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Project OART - WDM, EDFAs and Mixed Data Rates in a Real-World Testbed

Lee Thombley
Keith Hugenberg
Daren Sweider
Rodrigo Arce

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Lee Thombley
Keith Hugenberg
Daren Sweider

Lawrence Livermore National Laboratory
Livermore, CA 94551
(510) 423-2586
FAX (510) 423-8534

Rod Arce

Pacific Bell
San Ramon, CA 94583
(510) 823-5456
FAX (510) 867-2998

1. Introduction

Pacific Bell, Lawrence Livermore National Laboratory (LLNL), and the University of California at Berkeley have established a joint fiber testbed located in the San Francisco Bay Area. (Slide 1) The fiber to be used in the trial is representative of Pacific Bell's current fiber plant. This ongoing project is a year long collaboration involving the wavelength division multiplexing (WDM) of data and video on a link using erbium doped fiber amplifiers (EDFA). Designated Project OART, for Optical Amplifier Reliability Trial, this project will provide the Network Technology District of Pacific Bell a valuable testbed for gathering information and experience with future network designs that will use WDM, EDFA's, and the simultaneous transmission of high-speed digital and video information. LLNL's interest in this link is driven by a need to evaluate various future means of interconnecting high performance users with high performance storage and computation sites over remote connections.

The OART link will consist of a four channel WDM system on a pair of fibers over a link amplified by two pairs of EDFAs. Three wavelengths will be data communication channels transmitted between LLNL in Livermore and UCB in Berkeley at a distance of 98 km. A fourth channel of video will be carried from a Pacific Bell test facility in Concord on 73 km of fiber to a video lab at LLNL. (Slide 6)

2. Data Communication and Video Transport

The three high-speed data channels to be transmitted over the link will consist of 266 Mb/s Fibre Channel, 622 Mb/s ATM, and 1 Gb/s Fibre Channel. LLNL is currently serving as a Fibre Channel testbed site investigating among other things, long distance connection of Fibre Channel sites, Fibre Channel over SONET using FC/SONET adapters, and Fibre Channel over ATM using FC/ATM adapters/gateways. The fourth wavelength will be used to evaluate AM-VSB and digital video transmission on a long haul link. System performance issues of video transmitted through the link will be assessed relative to power levels through the EDFA's, connector issues, crosstalk, etc. (Slide 7).

The four wavelength demonstration will be a phased implementation over the course of the year (Slide 8). The first phase of the link will carry

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demonstration traffic at 622 Mb/s connecting two switch nodes on the eXperimental University NETwork (XUNET-II). XUNET is an ATM network used by university researchers and students to test various data communications protocols. Phase II-A will follow very closely with Phase I and will be the addition of the 266 Mb/s Fibre Channel. Fibre Channel is being positioned predominantly as a high bandwidth peripheral interconnection standard, with some additional support as a campus datacom network interconnection standard. The Advanced Telecommunications Program at LLNL believes there will be a niche for super performance applications interconnecting two remotely located Fibre Channel nodes. Phase II-B adds video and will be completed in two parts. Namely, the first part will be the transport of digital video only with the data channels, and part two will test the prospect of sending AM-VSB video only with the data channels. Although many of the system issues for these tests have been well documented in the literature, there is a desire from Pacific Bell's perspective to gain experience and knowledge related to the fielding of this technology. Finally, the last phase will add a 1 Gb/s Fibre Channel to the system.

3. Link Description

The fiber optic components that will be used for the OART link are shown in Slides 9 & 10. The DFB lasers we selected for the data channels have output powers around 0 to +2 dBm with the tentative wavelengths of 1533, 1541, and 1548 nm. They will be followed by isolators with isolation > 50 dB. In order to provide a long haul laser transceiver interface compatible with short haul Fibre Channel (typically 780-850 nm) transceivers and XUNET (1310 nm) intermediate transceivers, a wavelength translation chassis was designed. (Slide 12) The long haul PIN photodiode receivers have sensitivities of –34 dBm at 266 Mb/s and –30 dBm at 622 Mb/s. A clock resynchronization circuit is included in this chassis on the receiver.

Because the intent of the trial was to provide the most flexible testbed for laser wavelength selections, we decided to perform the WDM/WDDM functions using passive couplers with tunable fiber Fabry-Perot (FFP) filters (Slides 13 & 14). In addition, the FFP filters will provide us with excellent suppression of the amplifier spontaneous emission (ASE) from the EDFA's due to their availability in very narrow bandwidths. In anticipation of higher bit rates in the future, the bandwidths we are using are 40 GHz. The free spectral range we chose is > 40 nm in order to avoid transmitting multiple wavelengths inside the usable EDFA spectrum from the same filter. Finally, the FFP can be locked to the wavelength of interest using a phase lock loop (PLL) feedback controller to help track any laser spectral drifts.

In order to provide a sufficient power budget margin to adequately study the relative power level difference effects on the high-speed data channels and the simultaneous transmission of AM-VSB video, the decision was made to use two EDFA's on each fiber going from LLNL to UCB. This was primarily because of the much more stringent performance requirements of transmitting AM-VSB video over long distances. However, in addition we wanted to allow for higher than average (Biconic) connector losses, dispersion compensation experiments and longer link tests. A comprehensive survey of domestically available erbium doped fiber amplifiers was made by LLNL in mid-1993. Two pairs of amplifiers were subsequently purchased: a high power (+21 dBm) laboratory model to be located at Livermore and Berkeley, and a 12.5 dBm central office compatible system that could be installed anywhere along the link. The measured gain plot of the 12.5 dBm EDFA is shown in Slide 15.

4. Laboratory Demonstrations

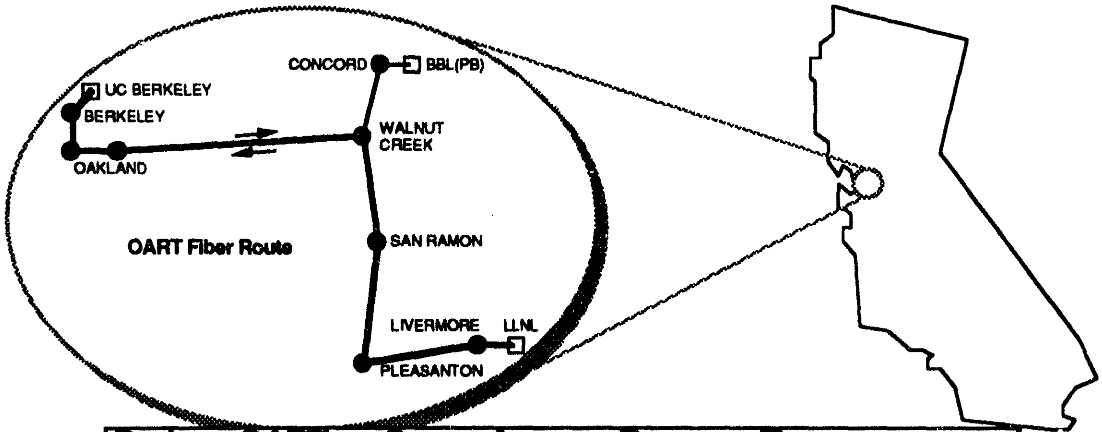
A high-speed fiber-optic laboratory at LLNL has been created to be able to showcase and test numerous kinds of telecommunication hardware and software. For the OART project, we used the laboratory to evaluate the wavelength converters built at LLNL (Slide 12), along with the other fiber optic components purchased from vendors. Two single channel link tests were performed in the lab to test the XUNET ATM and Fibre Channel data link cards and protocol adapters. In the XUNET test, the 622 Mb/s XUNET TAXI link was looped back through 100 km of fiber using one EDFA and successfully operated for several hours. In the Fibre Channel test, two 266 Mb/s Fibre Channel adapters communicated successfully over the same 100 km link with no detected transmission errors.

Two configurations of a two channel WDM were evaluated for qualitative performance. (Slide 17) The 12.5 dBm EDFA was used as a power amplifier in the first configuration, and as a preamplifier in the second configuration. The DFB lasers operated at 1533 and 1541 nm. The spliced and connectorized 100 km fiber link had a measured loss of - 24.7 dB. As these are data communication channels, the bit error rate (BER) performance we are trying to achieve is $< 10^{-12}$. In the power amp configuration using the 12.5 dBm EDFA, the measured power margins were 3.9 dB for the 1533 nm channel and 3.3 dB for the 1541 nm channel. In the preamp configuration, the measured power margins were 26.1 dB and 19 dB for the 1533 and 1541 nm, respectively. The DFB lasers were directly modulated by a 622 Mb/s pseudo random bit stream (PRBS). The resulting eye diagram for the 1533 nm channel in the preamp configuration is shown in Slide 17. As you would expect from the very large power margin, the eye is very open.

5. Project Status

The anticipated fielding date for the first two channels of the link is June 1994. The test will continue for one year from the first fielding date. The video overlay design effort is expected to begin in early fall 1994 with fielding expected in the first quarter of 1995. The fourth data channel is expected to be fielded in the first quarter of 1995. We are also considering a short term test using borrowed OC-48 SONET terminals which will allow us to evaluate our OC-12 Fibre Channel/SONET adapters.

OART is a joint Pacific Bell / LLNL / UCB Project



Project OART — Optical Amplifier Reliability Trial

A field trial of fiber amplifiers in a 100 km fiber optic data link between Lawrence Livermore National Laboratory and the University of California at Berkeley. Wavelength division multiplexing will be used to simultaneously transport data at Fibre Channel rates of 266 Mbit/sec & 1.062 Gbit/sec and XUNET ATM at 622 Mbit/sec.

Video will be tested on a fourth channel over a 73 km segment between Pacific Bell's Concord Broadband Test Facility and LLNL.

This project will produce an infrastructure used to evaluate Gb/s applications over Wide Area Networks

- **Test/evaluation of erbium doped fiber amplifiers (EDFAs) in long haul data links**
- **Test/evaluation of wavelength division multiplexing**
- **100 Km high speed data link connecting LLNL and UCB over borrowed fiber pair.**
- **73 km subsection to be used for video demo between Concord and LLNL**
- **Demonstration/evaluation of emerging network standards in a long link environment**
  - **622 Mbps ATM (XUNET) Demonstration**
  - **266 Mbps Fibre Channel Demonstration**
  - **1062 Mbps Fibre Channel Demonstration**

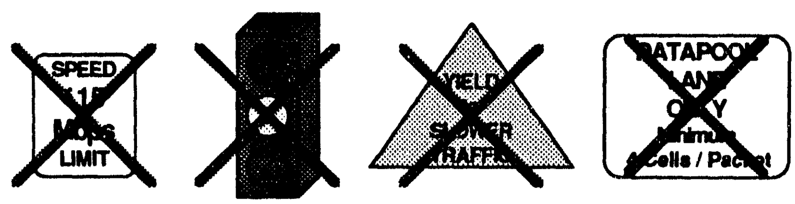
Mixed data rates/formats plus a video overlay make this an interesting project

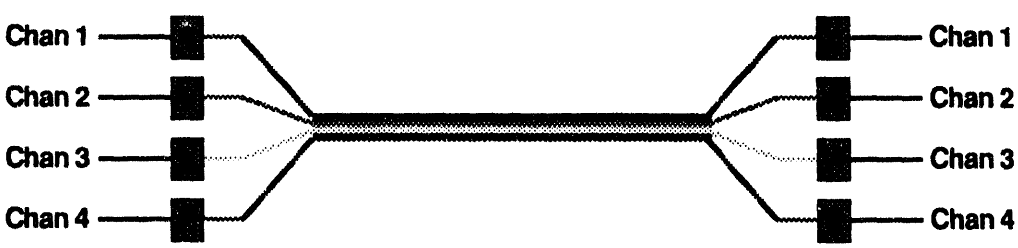
- LLNL is investigating the interconnection of remotely connected Fibre Channel sites:
  - Direct Fibre Channel interconnect over a long haul link; e.g. the OART link.
  - Fibre Channel over SONET using FC/SONET transport adapters.
  - Fibre Channel via ATM using FC/ATM adapters/gateways.

- The video overlay makes this WDM testbed much more interesting and challenging.

- The definition of the video overlay format is now in the early planning stage, but the preliminary proposal is for a two step comparison trial:
  - Analog VSB video [possibly 40-75 channels]
    then followed by
  - Digital video [channel count and format TBD].

Project OART provides a transparent 100 km path for four independent data channels





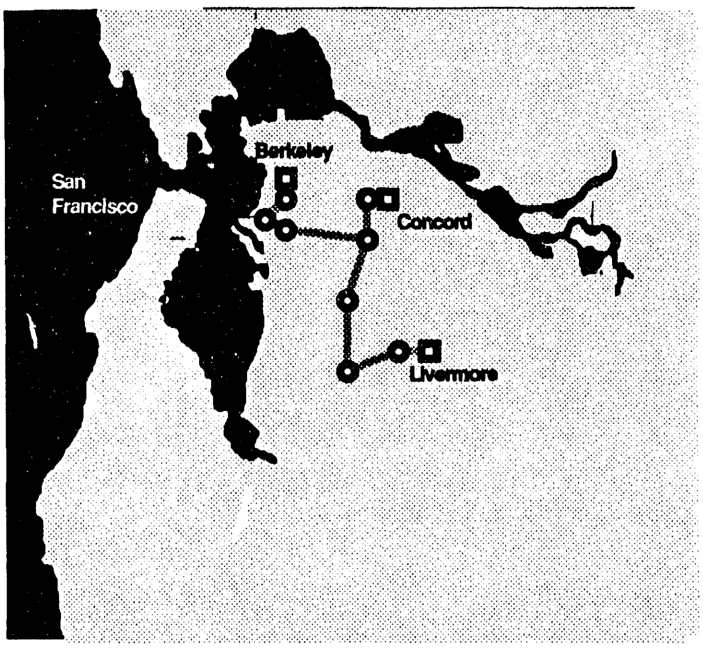
A Memorandum of Agreement has been signed between Pacific Bell, LLNL and UC-Berkeley.

> ☞ ***Lawrence Livermore National Laboratory, the University of California at Berkeley, and Pacific Bell have signed a Memorandum of Agreement to test the use of fiber amplifiers in long haul data links***

- What we've said we'll do
  - PacBell provides fiber pair
  - LLNL provides link design, fiber amps and optical terminals
  - LLNL provides access to one channel for video demo
- What we get out of it
  - PacBell gets experience with fiber amps
  - LLNL gets infrastructure to do high speed MAN research
  - UCB gets research access to high speed network
- One year term of demonstration
  - Possible extension

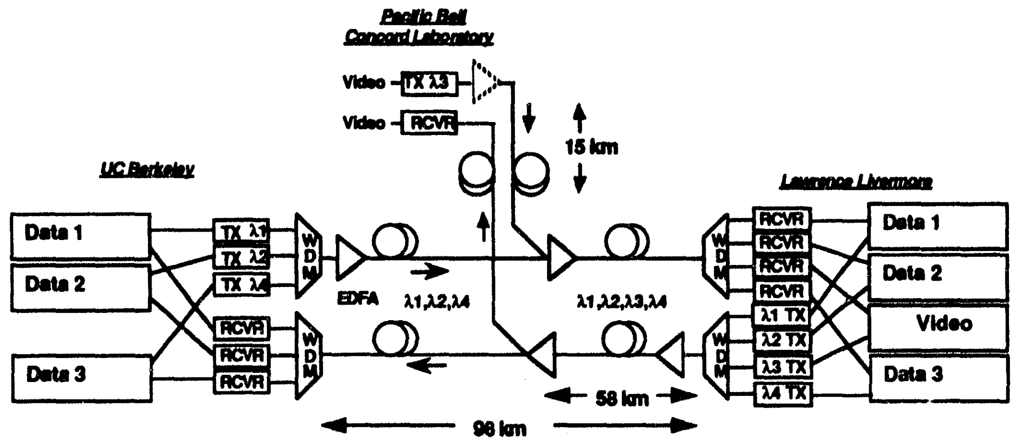
OART Regional Map

- Two fibers from UCB to LLNL — 100 km.
- Two fibers from Concord to Walnut Creek CO will be "muxed" onto UCB to LLNL line to allow video overlay — 73 km total.
- Fiber is non-dispersion shifted.
- The OART fiber route transits 8 Pacific Bell central offices.
- Livermore terminal end is in LLNL's central office (B256).
- Berkeley terminal end is in Evans Hall (Dept of CS).
- Concord terminal end is in the Pacific Bell Broadband Laboratory.



The Fully Implemented OART Link Will Carry Four Wavelength Division Multiplexed channels

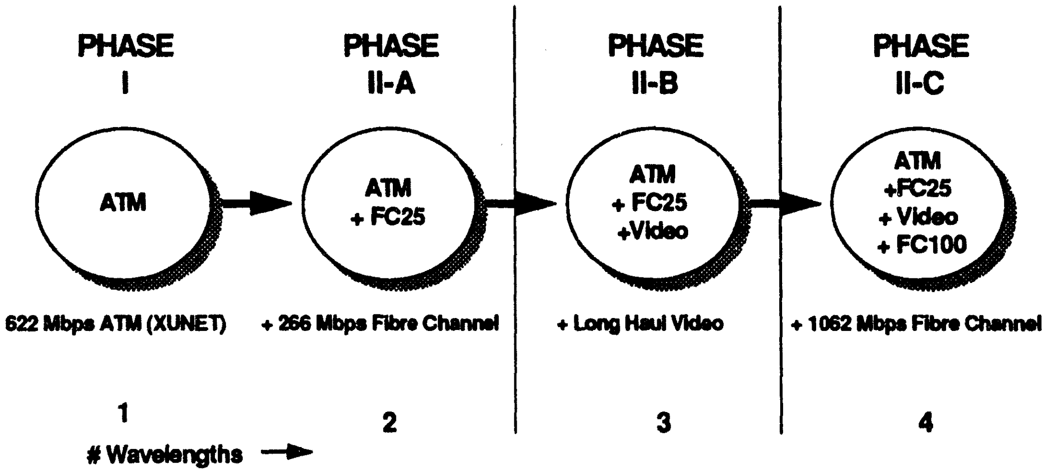
- The project will be implemented in four phases, with the performance of the link analyzed after each phase.
- Two of the EDFAs will be moved to a Pacific Bell central office after Phase IIA to accommodate the increased power budget requirements of video transmission and a fourth data channel.



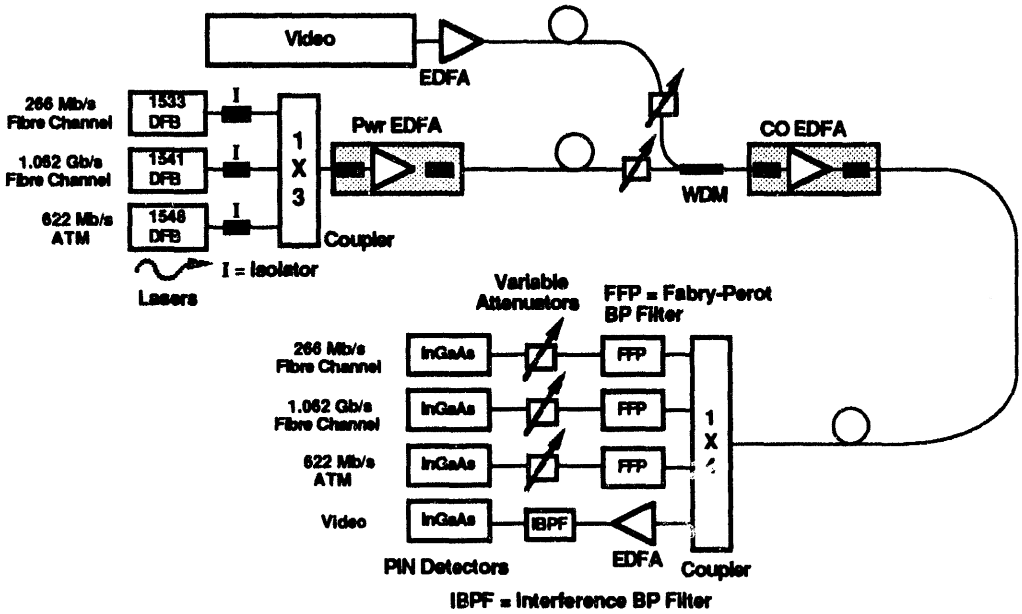
WDM — Wavelength Division Multiplexer/Demultiplexer
EDFA — Erbium Doped Fiber Amplifier

Multi-Wavelength Migration Path

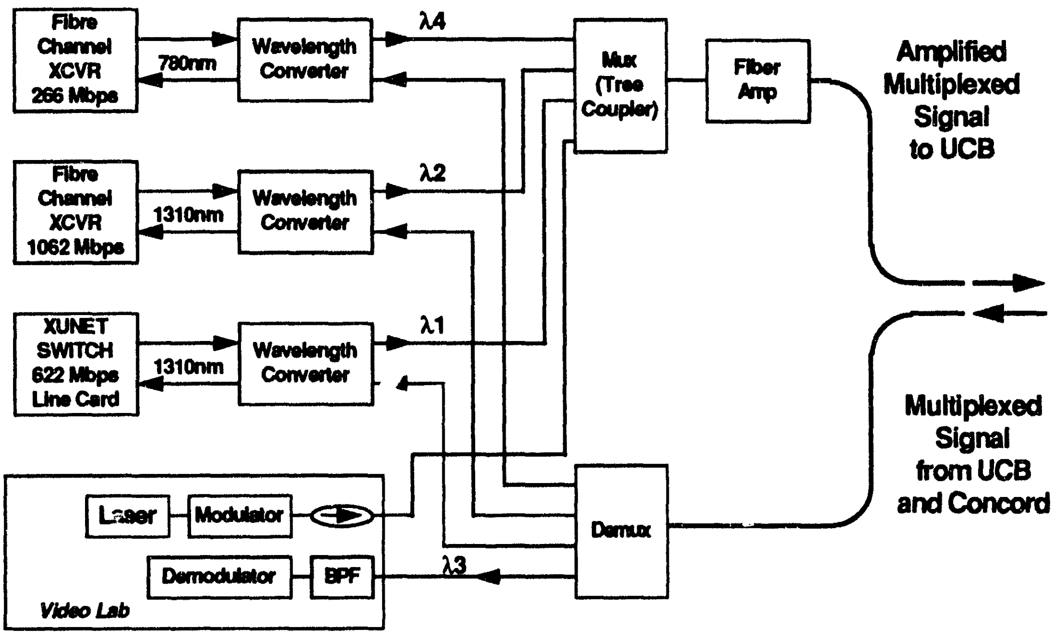
- The OART fiber link will evolve from a single wavelength to multiple wavelengths at various data rates.



Block Diagram of the Fiber Optic Link Components



LLNL OART Terminal — Block Diagram

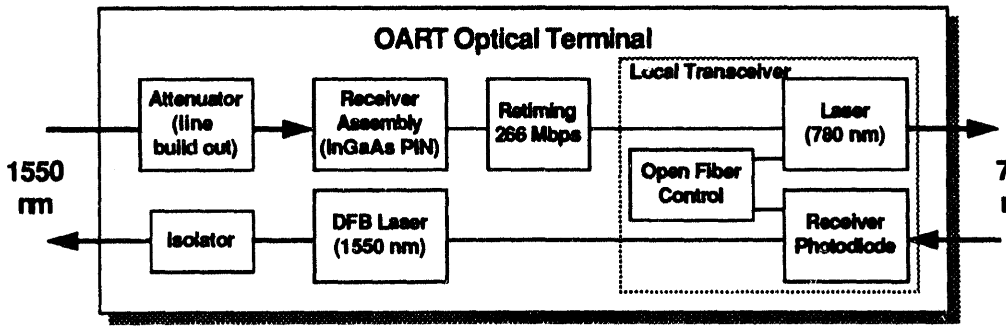


OART Transceiver Design — Wavelength Conversion

- Offers the most flexibility for system integration with current communication boards (ie. Fibre channel, XUNET line cards, etc.)
- Summary of Lasers/Receivers
  - DFB (Distributed Feedback) lasers were selected over FP (Fabry-Perot lasers)
    - » Less noise: better link performance
    - » Required for long links due to dispersion (much narrower linewidths)
    - » Will use wavelengths of 1533, 1541, 1549, 1557 nm
  - » Receivers have sensitivities of –34 dBm @ 266 Mb/s and –30 dBm @ 622 Mb/s

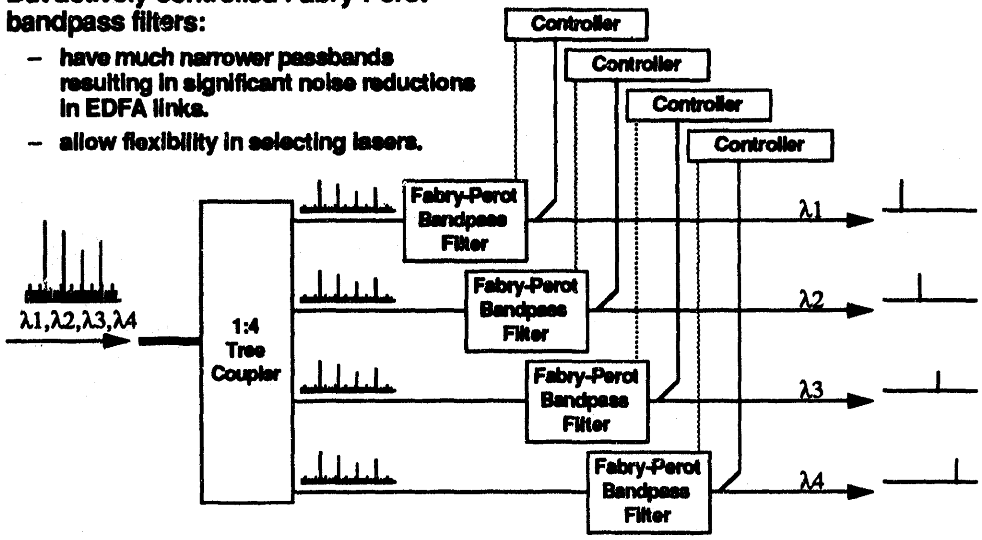
OART Wavelength Translator Chassis

- OART Wavelength translator costs ~ $12 - 15 K each.
- Standard 1.5µm DFB Laser is used.
- Retiming is optional.
  - Uses SAW filter rather than PLL.
- Optical filter is included in WDDM.
- Modification to support 1310nm:1550nm conversion is simple changeout of local transceiver card.

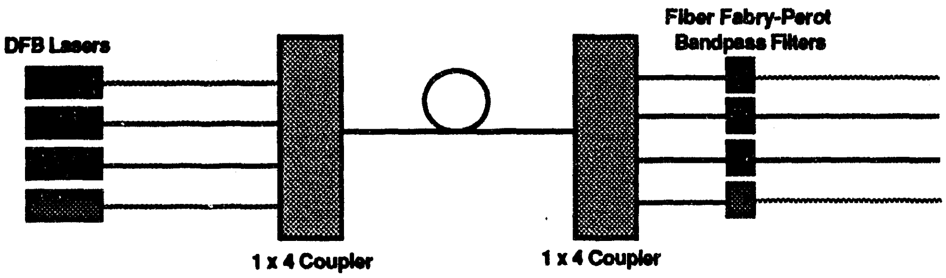


Wavelength Division Demultiplexing is done using couplers and fiber Fabry-Perot filters

- **WDDM using couplers and filters is lossier than thin film demultiplexers**
  - 10-11 dB loss for C&F
  - 6.0 dB loss for thin film (incl. BPF)
- **But actively-controlled Fabry-Perot bandpass filters:**
  - have much narrower passbands resulting in significant noise reductions in EDFA links.
  - allow flexibility in selecting lasers.



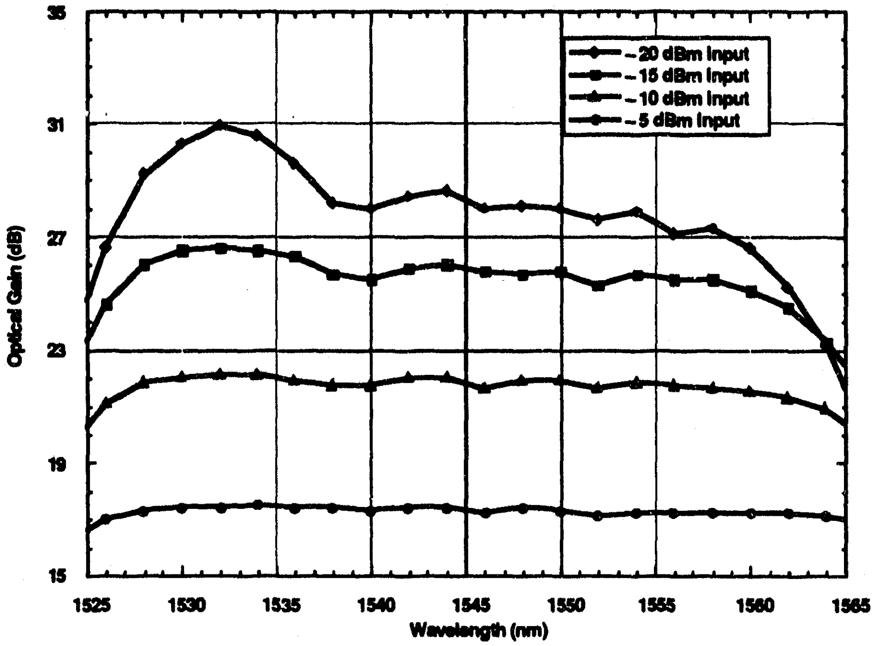
Link Design for Wavelength Division Multiplexing



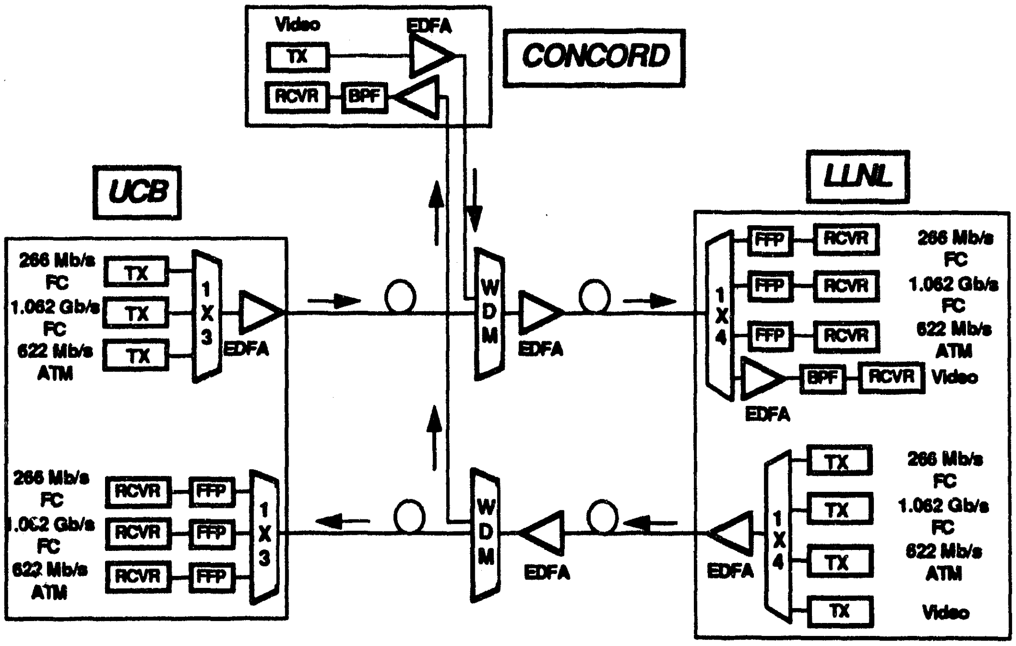
Couplers and FFP Filters for Mux/Demux of Multiple Wavelengths:

- Couplers were selected over gratings for the mux/demux of the wavelengths because they are cheaper, more robust, and they provide the system with the most flexibility for source selection
- FFP Filters were selected for channel demultiplexing because they have:
  - Narrow bandwidths which are important for the reduction of noise from the EDFA
  - Feedback circuitry with phase locked loop control that will track any wavelength drift
  - Tunability over the entire "usable" EDFA wavelength spectrum – allows for any laser wavelength to be used as a source

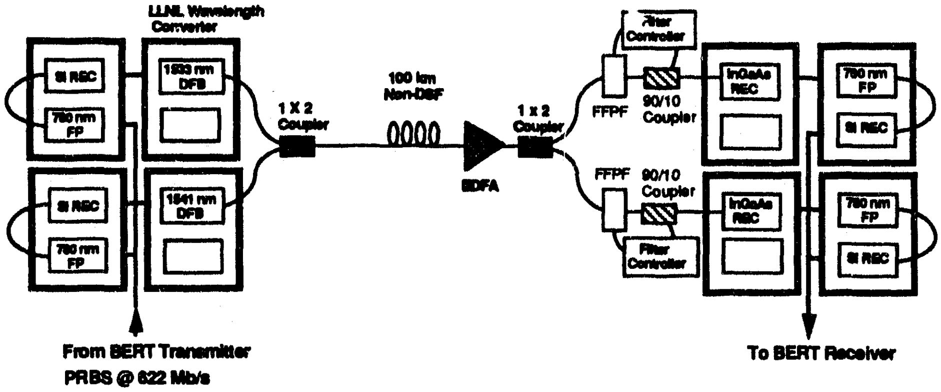
Measured Gain Plot of the 12.5 dBm EDFA



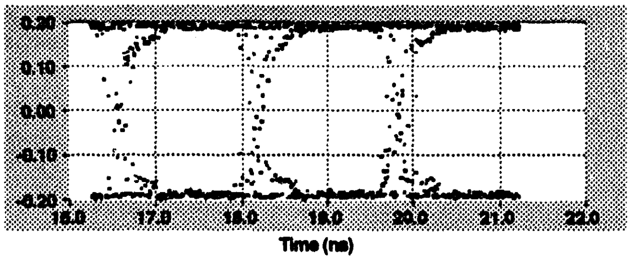
Fiber Optic Link Diagram of the OART Project Including Video



Demonstration of 2 channel WDM at 622 Mb/s using LLNL wavelength converters in 100 km lab testbed



Eye diagram of the 1533 nm channel



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