



Coherent Optical Fiber Communication Architecture, Modeling and Optimization

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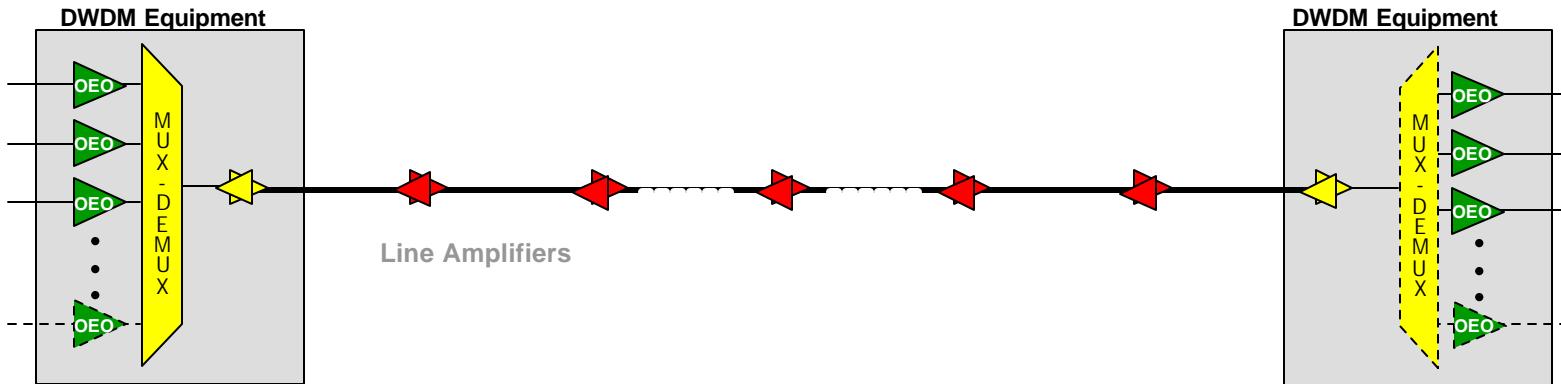
Outline

- Introduction
- Analysis Levels
- Analysis Results
 - Components
 - Modules
 - System
- Conclusions and Challenges



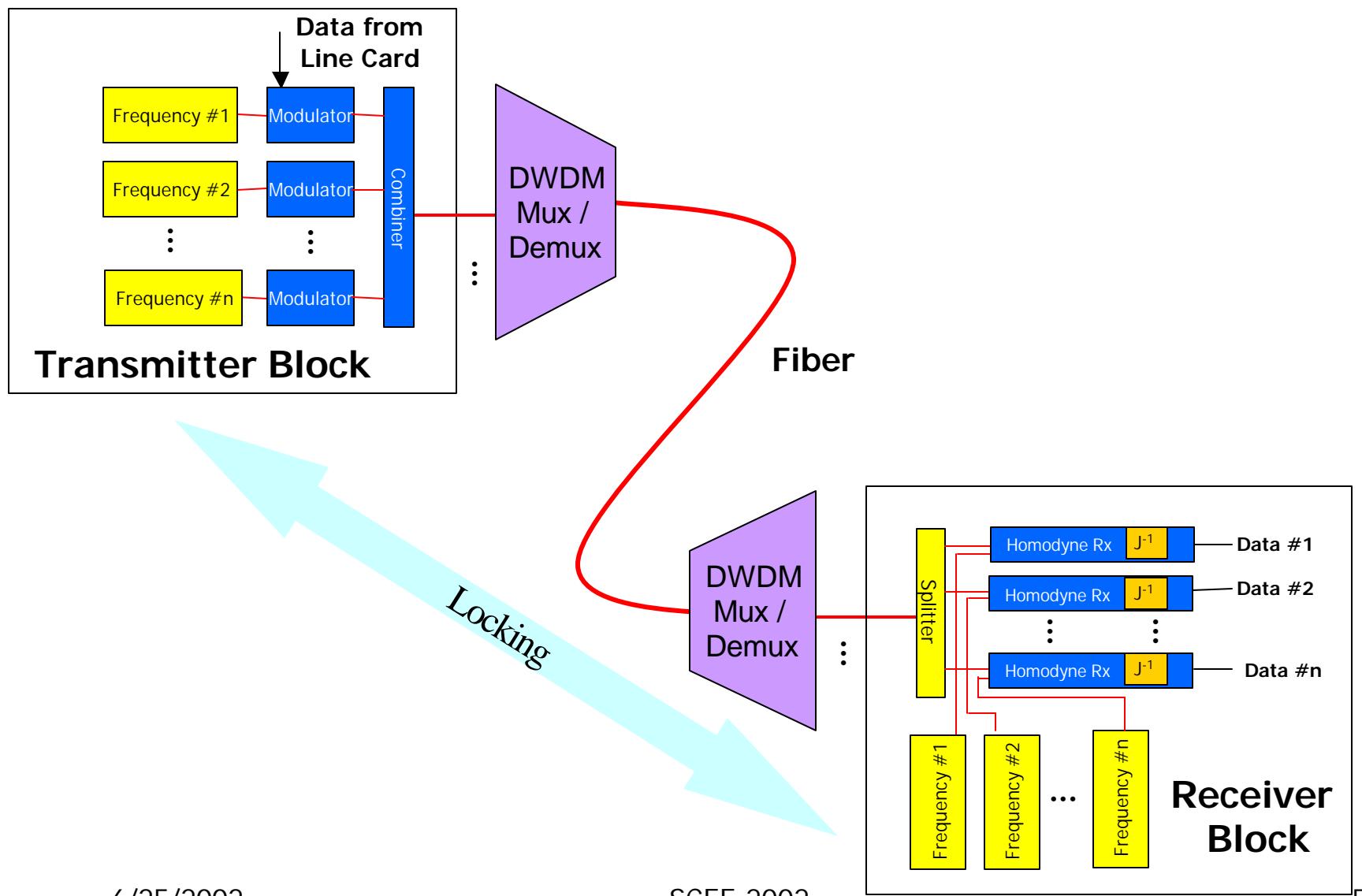
Introduction

Optical Ultra Long Haul System

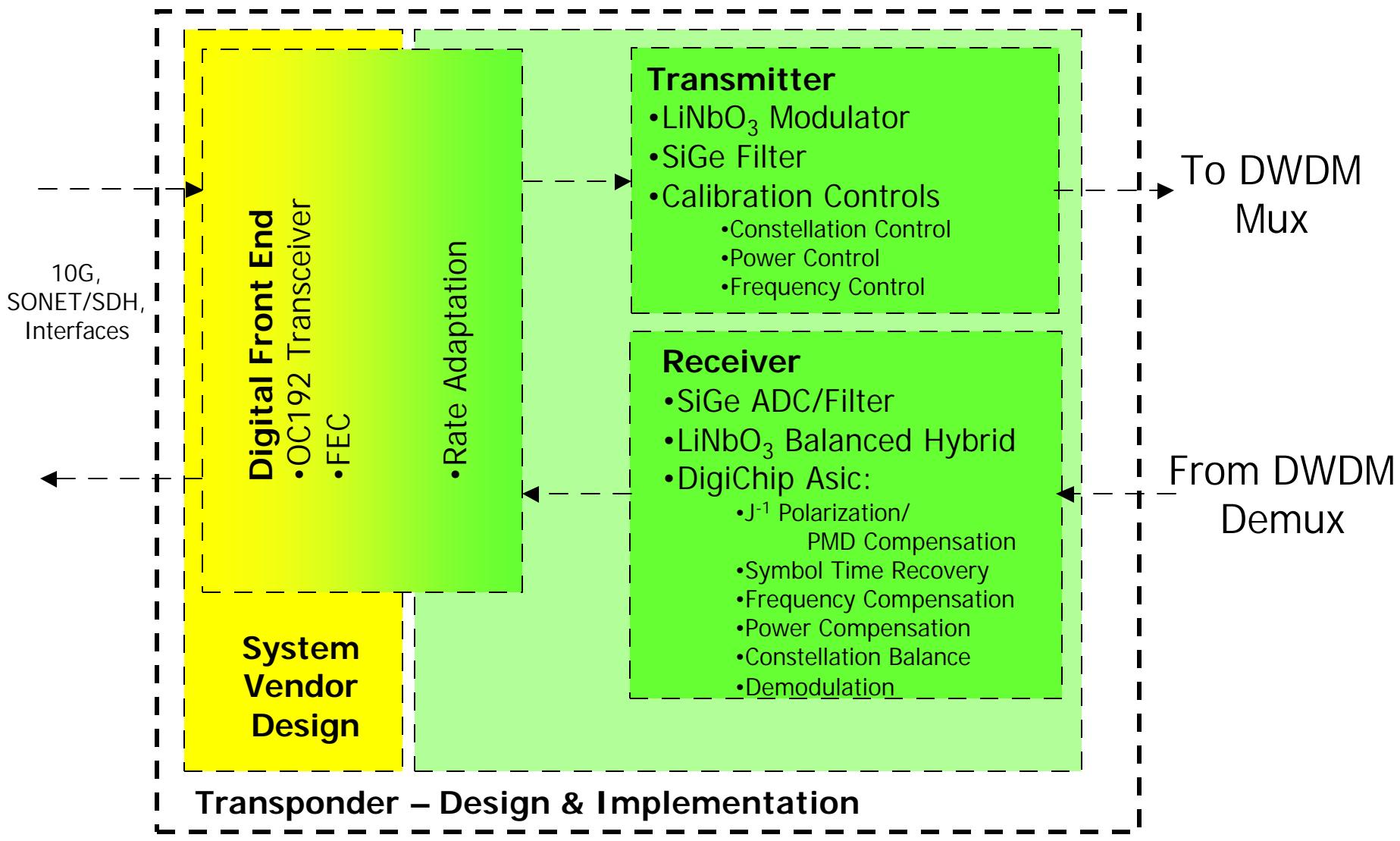


- Typical DWDM systems:
 - 10 Gb/s (OOK) per wavelength
 - 40-80 wavelength in C-band
 - Distance of several thousands KM
 - Spectral efficiency 0.1-0.2 bit/s/Hz
- Next Generation:
 - 40 Gb/s (OOK)
- VectorWAVE™
 - 10 Gsymbol/s
 - (D)QPSK, (D)BPSK
 - Polarization Multiplexing
 - Spectral Efficiency: 0.4 – 1.6 bit/s/Hz
 - Range: 1600 – 8000 Km

Homodyne System Architecture



Architecture Hierarchy



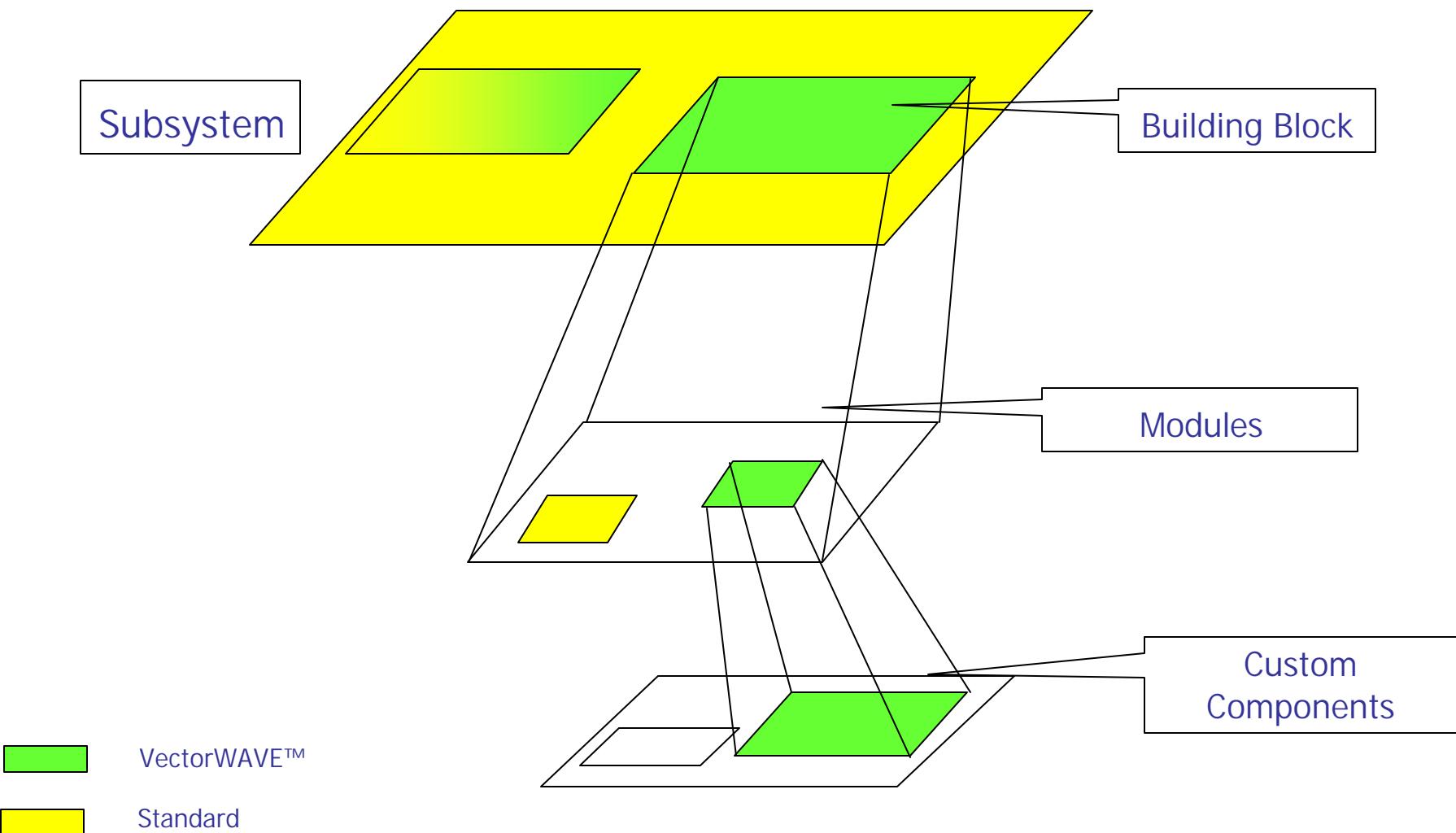
Technology

- Optical Coherent Communication
 - Quadrature Modulation
 - Coherent Detection (Homodyne / Self-Homodyne)
- Polarization Multiplexing
 - J-1 compensation
- Optical integration in CeLight LiNbO₃ FAB
- System Algorithms, Simulation and optimization tools

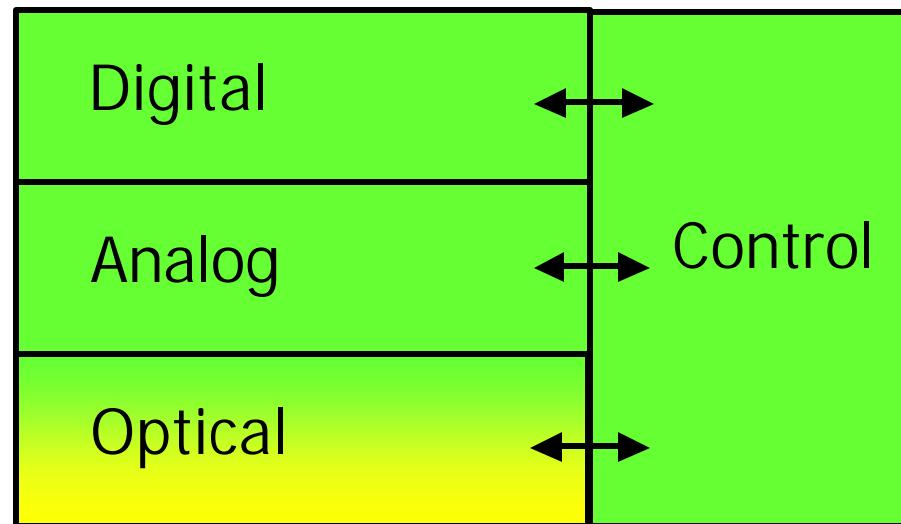


Analysis Levels

VectorWAVE™ Functional Levels



Signal Processing Levels



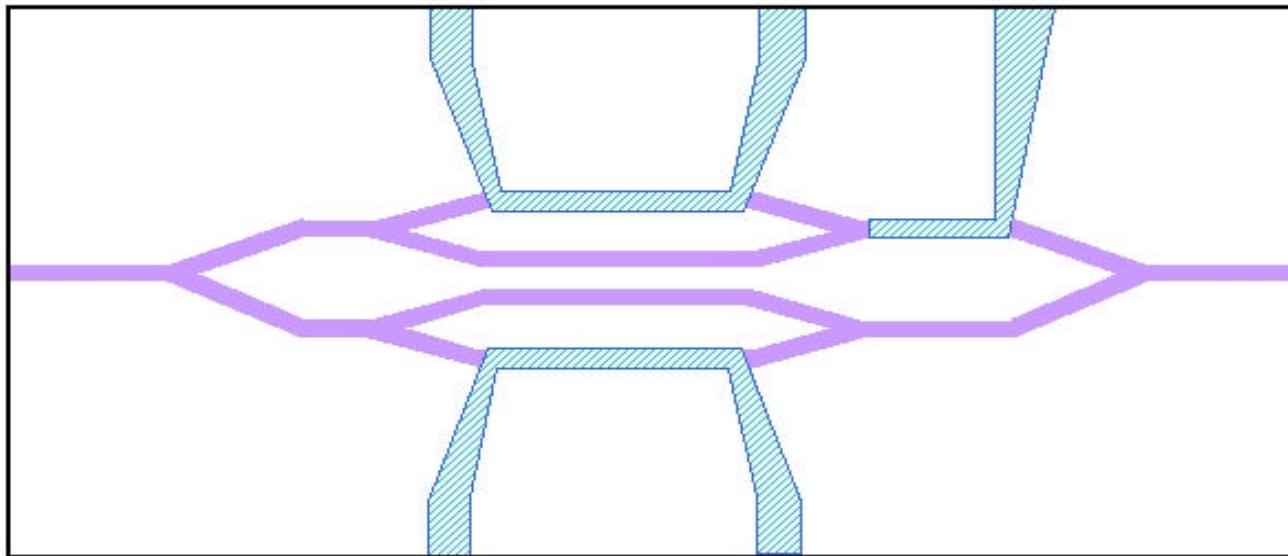
Analysis Levels

- Components
- Modules
- System Performance
- System Optimization



Analysis Results

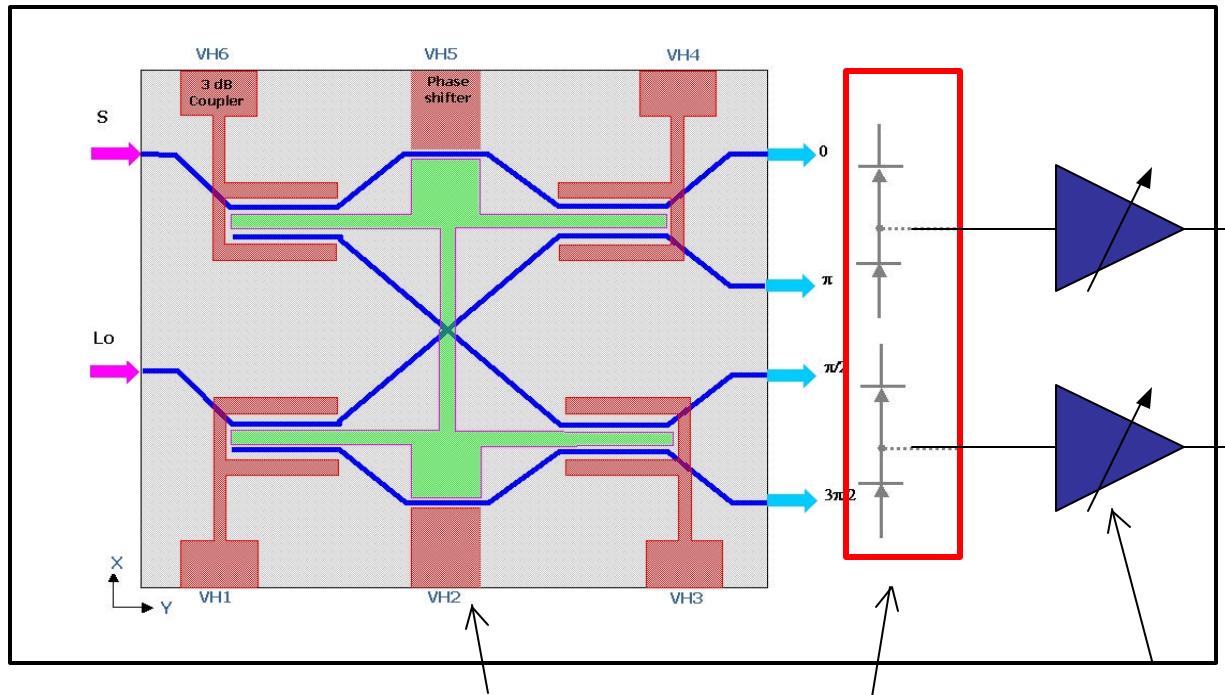
LiNbO₃ Integrated Quadrature Modulator



Features:

- Design optimized for 10 Gsymbol/s Quadrature Phase Shift Keying (QPSK) modulation (20 Gbit/s).
- Ti:LiNbO₃ diffused modulator technology.
- Dual Mach-Zehnder (MZ) configuration on single chip.
- Each MZ has 20Ghz bandwidth.
- 50 Ohm RF drive impedance.
- Separate external DC bias capability integrated on chip eliminates need for external bias "T".
- Additional DC bias input for quadrature phase difference between the two MZ arms.
- In package TEC and thermistor for temperature control and monitoring.

Integrated Single Polarization Quadrature Receiver

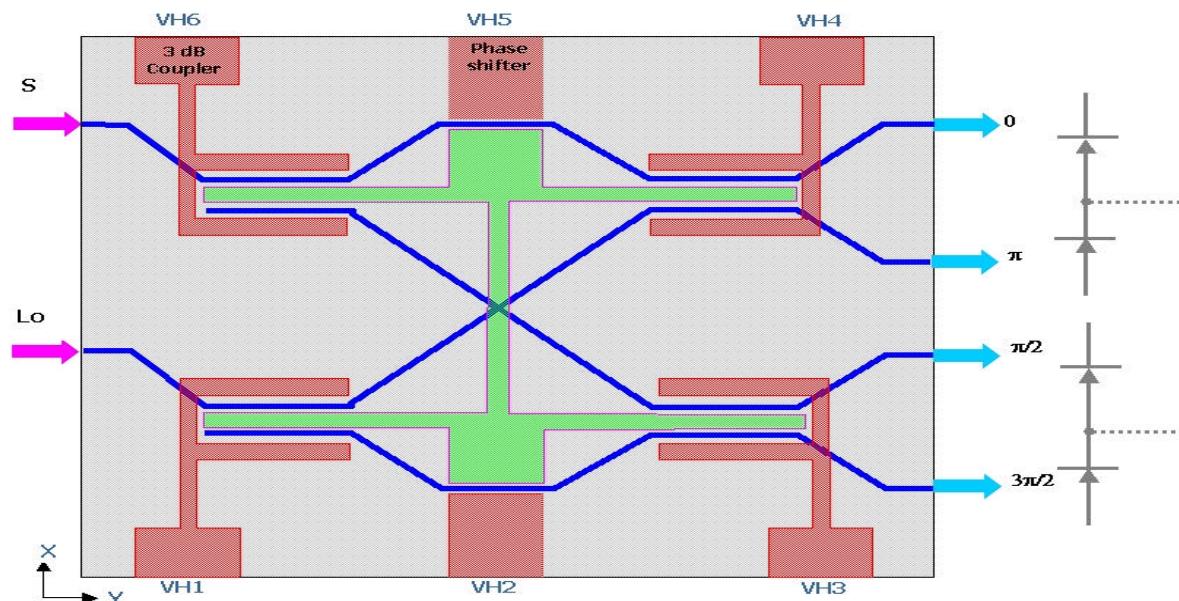


Balanced 90°
optical hybrid

Photo
detector
diode
array

Trans-
impedance
amplifier

LiNbO₃ 90° Hybrid



Features:

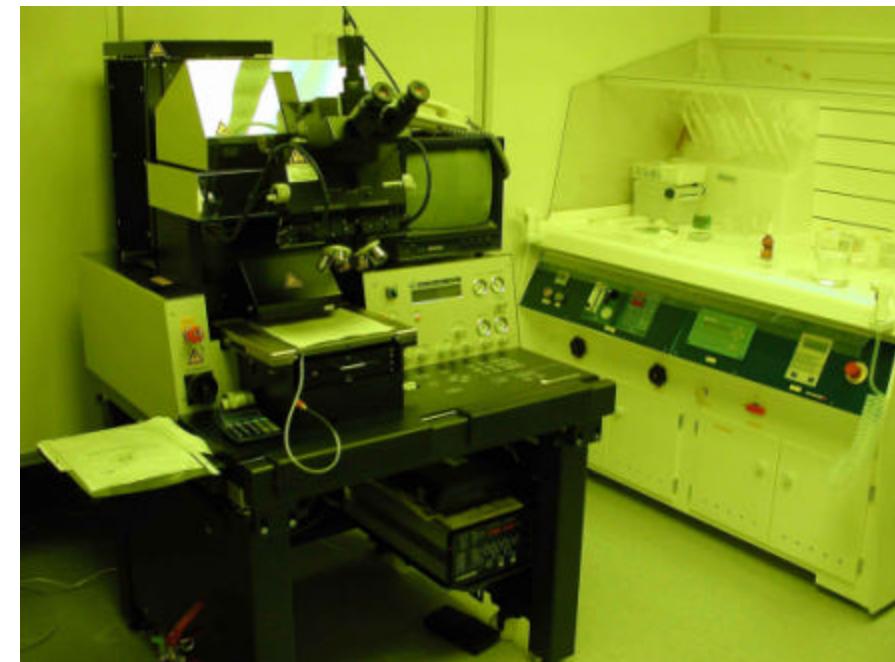
- Design optimized to use with balanced diodes.
- Optical "I" (in-phase) and "Q" (quadrature) outputs.
- External DC biasing capability of optical hybrid for optical amplitude and phase compensation.
- Separate optical input for LO laser to heterodyne (or homodyne) with signal on chip.
- Ti:LiNbO₃ diffused technology.
- In package TEC and thermistor for temperature control and monitoring.



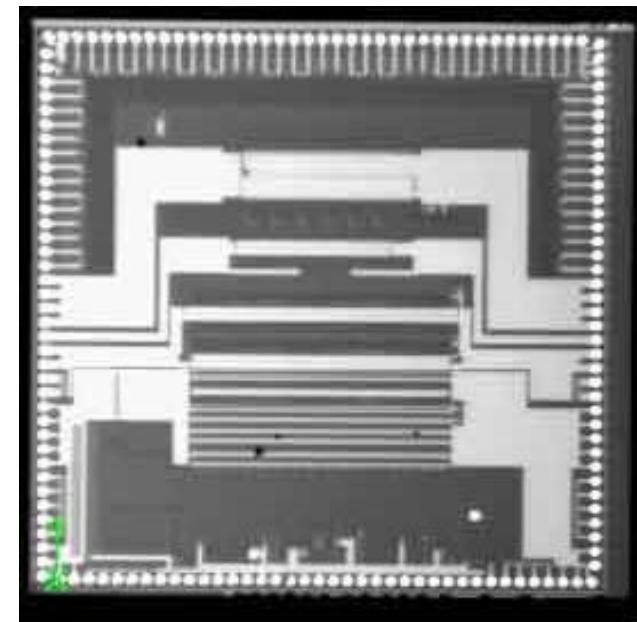
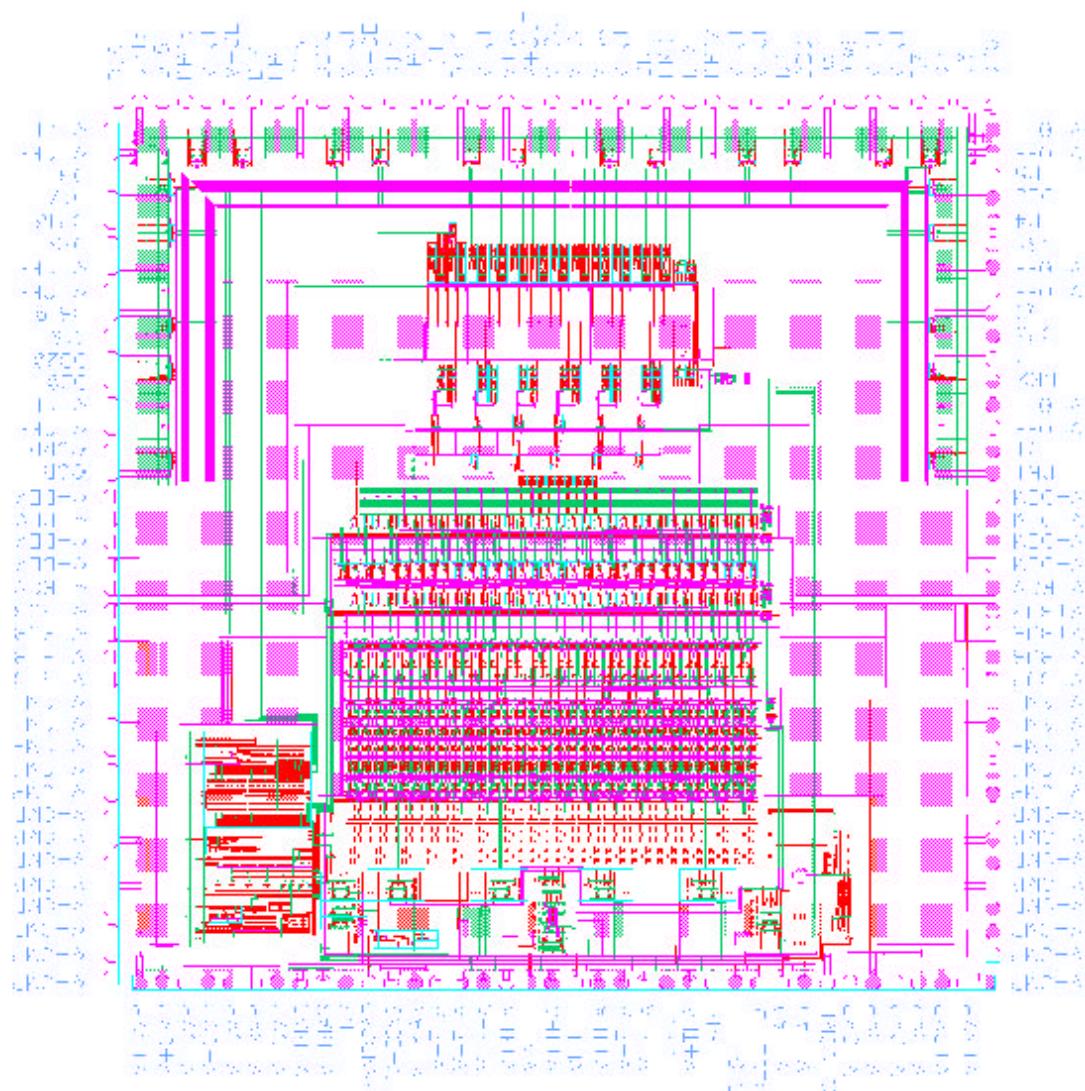
LiNbO₃ Hybrid Produced at CeLight R&D Fabrication Facility



CeLight Israel LiNbO₃ Fab



CeLight Prototype Analog to Digital Converter

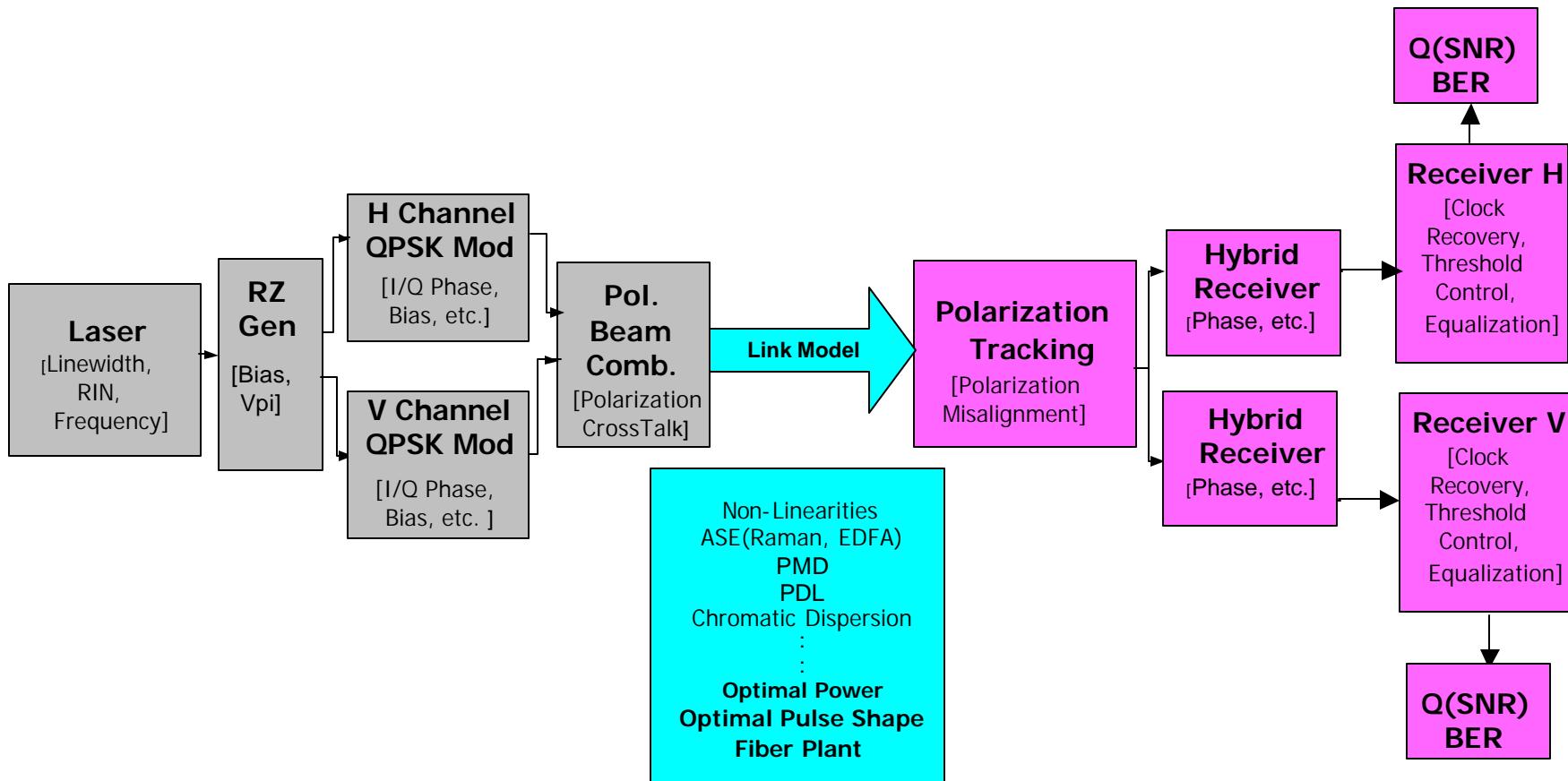


Signal-to-Noise Ratio in Fiber Communication

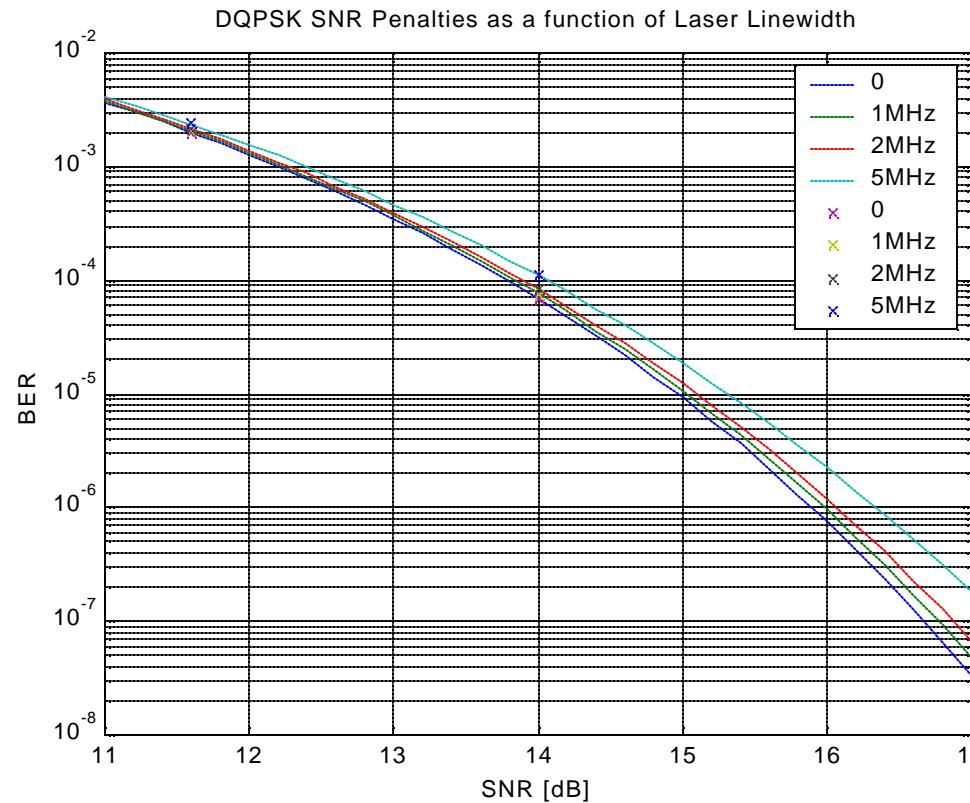
$$SNR = \frac{S}{N_0 + N_1 \cdot S + N_2 \cdot S^2}$$

- N_0 is due to ASE (amplified spontaneous emission).
- N_1 is due to various linear causes: ISI+ACI (inter symbol interference and adjacent channel interference), chromatic dispersion, polarization mode dispersion (PMD).
- N_2 is caused by nonlinear effects: self phase modulation (SPM), four-wave mixing (FWM), cross-phase modulation (XPM), etc.

VectorWAVE™ Simulation Model



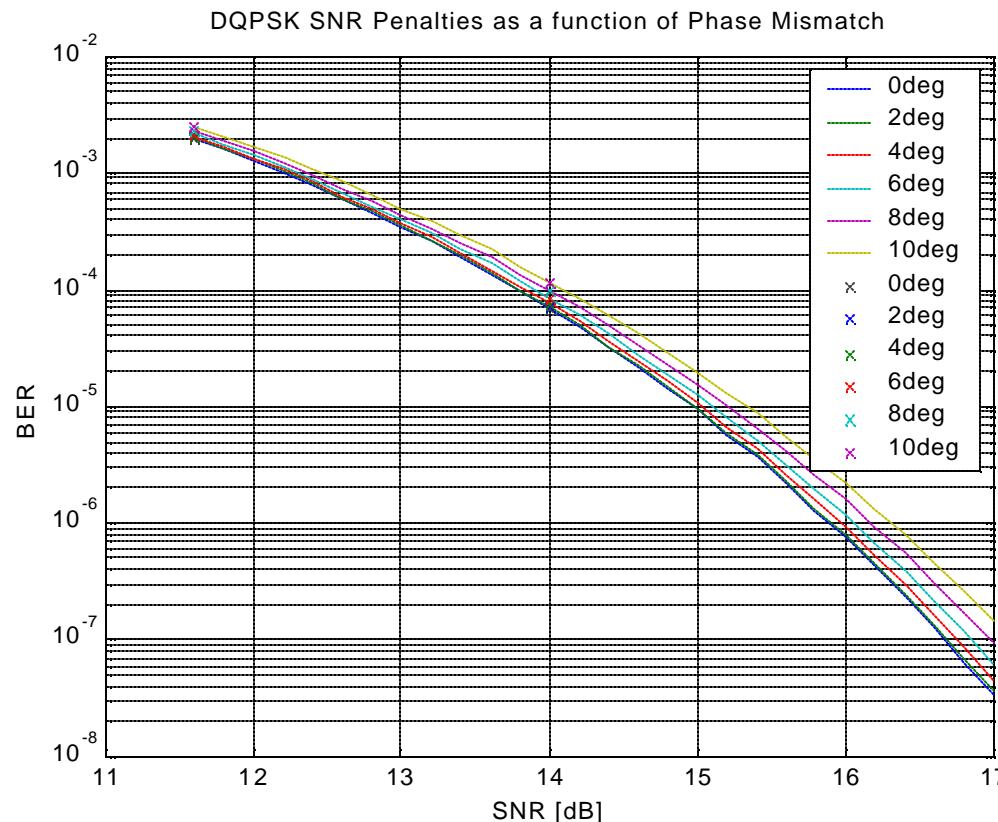
Laser Phase Noise Penalties



■ 10.7 Gsymbols/sec.

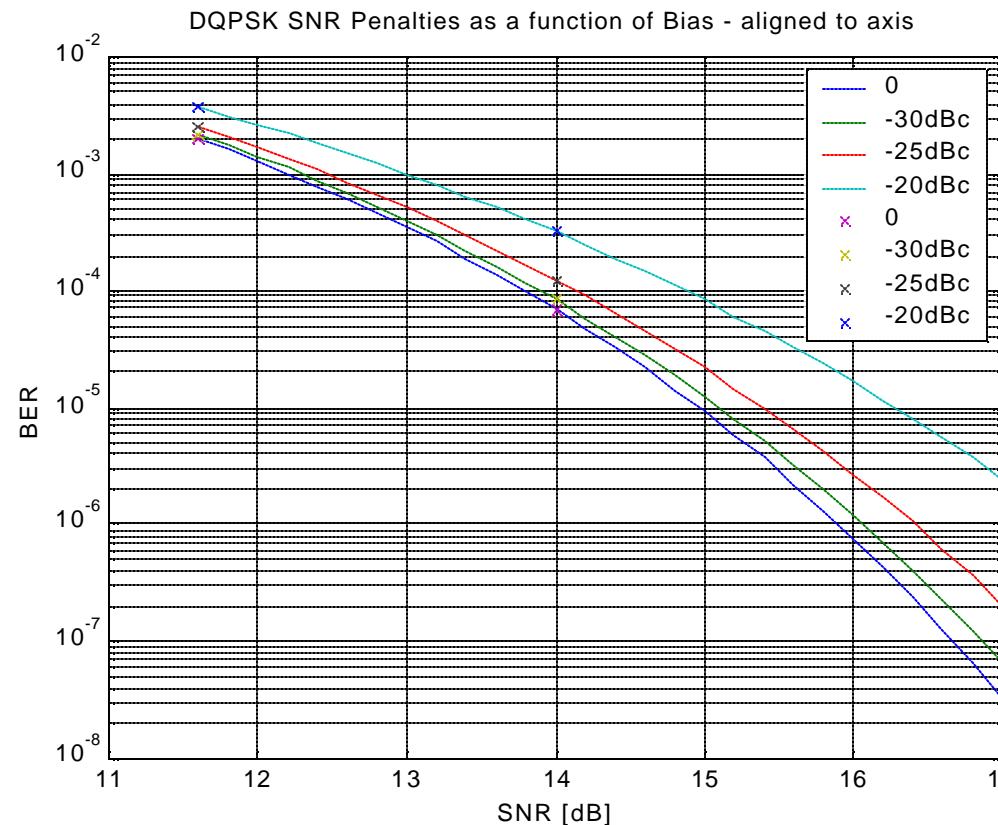
Modulation Penalties

DQPSK I/Q Phase Offset SNR Penalties



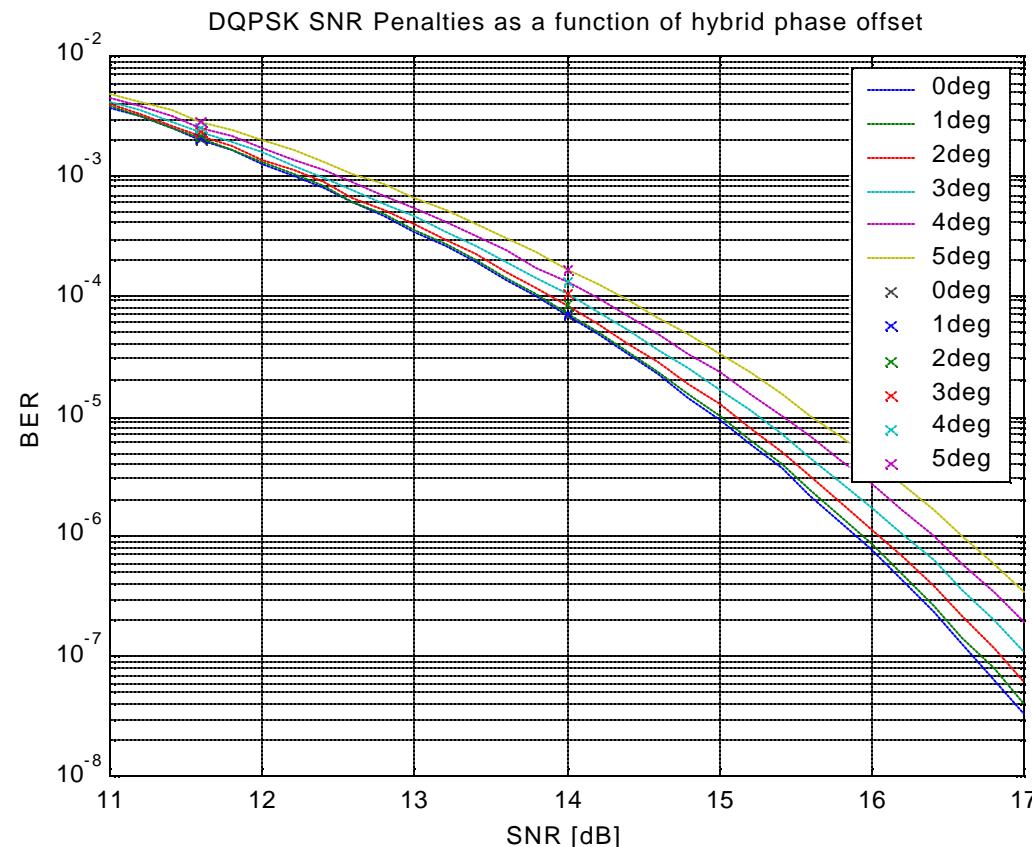
Modulation Penalties (2)

DQPSK Modulation Bias SNR Penalties

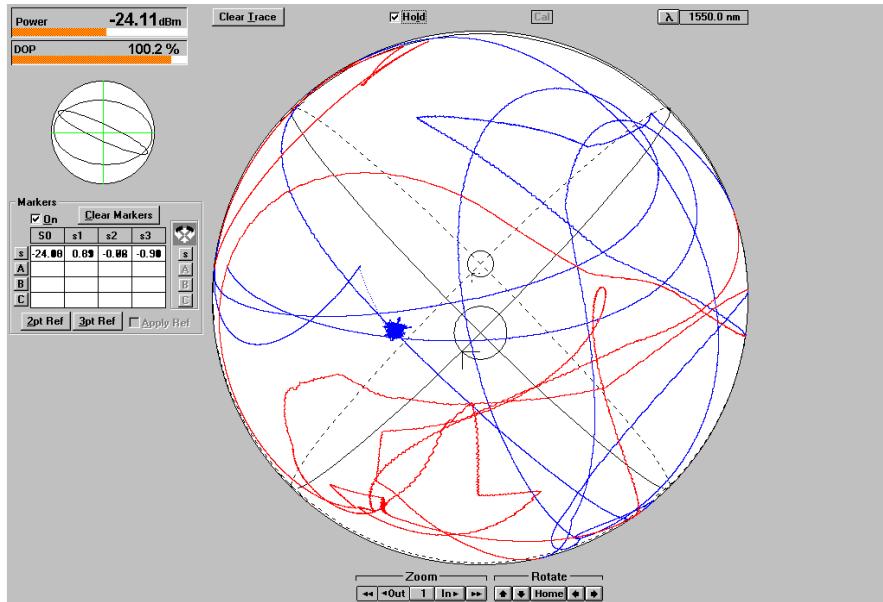


Receiver Penalties

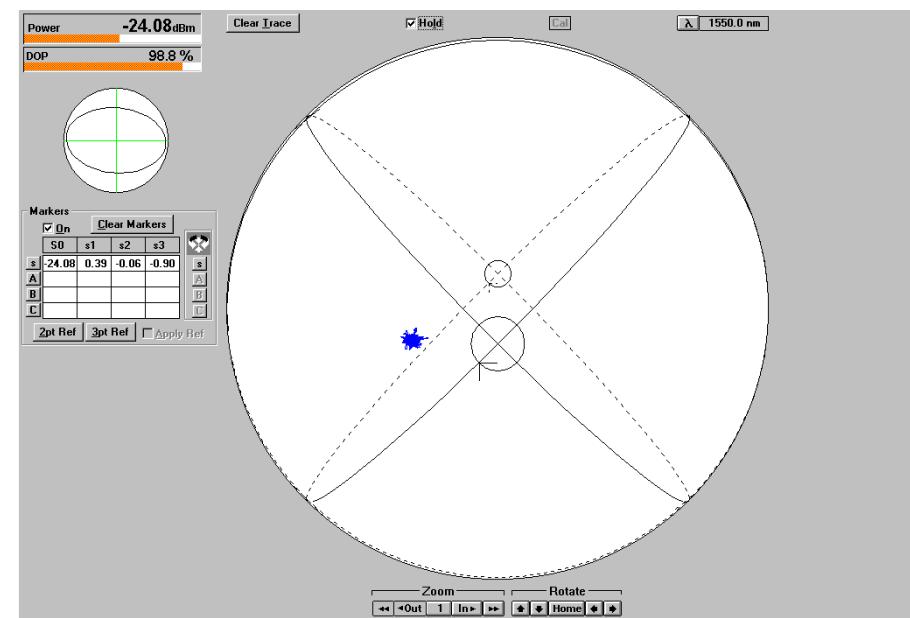
DQPSK Receiver Phase Offset SNR Penalties



Polarization Controller Testing

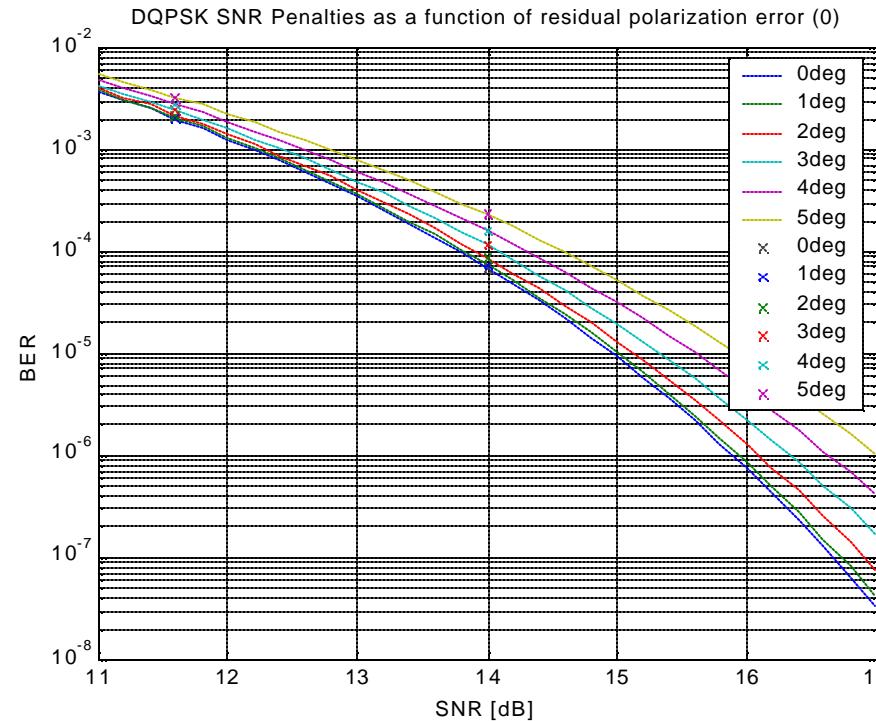


- Polarization variation with J^{-1} De-activated

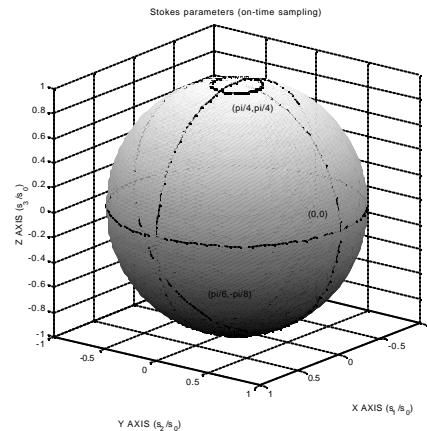


- Polarization Convergence with J^{-1} Activated

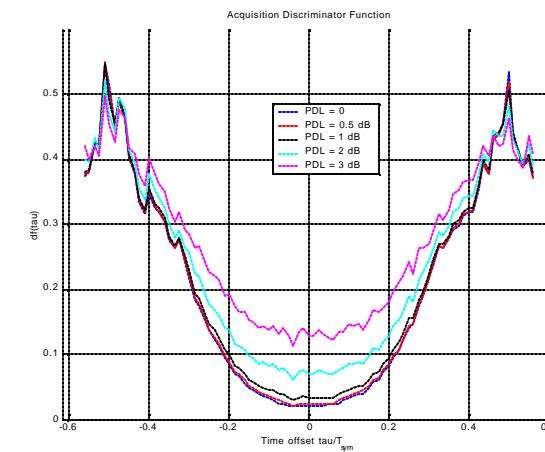
Polarization Tracking Penalties



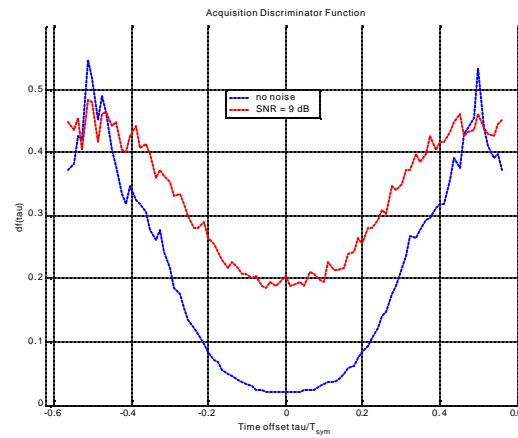
Acquisition Performance



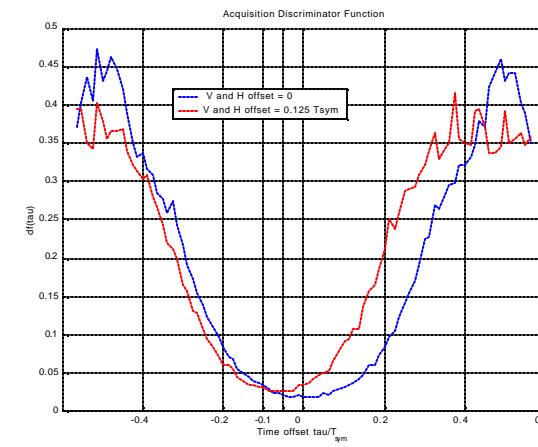
On Time Stokes Vectors



Acquisition Discriminator Function (PMD,PDL)

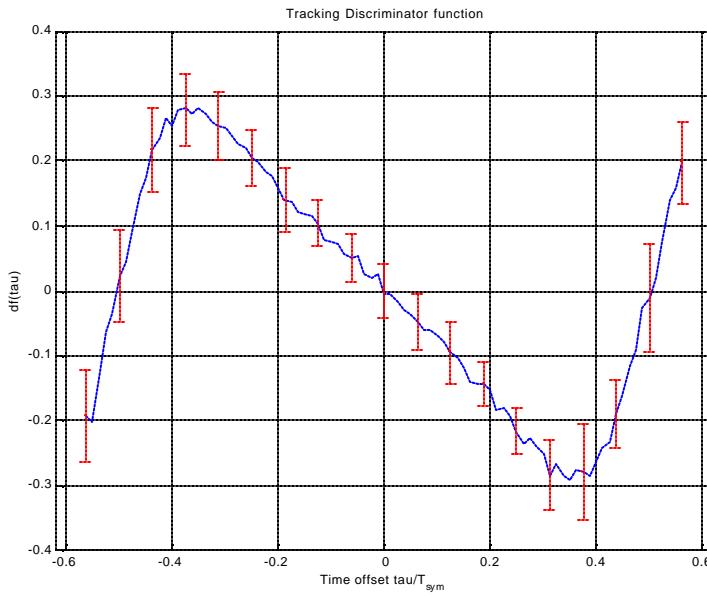


Acquisition Discriminator Function (AWGN Noise)

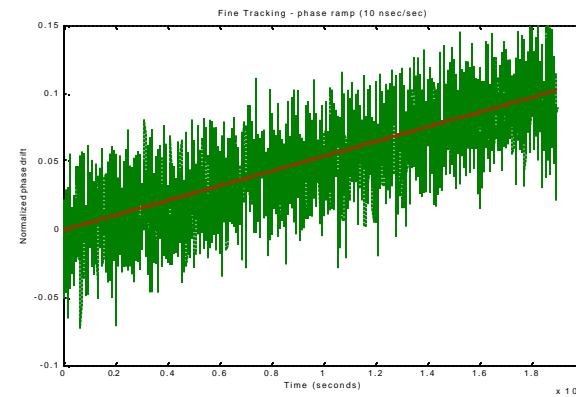


Acquisition Discriminator Function (V and H Misalignment)

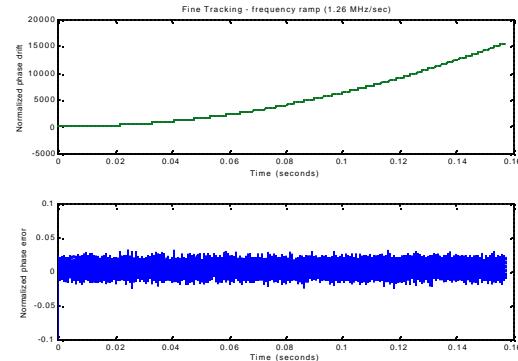
Tracking Performance



Tracking Discriminator Function (SNR=9 dB)



Fine Tracking – phase ramp of 10 ns/sec



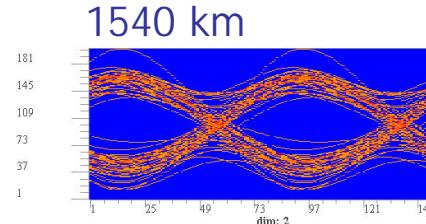
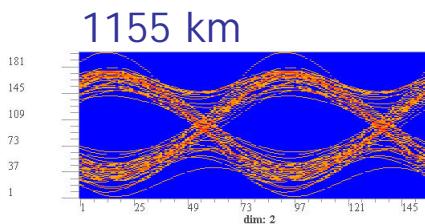
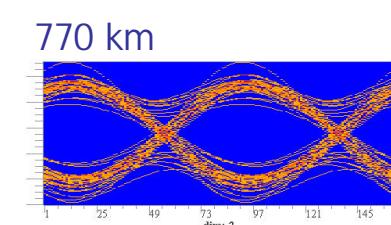
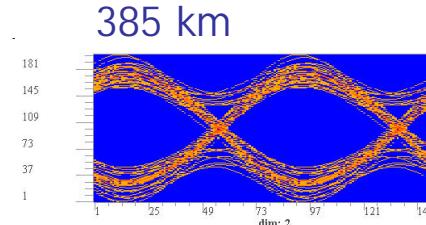
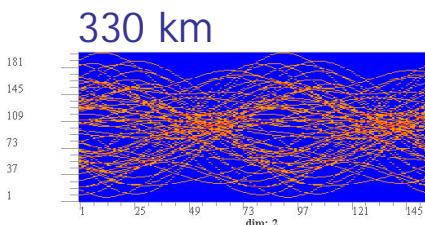
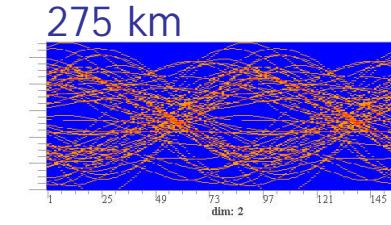
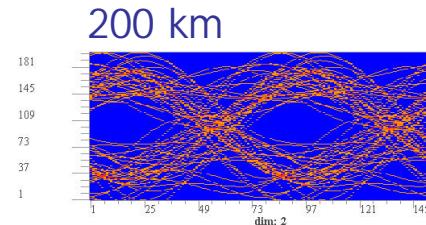
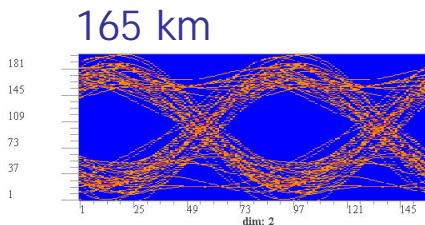
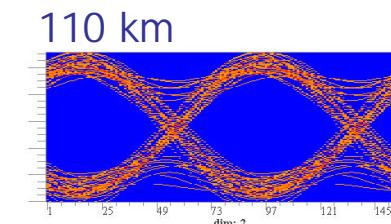
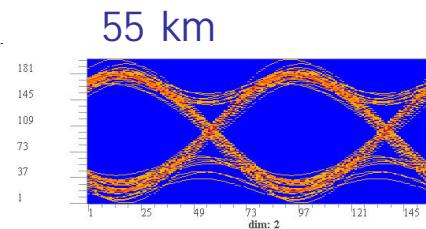
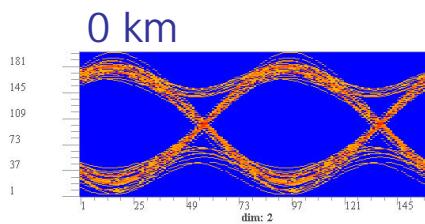
Fine Tracking – frequency ramp of 1.26 MHz/sec

Simulation Parameters

Client Tributary		[OC192/10GE]	
Dispersion Map	Dispersion Pre Compensation	[ps/nm]	For both in-line fiber and dispersion compensated fiber
	Dispersion Post Compensation	[ps/nm]	
	Dispersion Coefficients	[ps/nm-km]	
	Dispersion Slopes	[ps/nm ² -km]	
	PMD Coefficients	[ps/km ^{1/2}]	
	Effective Areas	[μm ²]	
	Loss Coefficients	[dB/km]	
	Span Lengths	[km]	
	Total Reach	[km]	
Raman - EDFA Amplification Map	Description		
Raman	Raman Pumping Type	[Backward / Forward or combined]	
	Raman Fiber Type		
	Number of Pumps		
	Pump Wavelengths	[nm]	
	Pump Powers per Pol.	[dBm]	
	GFF Specs	[dB vs. nm]	
EDFA	Noise Figure	[dB]	
	Output Power	[dBm]	
	EDFA Spacing	[km]	
	PDL per ampl. Spacing	[dB]	
	Gain Flatness	[dB]	
Link - General	Total Link PMD	[ps]	
	Temporal SOP Rate of Change	[rad/sec]	
	Total Link PDL	[dB]	
Demux	Description		stages, filtering, insertion loss ...

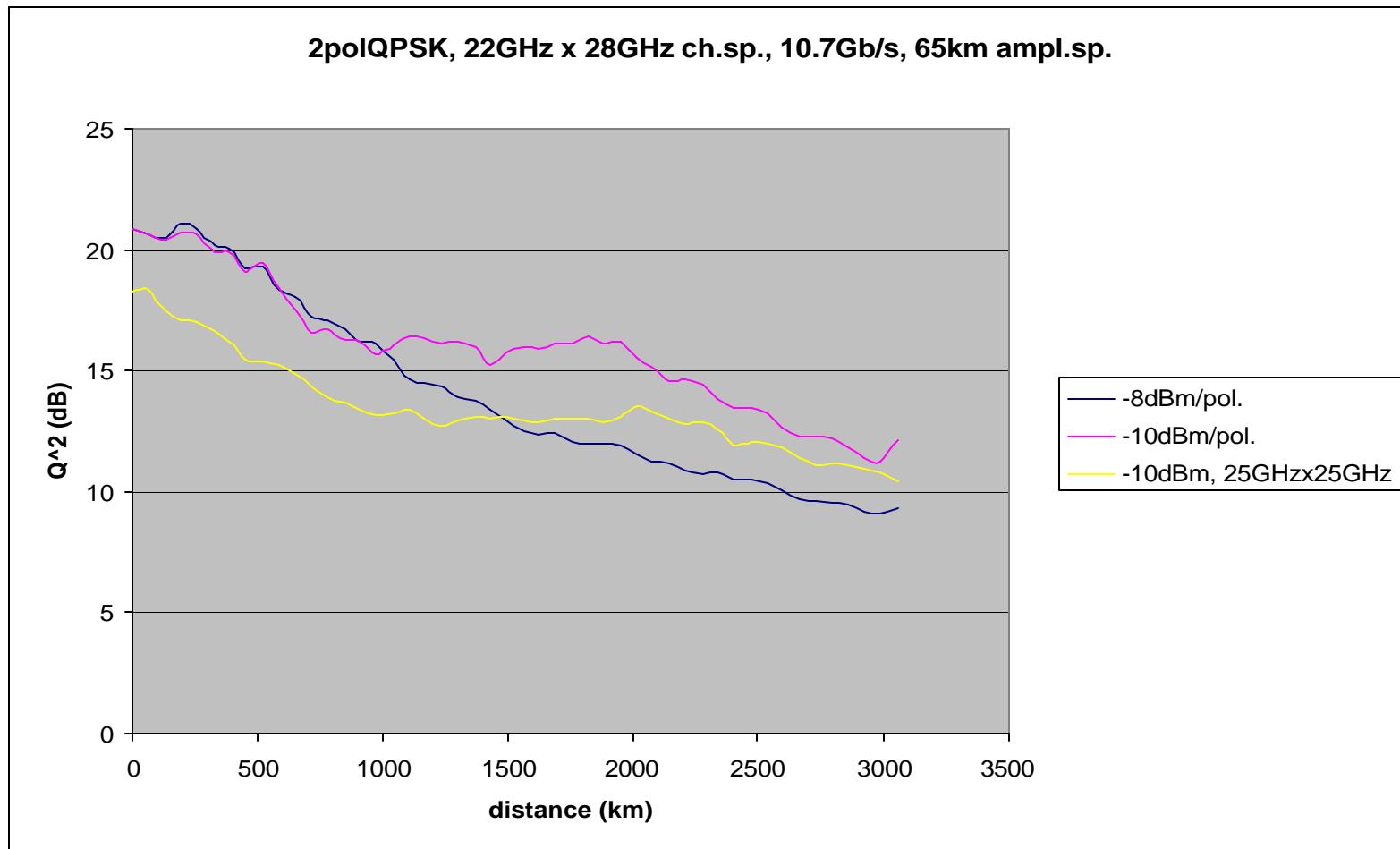
Eye Evolution

2P/DQPSK/OJ⁻¹/SH Overlay



1.6 bit/s/Hz

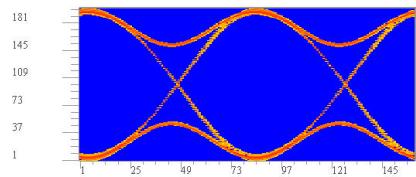
Optimum channel power per polarization is -10dBm



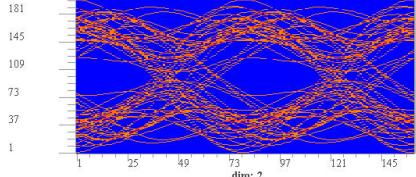
Eye Evolution

1P/Alt./DQPSK/OJ⁻¹/SH

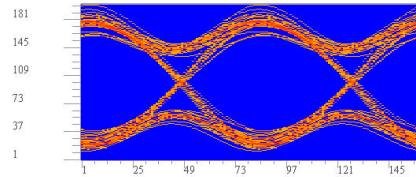
0 km



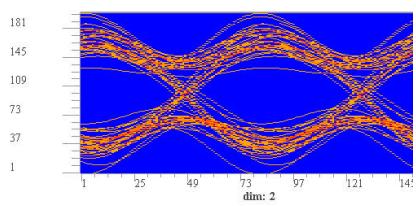
200 km



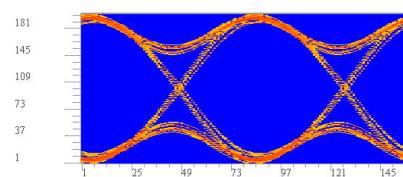
770 km



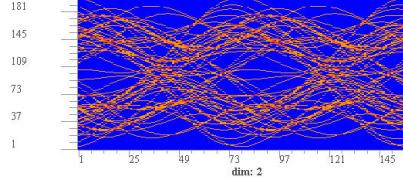
3080 km



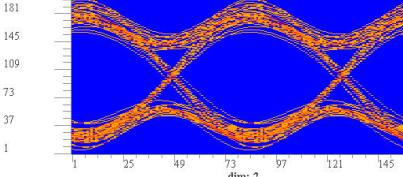
55 km



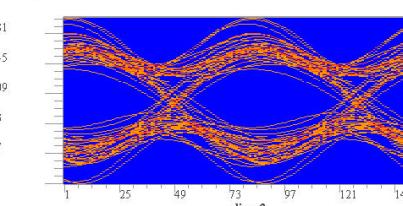
275 km



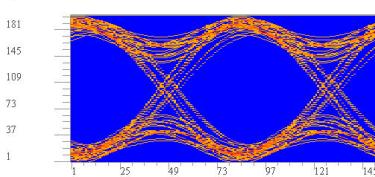
1155 km



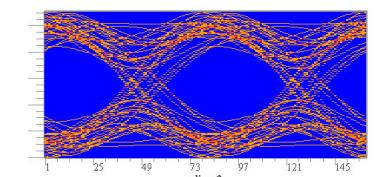
3465 km



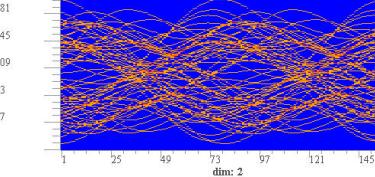
110 km



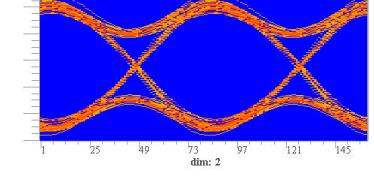
165 km



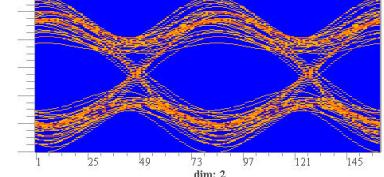
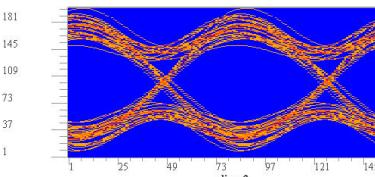
330 km



2310 km

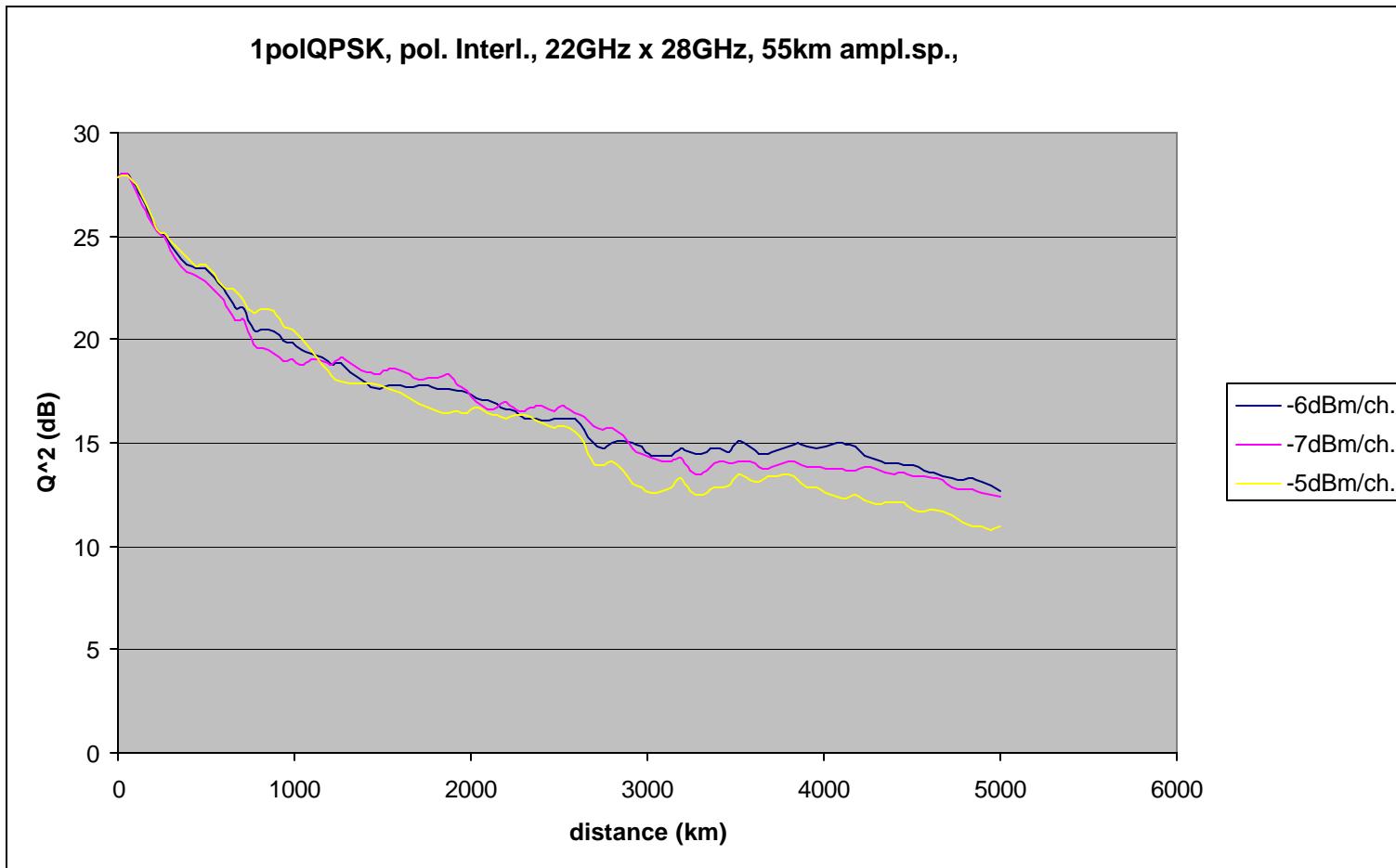


1540 km



0.8 bit/s/Hz

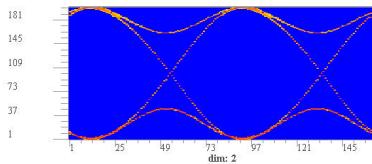
55km amplifier spacing; polarization interleaving



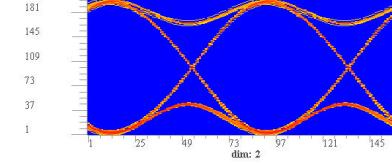
Eye Evolution

1P/Alt./DBPSK/OJ¹/SH Overlay

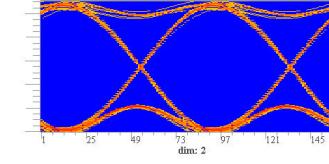
0 km



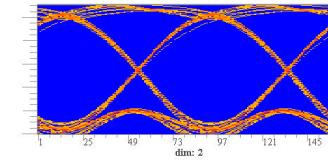
55 km



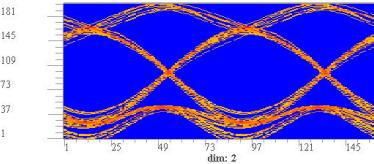
110 km



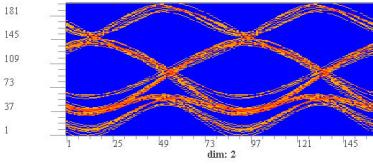
165 km



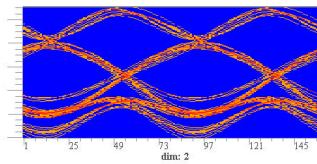
200 km



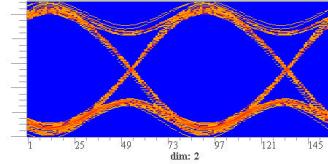
275 km



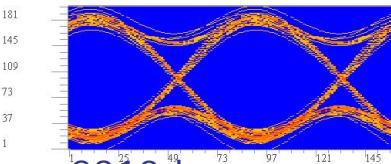
330 km



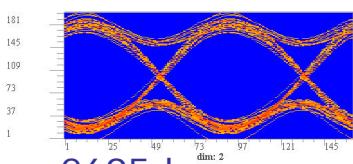
385 km



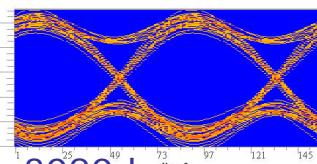
770 km



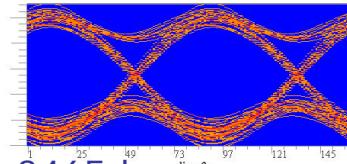
1155 km



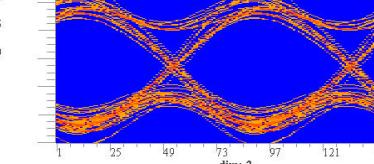
1540 km



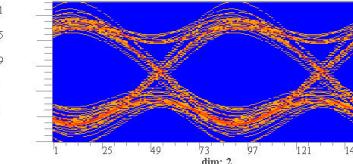
1925 km



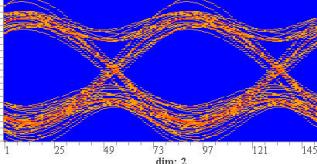
2310 km



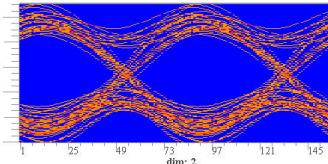
2695 km



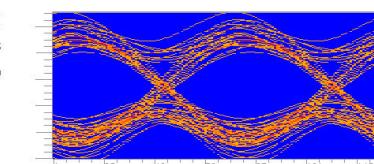
3080 km



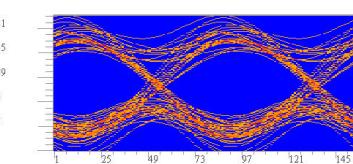
3465 km



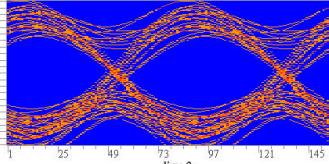
3850 km



4235 km

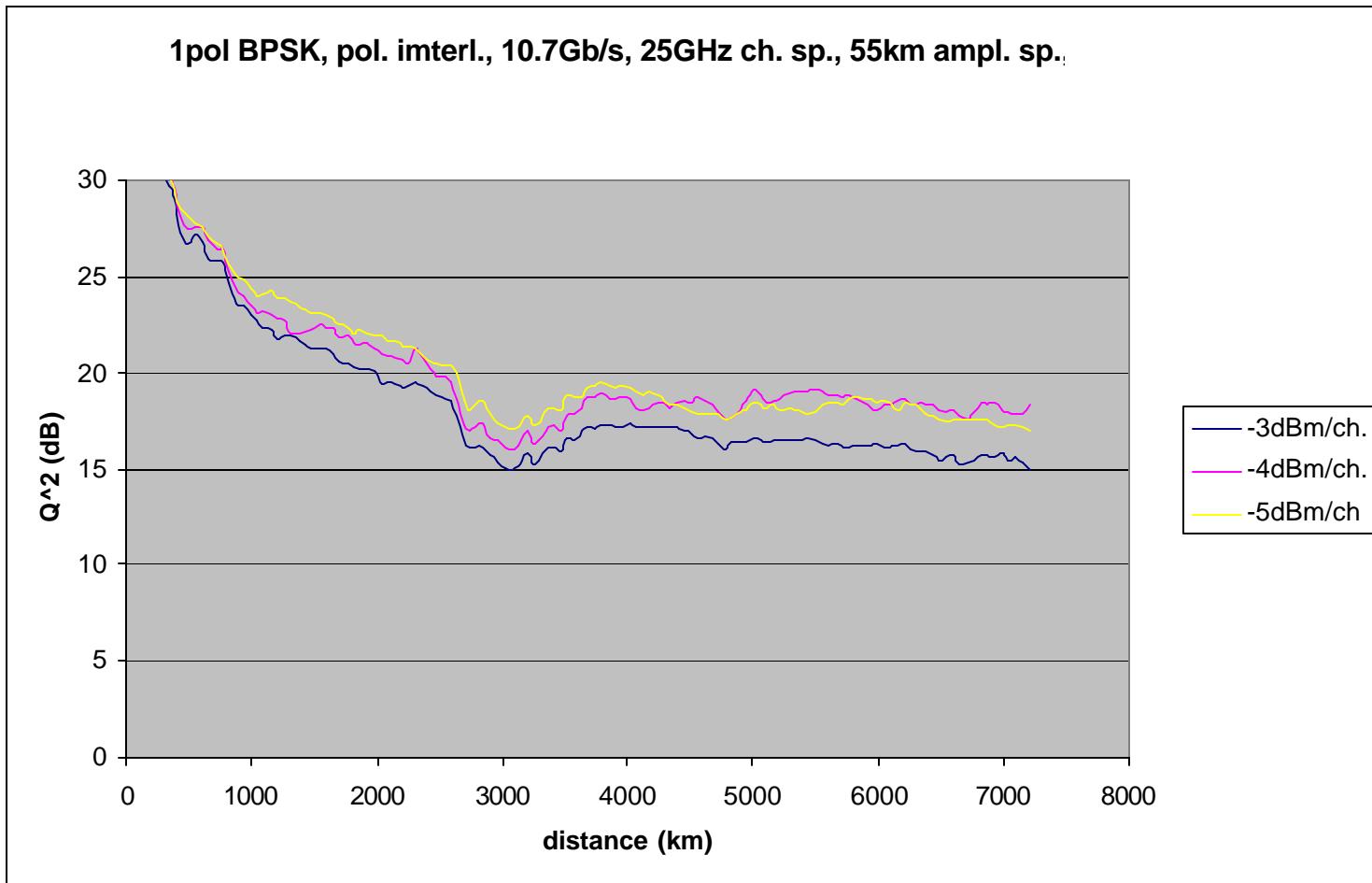


4620 km

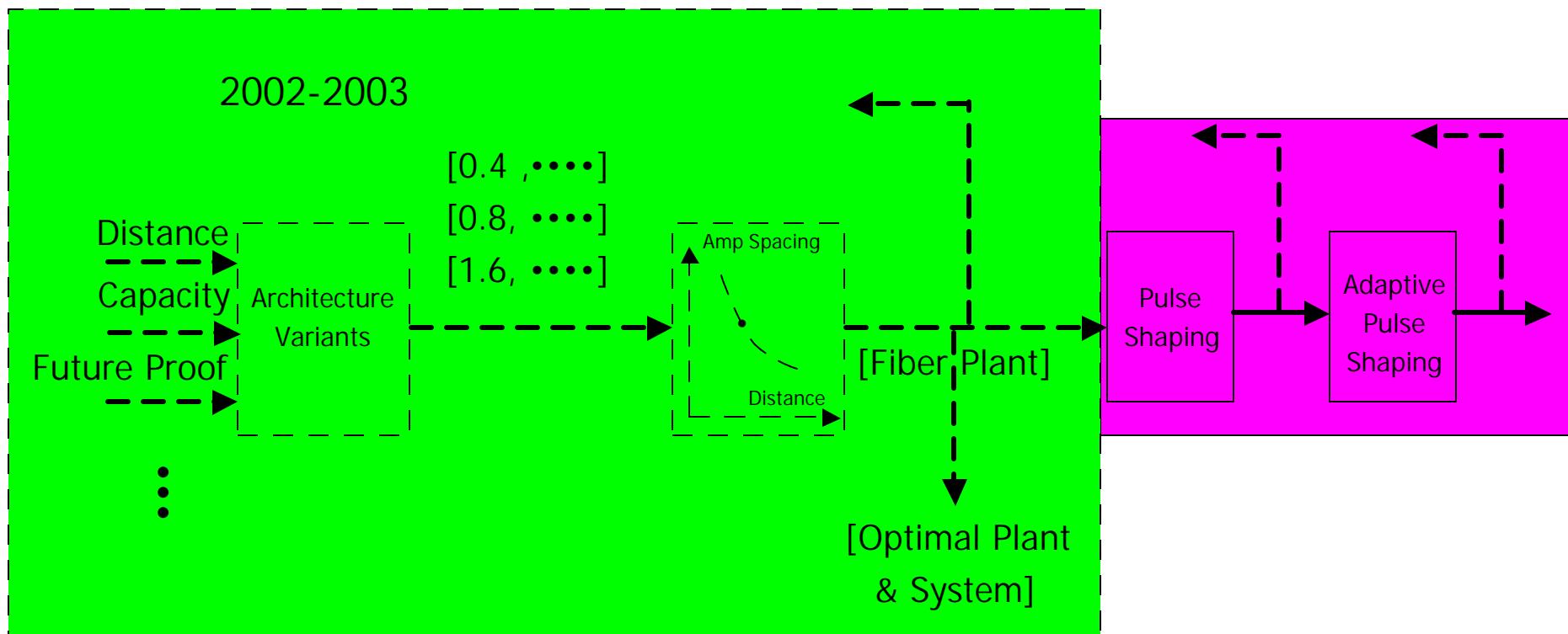


0.4 bit/s/Hz

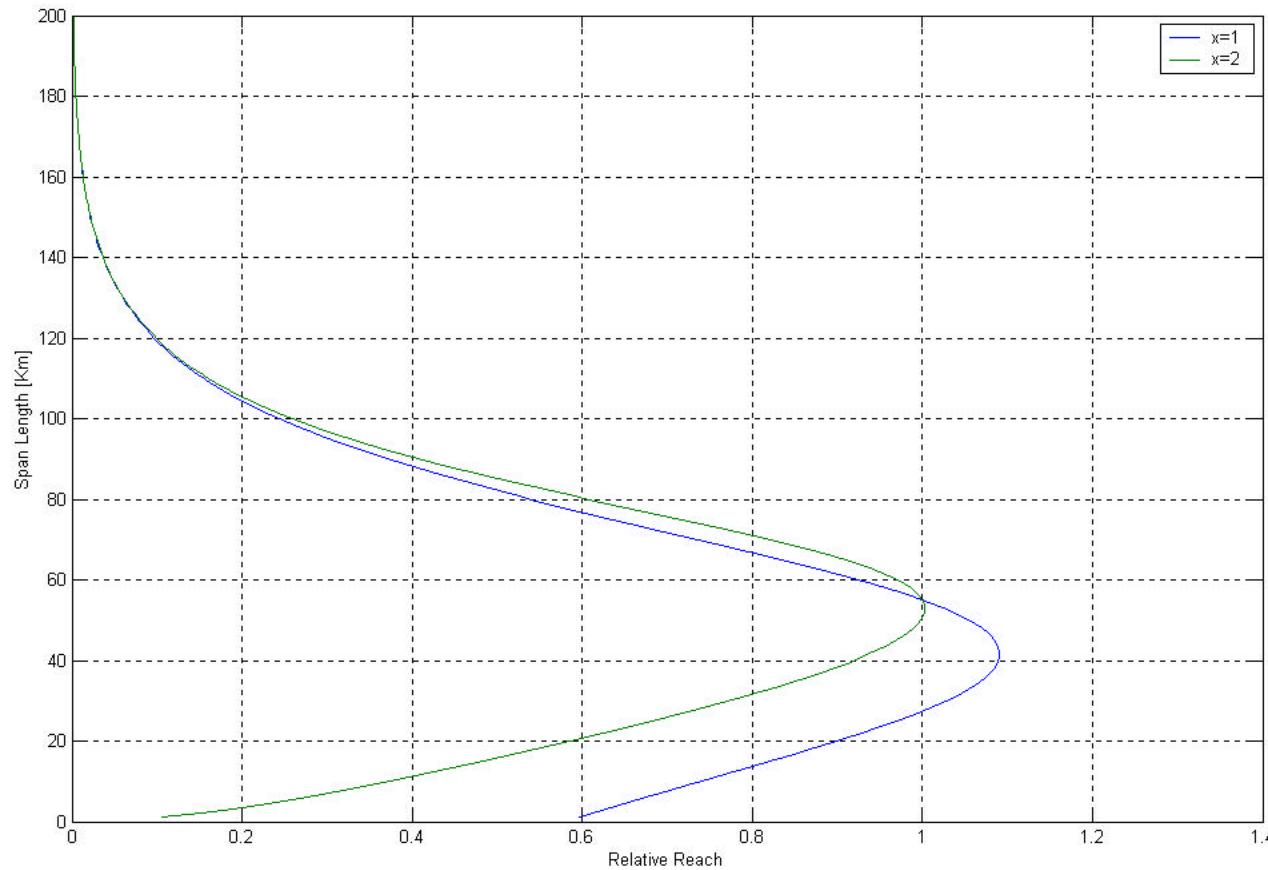
55km amplifier spacing, polarization interleaving



System Optimization Process



Plant Optimization



Validation

- Custom optical components – R&D Fabrication Facility
- Modules – Build engineering prototypes
- System performance – Test Bed
- System optimization – Open

Conclusion and Challenges

- No commercial “Optical Foundry” services
- Non-exhaustive nonlinear modeling
- Elaborate and expensive test beds
- Unified optical CAD tools and Foundry as for VLSI
- Exhaustive nonlinear modeling methods
- Improved system simulation tools