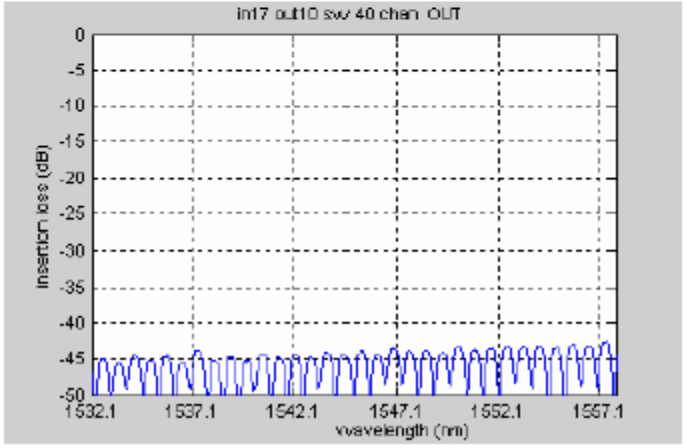








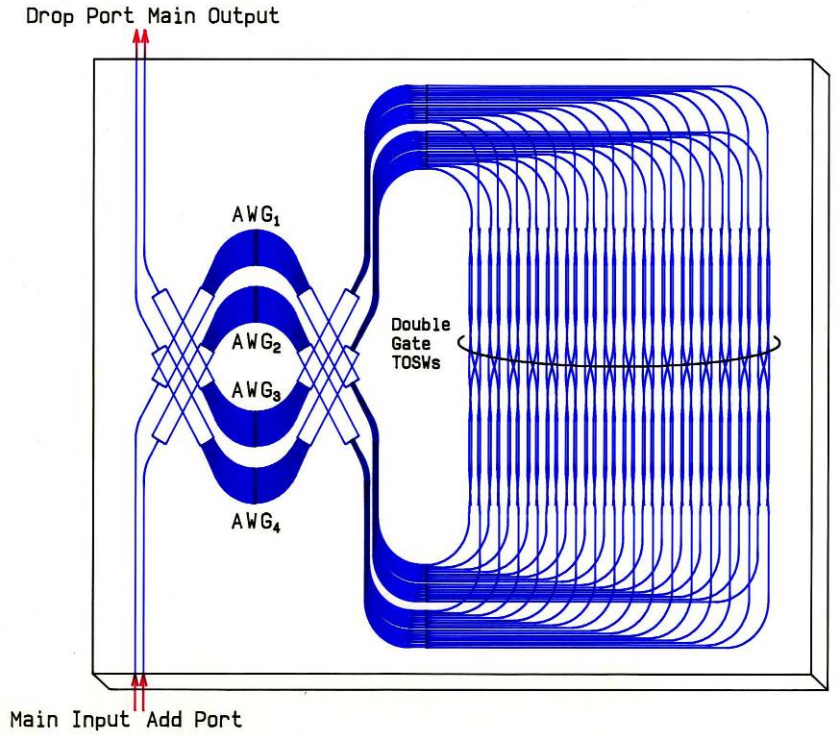




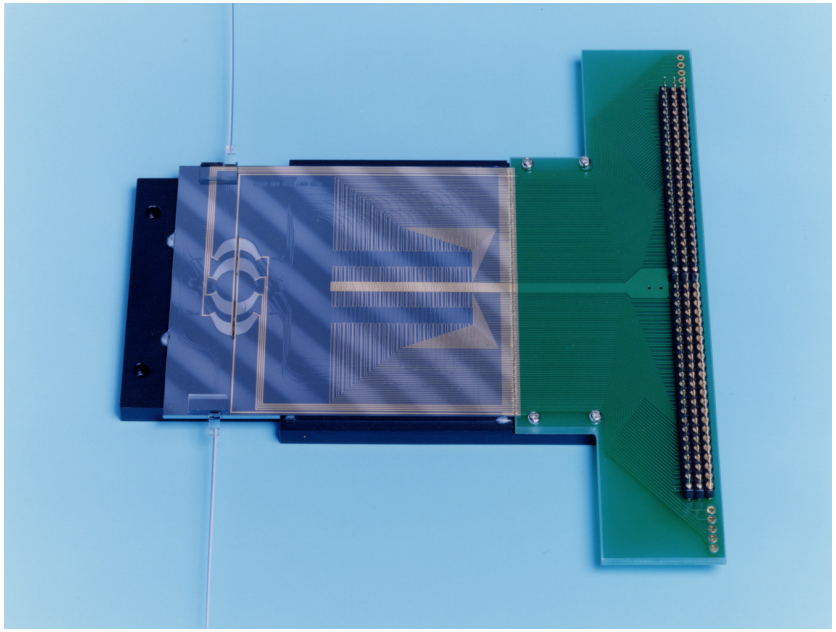
Courtesy of J. Lam from Neophotonics

Alcatel·Lucent

2 x 2 WSS

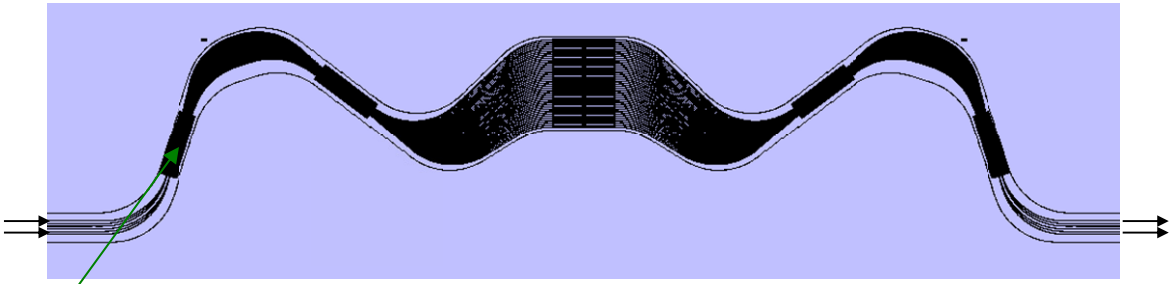


Silica

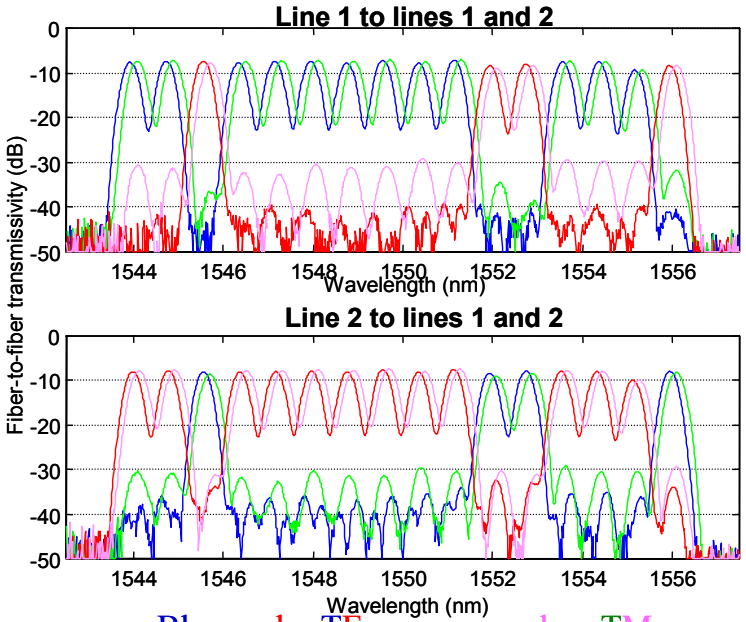


K. Okamoto et al., Electron. Lett., pp.723-724, 1995.

Another 2 x 2 WSS



Interleave-chirped AWG



Blue, red = TE; green, purple = TM

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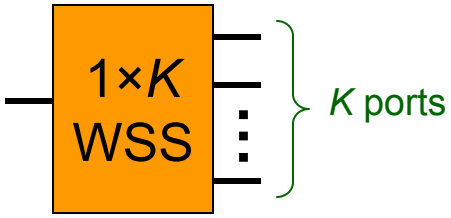
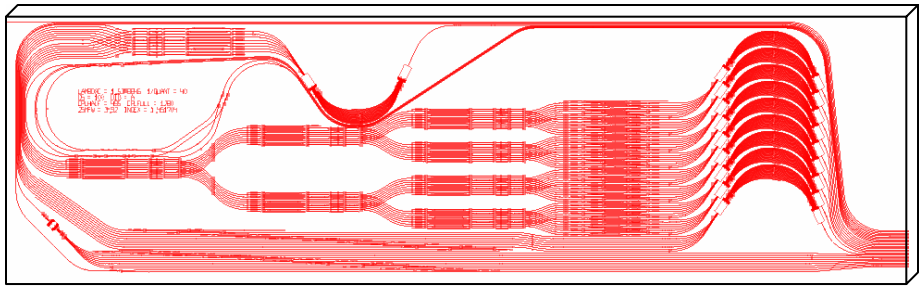
1×*K* WSS

There are two main types:

Transmission-type



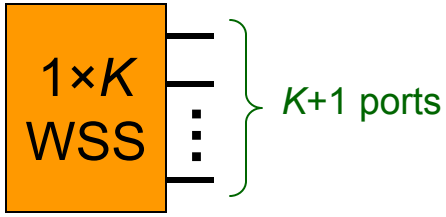
Example:



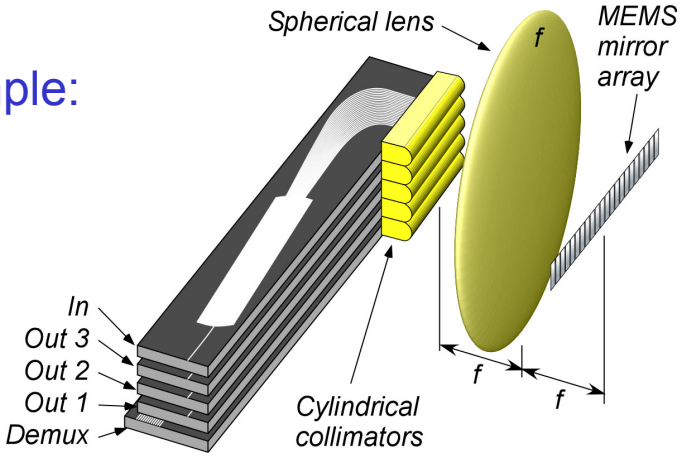
1x9 WSS

Only one possible input port

Reflection-type



Example:



1x4 WSS

Any port can be an input port

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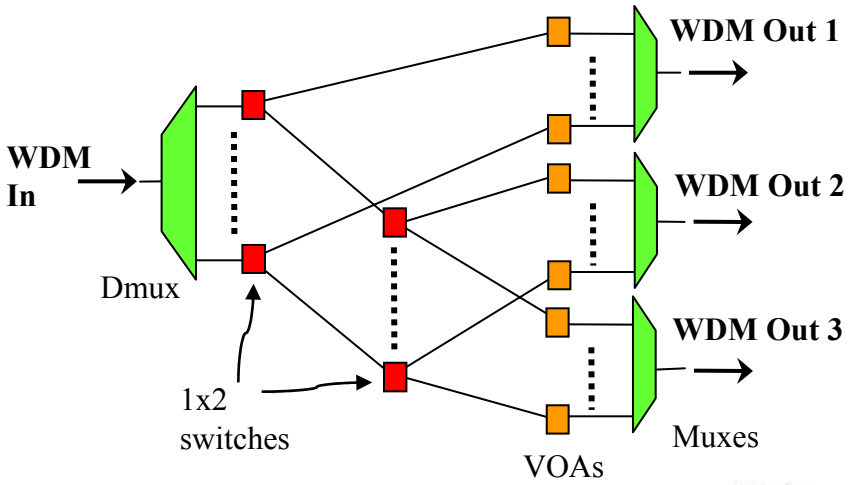
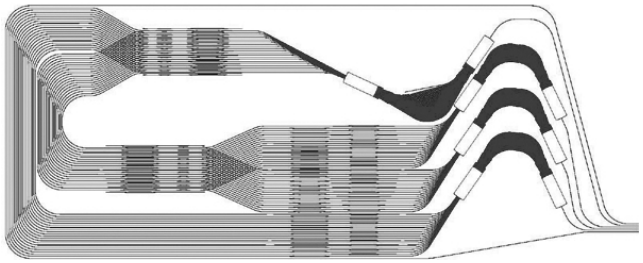
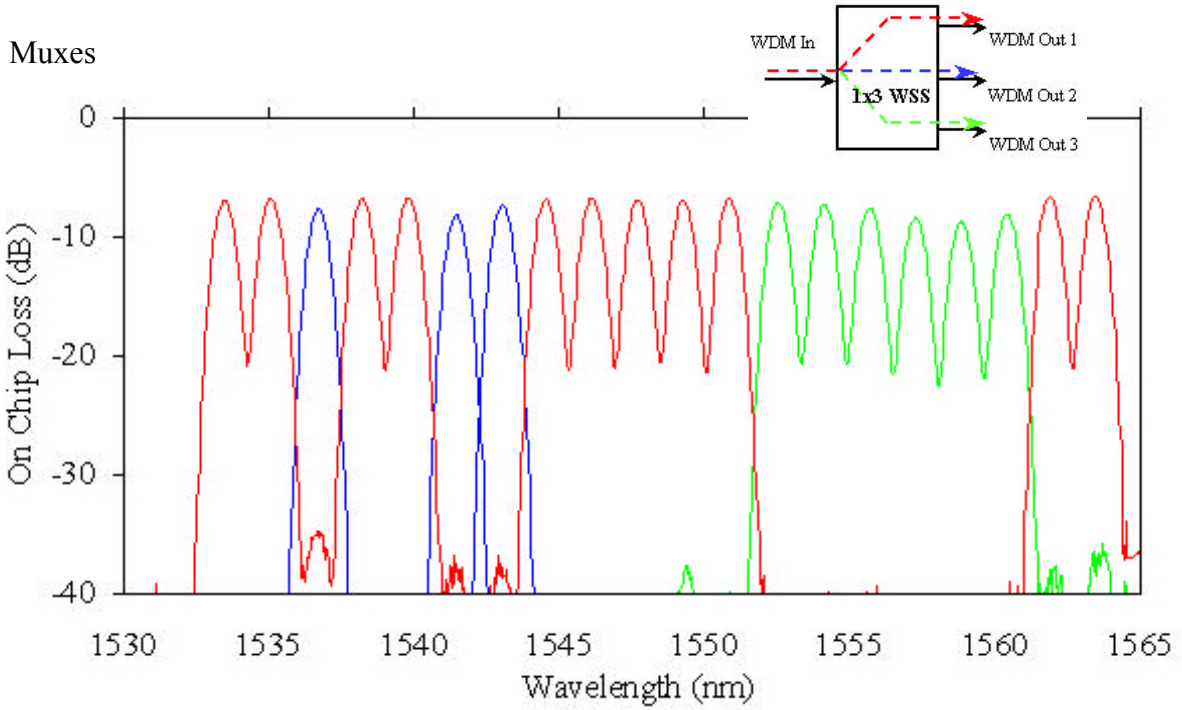
1 × 3 transmission-type WSS



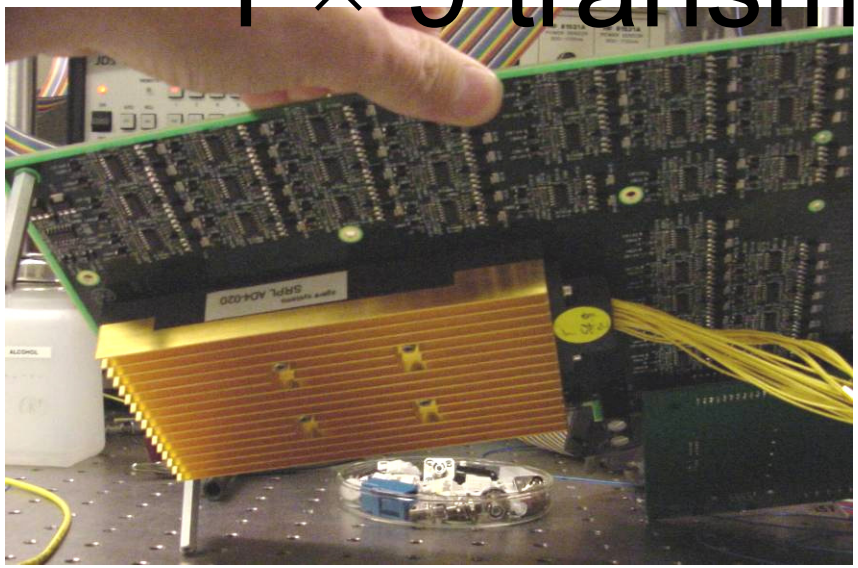




Courtesy of M. Earnshaw from Alcatel-Lucent

M.P. Earnshaw et al, IPR 2003, PD2

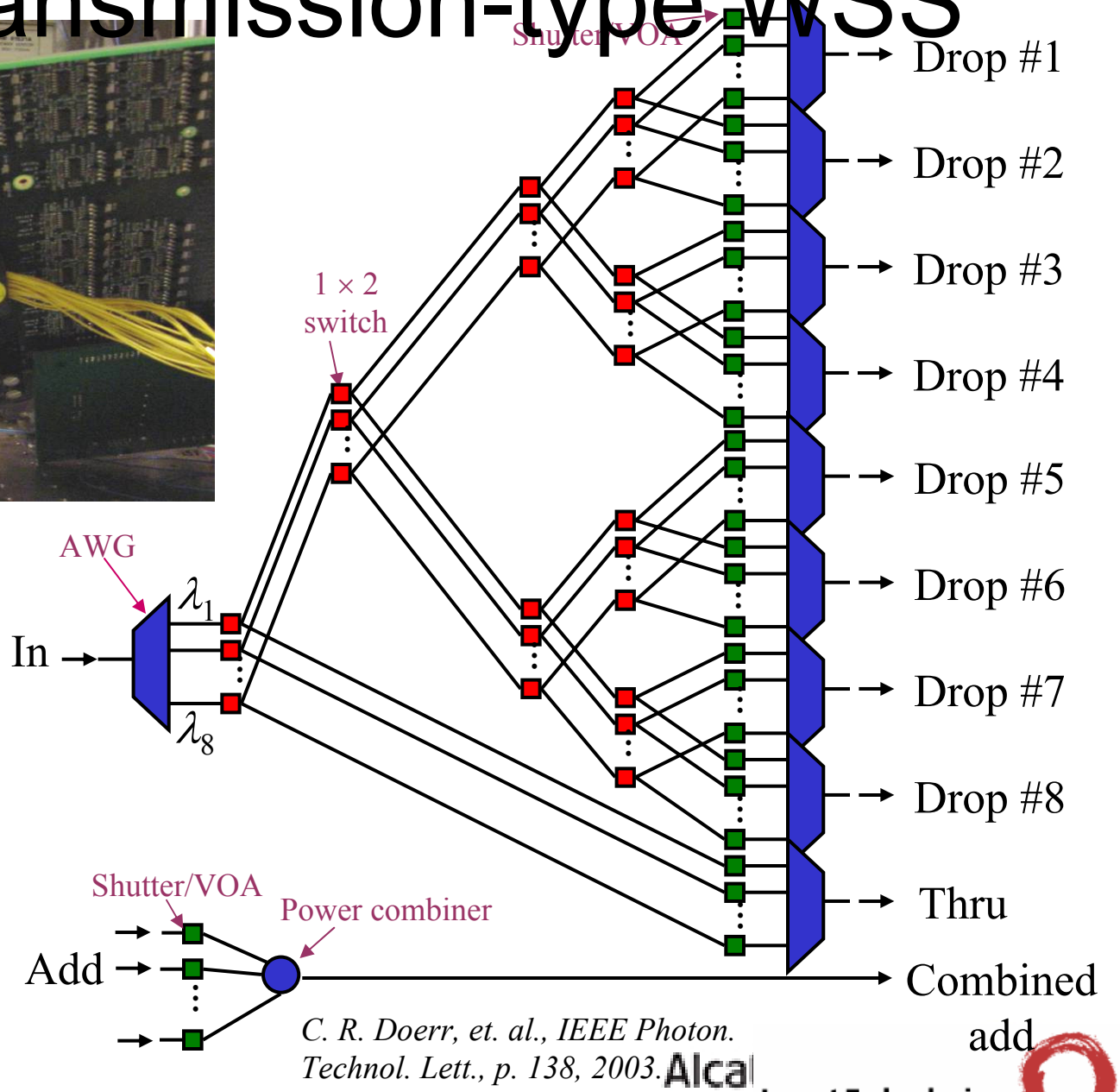
1 × 9 transmission-type WSS



Performance:

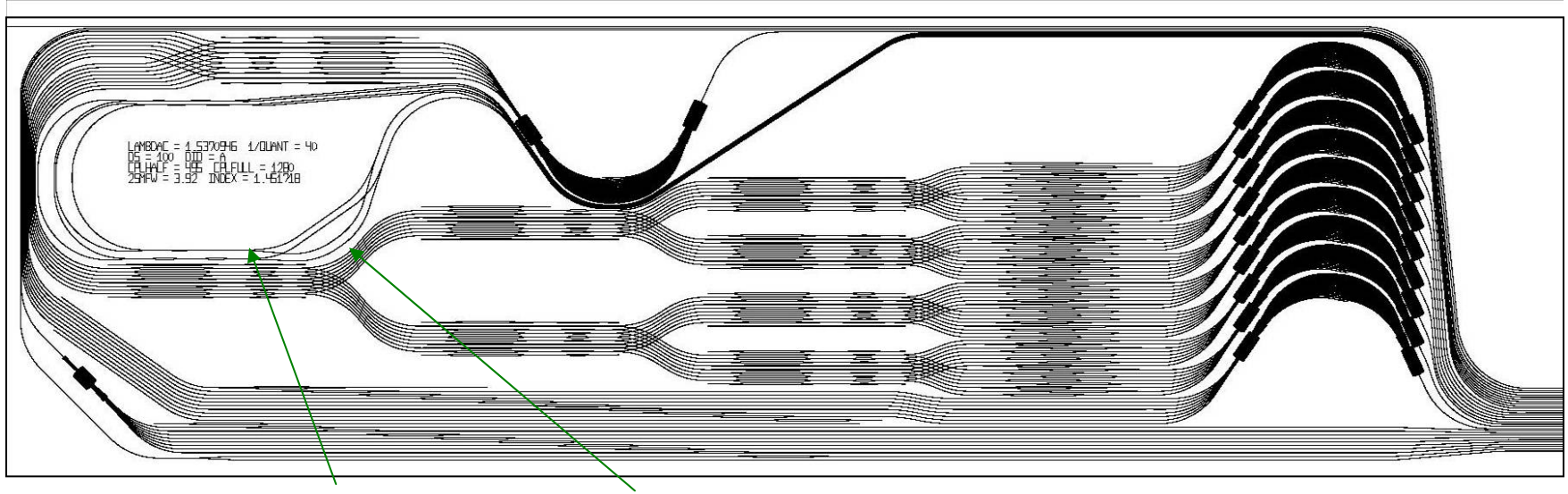
Thru IL	< 5.5 dB
Thru xtalk	< -45 dB
Thru PDL	< 0.2 dB @ 0-dB att.
	< 0.5 dB @ 12-dB att.
Drop IL	< 8 dB
Drop xtalk	< -40 dB
Drop PDL	< 0.3 dB
Add IL	< 12.5 dB
Add PDL	< 0.2 dB @ 0-dB att.
	< 1.0 dB @ 10-dB att.

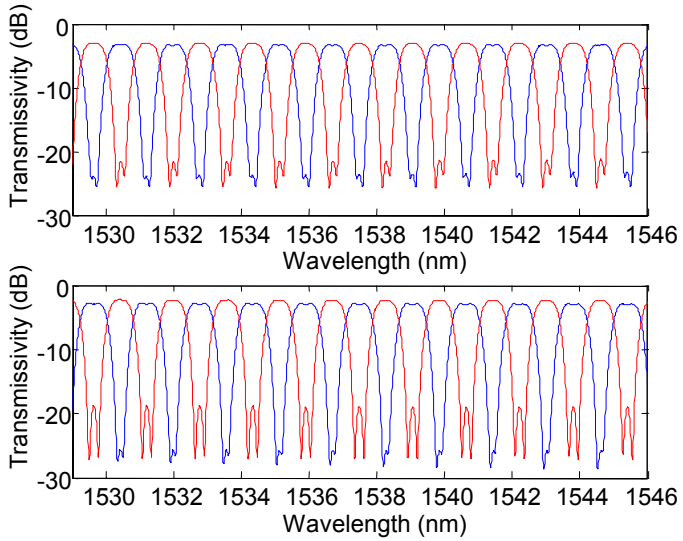
- 8 chs, 8 drop ports, 200-GHz sp.
- Any combination of any channels can be sent to any port
- All switching is hitless



C. R. Doerr, et. al., IEEE Photon. Technol. Lett., p. 138, 2003.

Lucent Technologies
Bell Labs Innovations





C. R. Doerr, et. al., OFC PD 2003.

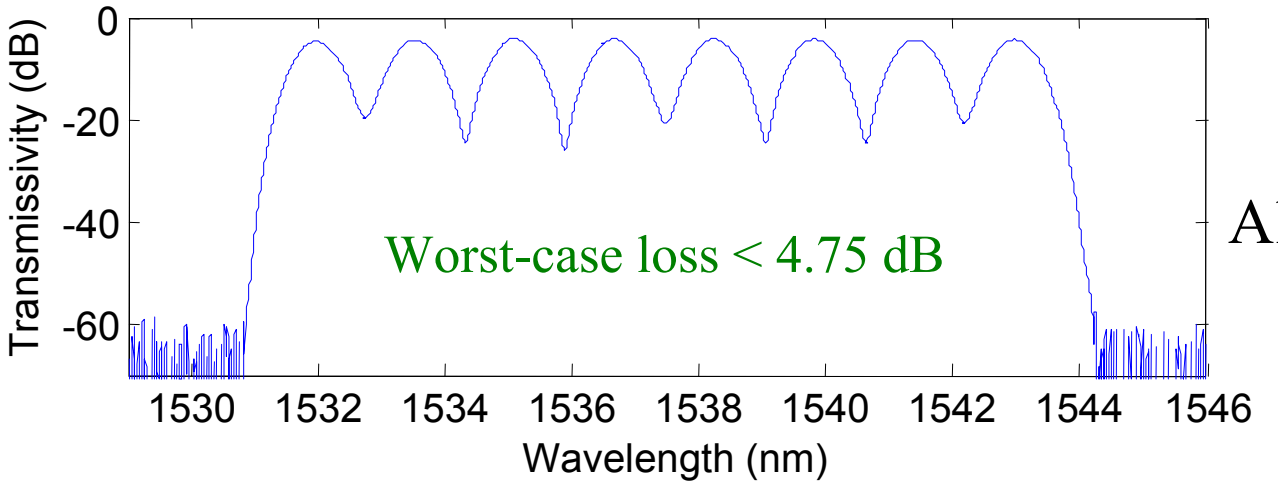
Lucent Technologies
Bell Labs Innovations

l-Lucent

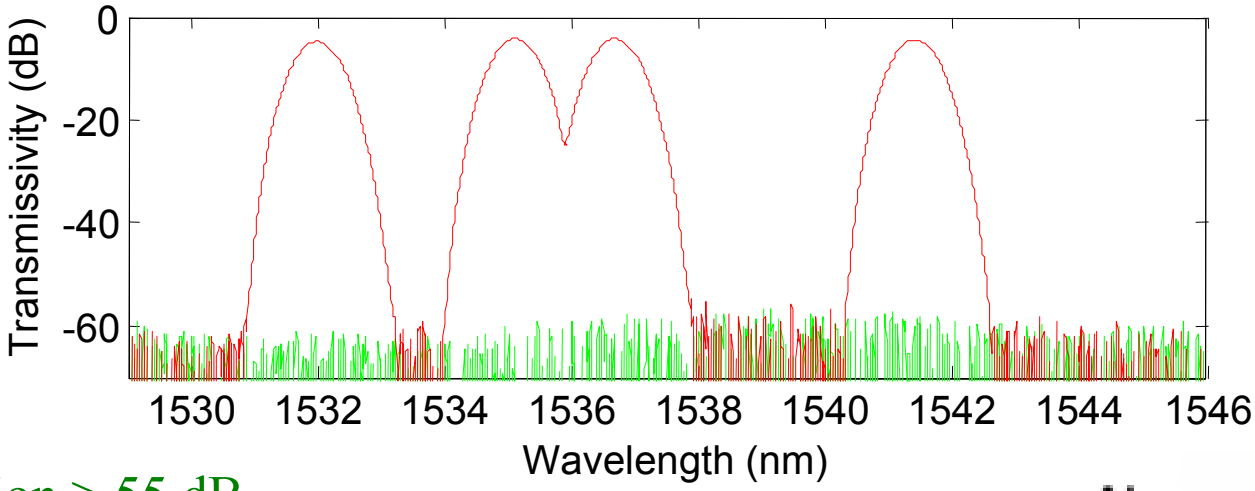
Alcatel·Lucent

Wavelength (nm)

Measured in-to-thru



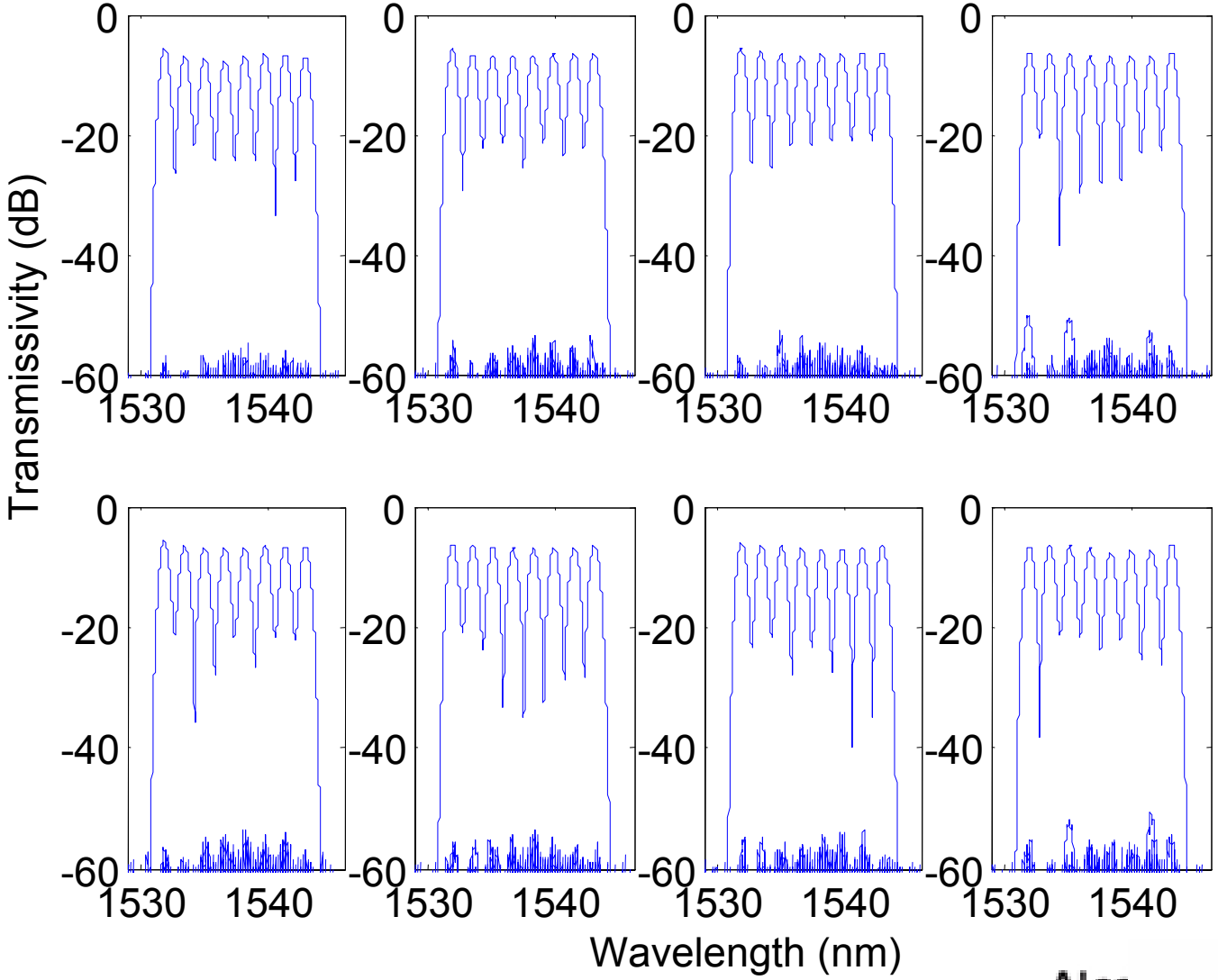
All chs. thru



Some chs. dropped

Isolation > 55 dB

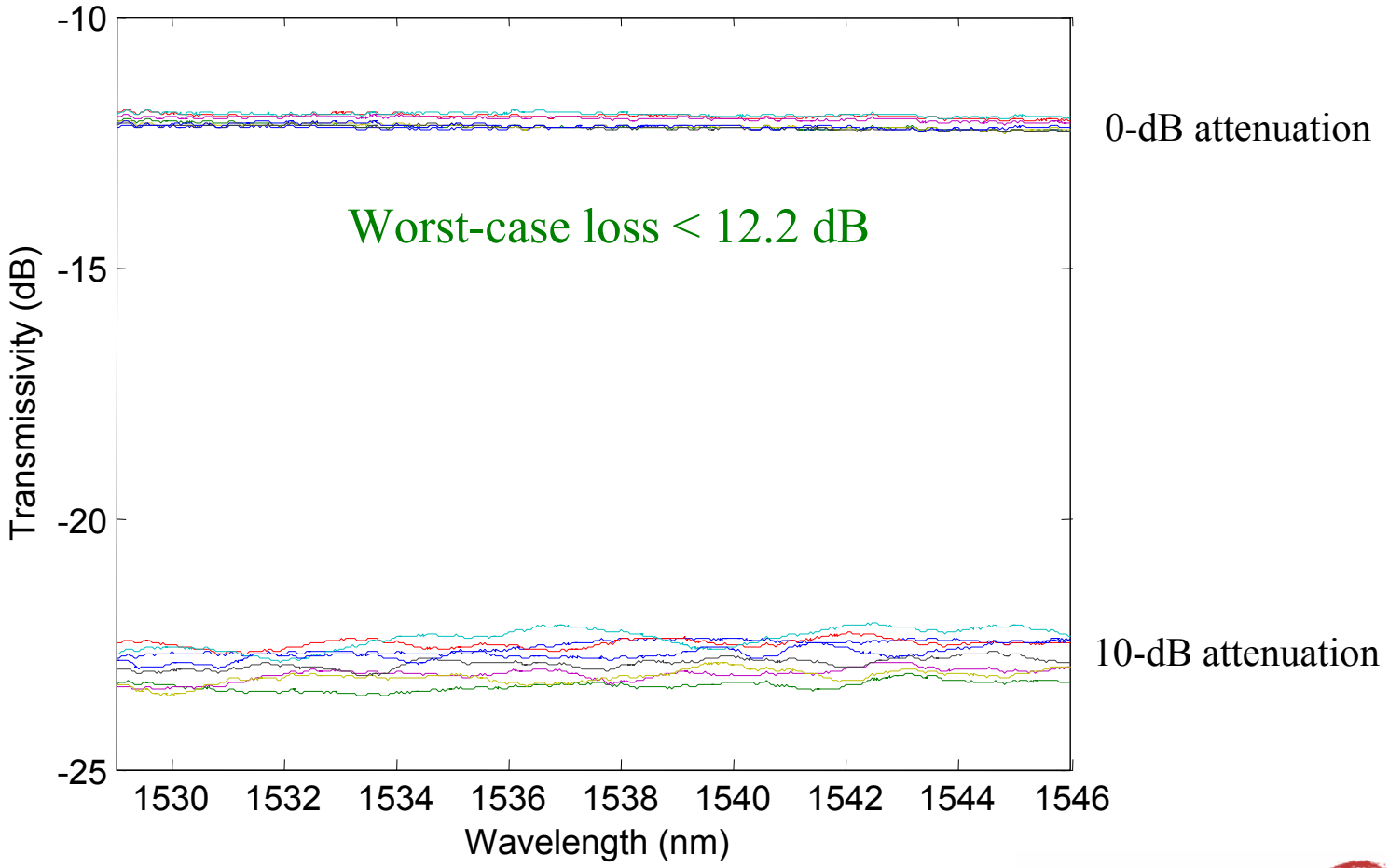
Measured in-to-drop



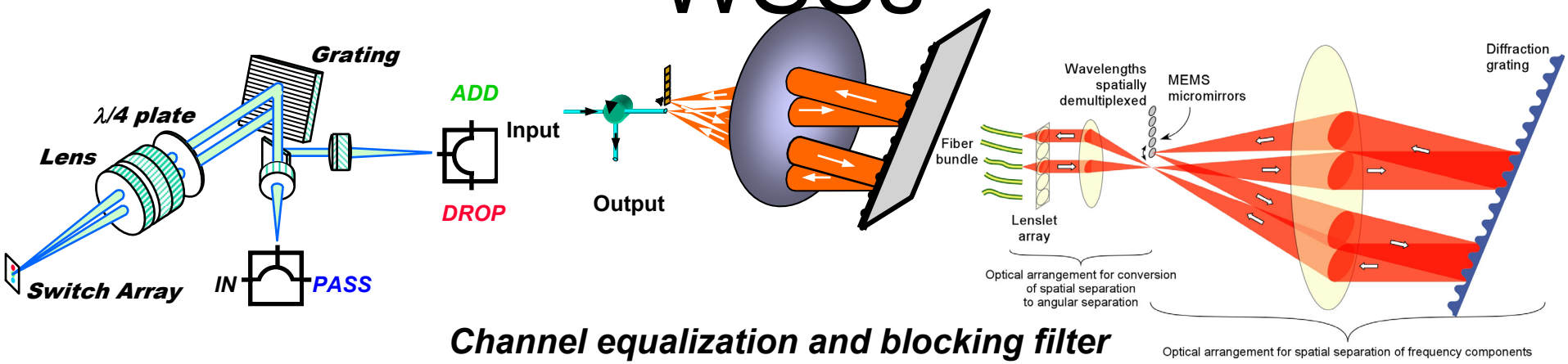
Worst-case loss < 7.5 dB

Alcatel-Lucent Technologies
Bell Labs Innovations

Measured add-paths



Common reflection-type WSSs



Channel equalization and blocking filter

Neilson D. T., et al., JSTQE 10 (2004) , pp. 563-569.

Wavelength Add-Drop Switching

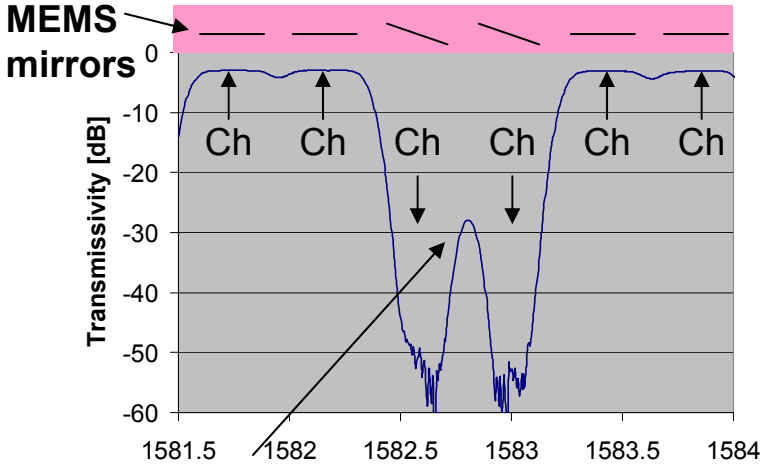
Ford J. E., et al., JLT 17 (1999) , pp. 904-911.

- A diffraction grating and imaging system disperses the light onto the modulator array (MEMS, LC or other).
- The interaction of the dispersed light and the modulation mechanism results in interference effects between channels

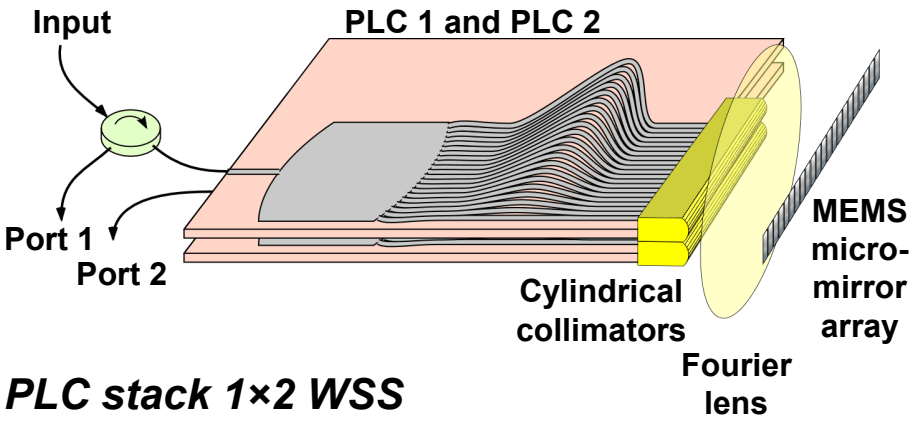
Oh S.-H. and Marom D. M., Appl. Opt. 43 (2004) , pp. 127-131.

Wavelength-Selective 1×K Switches

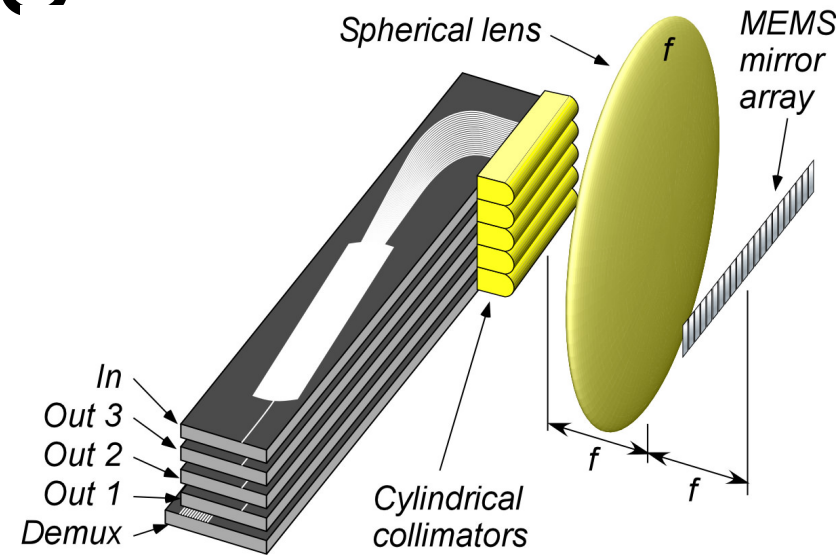
Marom D. M., et al., JLT 23 (2005) , pp. 1620-30.



Hybrid PLC reflection-type WSS



PLC stack 1×2 WSS
Marom D. M., et al., Optical MEMS 2004.

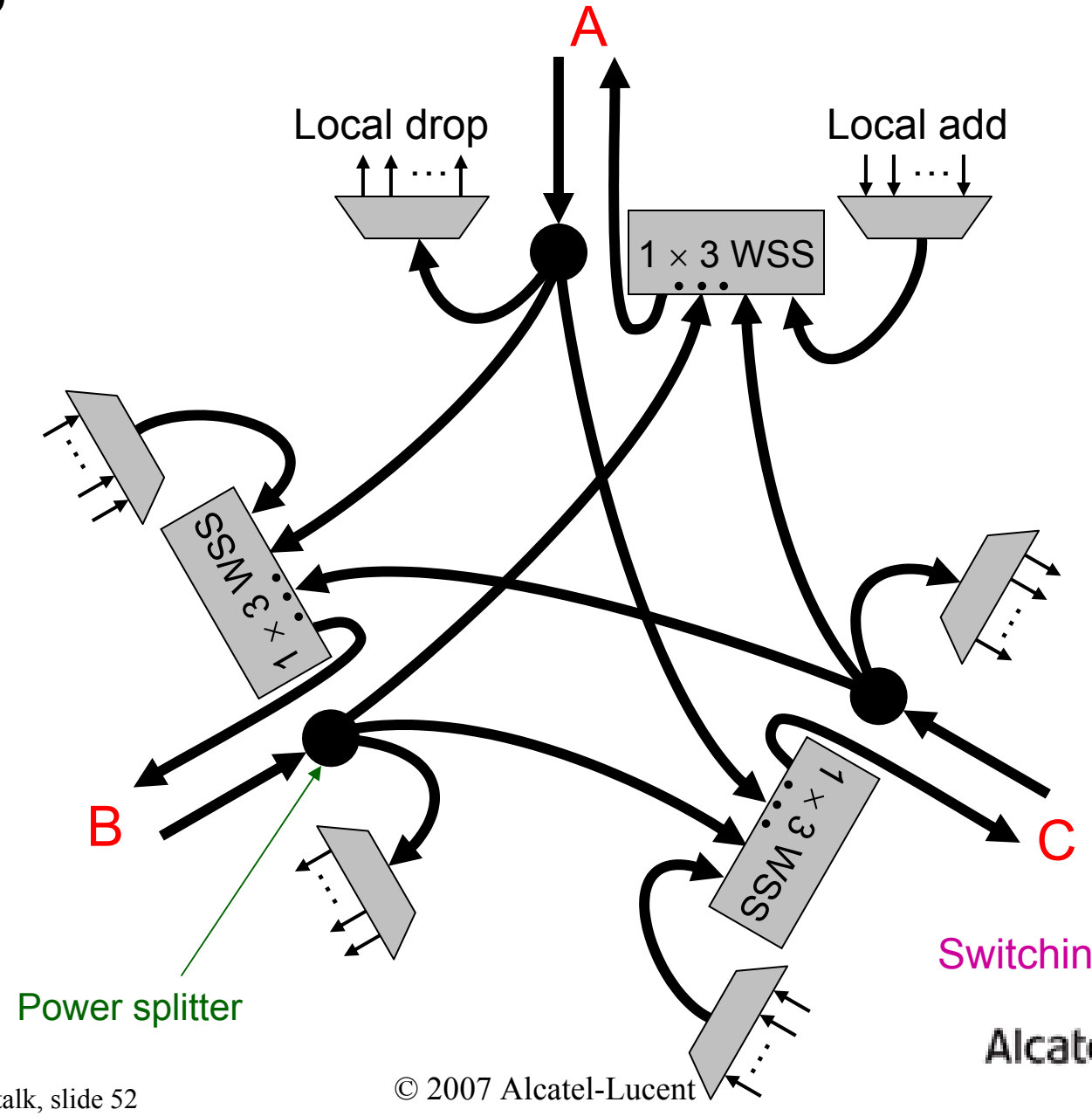


1×3 WSS with Integrated DEMUX
Marom D. M., et al., ECOC 2005.

Conventional WDM mesh nodes

Alcatel·Lucent

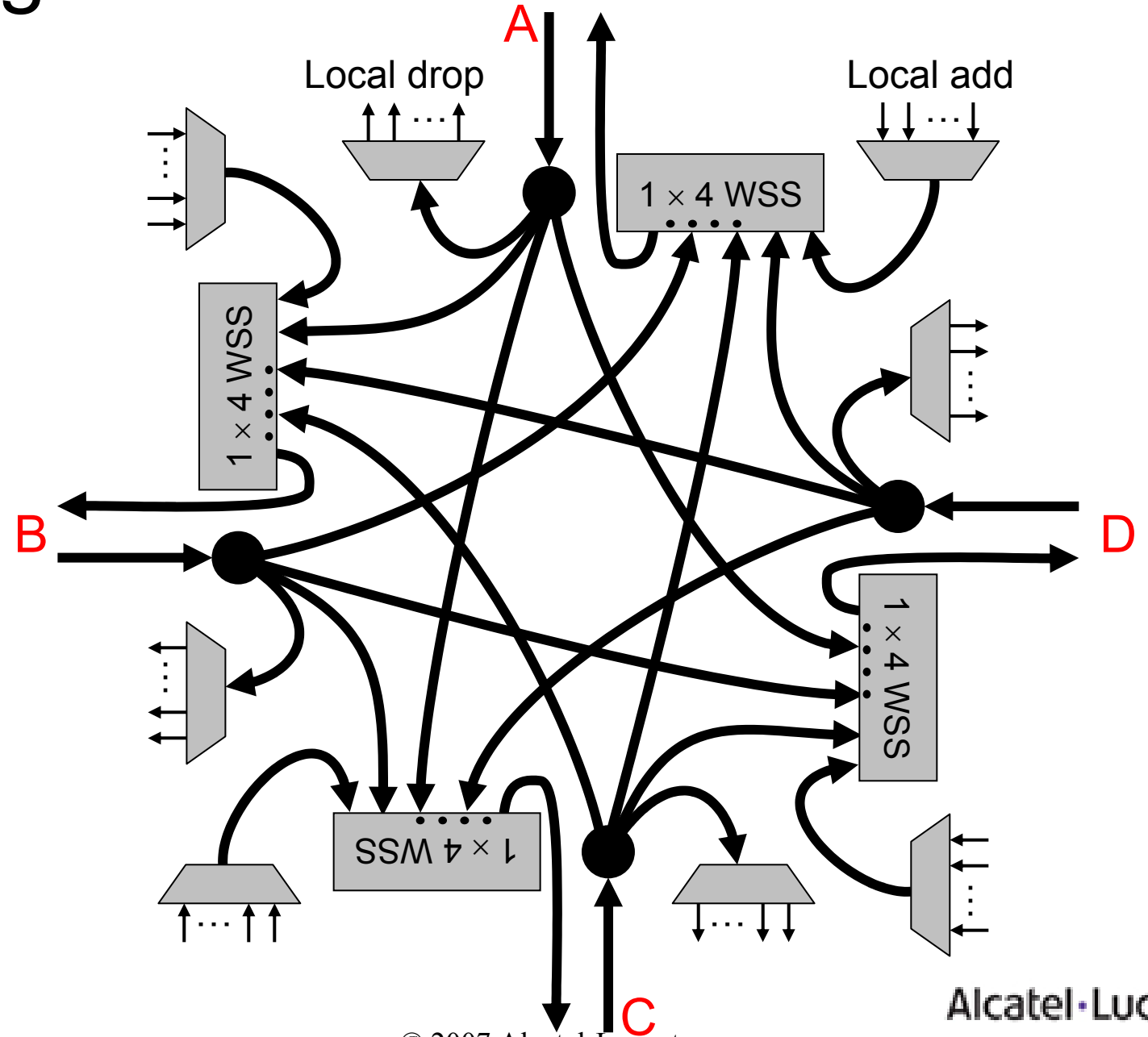
Deg-3 mesh node with local add-drop



Switching must be “hitless”

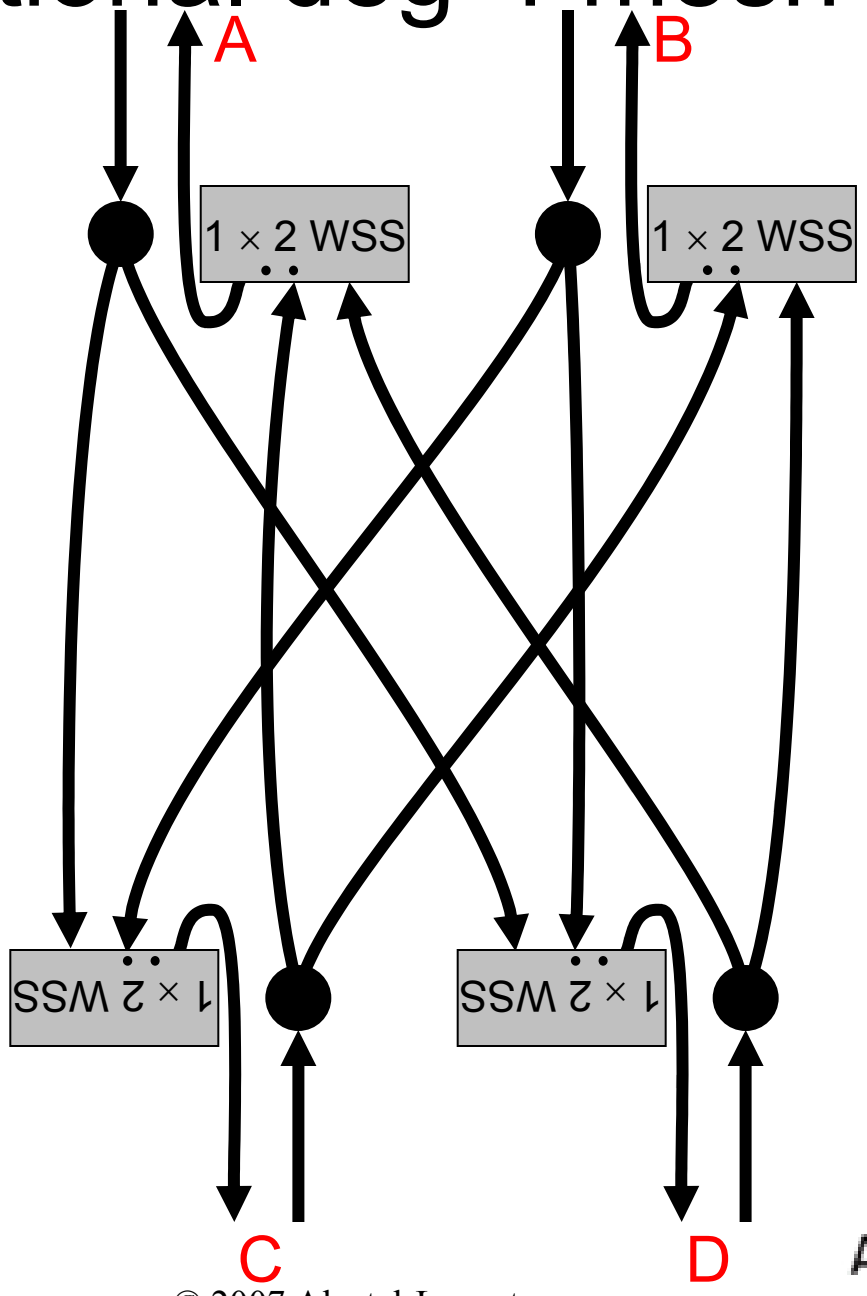
Alcatel·Lucent

Deg-4 mesh node with local add-drop



Alcatel·Lucent

Directional deg-4 mesh node



Alcatel·Lucent

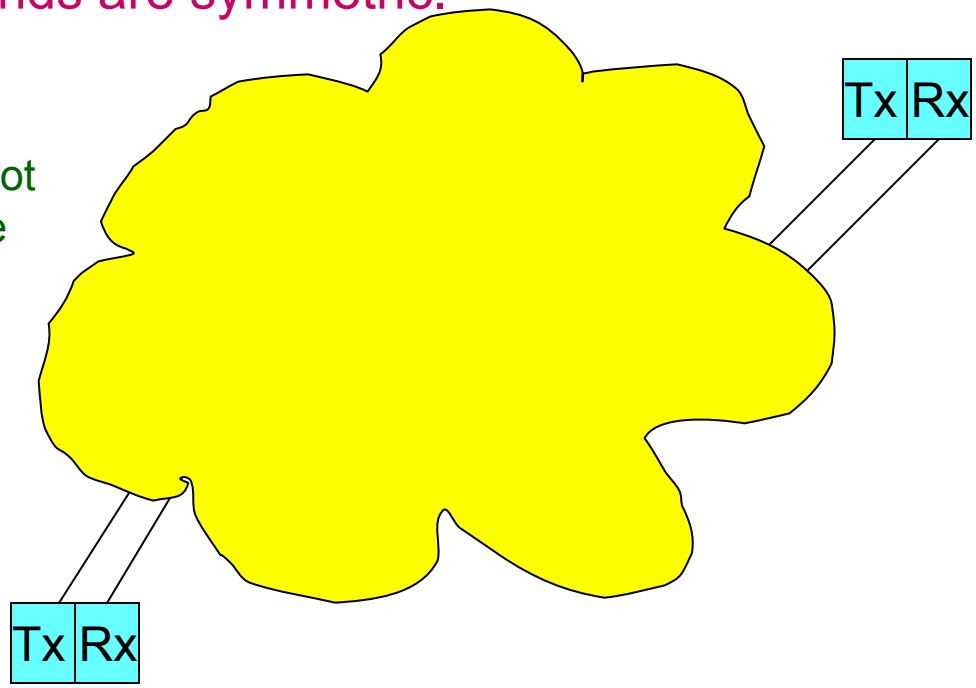
Novel WDM mesh nodes

Alcatel·Lucent

Symmetric demands

In optical networks, transceivers are almost always connected in pairs. Thus all demands are symmetric.

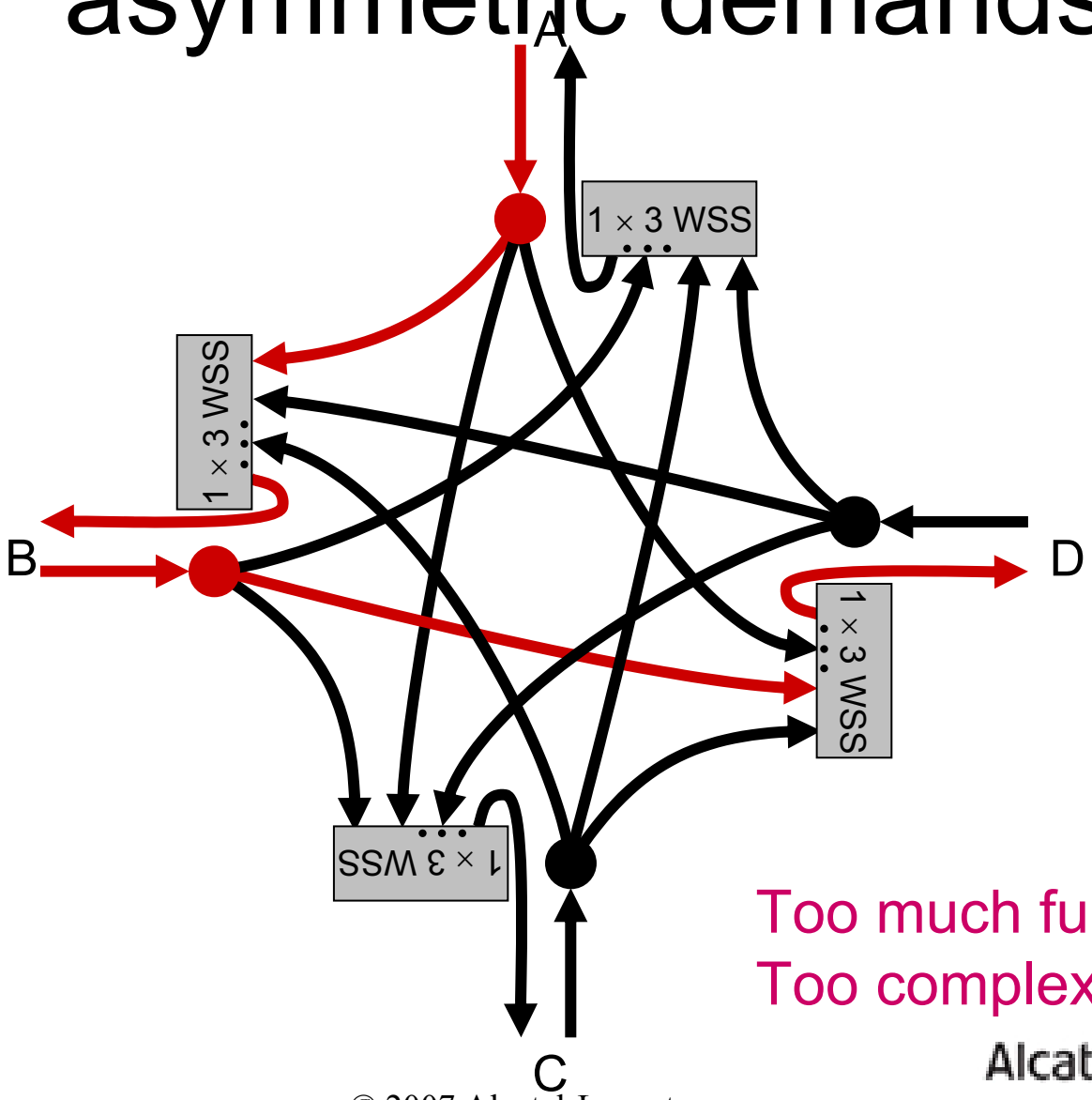
Traffic amount may not be symmetric, but the connections are



J. Simmons, et. al., IEEE Photon. Technol. Lett., vol. 10, pp. 819-821, 1998.

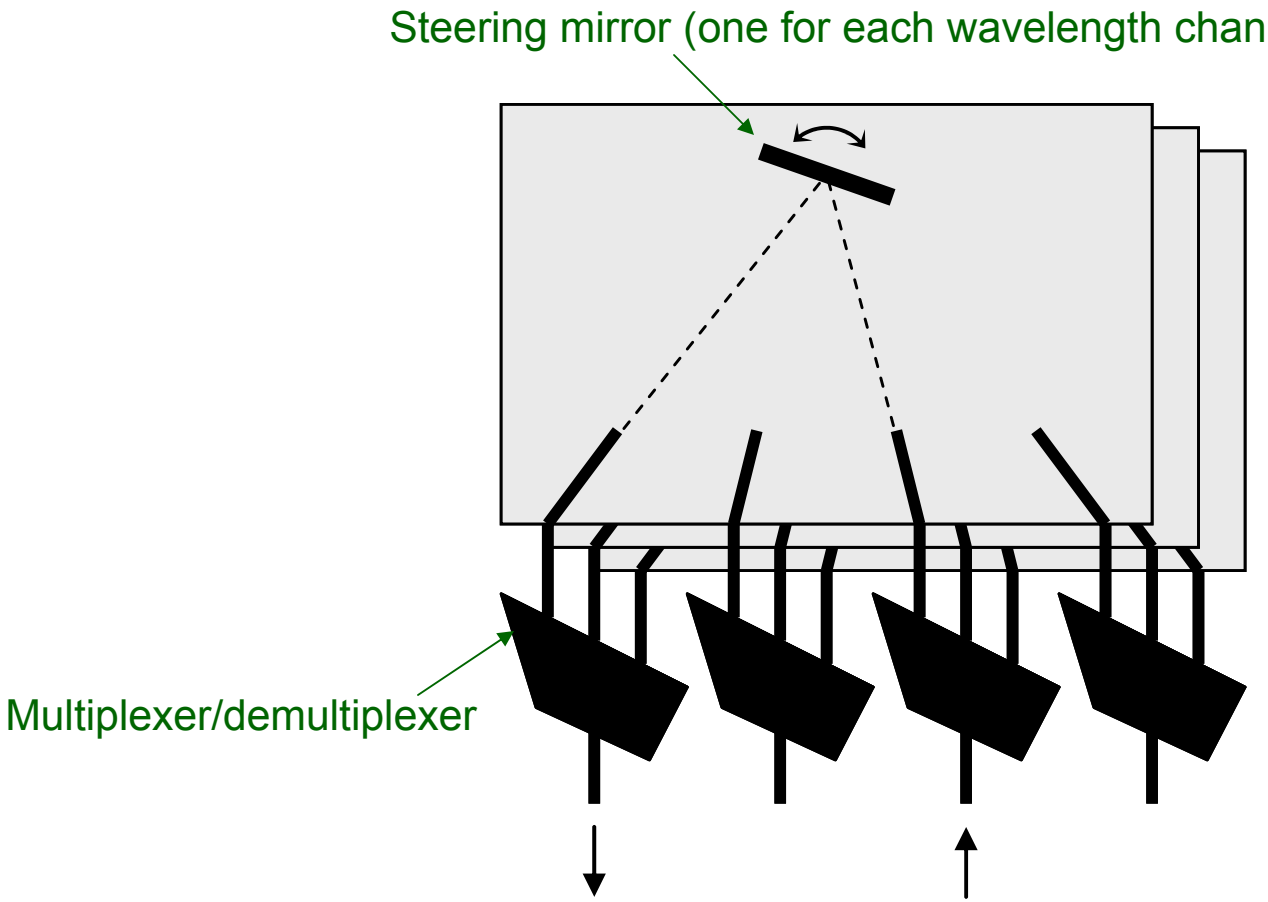
Alcatel·Lucent

Conventional design allows asymmetric demands



Too much functionality
Too complex

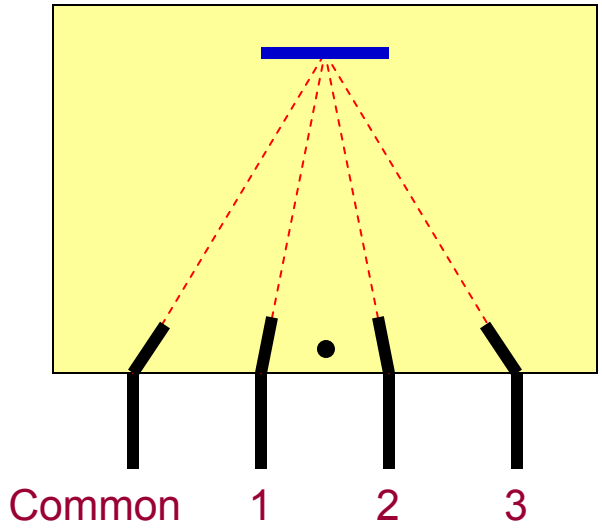
Reflection-type WSS



Example 1×3 WSS

Alcatel·Lucent

Multi terminal pair connection property of reflection-type WSSs



•*C. R. Doerr, Optical Fiber Comm. Conf., paper PDP40, 2006.*
•*C. R. Doerr, G. Wilfong, S. Chandrasekhar, JSTQE, p. 627, 2006.*

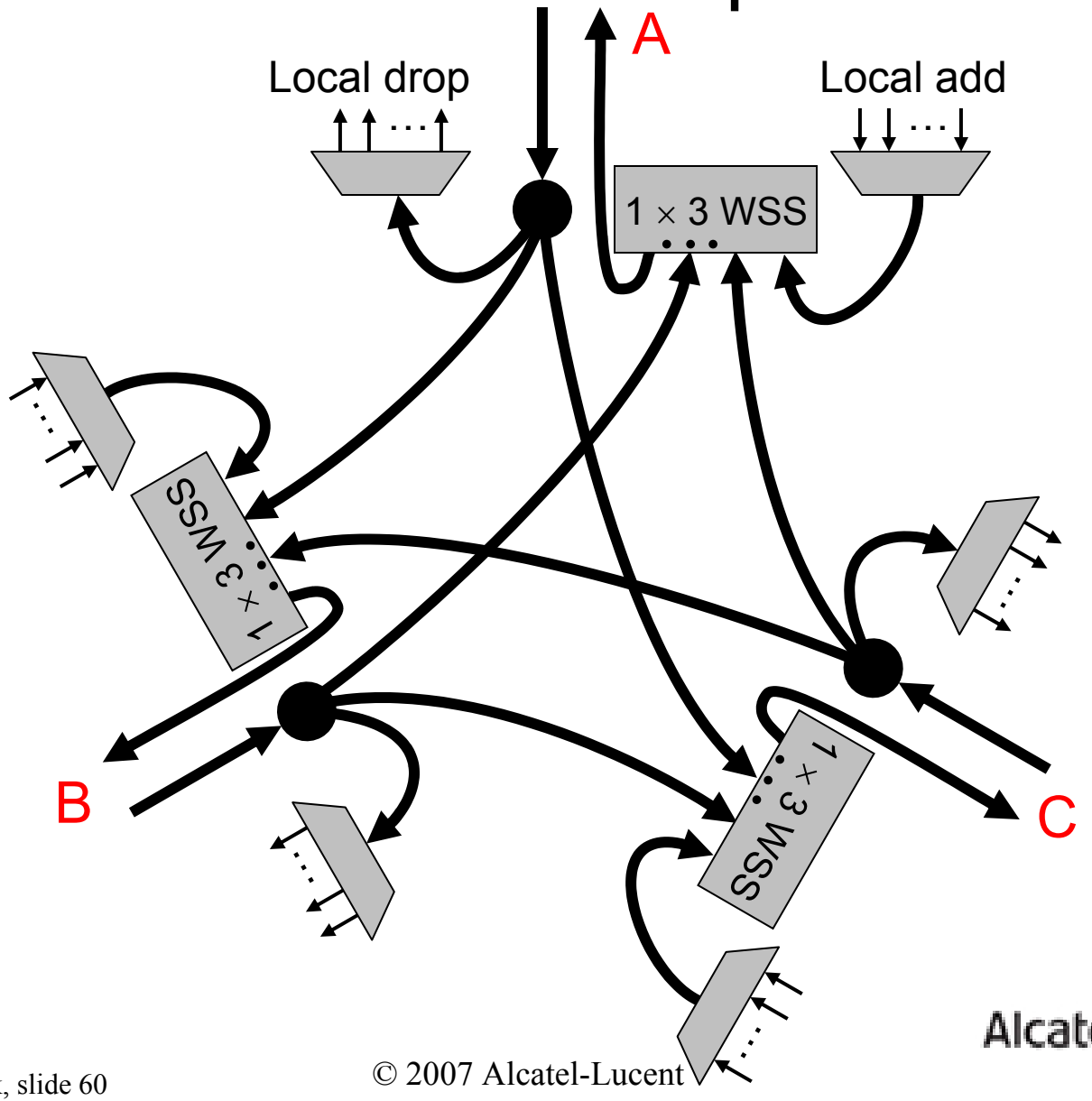
Represent mirror position by a “dot” notation

All terminals symmetric about the dot are connected

Port *p* is connected to port *q* for mirror position m, when $m - p = q - m$

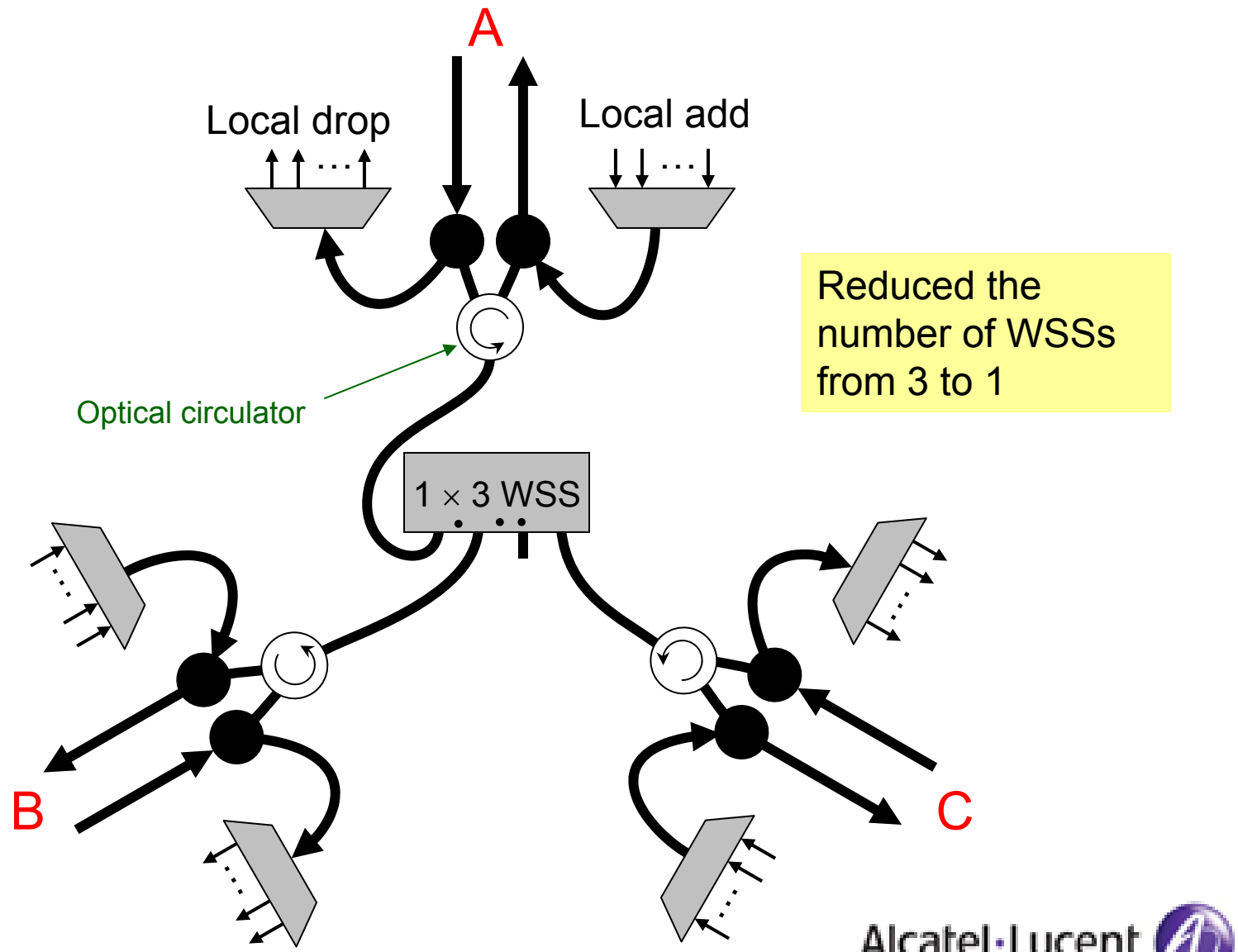
Alcatel·Lucent

Conventional deg-3 mesh node with local add-drop



Alcatel·Lucent

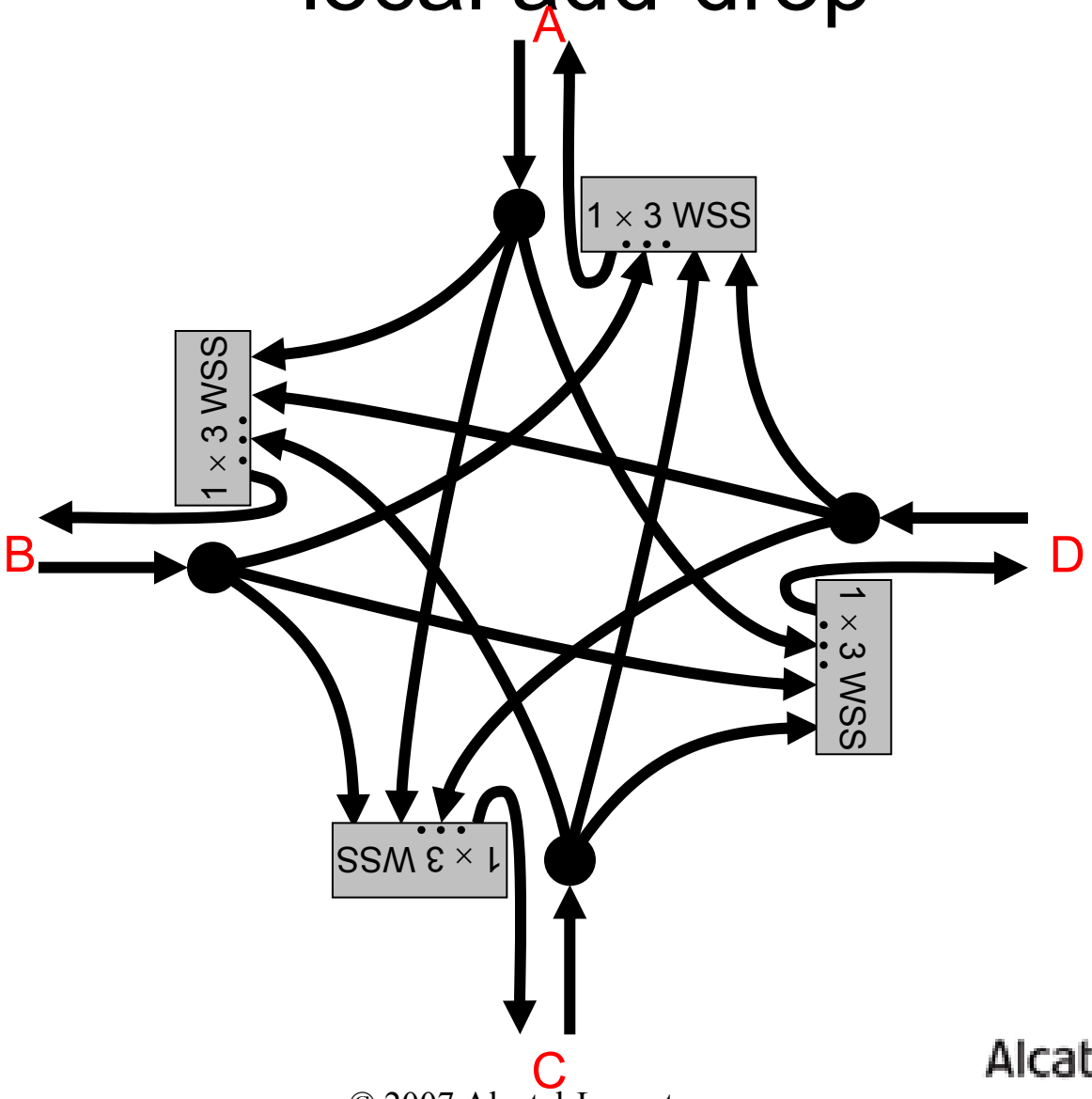
Novel deg-3 mesh node



Reduced the number of WSSs from 3 to 1

Alcatel·Lucent

Conventional deg-4 mesh node without local add-drop



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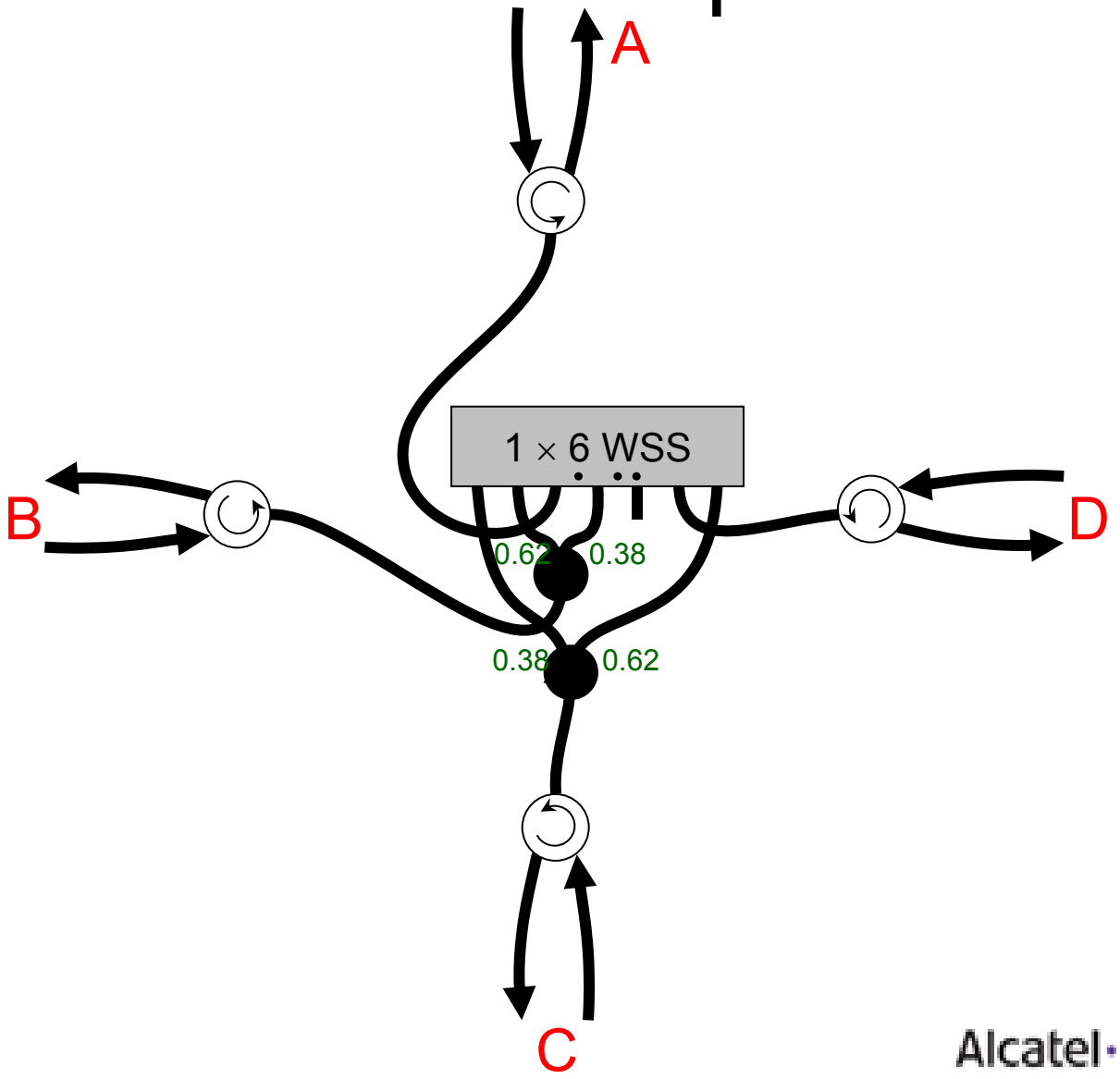
Novel deg-4 mesh node without local add-drop



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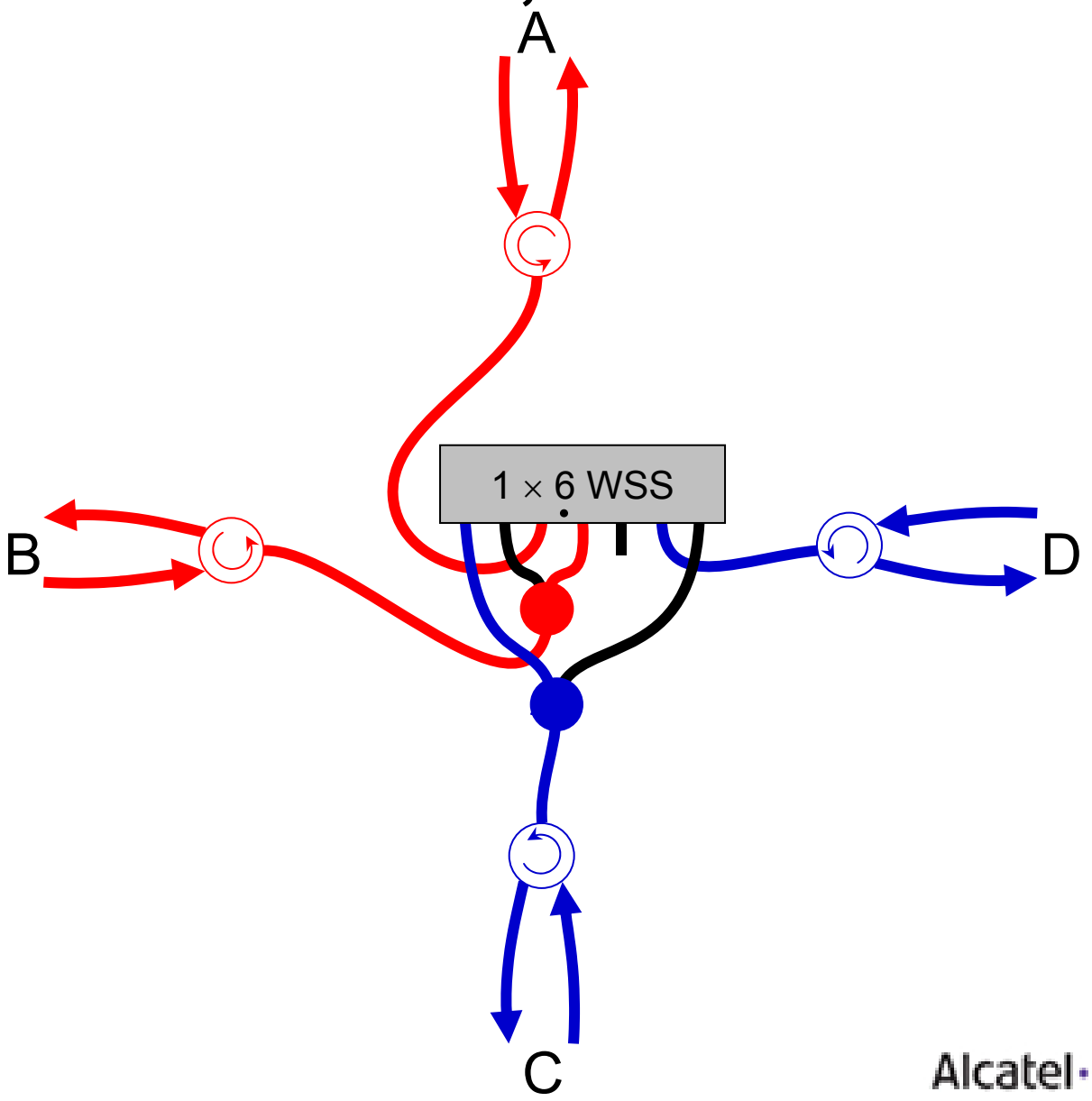
A-B, C-D



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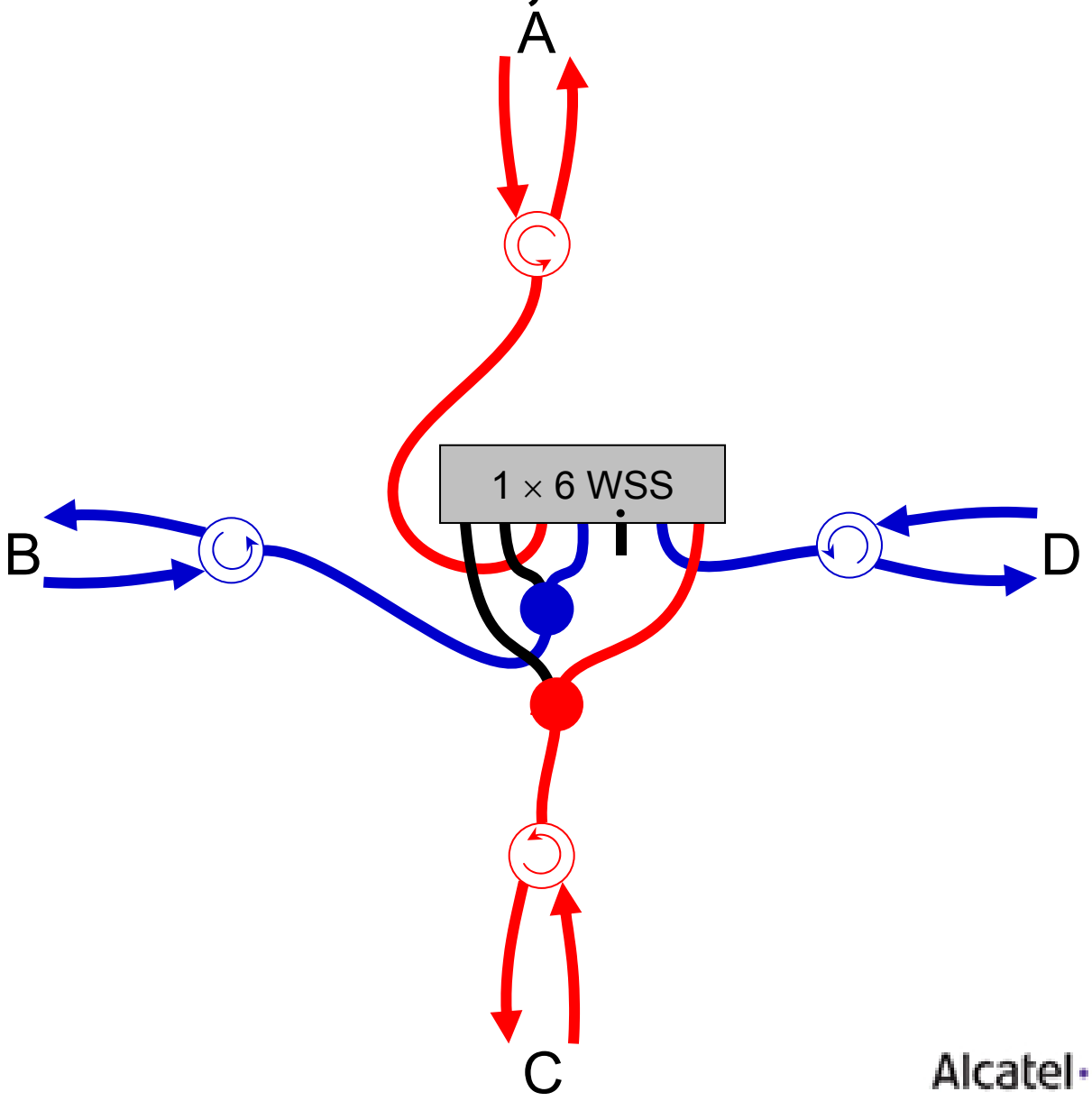
A-C, B-D



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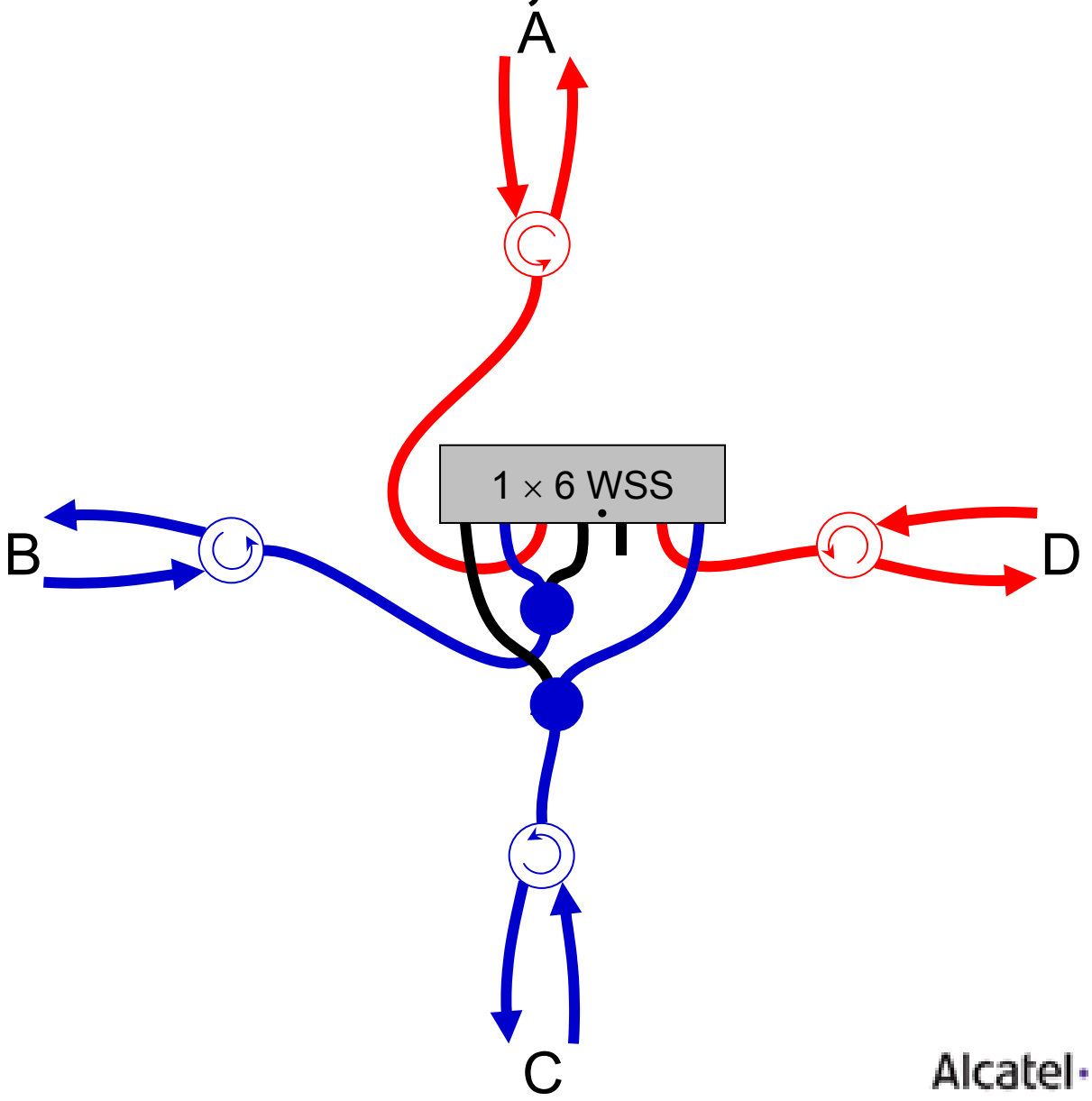
A-D, B-C



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Pros and cons of single-WSS design

Pros

- Only 1 WSS required instead of 4

Cons

- No channel power balancing function
- Demands must be symmetric (but can multicast)
- Single point of failure (but see next slide)

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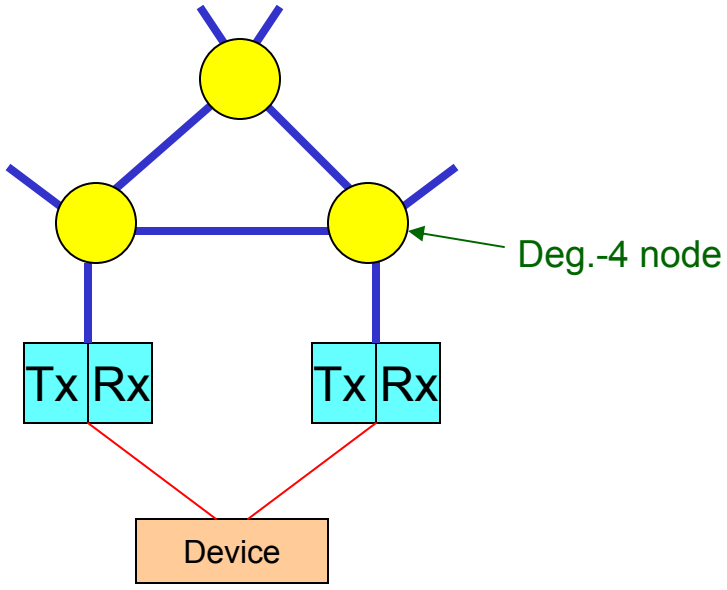
Can use as building block

Example deg.-5 node with diversity for source/sink



Solves the single point of failure issue

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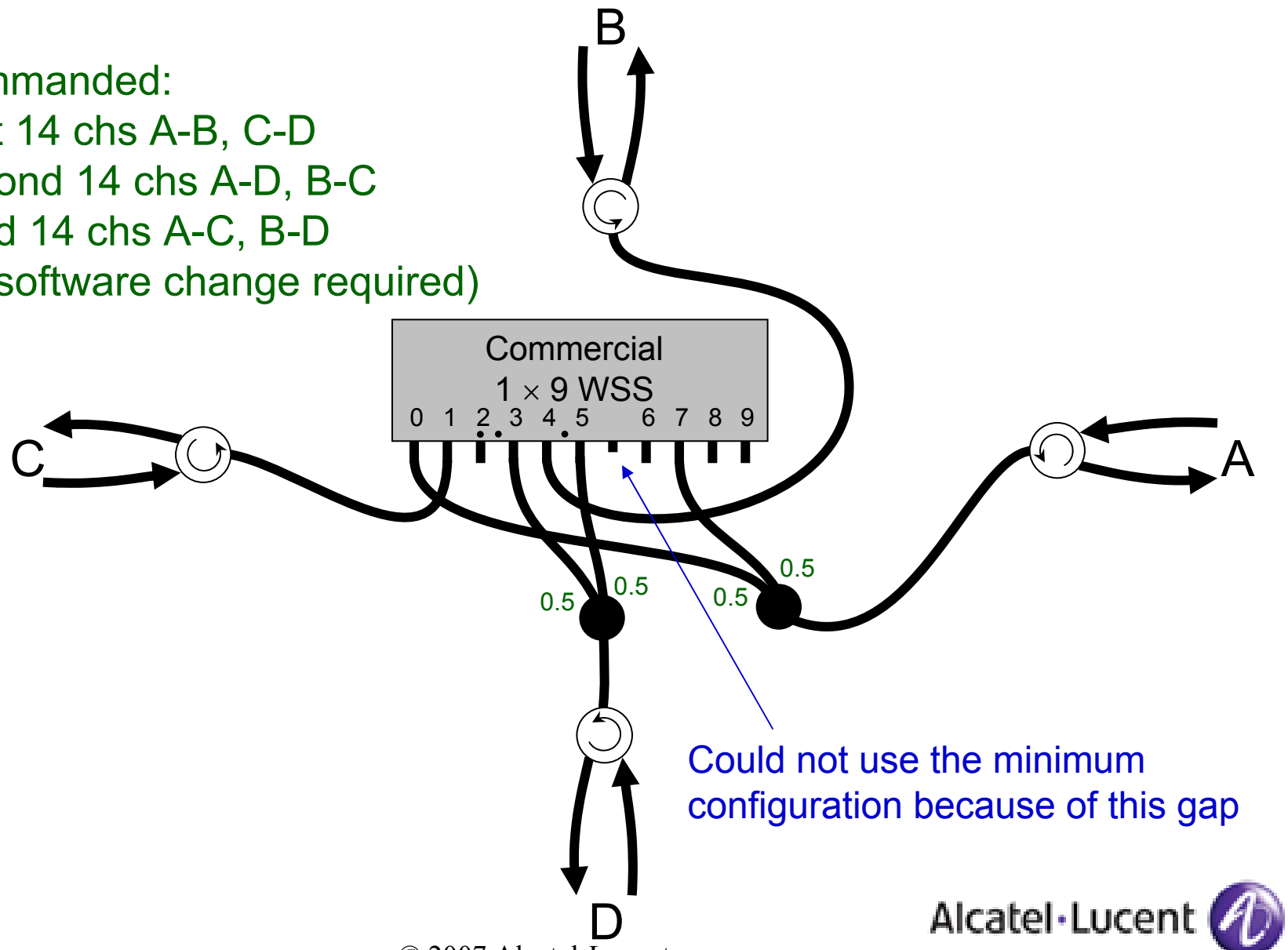
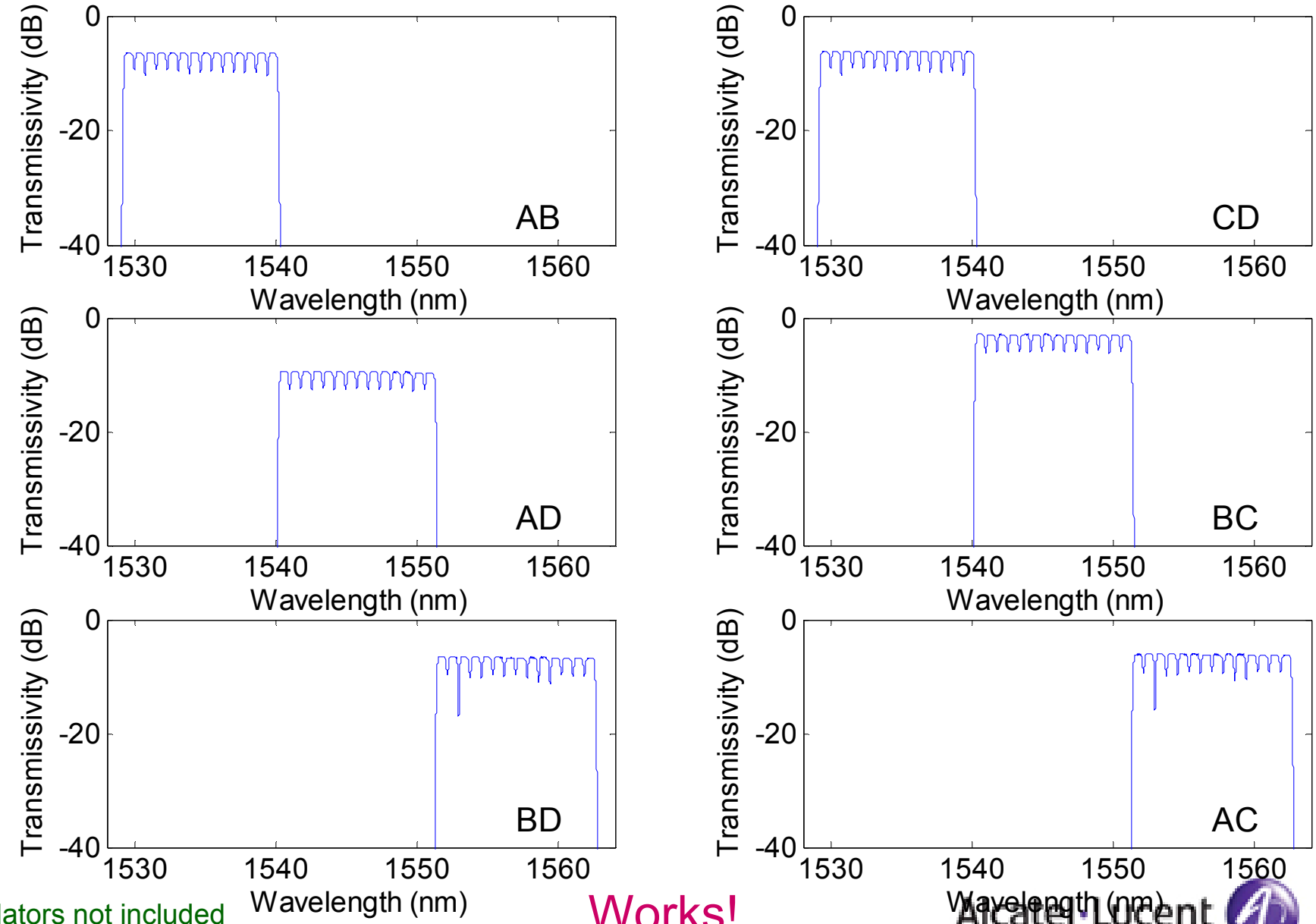
Config. used in the experiment

Commanded:
First 14 chs A-B, C-D
Second 14 chs A-D, B-C
Third 14 chs A-C, B-D
(no software change required)



Experimental results



Circulators not included

Works!

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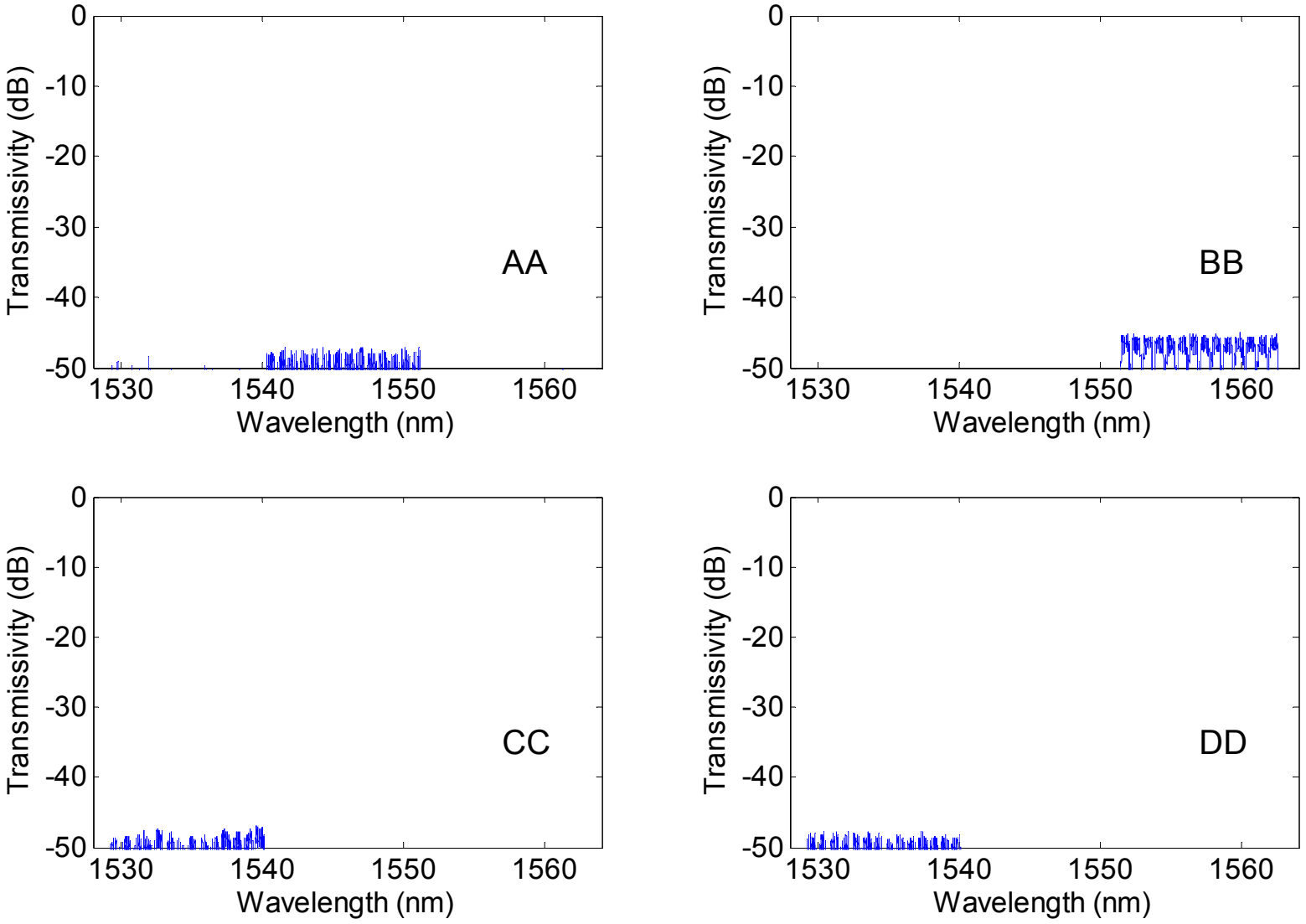
Back-reflection check



All ports have > 45 dB return loss

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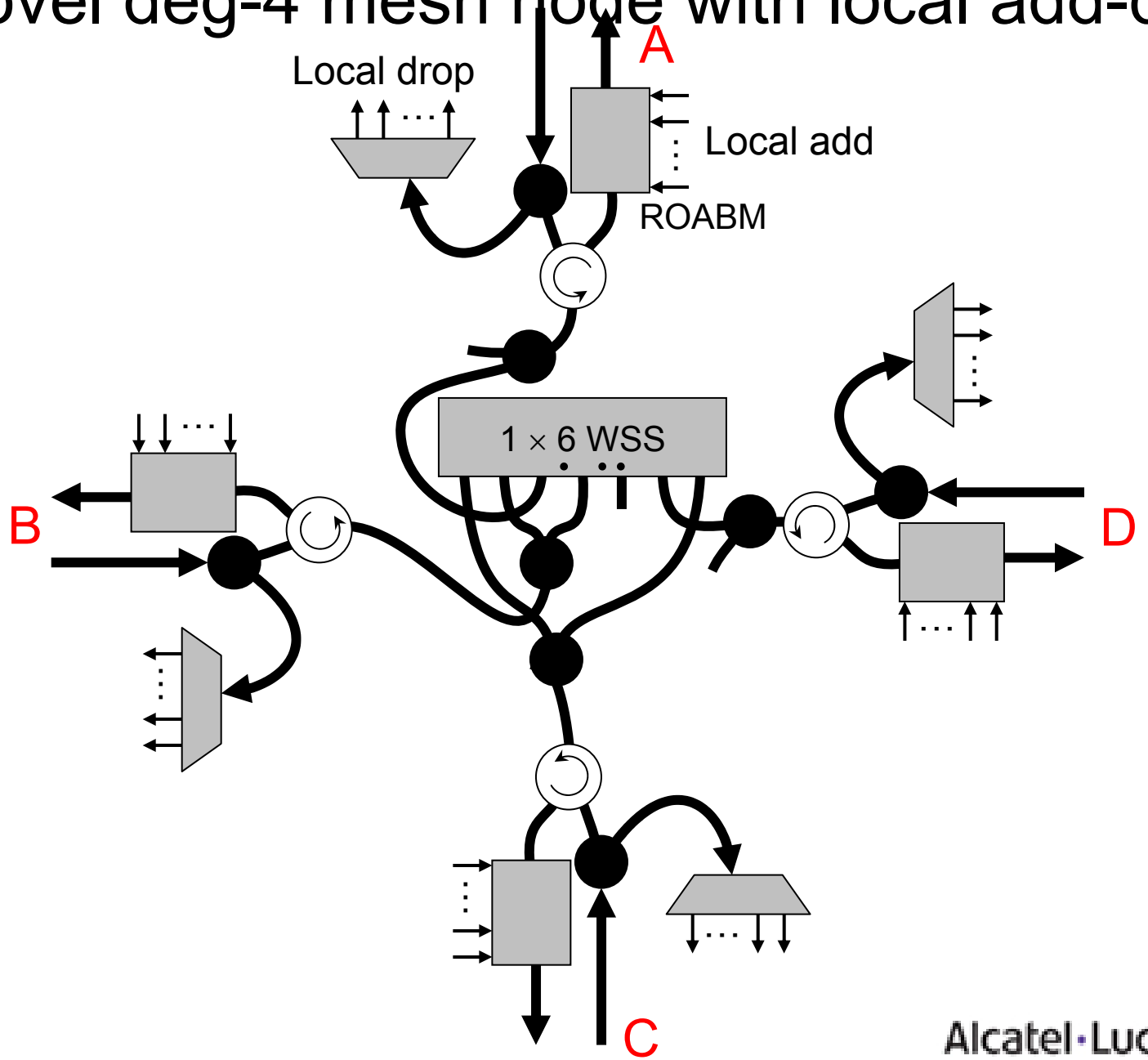
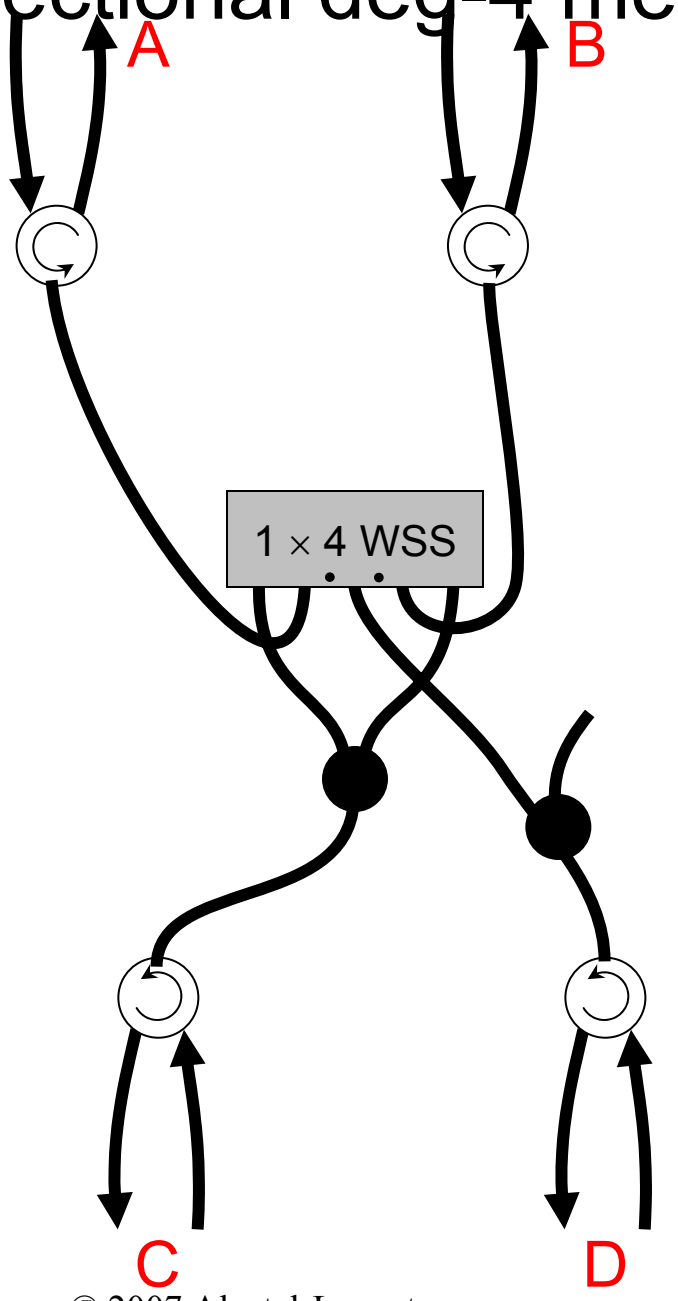
Novel deg-4 mesh node with local add-drop



Novel directional deg-4 mesh node



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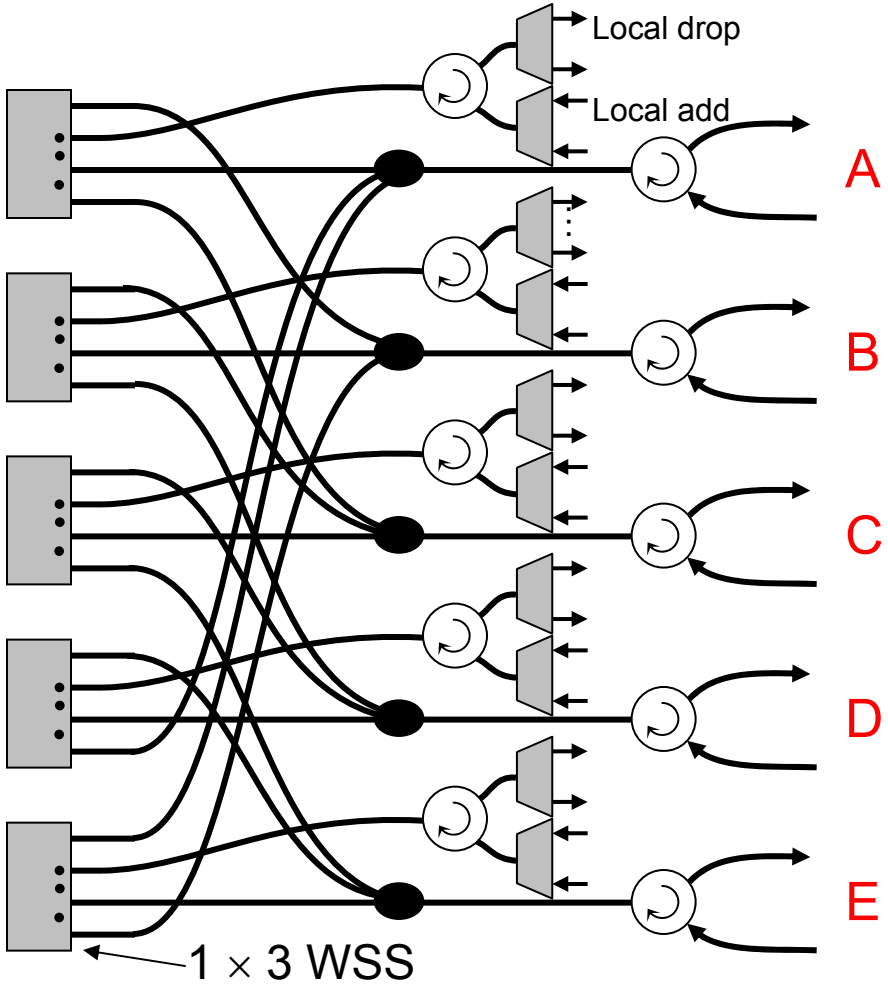
Novel deg-5 mesh node



Can use a single WSS only up to deg 4 because a single WSS has only one adjustable mirror.

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Electronic switching vs. optical switching

Electrical vs. optical switching

Optical switching

- Cost high but independent of bit rate
- Cannot access TDM channels
- Format and rate transparent

Electrical switching

- Cost low but increases with bit rate
- Can access TDM channels
- Format and rate dependent

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Conclusion

Conclusion

- Gave overview of TDM and WDM networks
- Presented novel optical mesh node design that reduces the required number of components
- Advantages of new design
  - Much less expensive
  - Much more compact
- Disadvantages of new design
  - Demands must be symmetric
    - but can do multicasting if use LCOS-type WSS
  - Cannot do individual channel power control
    - but WSS gets less costly if do not need individ. ch. pwr control
  - Single point of failure
    - but can get diversity if use multiple elements

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Future

- Degree number will increase in the future
- Conventional design requires many components and fiber connections
- Protection needs to be considered more carefully
- Must decide where best to do electronic switching and where best to do optical switching