Photonics Technology for Optical Access Networks

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http://cips.mit.edu
Outline

Key Points from Last Time

Burst-mode transceivers

WDM PON

Korea WDM PON

Photonic Integration in the ONU/OLT

Hardware Costs

Projecting the Future
Broadband access
Reference models

Cable TV companies

- HFC
- 1:1000
- Shared fiber media
- Powered node
- Shared coaxial drops
- 5% optics
- 3 million users/year

Local exchange carriers (LECs)

- FTTC vDSL
- 1:24
- 1:1
- Shared fiber media
- Powered node
- Dedicated wire drops
- 35% optics
- 0.6 million users/year

Municipalities, LECs

- FTTH PON
- 1 x 4
- 1 x 8
- 1:1
- Shared fiber media
- Passive node
- Dedicated fiber drops
- 25% optics
- 0.3 million users/year

Enterprises, LECs

- FSO
- 1:250
- Shared media (air)
- No outside plant
- No drops
- 40% optics
- 1 million users/year
Corning ‘Broadband Access Models’ 2003

- **HFC**
  - Headend electronics
  - Optics
  - Coaxial cable
  - Customer electronics
  - Labor

- **FTTC/vDSL**
  - Headend electronics
  - Headend optics
  - Fiber cable & hardware
  - Cabinet optics
  - Customer modem
  - Cabinet electronics

- **FTTH - PON**
  - Headend electronics
  - Headend optics
  - Fiber cable & hardware
  - Customer optics
  - Customer electronics
  - Labor

- **FSO**
  - Headend electronics
  - Telescope
  - Optics
  - Tracking system
  - Customer electronics
  - Labor

R. E. Wagner
April 22, 2003

Broadband Access Network Options
CPE: Currently, $600 extra for a burst mode laser and a PON driver device. Expected to drop to $200 in the future.

MAN: Currently, $4600 extra for the high power distributed feedback (DFB) laser required to drive the PON at 1550 nm downstream, a burst mode receiver, and control electronics. Expected to drop to $2300 in the future.
Lucent ‘Economics of Fiber to the Home’ 2003

100% Homes Passed Subscribe

AGG—Aggregatore  
AON—Active optical network  
CPE—Customer premises equipment  
DSL—Digital subscriber line  
FTTH—Fiber to the home  
MAN—Metropolitan area network  
PON—Passive optical network  
VDSL—Very high bandwidth DSL
Burst Mode Optics for TDM-PON

Burst mode triplexer
- optics stays the same
- need to change the low-frequency cut-off of all of the stabilization circuits
- need to sense and quickly wake-up receivers and laser drivers

If there is an additional cost associated with burst-mode, it is in the electronics
Burst-Mode Optics for TDM-PON

SCF15530

Lucent (2000)
- 155 Mbps burst mode ICs
  - laser driver IC, US$25
  - receiver IC, US$23
  - clock data recovery IC, US$28

Vitesse (March 2005)
- 2.5 Gbps IC
  - laser driver + limiting amp
  - VSC7965 $2.25

Supports Burst Mode at 155mbps or 622mbps Per G983.1

The burst-mode optics cost has been driven down since 2003
30% of ONU Cost is the optical front end
- Brecht Stubbe, Alcatel, 2002

ONU Cost is approx $100
- OFC/NFOEC 2005 in OPN News
WDM PON Architecture

- **Wavelength division multiple access**
  - High security
  - Unlimited Bandwidth - Higher
  - High link budget - Less power loss than PONs
  - Protocol transparency
  - Medium cost (Low cost source is required)

![Diagram of WDM PON Architecture](image-url)
WDM PON Benefits

<table>
<thead>
<tr>
<th>Access method</th>
<th>TDMA</th>
<th>WDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency (independency)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protocol</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Bit rate</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Collision</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Legacy support</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Graceful upgrade</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Security and privacy</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

TDMA

- N-fold power budget penalties $\Rightarrow$ due to the power splitting approach and the shared OLT source
- OLT and all ONU must work at aggregate bit rate

**Consequences:**
- Limited transmission bit rate
- Complicated TDM/TDMA upgrade

**Concerns about:**
- Privacy $\Rightarrow$ broadcast of the downstream information
- Network integrity $\Rightarrow$ one ONU can corrupt the entire upstream transmission
CWDM: Low Cost WDM

- 4-channel optical CWDM as cheap as $300
  - OMRAM, Japan

ZWPF
- Adds 6 additional low cost optical channels

Full Spectrum Wavelength grid
- ITU G.694.2 (1270 – 1610 nm)

CWDM
- 40% lower cost than DWDM
- Multiple vendor support

• 20 nm channel spacing
• 13 nm channel window
• 7 nm guard band
Comparison of CWDM and DWDM

<table>
<thead>
<tr>
<th>Comparison</th>
<th>CWDM</th>
<th>DWDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels</td>
<td>4-8, up to 18 with special metro fibers</td>
<td>16-32 (metro) and 40-80*</td>
</tr>
<tr>
<td>Bands</td>
<td>O+S+C+L</td>
<td>C+L</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>20 ± 6-7 nm</td>
<td>1.6 and 0.8 nm</td>
</tr>
<tr>
<td>Laser technology</td>
<td>Uncooled DFB</td>
<td>Cooled DFB</td>
</tr>
<tr>
<td>Filter technology</td>
<td>Thin film</td>
<td>Thin film, Grating, AWG</td>
</tr>
<tr>
<td>Channel capacity</td>
<td>&lt;2.5 Gbps</td>
<td>10 Gbps and higher</td>
</tr>
<tr>
<td>Fiber Capacity</td>
<td>10-20G, up to 45 Gbps</td>
<td>400-800 Gbps</td>
</tr>
<tr>
<td>Amplification</td>
<td>Not cost effective, some regen used</td>
<td>EDFA, Raman</td>
</tr>
<tr>
<td>Distance</td>
<td>Less than 80 km</td>
<td>Up to 1500 km and more</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High*</td>
</tr>
</tbody>
</table>

46% cost of DWDM for 8 ch MUX
66% cost of 2.5 Gbps transponder

- Lightwave
Thermal Stability of CWDM ‘Splitter’

Temperature dependence dominated by alignment of microoptics.

Statistical TDL data for different channels of CWDM devices.

Lightwave March, 2005
Athermal DWDM ‘Splitter’

Silica waveguide + polymer for thermal compensation

Temperature dependence dominated by change of index

Temperature stability < 30 pm at 0-60 °C
Free Spectral Range of DWDM ‘Splitters’

Two-colors can be routed along the same path by virtue of the periodicity of the wavelength response for an AWG.
Wavelength Independent ONU

TDM for Upstream/Downstream

Single fiber for upstream/downstream

No laser at ONU

Provisioning and stabilization all at OLT
Takes advantage of periodicity of AWG type optical MUX
Wavelength Independent ONU
WDM for Upstream/Downstream

Simultaneous multicast and unicast transmission…

Fig. 1. Network Topology
Wavelength Independent ONU
Injection Locked Fabry-Perot Laser
Wavelength Independent ONU
Injection Locked Fabry-Perot Laser

- FP-LD automatically emits at correct $\lambda$
- Can employ DWDM multiplexer without detuning loss
- Separate upstream/downstream using circulator (moderately expensive)
A hybrid WDM/TDM-PON serving 128 subscribers at the data rates of 1.25-Gb/s downstream and 622-Mb/s upstream is presented. It has 16 100-GHz-spaced WDM channels, each of which is shared by eight subscribers in TDM. With the ASE injection of about $-15$ and $-2$ dBm provided from the 20-dBm BLS for the upstream and downstream transmissions, respectively, the single TO-packaged uncooled FP-LD presents reliable transmissions over the temperature range from 0 to 60 °C in any wavelength channel without wavelength tuning. The
### BcN Roadmap

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Service</strong></td>
<td>Broadband Internet access, VDSL, Ntopia, Metro-Ethernet</td>
<td>Broadband access (100Mbps), Digital broadcasting (MPEG-2), Convergence service of video, &amp; data, Audio</td>
<td>Broadband access (Gbps), HDTV broadcasting, Convergence of telecommunication and broadcasting, High quality Internet broadcasting</td>
</tr>
<tr>
<td><strong>Access Network</strong></td>
<td><strong>ADSL / FTTC+ADSL</strong></td>
<td><strong>FTTC+VDSL / FTTH</strong></td>
<td><strong>WDM-PON</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FTTC+VDSL / FTTP</strong></td>
<td><strong>Ethernet PON</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>HDSL/SDSL</strong></td>
<td><strong>WDM-PON</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Metro Core &amp; Backbone</strong></td>
<td><strong>Metro-Ethernet (GbE)</strong></td>
<td><strong>10GbE</strong></td>
<td><strong>QoS enabled Integrated IP network</strong></td>
</tr>
<tr>
<td></td>
<td><strong>ATM</strong></td>
<td><strong>MPLS</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Promotion</strong></td>
<td>FITL (Fiber In The Loop) on MTU / MDU, Promotion of VDSL</td>
<td>FTTC to residential area, Launching FTTH</td>
<td>Promotion of FTTH</td>
</tr>
</tbody>
</table>

Source: Ministry of Information and Communication Republic of Korea
KT plans to install WDM-PON infrastructure by August this year in its first phase, procuring WDM-PON equipment of Novera Optics that can accommodate 42,000 circuits, worth approximately $13.6 million.

- Friday, March 25, 2005
Korea Telecom WDM PON

- 16 wavelengths
- 20 km
- 125 Mbps bidirectional

No power to the remote node (WDM splitter)

Wavelength independent ONU

24 ethernet ports per ONU
Korea NovaPON

- Based on Wavelength locked FP lasers
- One wavelength per each subscriber
- High security and privacy
- Unlimited Bandwidth
- Protocol transparency
- Legacy support

TPS (triple play service)
- Ready IP Technology
30% of ONU Cost is the optical front end
   - Brecht Stubbe, Alcatel, 2002

ONU Cost is approx $100
   - OFC/NFOEC 2005 in OPN News
Optically Integrated Triplexers

Radical Solutions: Multiwavelength Sources

Simultaneous NRZ Pulse train for 20 channels from ps mode-locked laser

Pulses carved in the wavelength domain...

Only for DWDM requires power to the field
The MIT/CTR Optoelectronics Fabrication Model

- Mimics production from bare substrate through assembly, packaging, and final test
- Provides full flexibility in building a process flow
- Captures effect of process derived yields at testing

Currently 46 Process Modules Available

- Surface Treatment
  - Etch
  - Thermal
  - Backend Assembly
- Growth/Deposition
  - Lithography
  - Test
  - Backend Packaging
Process Modules Building Blocks in Product Flow

Clean

Incoming Inspect

Laser MQW
LP-MOVPE (3x)
PL Test

PECVD SiNx
Lithography
Plasma Etch SiNx
Asher

Vis. Inspect.

Bake

Alignment

Test

Lidding, Lead check

Clean

Fiber w. Grin
Lens Attach

Sleeve attach

Test

Temperature cycle

SiO2 Wet Etch

PL Test

PL-MOVPE (3x)
Modulator MQW

Auto. Inspect.

Test

Bench Attach

Bench Assembly
Package Assembly

Test

Burn-In

Wirebond

Test

Cure

Chip Bond

Laser on Carrier

n-InP Cladding

Epi Overgrowth

Wafer Cleaving

Laser MQW
LP-MOVPE
PL Test

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PL Test

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Lithography
Plasma Etch SiNx
Asher

Vis. Inspect.
Cost Modeling Benefits to Roadmapping

1. Provides a generic platform to discuss the cost of process and product developments

2. Quantifies impact of future scale growth

3. Identifies key cost drivers

4. Quantifies necessary process performance hurdles
Quantifying Cost-Sensitivity to Scale
Models Derive Cost from Projected Optimal Fab Line

(Monolithically Integrated Device)
Cost Modeling Benefits to Roadmapping

1. Provides a generic platform to discuss the cost of process and product developments

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Identifying Key Cost Drivers
Models Provide Unequaled Resolution

(Monolithically Integrated Laser-Modulator)

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit Cost (USD)</th>
<th>Other Fixed %</th>
<th>Equipment %</th>
<th>Other Var %</th>
<th>Material %</th>
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<td>Assembly Test</td>
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<td>26</td>
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<tr>
<td>Front-to-Back</td>
<td>$60</td>
<td>35</td>
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<tr>
<td>Chip Bond</td>
<td>$40</td>
<td>35</td>
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<tr>
<td>Fiber Attach</td>
<td>$20</td>
<td>35</td>
<td>26</td>
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<td>15</td>
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<tr>
<td>Bench Assembly</td>
<td></td>
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<tr>
<td>Spin-On Resist</td>
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<tr>
<td>Visual Test</td>
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<tr>
<td>Bench Attach</td>
<td></td>
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<td></td>
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<tr>
<td>Wirebond</td>
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</tbody>
</table>

(APV 30,000)
Identifying Opportunities for Improvement: Unit Cost Elasticity to Yield

- Yield is key issue for optoelectronics manufacturing cost
- What processes provide the most leverage?
  - Position in flow
  - Embedded yield
- Cost elasticity to yield
  - Identifies process yield impact on aggregate cost

(Monolithically Integrated Device)
Cost Modeling Benefits to Roadmapping

1. Provides a generic platform to discuss the cost of process and product developments

2. Quantifies impact of future scale growth

3. Identifies cost drivers

4. Quantifies necessary process performance hurdles
Cost Sensitivity to Final Test Yield

(Monolithically Integrated Laser-Modulator)
Phase II: Optoelectronics Subassembly Model

• Initial model development case:
  – 2.5G VSCEL and FP optical subassemblies

• Current work:
  – 10G DFB and 10G DWDM optical subassembly

• Upcoming work: Benefits of integration
Cost Modeling Benefits to Roadmapping

1. Provides a generic platform to discuss the cost of process and product developments
2. Quantifies impact of future scale growth
3. Identifies key cost drivers
4. Quantifies necessary process performance hurdles
How do TOSA/ROSA design & assembly choices effect production cost?

Are the cost-optimal development paths different if producing in the U.S. vs. low-wage environments in Asia?
Preliminary Results: Sensitivity to Scale

(Low-Wage Production Environment)
Preliminary Results: Cost Breakdown

(Low-Wage Production Environment)
Early Estimates: U.S. Production

LW FP – VCSEL Crossover?

Unit Cost (USD)

Annual Production Volume

- 2.5G LW FP TOSA
- 2.5 VCSEL
- 10G FP TOSA
Early Estimates: U.S. vs. Asia Production

LW FP – VSCEL Crossover?

Unit Cost (USD)

Annual Production Volume

- 2.5G LW FP TOSA (Asia)
- 2.5 VCSEL (Asia)
- 2.5G LW FP TOSA (US)
- 2.5 VCSEL (US)
Early Estimates: U.S. Cost Breakdown

(Labor Dominant in the 2.5G and 10G FP TOSAs)
Process Based Cost Modeling for Access Technology

Dicrete Diplexer

- WDM beam splitter
- Glass lens
- Fiber
- TO-detector

Monolithic Diplexer

- 1,310 nm FP Laser
- MPD
- 14xx nm PD

How does price scale for 1M parts?

Manufacturing cost for various designs?
Developing a Roadmap for PON
Architectures and Components

100 km at 10 Gbps  
20 km at 2.5 Gbps

Dramatically different photonic components…external vs. direct modulation, etc.

Dramatically different architectures

Dramatically different network economics
Developing a Roadmap for PON
Architectures and Components

![Bar graph showing subscriber coverage at different distances (75%, 80%, 85%, 95%, 99%) for Verizon, SBC, and Bellsouth. The graph indicates that 20 KM CO to subscriber covers approximately 99% of subscribers.]

Source: “Customer Distance From CO Report and Telco Operator Service Requirements For PON Architectures” (ford_1_1101.pdf presented to IEEE 802.3ah), and Verizon. 99% distance is OFS estimate.
Developing a Roadmap for PON
Architectures and Components

Access/backhaul integration step 1

Tier 1 Exchange

Local Exchange (RCU)

super PON

2.5 or 10 Gb/s

Reach of ~100 km

optical amp

Customers

512x Split

British Telecom 21st Century Network ($19b)
Developing a Roadmap for PON
Architectures and Components