The Outlook of Broadband Optical Access Networks

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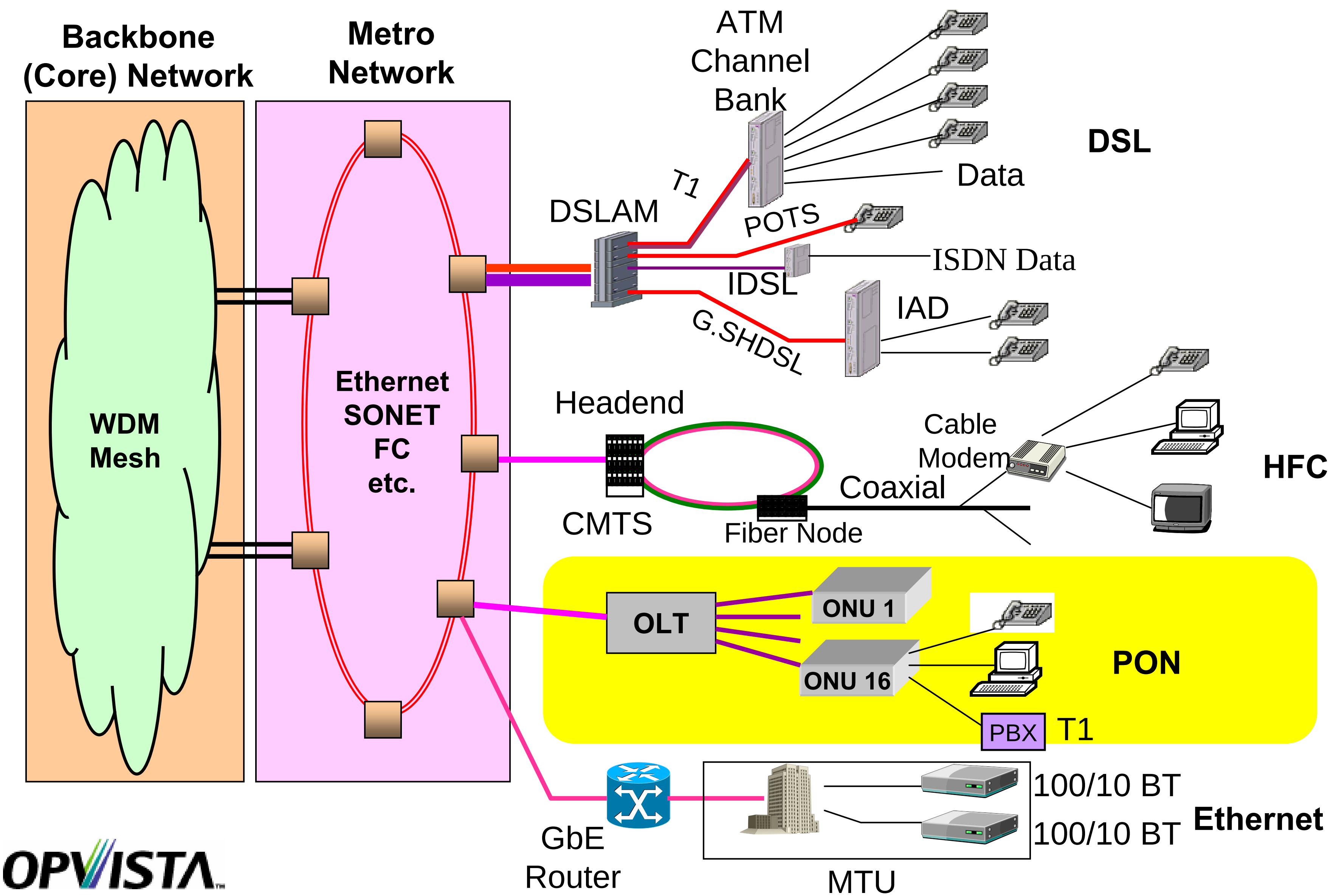
Acknowledgement & Disclaimer

- **Acknowledgement**
  - Jessica Xin Jiang (Salira Networks)

- **Disclaimer**
  - The materials presented here represents my own personal view which could be biased.

Telecommunication Networks



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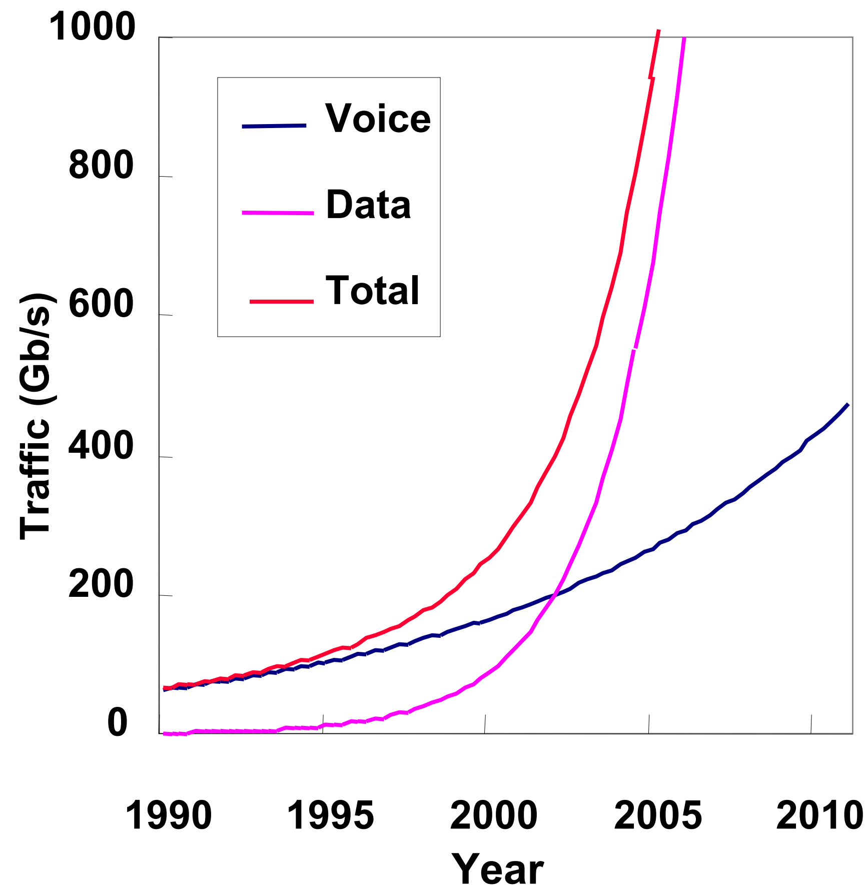
Broadband Access Network Drivers

- **Continuing growth of Internet and new applications**
  - Quadruple play:
    - VOIP, IPTV, Broadband Data, Wi-Fi /Wi-Max (backhauling)
  - Storage Area Networks
  - Peer-to-peer networking
    - Picture, movie & music sharing
  - Network gaming
- **Deregulation of the telecom service market**
  - Telcos and MSOs get into each other's market



Coffman and Odlyzko, AT&T Labs, 1997

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VoD – Killer Application

NETFLIX the Post-Office Model

4 ~ 8 GBytes per DVD

24 to 48 hours

160 ~ 740kbits per second

FY 2006, Revenue : $997mil, Net Income : $49mil.

Source: www.netflix.com

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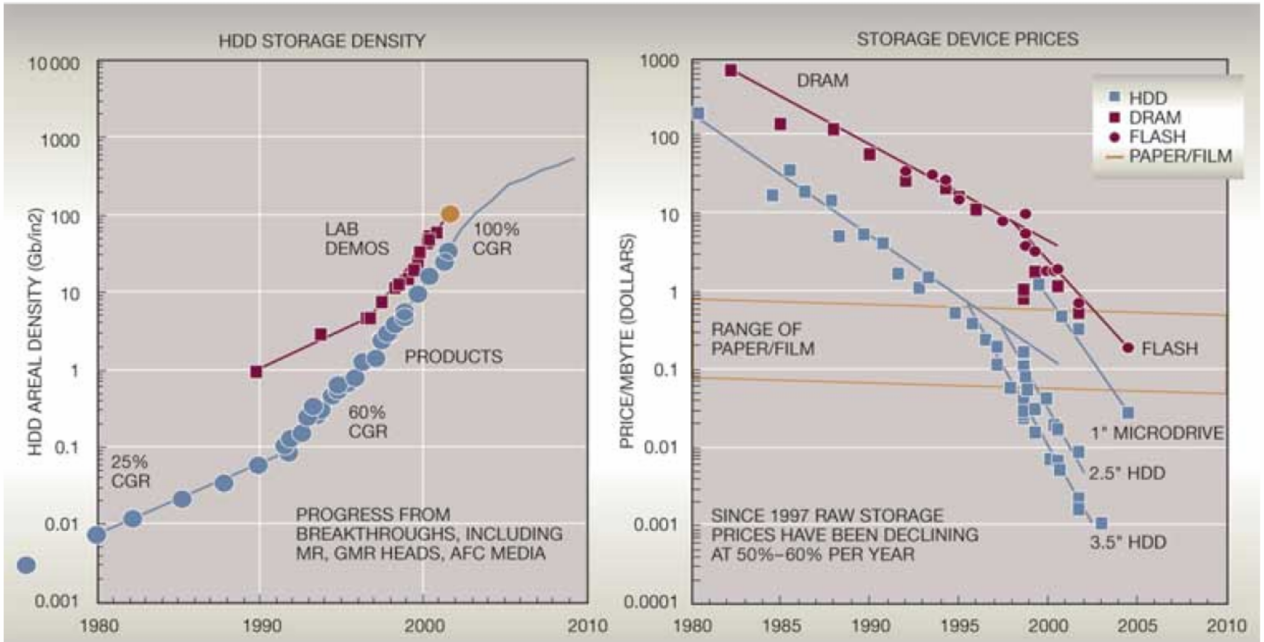
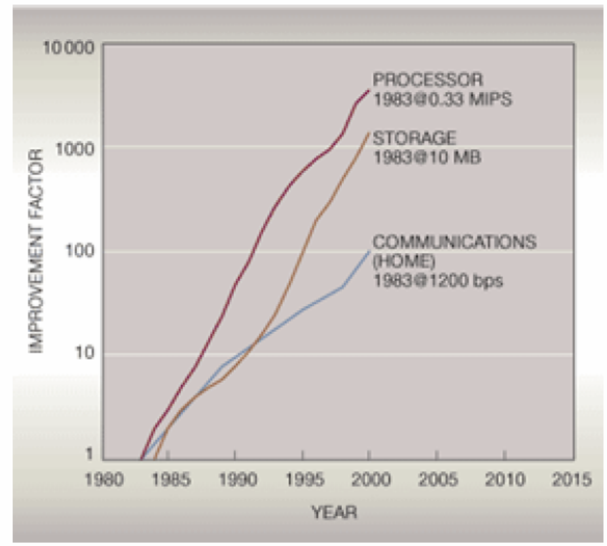
Rapid Storage and Processing Improvements

Figure 1 HDD storage density is improving at 100 percent per year (currently over 100 Gbit/in2). The price of storage is decreasing rapidly and is now significantly cheaper than paper or film.



MR, GMR: (Giant) Magnetoresistive, AFC: Antiferromagnetically coupled

Figure 2 Improvement factors for PC technologies; since 1990 storage technology has outpaced both processor and communication technologies.



Morris and Truskowski, IBM Systems Journal, Vol. 42, (2), 2003.

Toshiba's 0.85" 4 GB HDD

Seagate's 1" 5 GB USB External HDD

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Source: E. Ayanoglu, UCI

VoD Enablers

Disk Based Video Servers

$\Rightarrow$

DRAM Based servers

Courtesy: Motorola (Broadbus)

- **High capacity storage**
- **Advanced video processing and compression technologies**
  – SDTV: ~ 3.5 Mpbs (MPEG-2)
  – HDTV: ~ 8-15 Mbps (MPEG-4)
- **Low-cost and high-bandwidth made available by WDM and Gigabit Ethernet**

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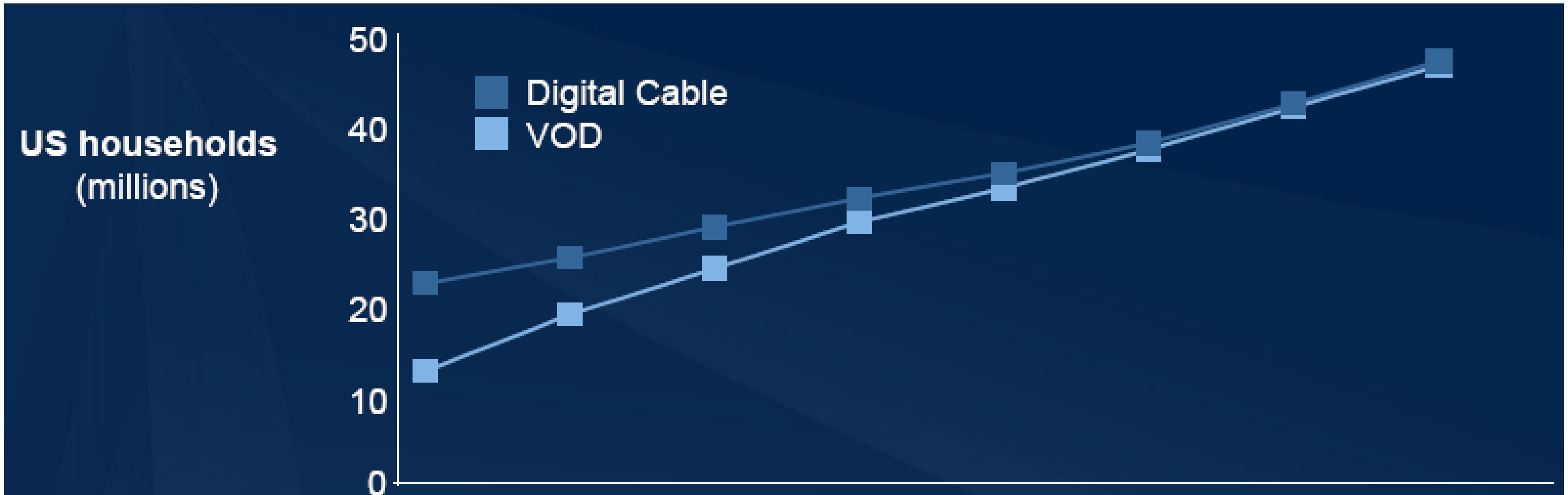
VoD Penetration in the USA



	2003	2004	2005	2006	2007	2008	2009	2010
Digital cable	22.2	25.1	28.5	31.7	34.5	37.8	42.2	46.9
Video-On-Demand	12.5	18.8	23.9	29.1	32.8	37.1	41.8	46.4
VOD penetration of digital cable	**56%**	**75%**	**84%**	**92%**	**95%**	**98%**	**99%**	**99%**

Total number of households in the US: 116Millions

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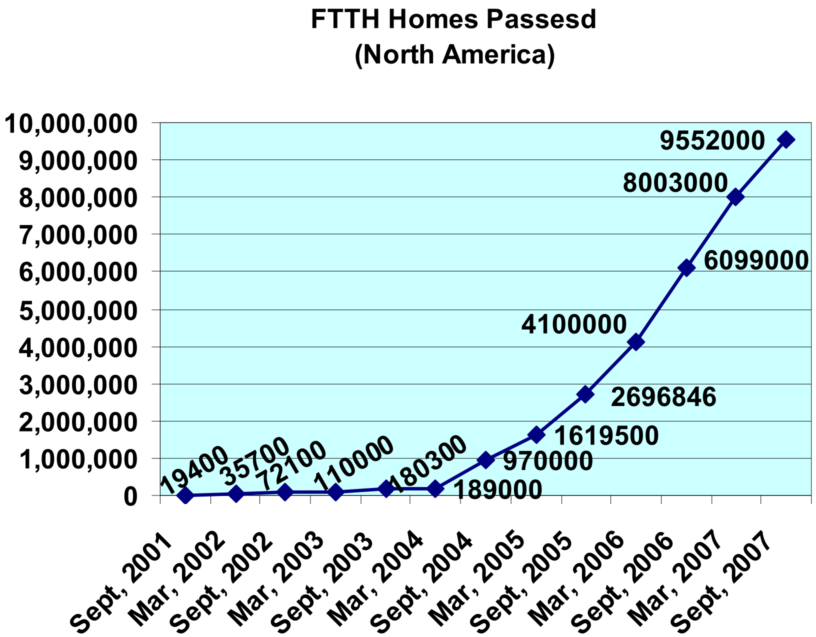
Source: Forrester Research, 2005

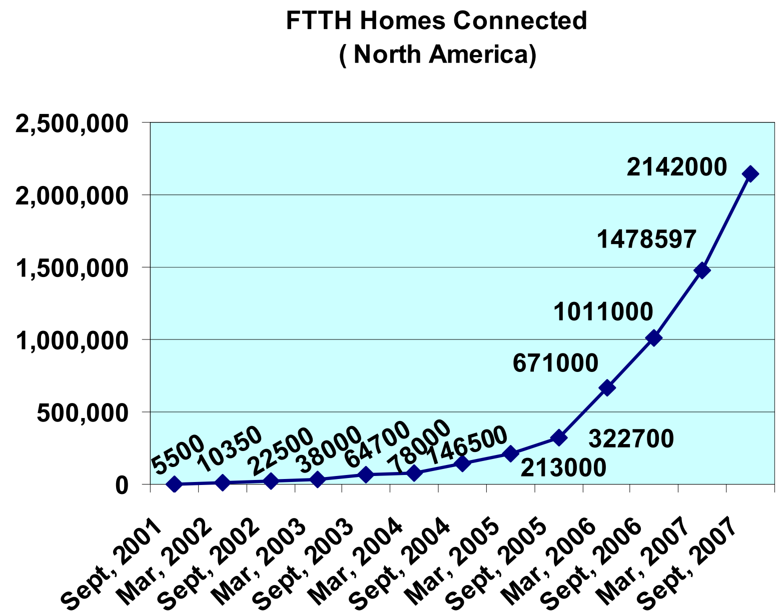
Global FTTX Development

- **Fiber to the Premises (FTTP)**
  - RBOCs' new weapon to compete with MSOs
  - FCC incentive, no need to unbundle the link
  - Joint RFP issued in January 2003
    - Verizon, SBC (now AT&T) and Bell South
    - Promote interoperability, create economy of scale
  - AT&T: Uverse; Verizon: FIOS
- **NTT**
  - GE-PON based FTTH
- **Korea**
  - WE-PON (WDM-Ethernet-PON) trial
- **Europe**
  - Many carriers have selected G-PON for FTTx

US FTTH Deployment

Source: RVA Render





- **Up to Sept 2007**
  - 2.14mil homes connected
  - 9.5mil households passed
- **Growth rate:**
  - 112% annually
  - 300,000 households passed every month

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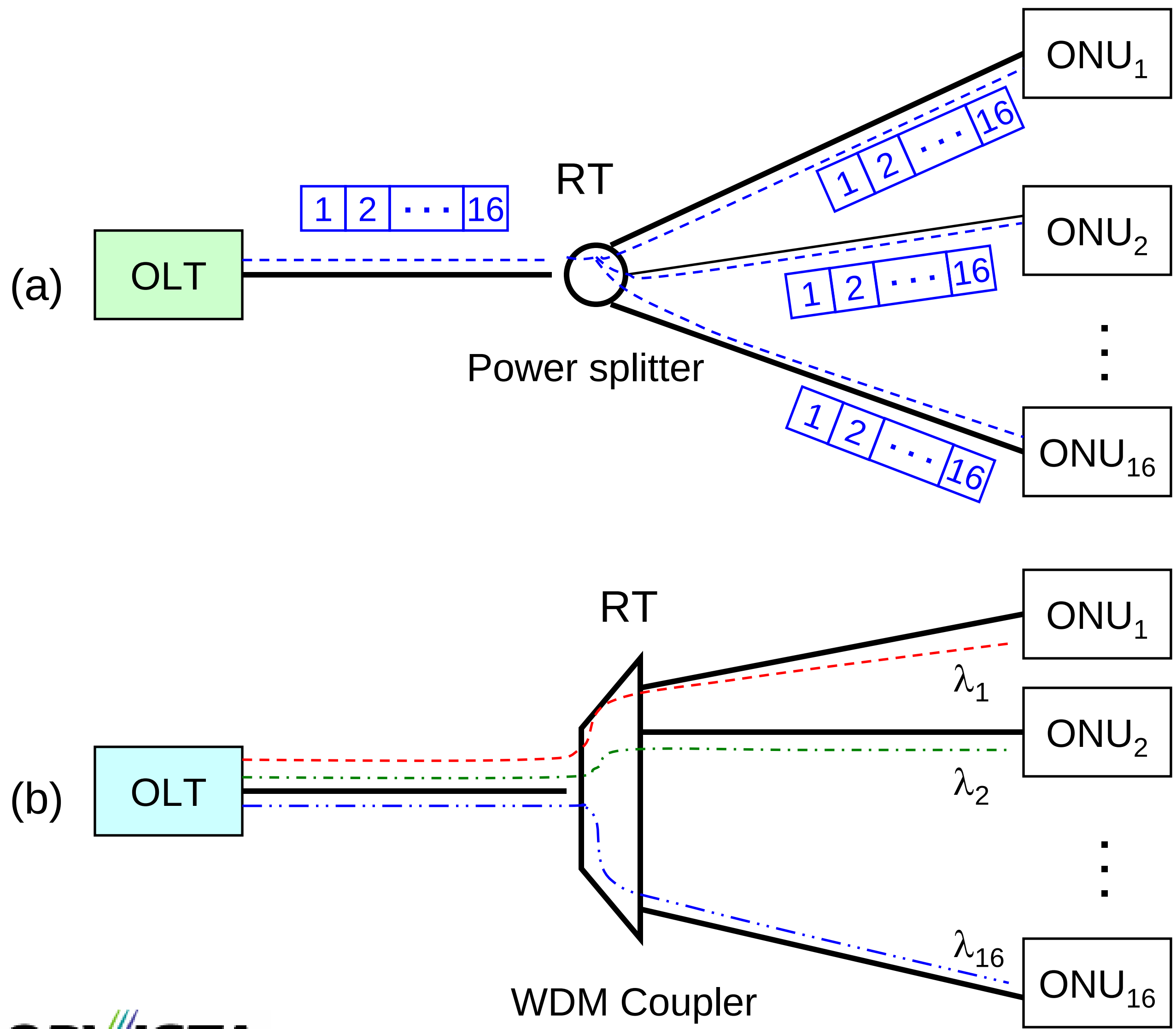
TDM vs. WDM



- **APON**
- **BPON**
- **GPON**
- **EPON**

- **Future Upgrade**

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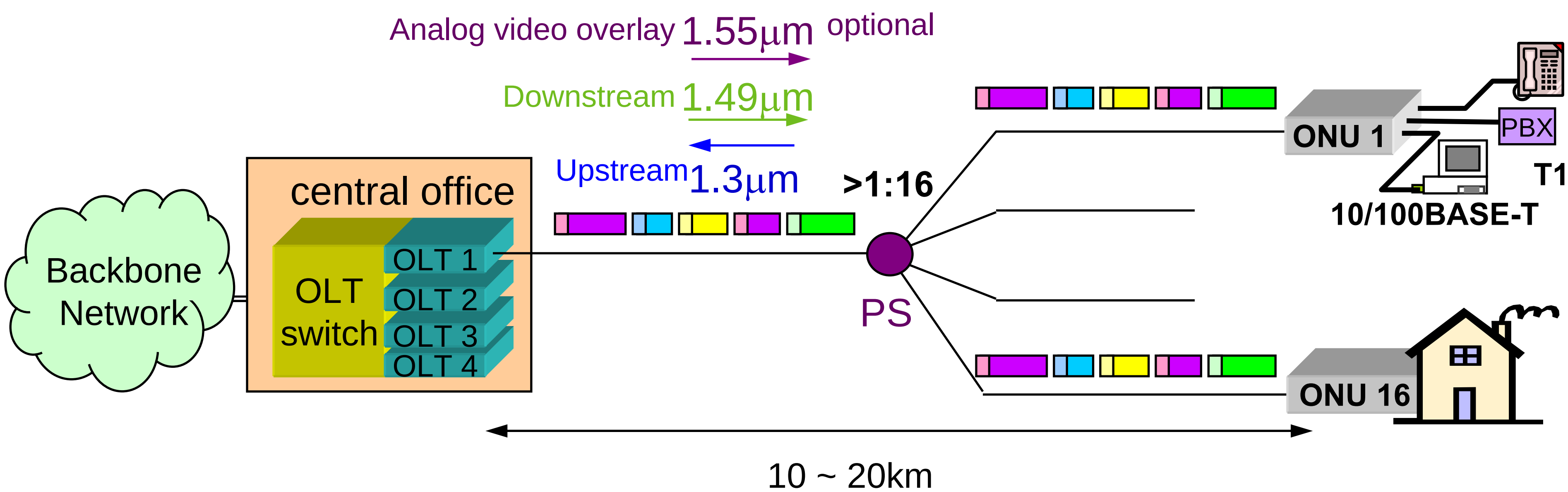
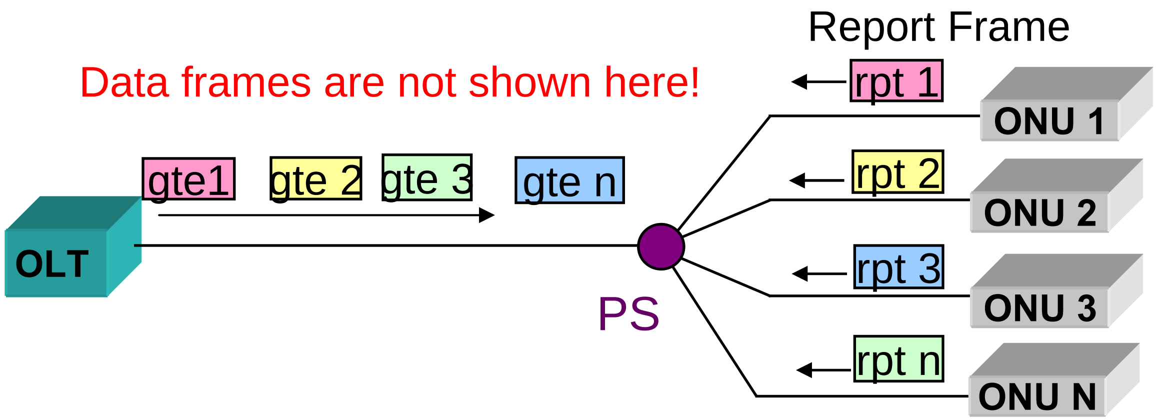
Power Splitting TDM PON Infrastructure



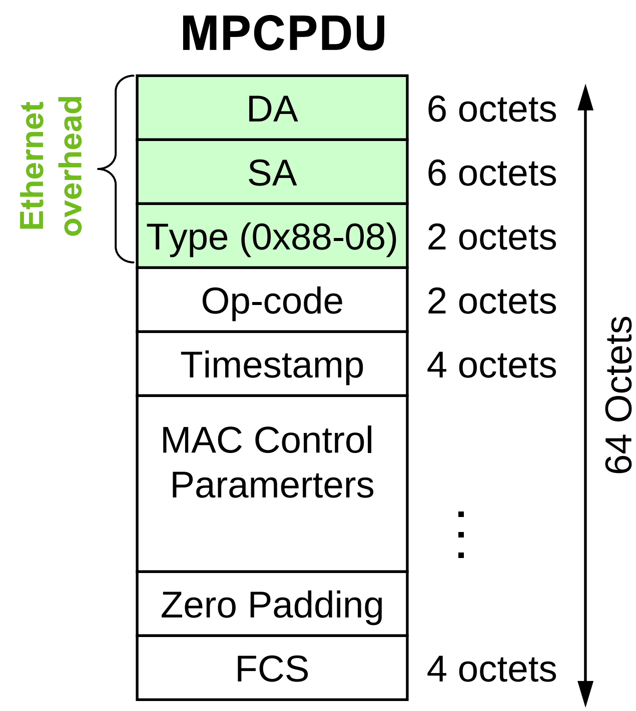
- **Power splitter remote node**
- **Single fiber connection**
- **Upstream and downstream signals separated by wavelengths (1.3μm/1.49μm)**
- **Optional 1.55μm broadcast analog signal overlay**

EPON vs. GPON

EPON Multi-Point Control (MPCP) Protocol



- **Bandwidth request and grant are achieved through MPCP protocol**
  - ONU request upstream BW through REPORT frames
  - OLT send BW allocation to ONU using GATE frames
- **Pros**
  - Only standard 802.3 Ethernet MAC frames are used
  - Maximum compatibility with Ethernet
- **Cons**
  - Each MPCPDU is a 64-byte Ethernet MAC frame with its own overhead
  - OLT sent GATE frames individually addressed to each ONU for BW allocation
    - ⇒ Large protocol overhead, less efficient use of BW



New MAC control messages

GATE	**op-code = 02**
REPORT	**op-code = 03**
REGISTER_REQUEST	**op-code = 04**
REGISTER	**op-code = 05**
REGISTER_ACK	**op-code = 06**

Ref: IEEE 802.3ah

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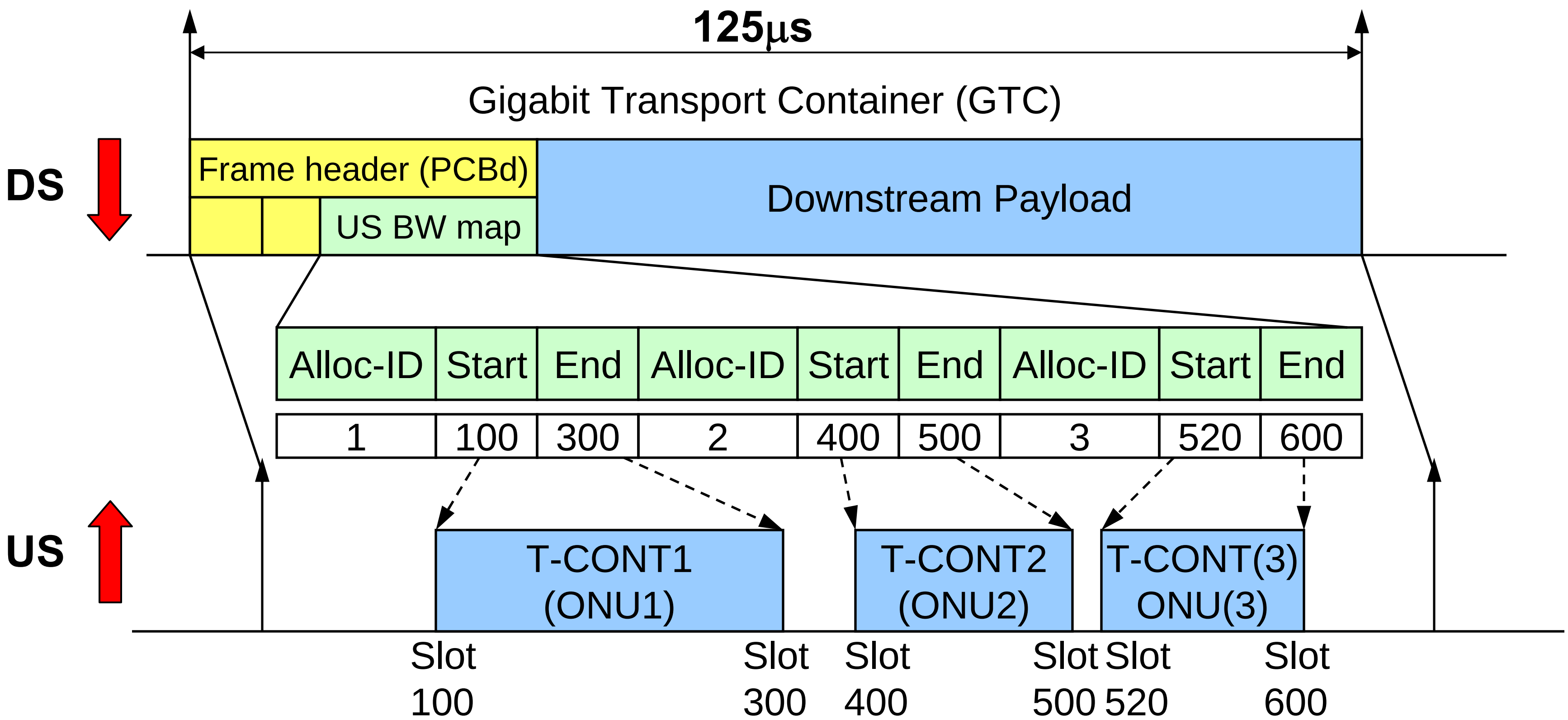
GPON (GTC) Downstream Encapsulation



- **Less overhead**
  - Media Access Control (MAC) information for **ALL** ONUs piggybacked into the same frame.
- **ITU-T G.984.3**

Source: ITU-T G.984.3

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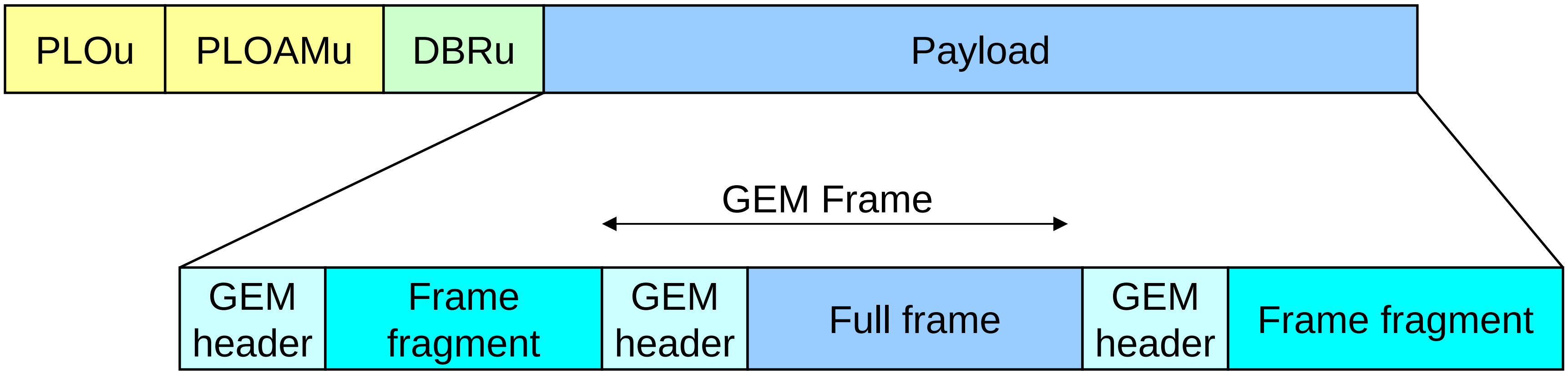
GPON (GTC) Upstream Encapsulation



- Dynamic bandwidth report piggybacked to upstream encapsulation. No separate frames used.
- G-PON Encapsulation Mode (GEM)
  - Support Ethernet frame fragmentation
  - Support encapsulation of other formats
  - More efficient packing of data
  - Native support of TDM traffic

Source: ITU-T G.984.3

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EPON vs GPON – Physical Layer

		EPON	GPON
Downstream data rate (Mbps)		**1000**	**1244 or 2488**
Upstream data rate (Mbps)		**1000**	**155, 622, 1244, or 2488**
Payload Encapsulation		**Native Ethernet**	**GEM**
TDM Support		**Circuit Emulation**	**Native**
Upstream burst mode receiver	Laser on/off	**512ns**	**≈13ns**
	AGC	**≤400ns**	**44ns**
	CDR	**≤400ns**	

- **GPON**
  - Power control required in GPON to achieve short AGC time
  - High speed laser drivers required for fast on/off time in GPON, difficult to realize
- **EPON**
  - Relaxed component requirements (20~30% cheaper equipment)
  - Can even use traditional AC-coupled receiver as EPON burst mode receiver

Per-User Bandwidth

- **Fully loaded 32-way split**

		EPON	GPON
Raw Bandwidth (Mbps)	Downstream	**31.25**	**78**
	Upstream	**31.25**	**39 / 78**
Bandwidth Efficiency		**72%**	**92%**
Effective Bandwidth (Mbps)	Downstream	**22.5**	**71.8**
	Upstream	**22.5**	**35.9 / 71.8**

- **US RBOCS don't think EPON meets their future bandwidth requirements**
  - To compete with GPON, IEEE started 802.3av 10GbE-PON task force in March 2006

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Typical Applications' Bandwidth Requirements

Application	Bandwidth	QoS
Video (SDTV)	3.5 Mbps	Low loss, low jitter, constant bit rate
Video (HDTV)	**8-15 Mbps**	**Same as above**
Telecommuting	10 Mbps	Best effort, bursty
Video gaming	10 Mbps	Low loss, low jitter, bursty
Voice	64 kbps	Low loss, low latency, constant bit rate
Peer-to-Peer downloading	100 kbps – 100 Mbps	Best effort

- **100Mbps**
  - Download an 8GB DVD movie in 10 minutes
  - Blue Ray: 25 to 200GB per disk

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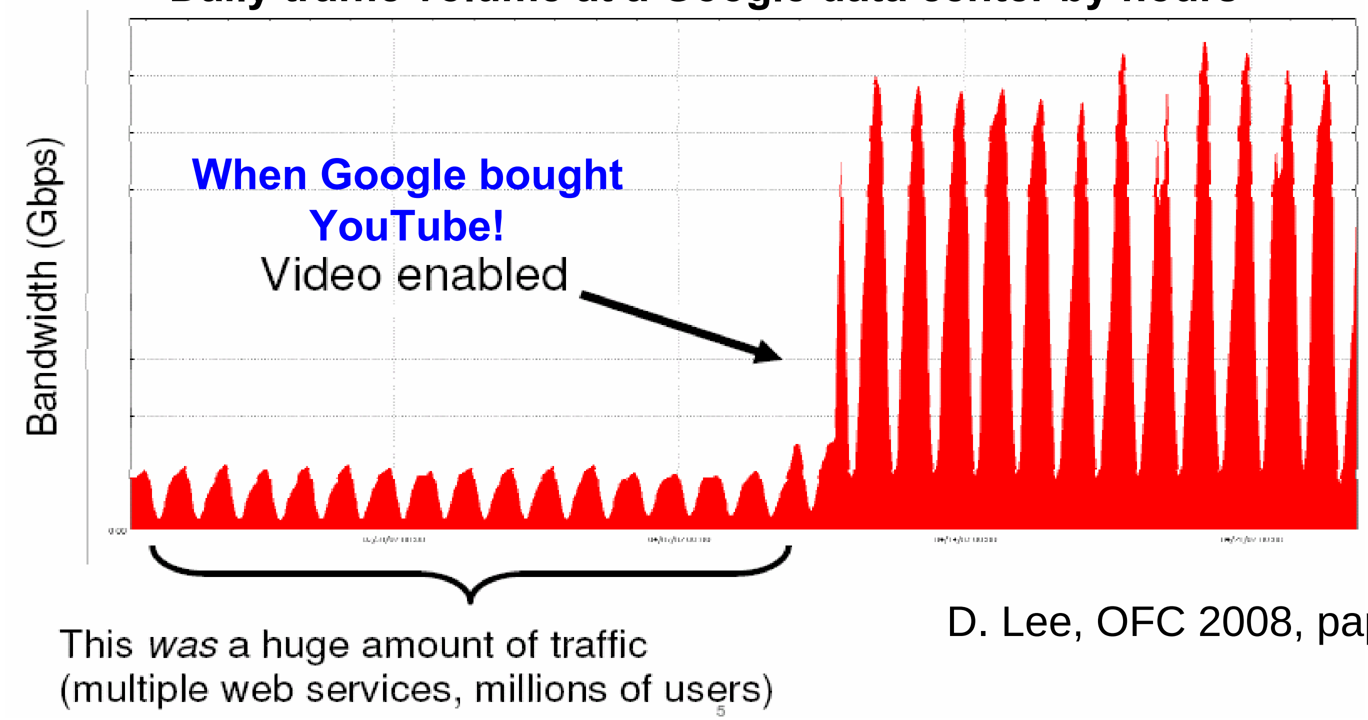
Changes in Network Traffic

Daily traffic volume at a Google data center by hours



D. Lee, OFC 2008, paper OThB1

- **Traditional web surfing is user active, network passive**
- **Video is user passive, network active.**

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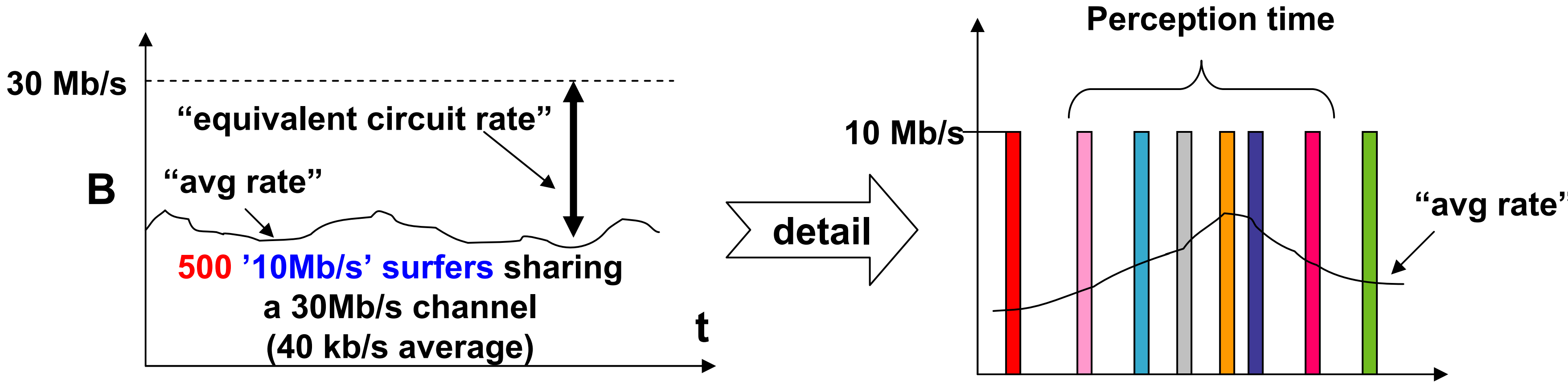
Statistical Multiplexing Gain



- **Web-surfing**
  - Poisson packet arrival distribution
- **Equivalent circuit rate**
  - The perceived circuit rate experienced by users
  - 500 users with average usage of 40kb/s
  - Each user perceives as if he/she has 30Mb/s – (500x40kb/s) = 10Mb/s

N.K. Shankaranarvanan, ATT, "User-perceived peformance …" Proc. ICC, June 2001
N.J. Frigo, "Fiber to the home: niche market …" OFC 2004 Tutorial

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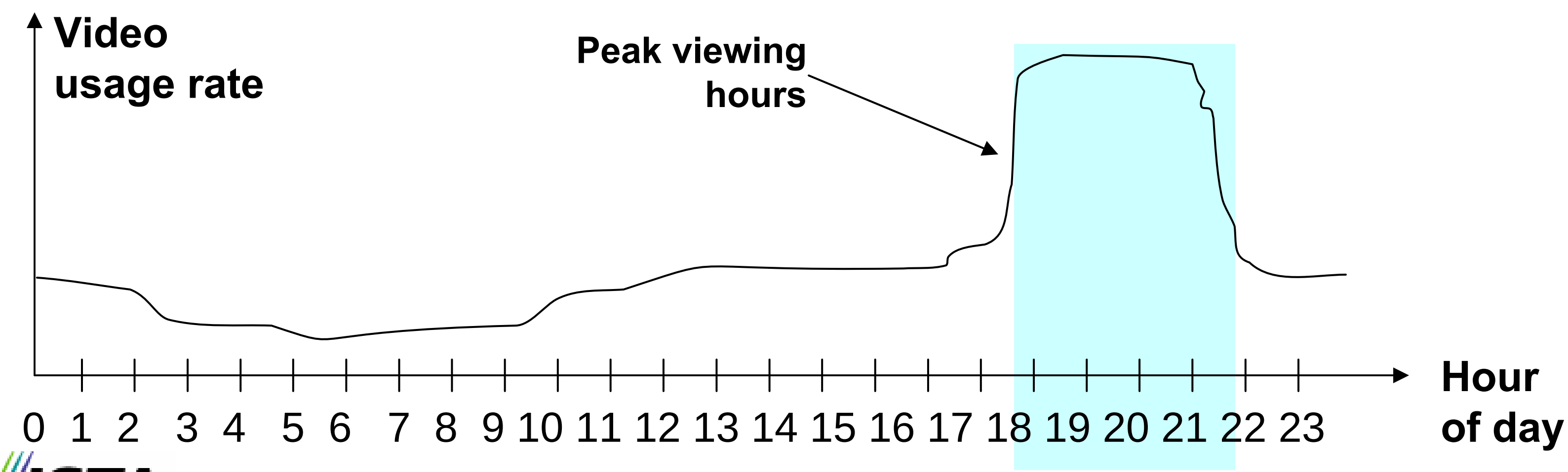
VoD Bandwidth Characteristics

- **Video streams characteristics**
  - High bandwidth usage
  - Highly asymmetric
  - Uniform and steady packet arrival rate
- **Video consumptions are highly peaked during prime viewing hours or special events such as soccer games.**
- **Statistical multiplexing gain no longer valid**



How Much Bandwidth is Needed?

- **US Population Statistics (US Census Bureau http://www.census.gov)**
  - Total Population: 300mil, Number of households:116mil
  - Average 2.6 people per household
- **24 ~ 45Mb/s bandwidth per household**
  - Enough for everyone at home to watch a different HDTV at the same time (without counting background download jobs, which can take advantage of statistical multiplexing).
  - Good before another killer application emerges
- **GPON will be able to support fully loaded VoD BW requirements and have room to grow …**
- **EPON have barely enough BW when VoD takes off.**
  - Shrink the service group, 1:8 ONUs per OLT
  - Develop 10GbE PON

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10GbE-PON

- **IEEE 802.3av, started March 2006**

	Downstream	Upstream
Symmetric	10Gb/s	10Gb/s
Asymmetric	10Gb/s	1Gb/s

- **Backward compatible with 1G E-PON**
  - WDM overlay
  - Dual rate OLT receiver

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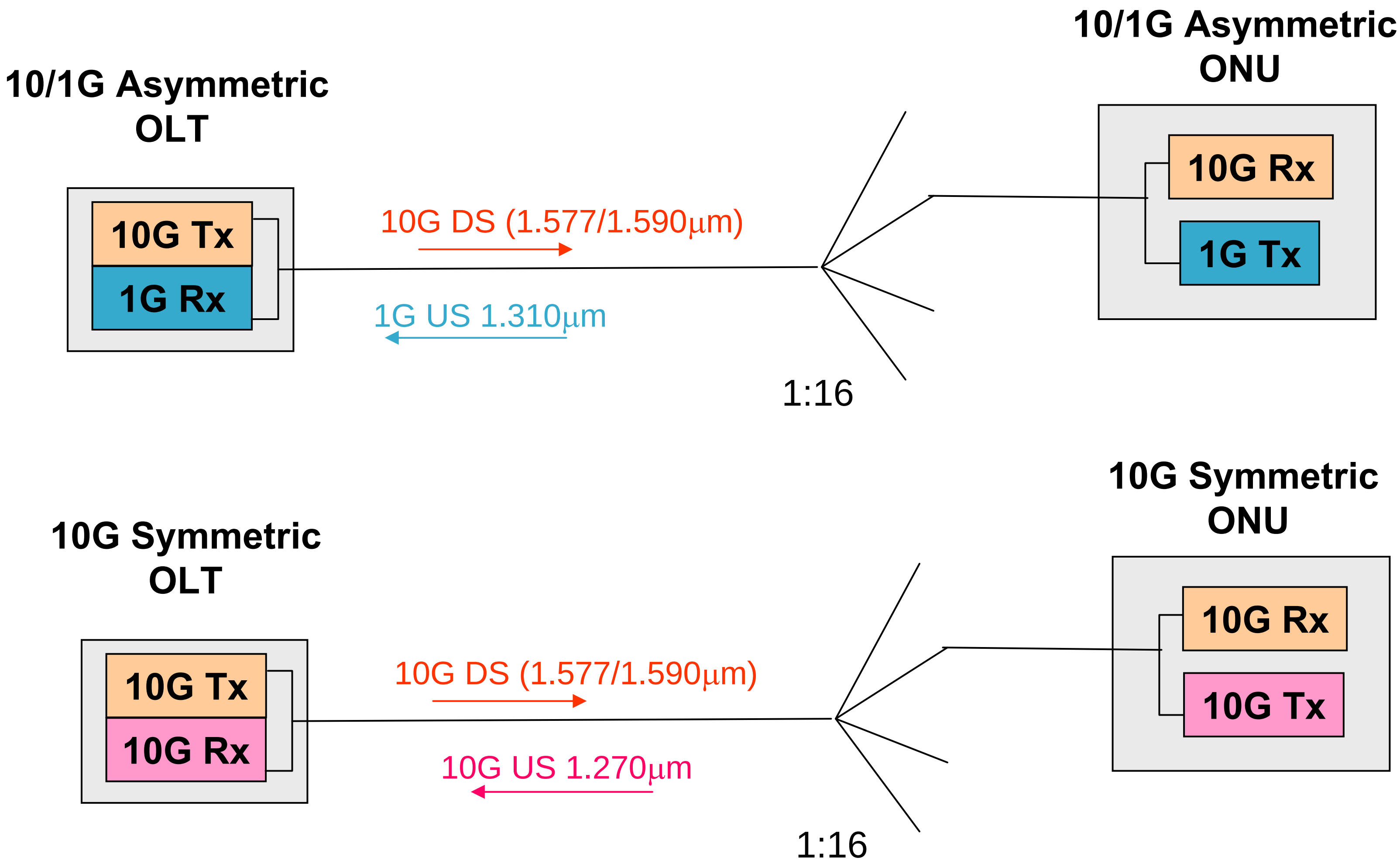
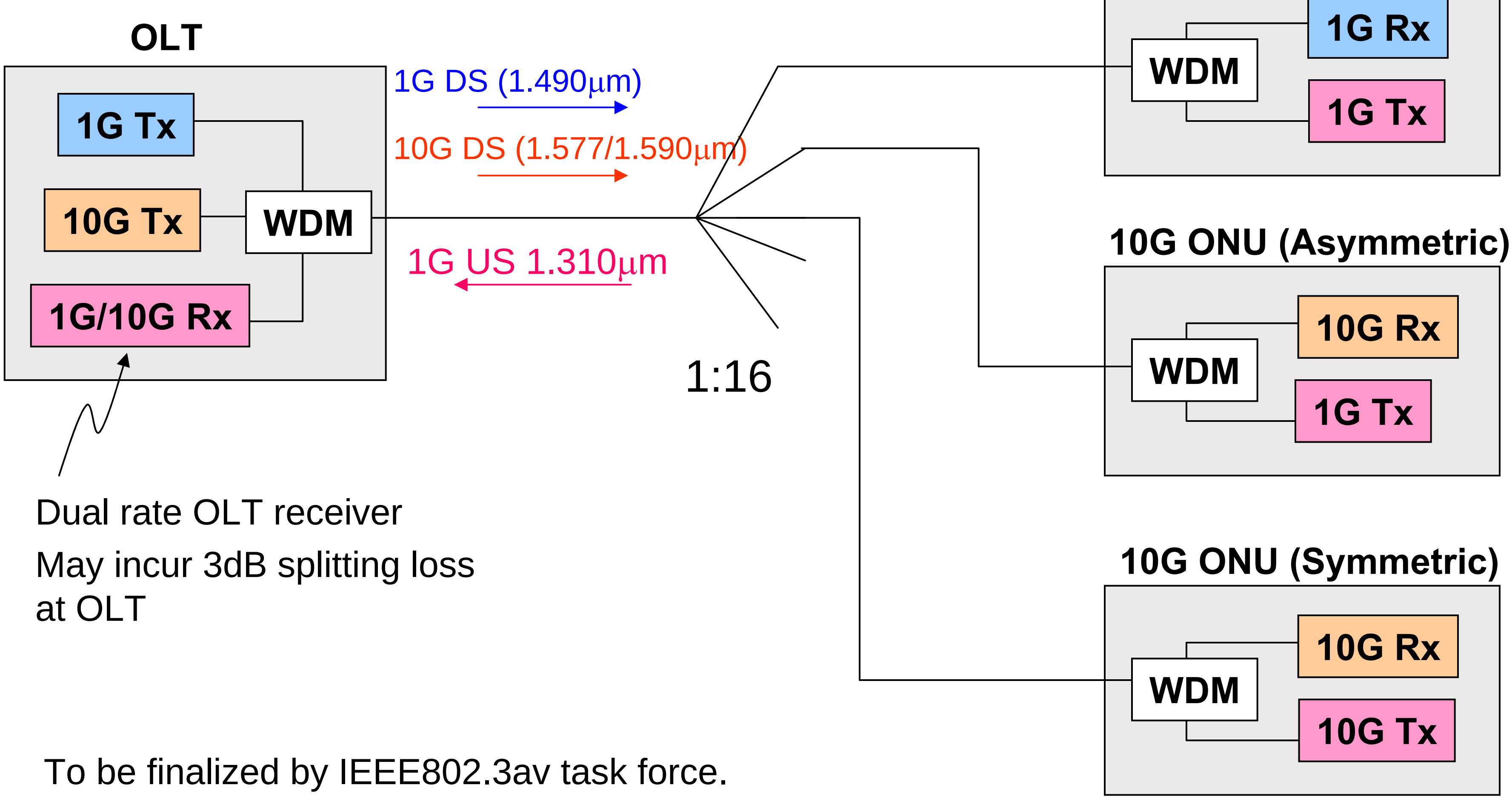
Symmetric and Asymmetric 10Gb-EPON Operation



To be finalized by IEEE802.3av task force.

10Gb-EPON Optical Spectrum Management - 1

Upstream TDM Overlay



To be finalized by IEEE802.3av task force.

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Dilemmas of 10GbE-PON

Split Ratio	1:16	1:32	1:64
Effective BW (Mbps)	545	272.5	137

- **Higher splitting ratio desirable to achieve better cost sharing and more efficient use of available BW**
  - 1:64 or 1:128 (recall that each HH requires only ~45Mb/s BW)
  - May need to extend coverage distance for bigger share group size (e.g. up to 60km)
- **Further worsens the physical challenges for 10Gb/s PON signal transmission**

10GbE-PON Transmission Challenges

- **Dispersion Effect (increases as square of bit-rate)**
  - EML (narrow modulated line width)
  - EDC may be needed at ONU receiver
- **Power Budget Extension**
  - 9.1dB more theoretical received power requirement compared to EPON (8B10B GbE vs. 6466B 10GbE coding)

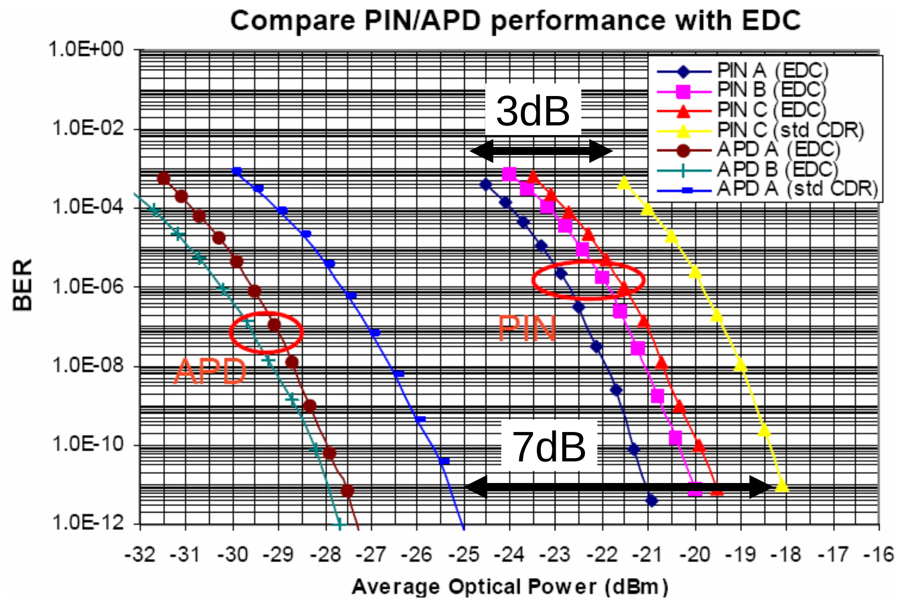
Split Ratio	1:32	1:64	1:128
Loss (dB)	15	18	21

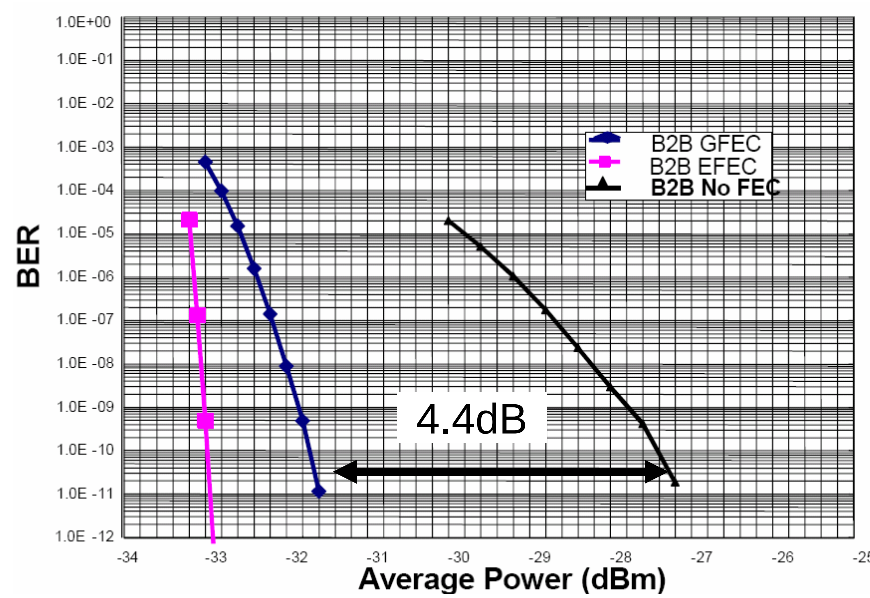
Fiber length	20km	40km	60km
Loss (dB)	4	8	12

  - 15 to 27dB more power budget required from OLT to ONU
  - Penalties (dispersion, fiber non-linearity)
- **Fiber non-linearity**
  - Limit power budgets

Technologies for 10Gb-EPON Transmission

- **APD**
  - Improves sensitivity by 7~8dB
- **EDC**
  - 2~3dB gain
- **FEC**
  - Improves power budget by 3~5dB





F. Chang, "10G EPON Optical Budget Considerations"

http://grouper.ieee.org/groups/802/3/10GEPON_study/public/july06/chang_1_0706.pdf

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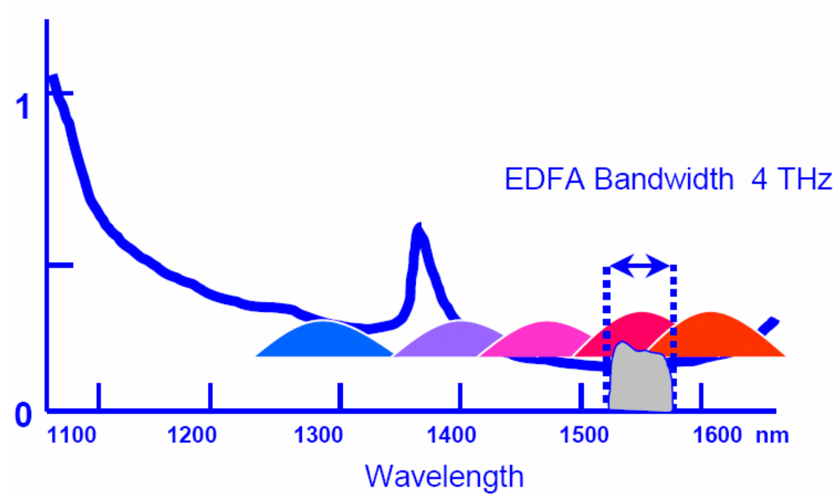
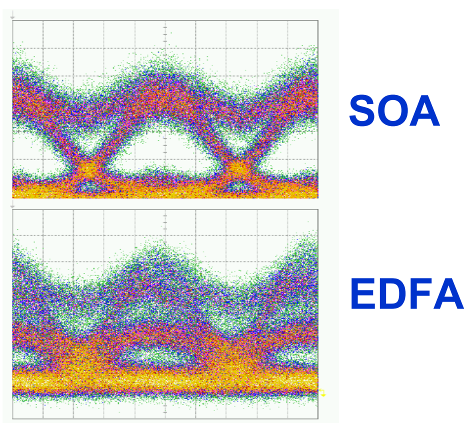
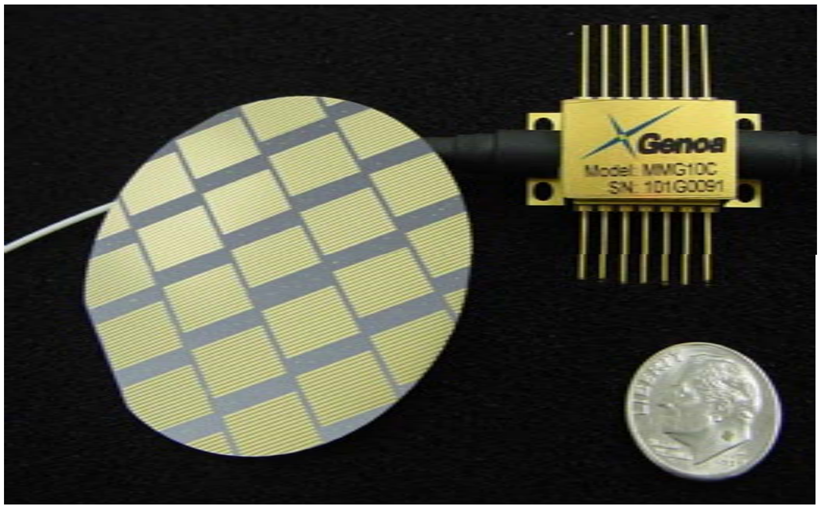
Technologies for 10Gb-EPON

- **SOA**
  - 15dB gain
  - Operate at all λ
  - Planner technology (mass manufacture)
  - Compact size, (multi-channel packaging available)
  - Beneficial for burst data



Burst data





L. Spiekman, IEEE802.3av meeting, Nov, 2006, Dallas, Tx
http://grouper.ieee.org/groups/802/3/av/public/2006_11/3av_0611_spiekman_1.pdf

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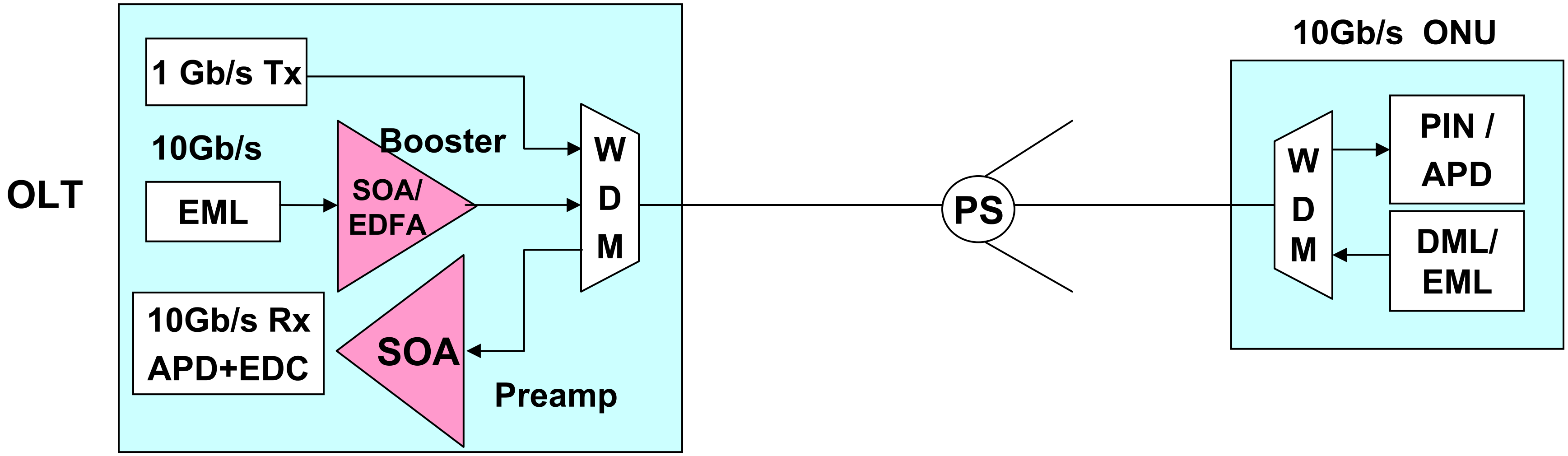
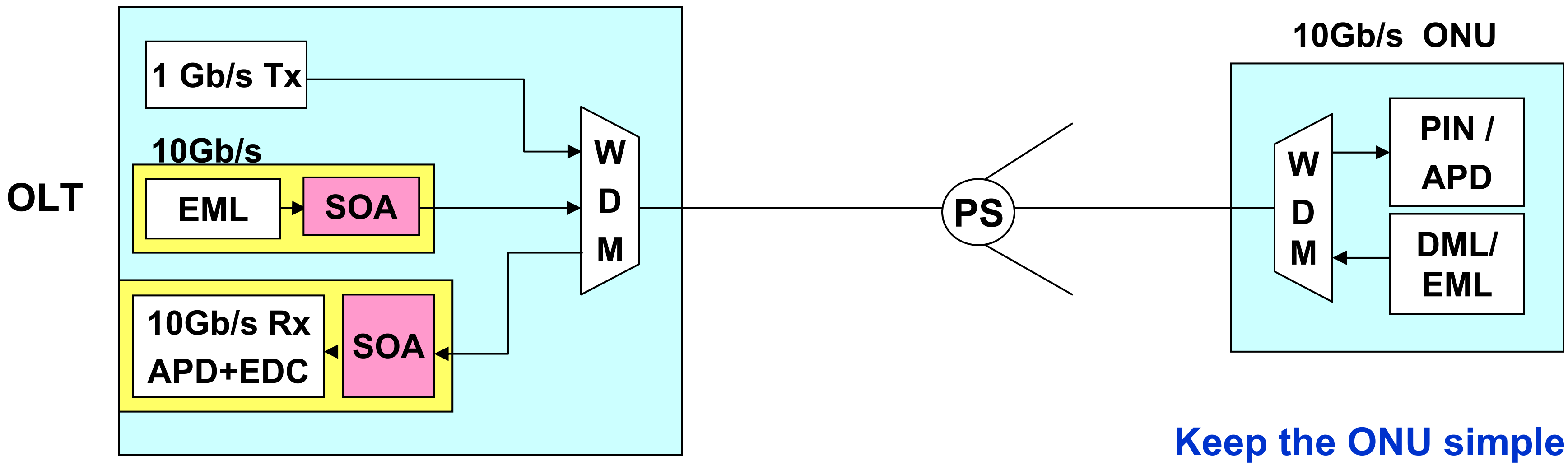
SOA / EDFA in 10Gb EPON



Integrated Solution



Keep the ONU simple !

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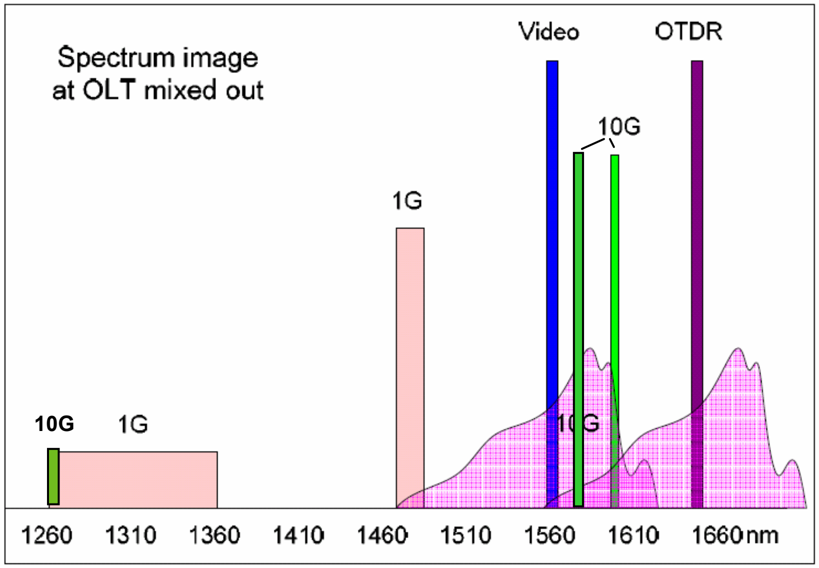
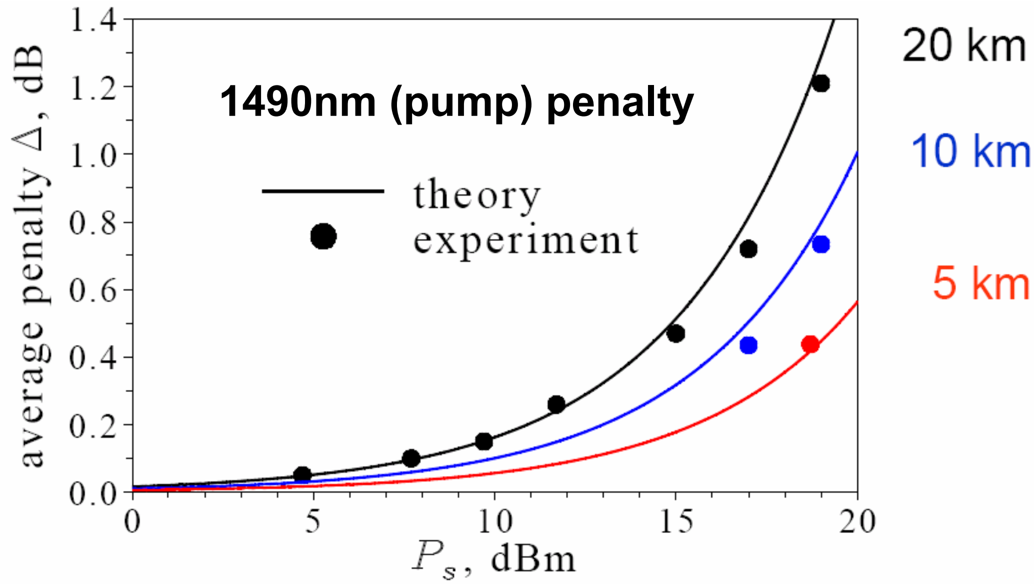
SOA may be used as data modulator

Fiber Non-linear Effect (SRS)





1550nm (10G DS)

1. S. Tsuji, “Issues for wavelength allocation,” IEEE802.3av meeting, Sept. 2006
http://grouper.ieee.org/groups/802/3/av/public/2006_09/3av_0609_tsuji_1.pdf

2. S. Ten and M. Hajduczenia, “Raman-Induced power penalty in PONs using order approximation, IEEE802.3av meeting, Jan 2007,
http://grouper.ieee.org/groups/802/3/av/public/2007_01/3av_0701_ten_2.pdf

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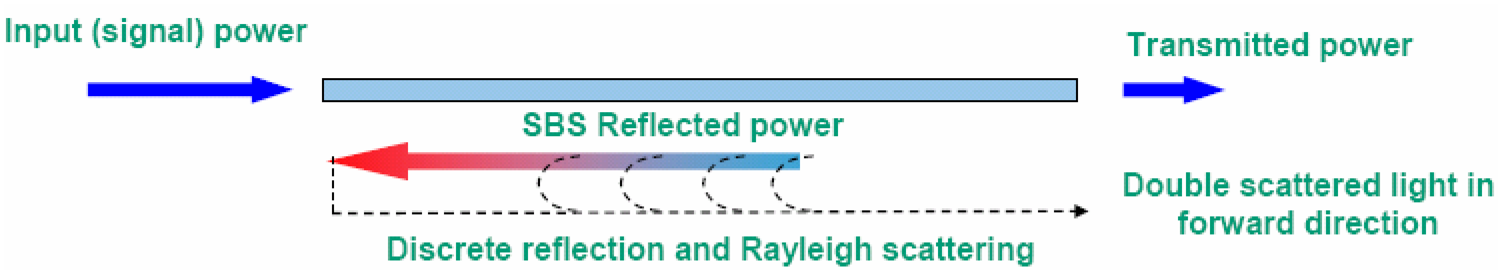
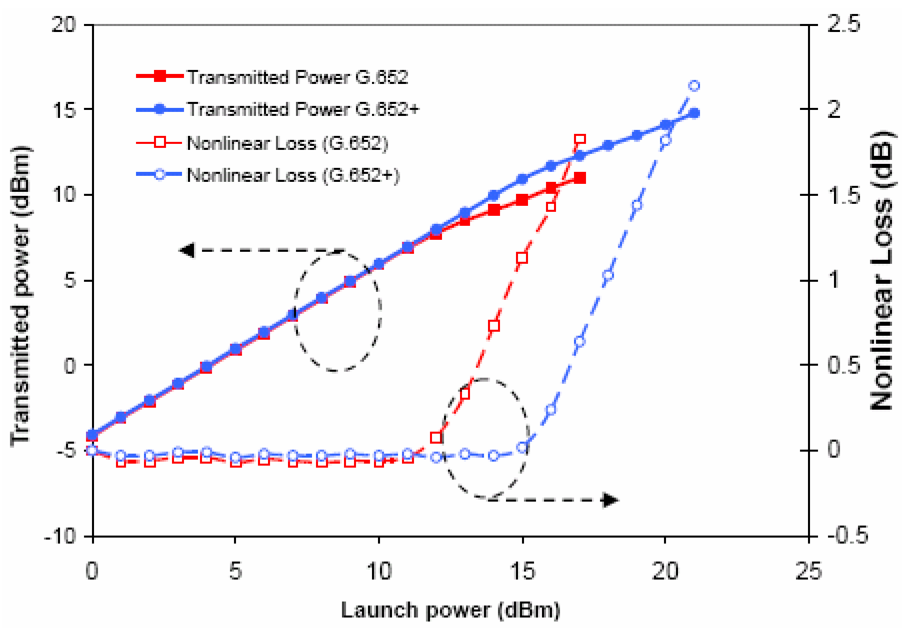
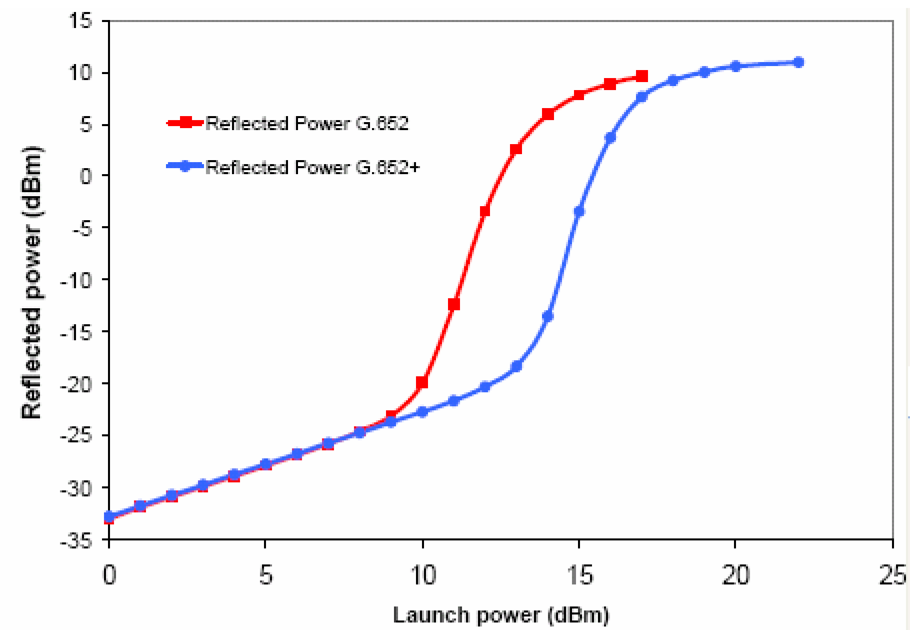
Fiber Non-linear Effect (SBS)

Limits transmitted power







S. Ten, “SBS degradation of 10Gb/s digital signal in EPON: experiment and model”
IEEE 802.3av meeting, Jan 2007
http://grouper.ieee.org/groups/802/3/av/public/2007_01/3av_0701_ten_1.pdf

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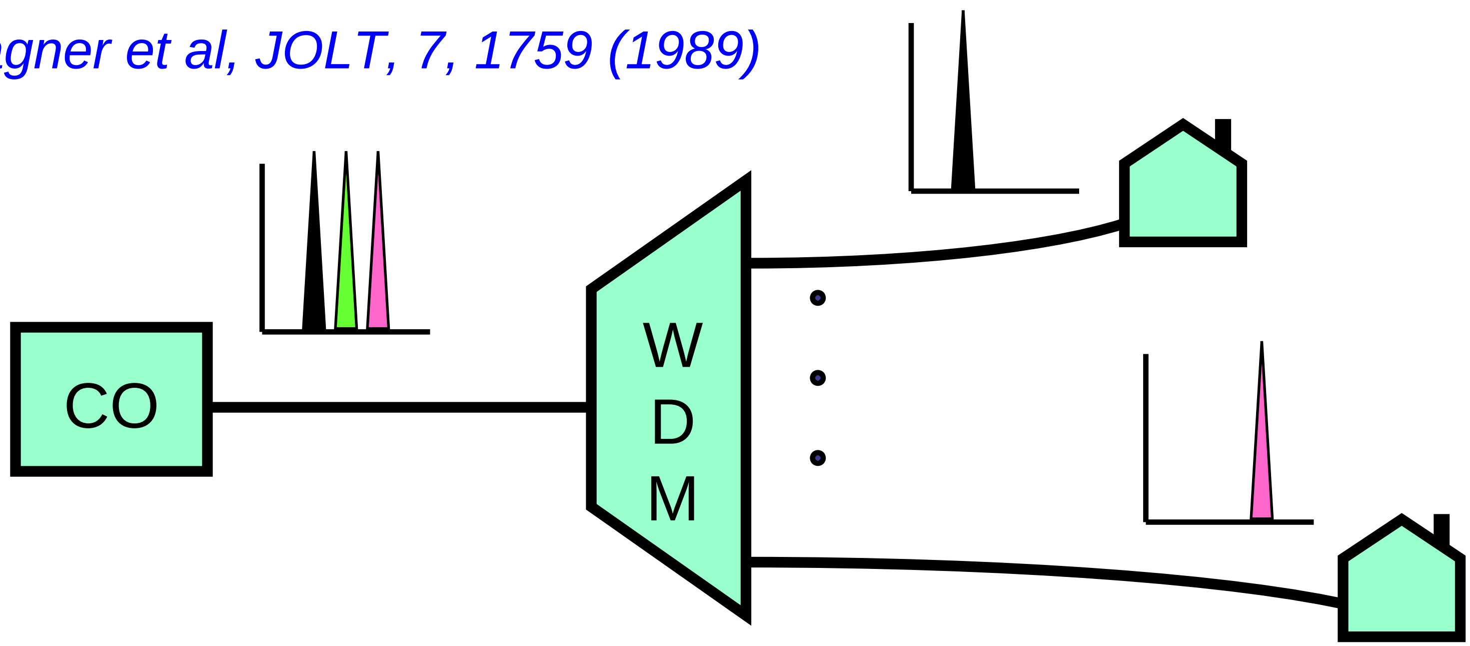
S. Wagner et al, JOLT, 7, 1759 (1989)



- **PS PON advantages**
  - passive & future proof
- **Point-Point connections**
  - Privacy / Security
- **Simultaneous Service Diversity**
- **Subscriber buys upgrades**
- **Expensive components**
  - WDM mux-demux cost still high
  - accurate wavelength lasers required
  - temperature stability

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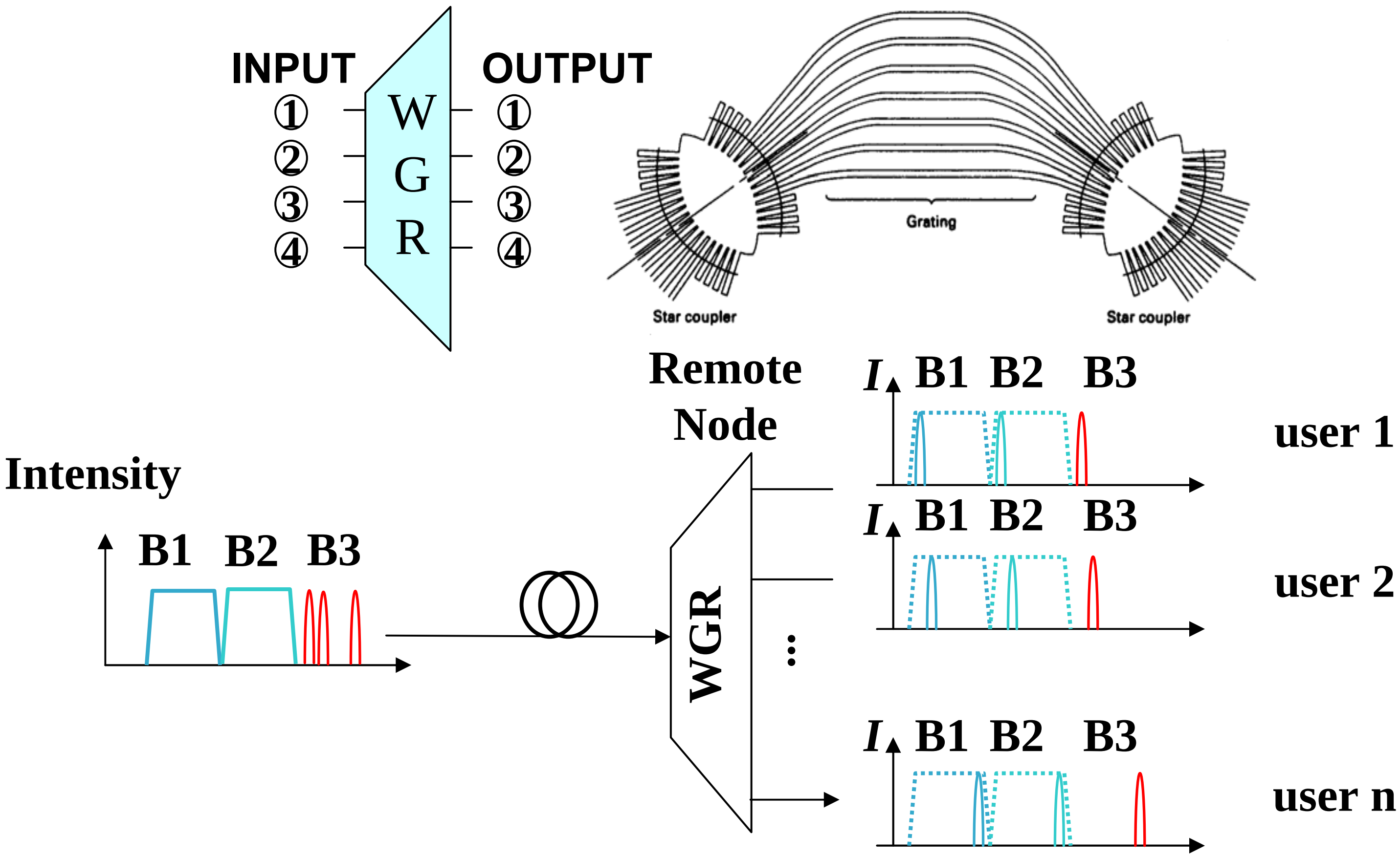
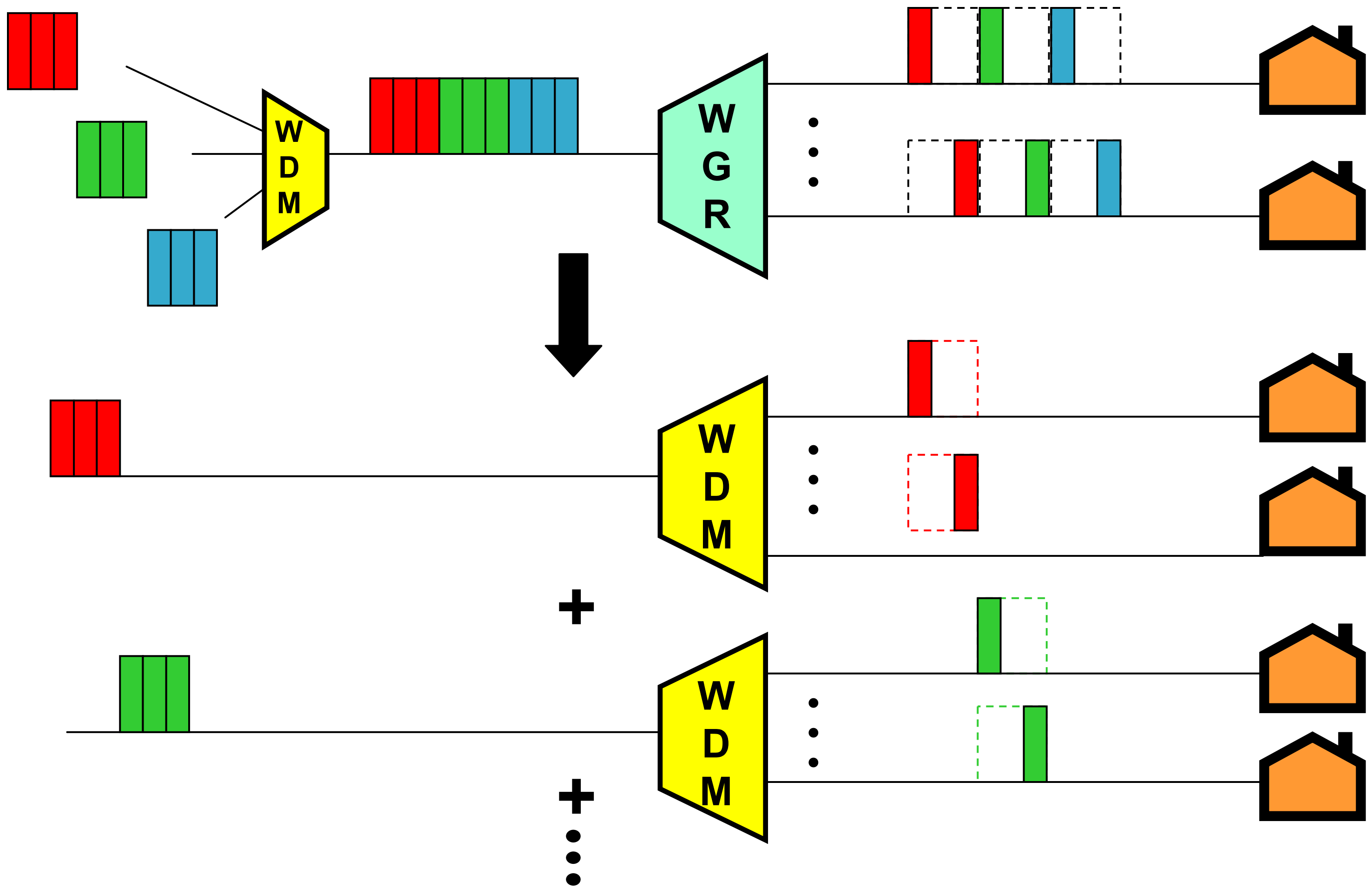
Waveguide Grating Router



- Also called Arrayed Waveguide Grating (AWG), phase array or Dragone Router
- Fabricated on Silicon

WDM on WDM



Ref: Iannone, et al., PTL 8, 930 (1996), Frigo, et al., OFC'97 PD24

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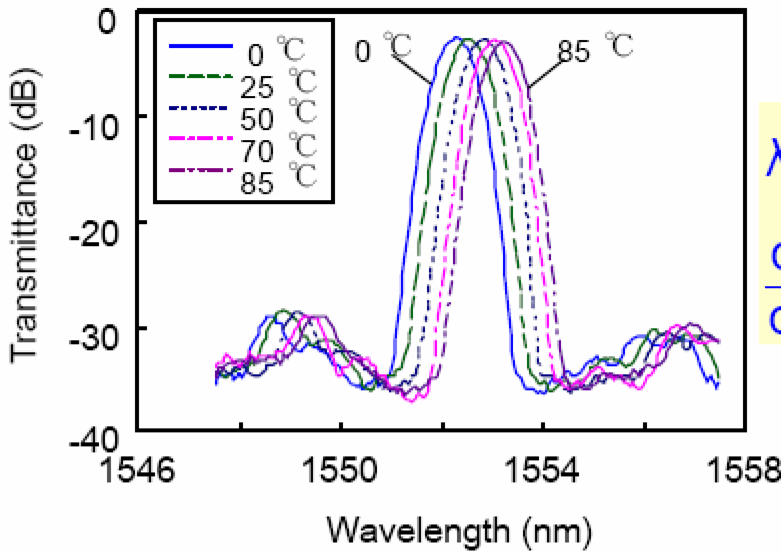
Athermal AWG Devices

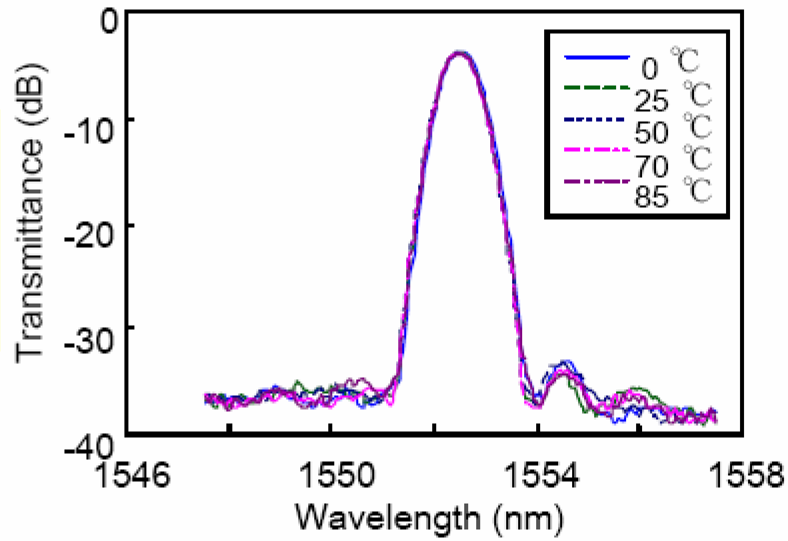
Conventional All-Silica AWG



$$\lambda = \frac{n_c(\lambda)\,\Delta L}{m}$$

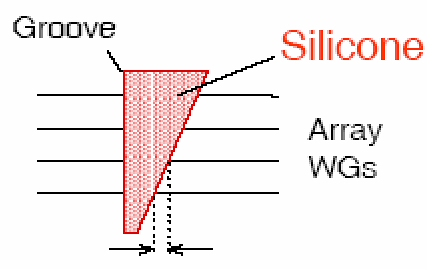
$$\frac{d\lambda}{dT} = \frac{\Delta L}{m} \cdot \frac{dn_c}{dT}$$

Athermal AWG with Silicone



$$n\Delta L = n_c \Delta\ell + \hat{n}_c \Delta\hat{\ell}$$

$$\frac{d(n\Delta L)}{dT} = \frac{dn_c}{dT}\Delta\ell + \frac{d\hat{n}_c}{dT}\Delta\hat{\ell}$$



$$\frac{dn_c}{dT} = 1 \times 10^{-5} \quad (^\circ C^{-1})$$

$$\frac{d\hat{n}_c}{dT} = -37 \times 10^{-5} \quad (^\circ C^{-1})$$

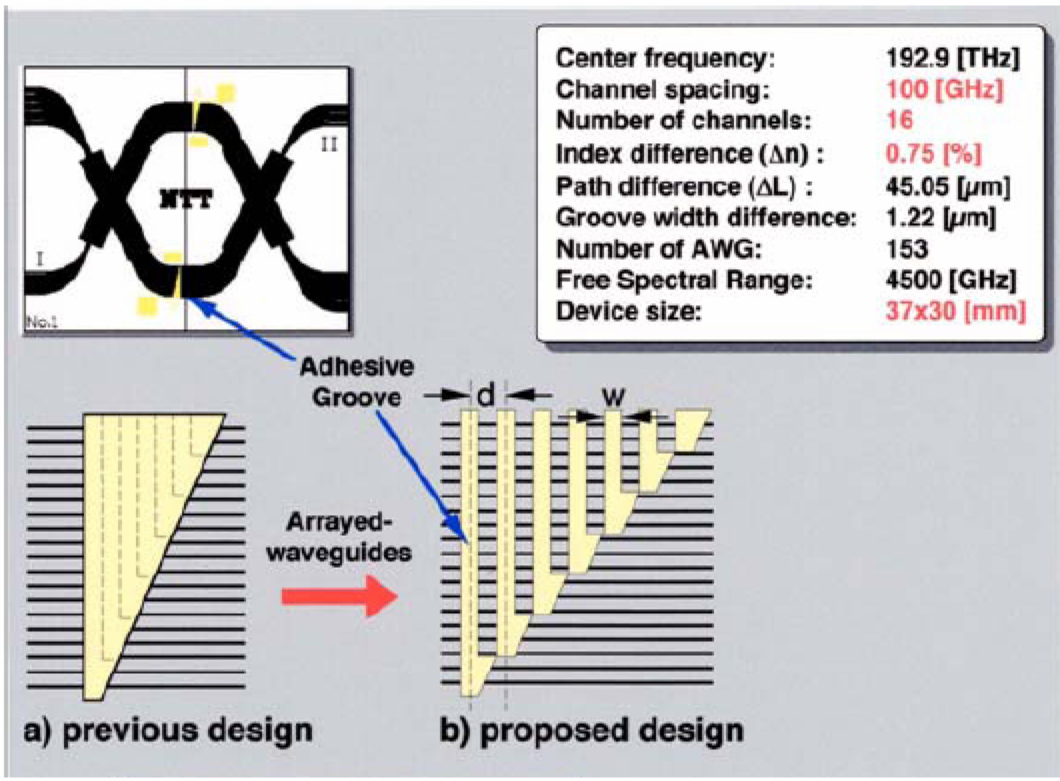
$\Delta\ell$: Path length difference in Silica WG

$\Delta\hat{\ell}$: Path length difference in Silicone

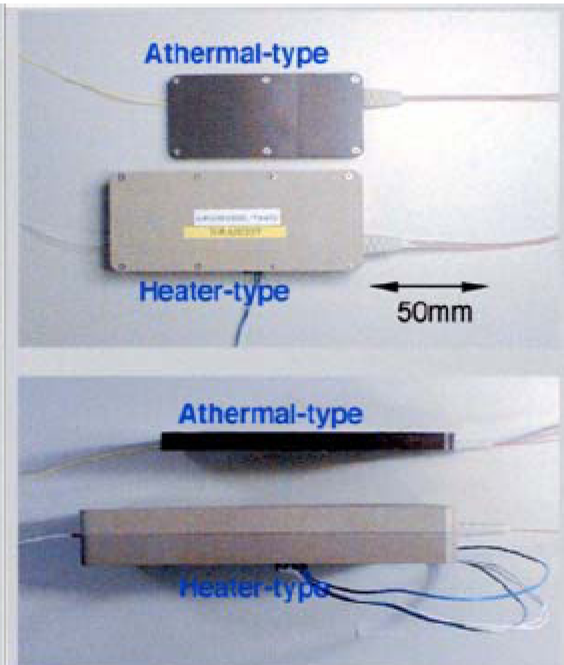
Y. Inoue et al., Electron. Lett., vol. 33, pp.1945-1946, 1997

Athermal AWG

Temperature stability of λ < 20 pm at 0 – 85 °C



Center frequency:	192.9 [THz]
Channel spacing:	100 [GHz]
Number of channels:	16
Index difference (Δn) :	0.75 [%]
Path difference (ΔL) :	45.05 [μm]
Groove width difference:	1.22 [μm]
Number of AWG:	153
Free Spectral Range:	4500 [GHz]
Device size:	37x30 [mm]



Diffraction Loss 6.0 dB ・・・ Single Groove

0.4 dB ・・・ Segmented Grooves

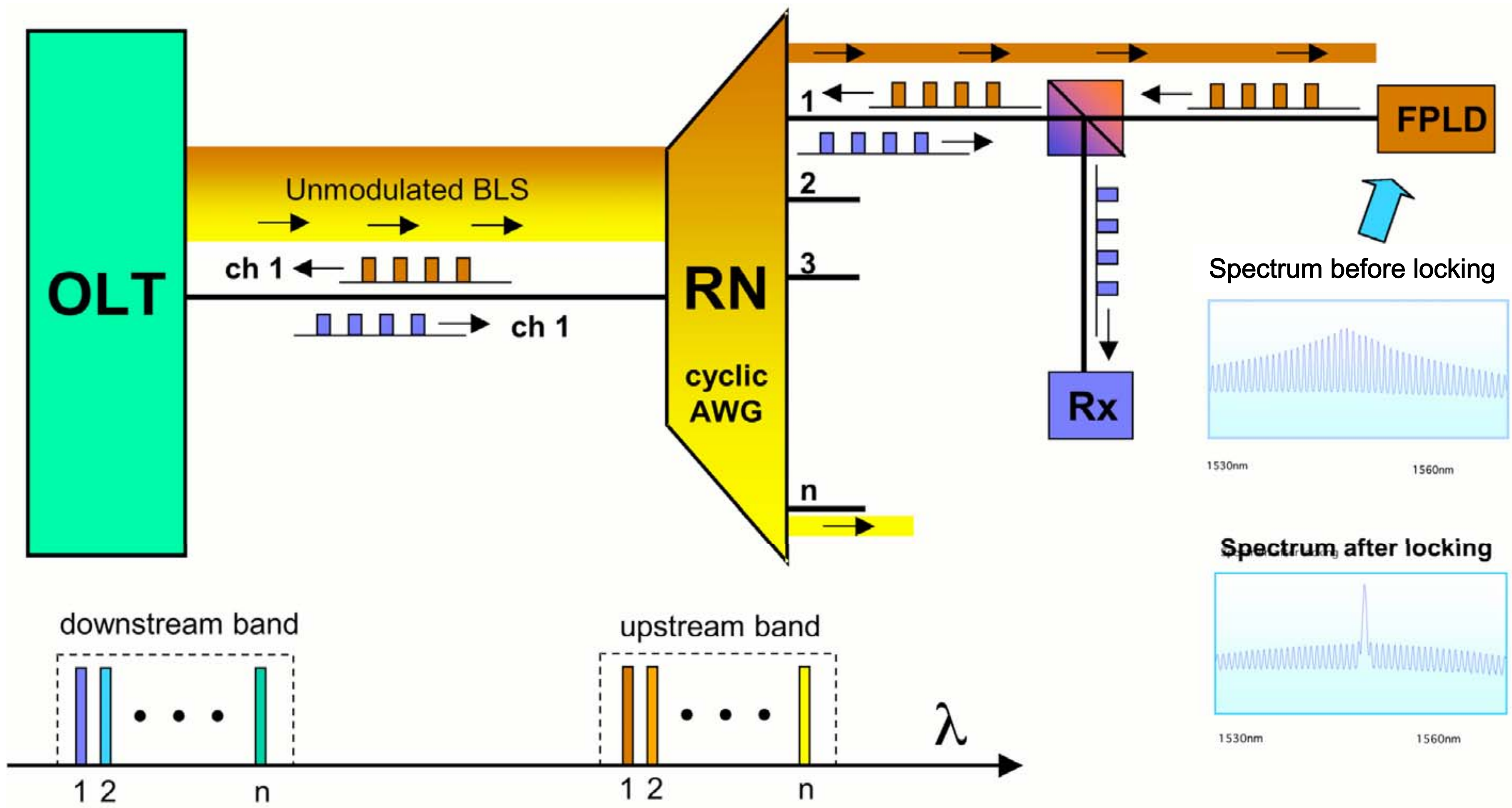
Dimensions

Athermal:	**100x40x7 [mm]**
Heater:	**125x50x25 [mm]**

A. Kaneko et al., Electron. Lett., vol. 36, pp.318-319, 2000.

K.Maru, et al., OFC ’00, March 7-10, WH3, Baltimore, MD

Injection Locking of Upstream Laser



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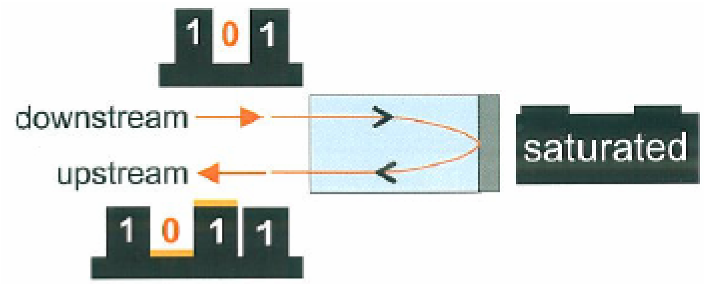
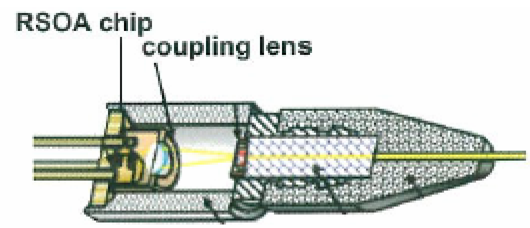
Courtesy: Novera Optics

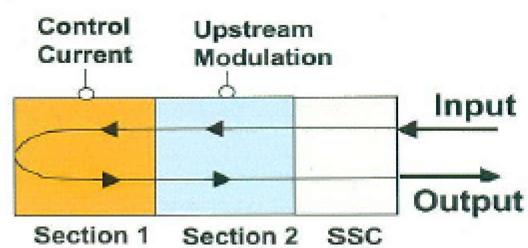
Reflective SOA

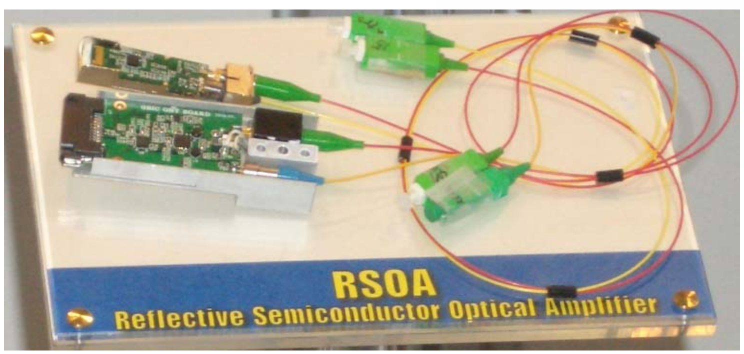


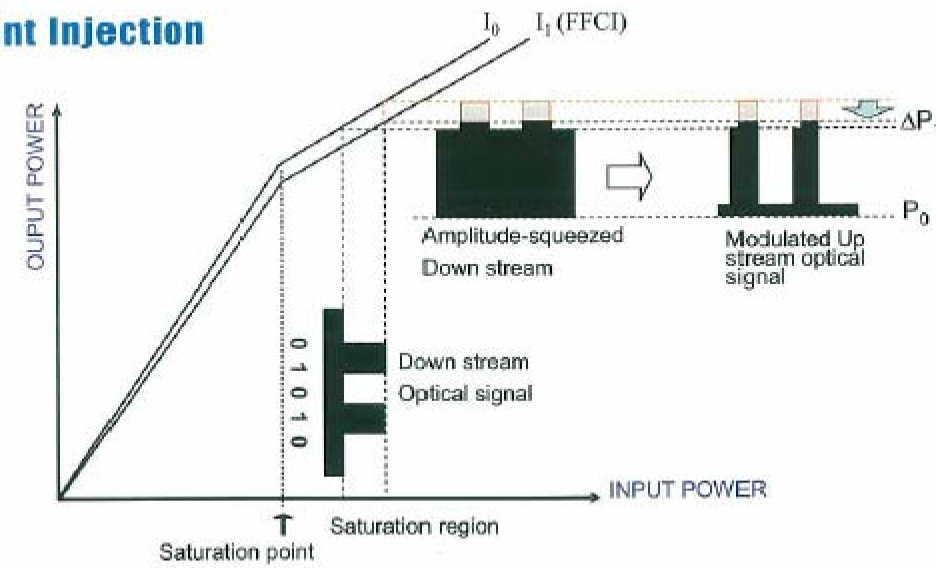


FFCI : Feed-Forward Current Injection

☐ **FFCI into Two-Section RSOA**

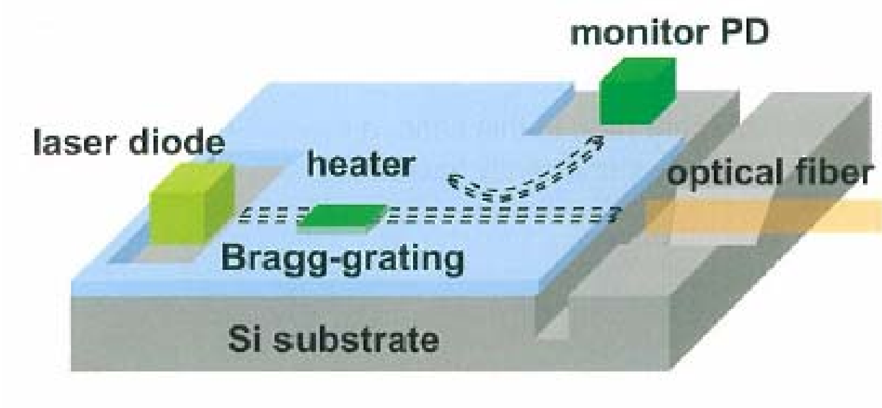


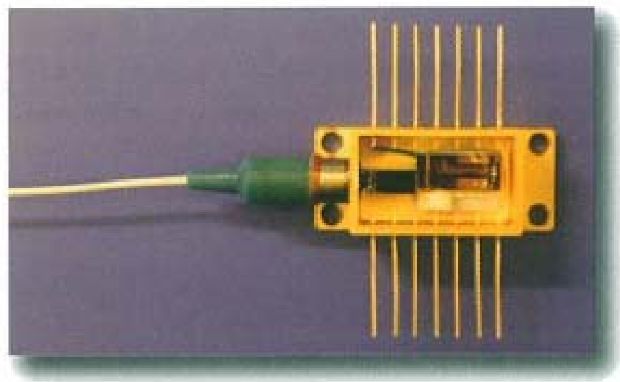


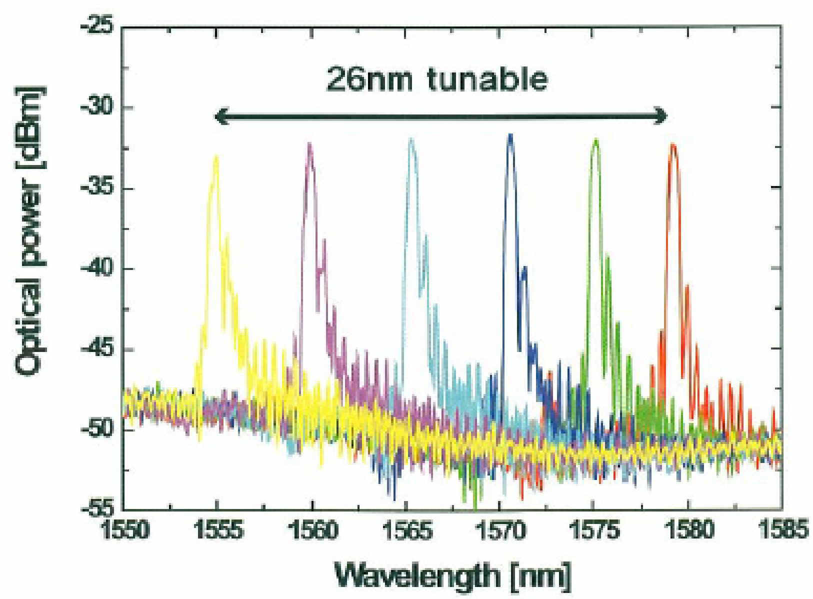


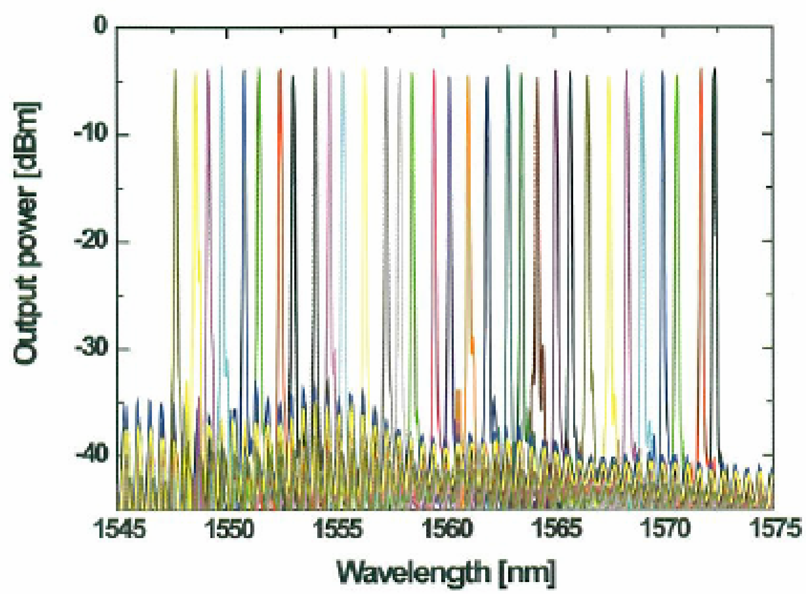
Courtesy of ETRI and Korea Telecom

Planar Lightwave Circuit - ECL





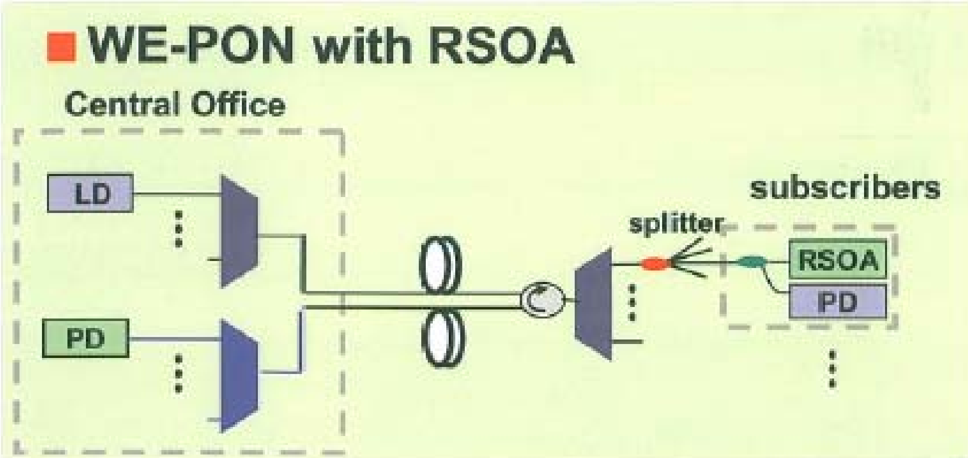




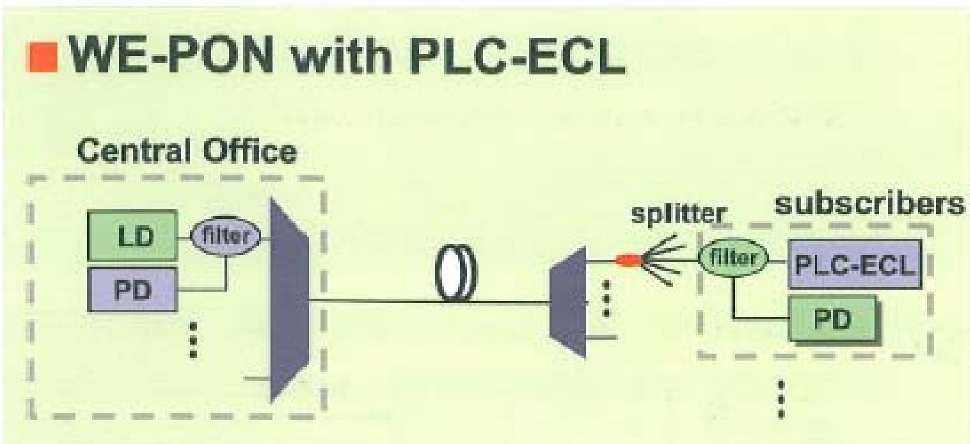
Courtesy of ETRI and Korea Telecom

WE-PON (WDM-E-PON)

~ 1000 users per feeder fiber (32λ x 32 TDM)



- Wavelengths
  - 100~200GHz spacing (16~32 λ's)
  - The same wavelengths for downstream and upstream in C-band
- Optical Tx
  - OLT: Single Mode Light Source or seeded RSOA
  - ONT: RSOA for colorless feature within 35nm
- TDMA (E-PON) Extensions
  - 4 ~ 32 splitting per λ



- Wavelengths
  - C-band, L-band, 100~200GHz spacing (16~32 λ's)
  - C-band for upstream and L-band for down stream
- Optical Tx
  - OLT: Single Mode Light Source
  - ONT: PLC-ECL with 26nm tunable light source
- TDMA (E-PON) Extension
  - 16 ~ 32 splitting per λ

WDM-PON used for metro backhauling

WDM is an efficient way to increase splitting ratio

Courtesy of ETRI and Korea Telecom

Conclusion

- **Demands for bandwidth continue to drive broadband optical access network development**
  - Digital and packetized video becomes the killer application
  - Bandwidth usage pattern is changing, statistical multiplexing no longer holds for new broadband applications (VoD)
- **FTTx – a personal view:**
  - GPON delivers the right FTTH BW for the next a few years.
  - EPON offers the initial cost advantage
- **FTTx development is good for economy**
  - 10GE-PON and WDM-PON developments will create new component industries
- **Don't let our lack of imaginations limit the development of broadband access networks**
  - FTTx research took 20 years to get to today's deployment stage
  - Bandwidth is always good and will finds its applications to benefit human societies.
- **Question: Are there any other better ways to make a PON?**

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Thank you!

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