A Network Architecture for Bidirectional Data Transfer in High-Energy Physics Experiments Using Electroabsorption Modulators

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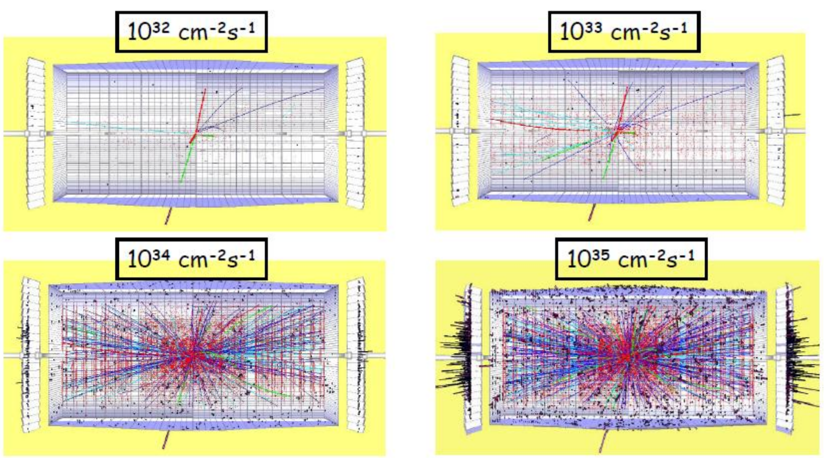
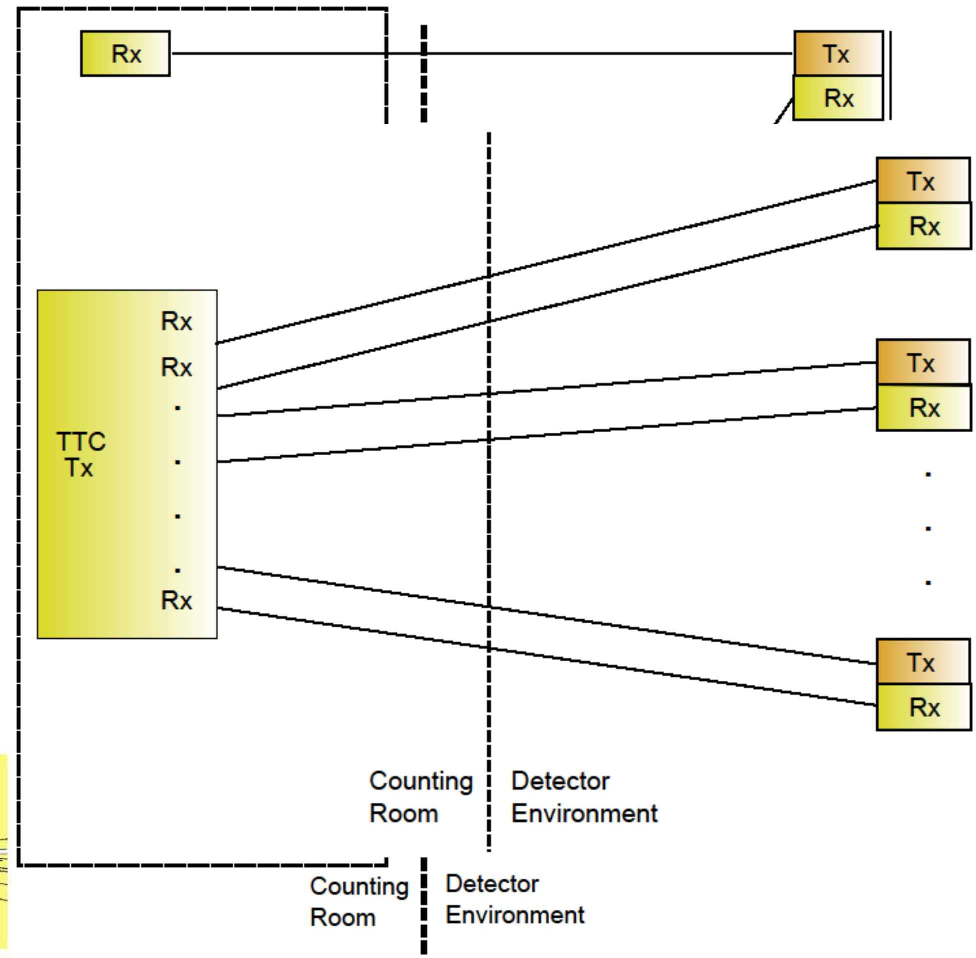
Presentation Overview

- Introduction/Motivation
- The network architecture
- The electroabsorption modulator – Principle of operation
- Results - Static Measurements
- Results - Dynamic Measurements
- Conclusion

Introduction/Motivation

- LHC upgrade:
  - Higher data rate required
  - Provides framework to explore new technologies and increase infrastructure efficiency
  - Use of low mass, low power consumption, radiation resistant components as front-end devices very important

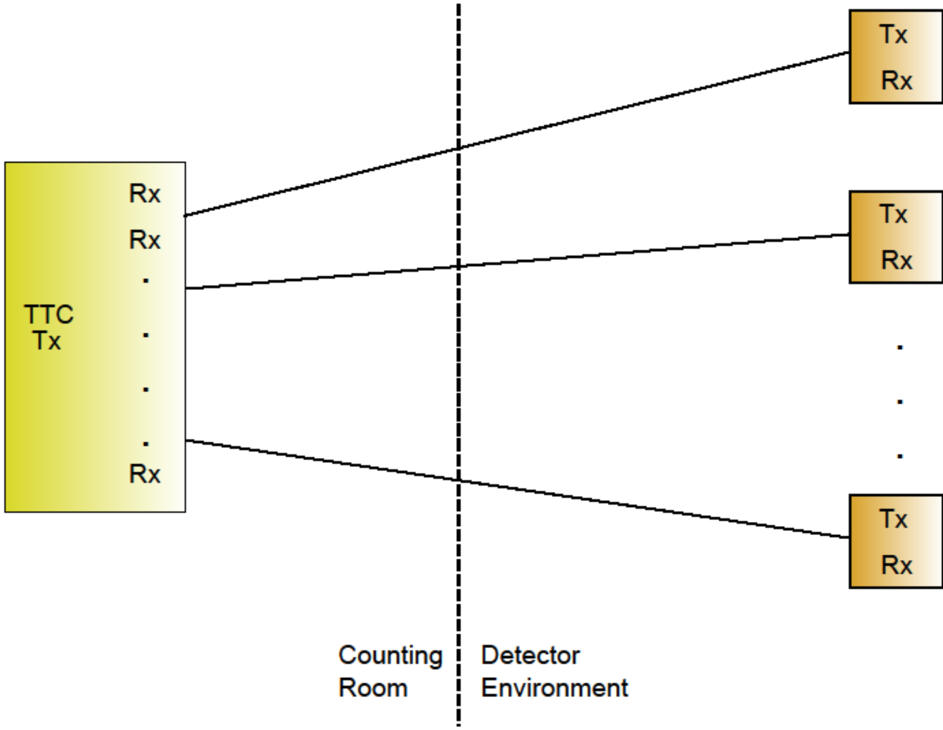




Link Requirements

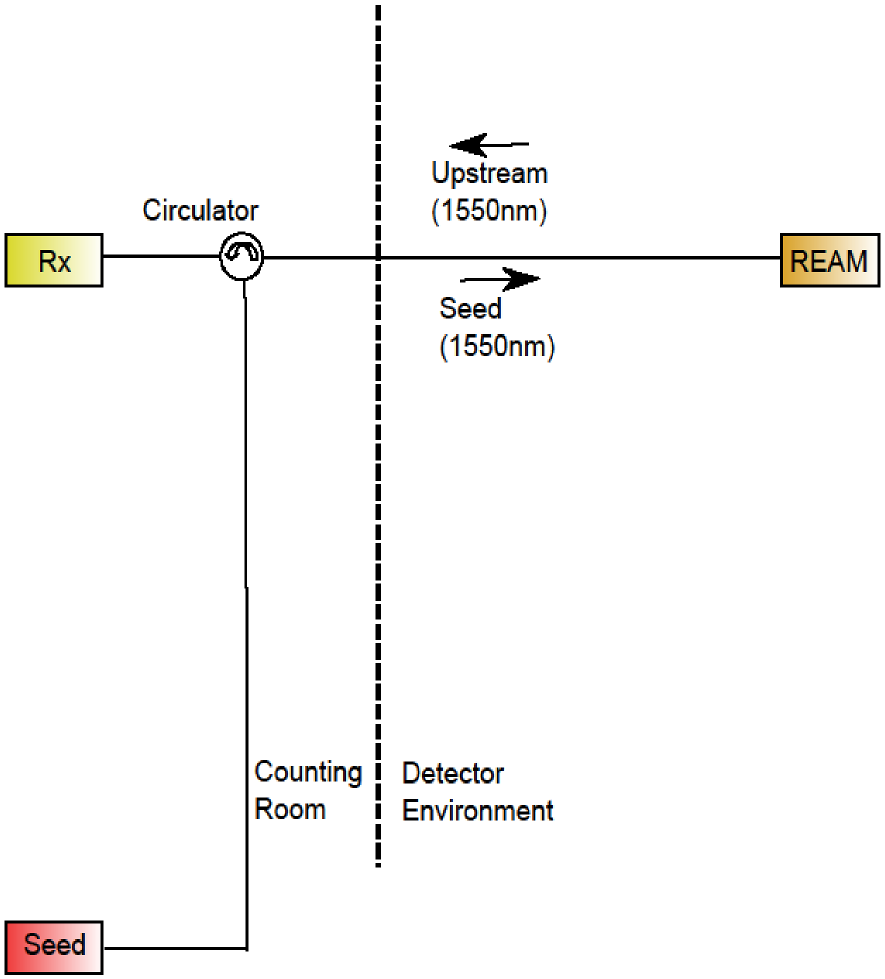
- A bidirectional link, transferring information to and from the detector over the same fiber would offer a more efficient infrastructure
- Information transferred over current TTC and data readout links could be transferred over single, unified infrastructure
- Unconventional requirements (highly asymmetric, upstream-intensive) compared to commercial networks (e.g. PONs)

Requirements for the upgraded optical links	
Upstream Data Rate/link (From Detector)	10Gbps
Downstream Data Rate (To Detector)	1Gbps -broadcast
Link Length	<1km
Target Splitting Ratio	≥1:16



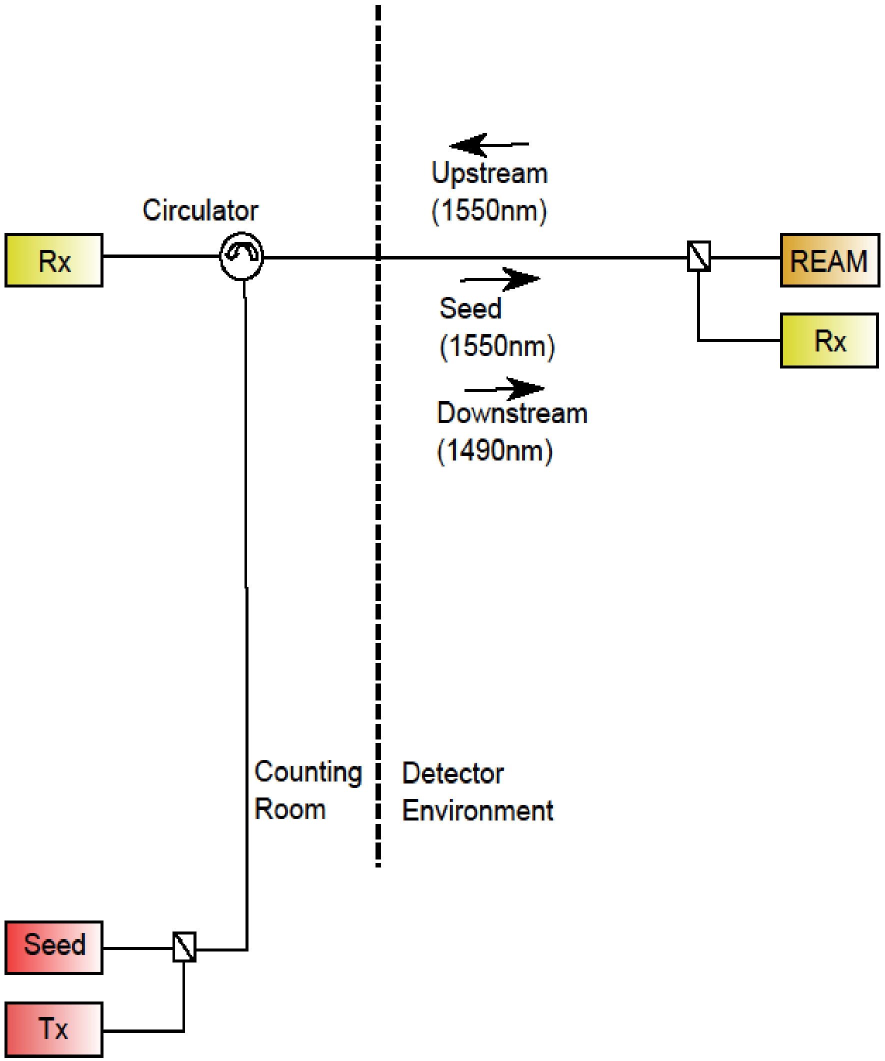
Upstream Transmission

- Use of Reflective Electroabsorption Modulators (REAMs) to transmit data upstream (from detector to counting room)
- REAMs probably radiation hard – as indicated by the results of RD-23
- REAMs potentially consume less power (intrinsic device power consumption <1mW Vs. 10s of mW for VCSELs)
- Upstream unknown component and system issues
- Investigate feasibility



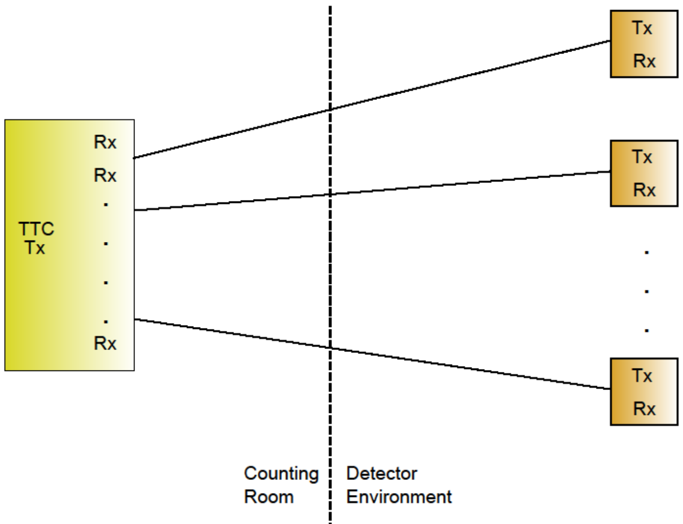
Downstream Transmission

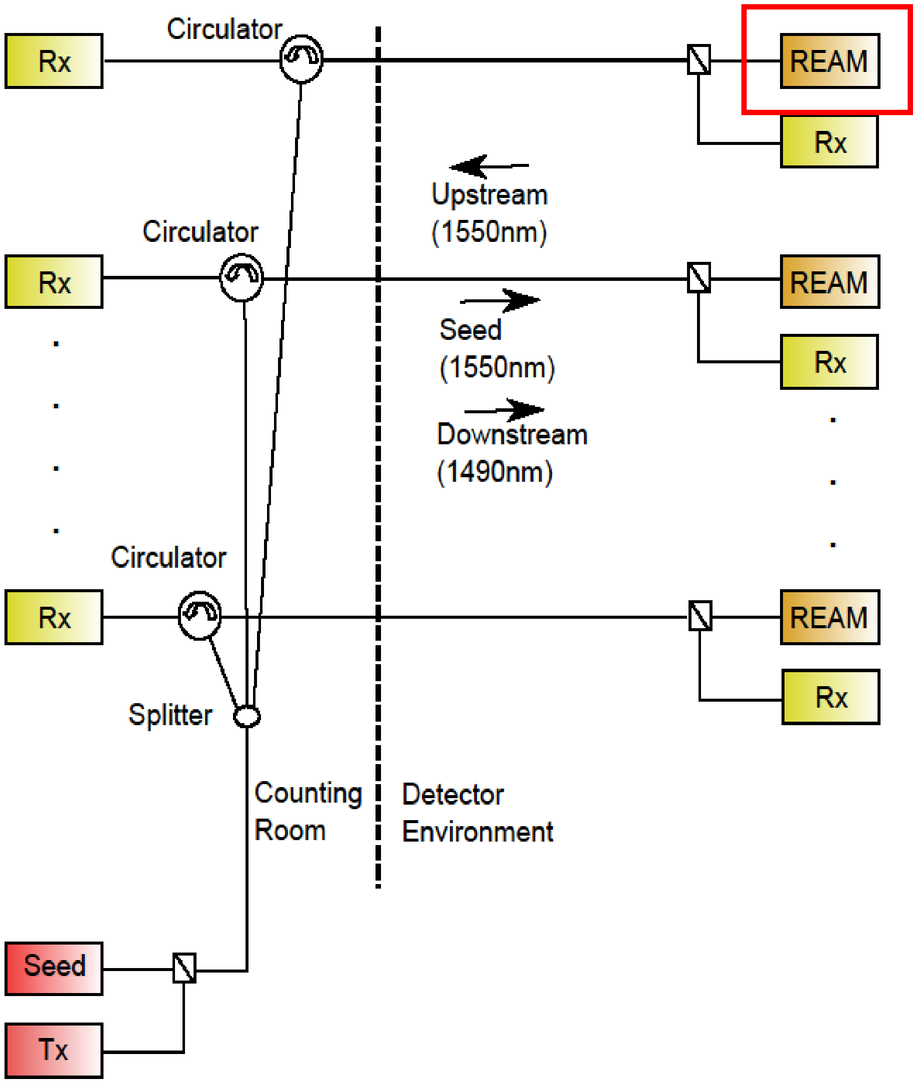
- Use of different wavelengths for upstream and downstream to achieve bidirectionality over single fiber
- Simultaneous transmission of data and information currently transferred over TTC network



Network Architecture

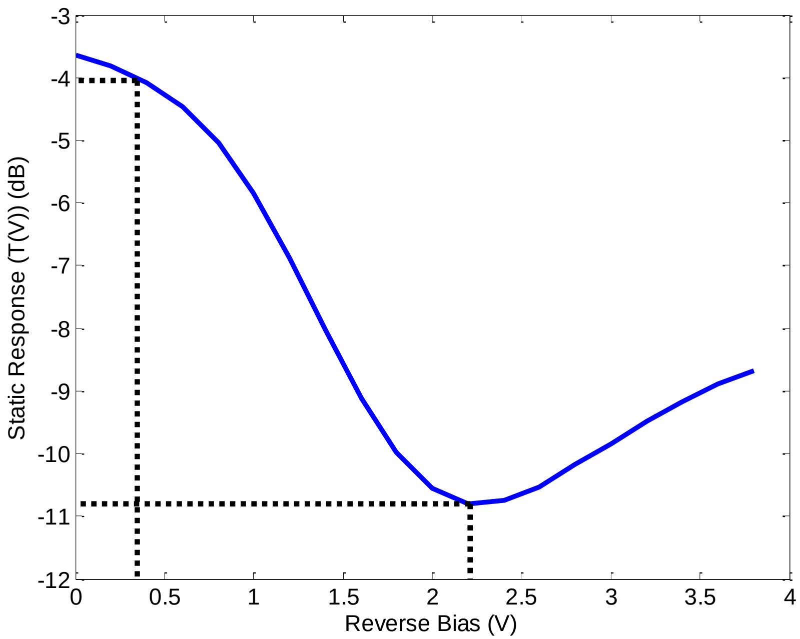
- Downstream simple and similar to current TTC broadcast system
- Bidirectional architecture, using single fiber for US and DS transmission meeting data rate requirements

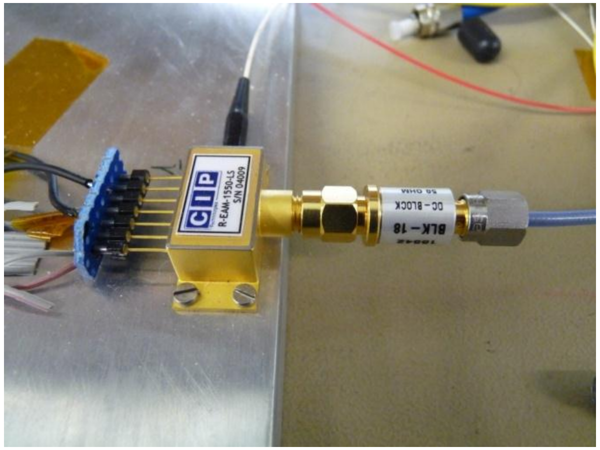


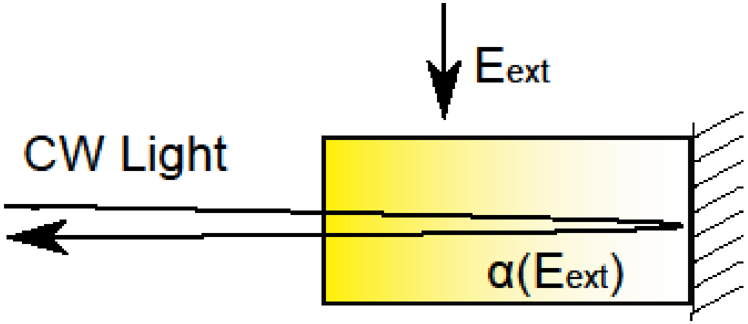


Electroabsorption Modulator – Principle of Operation

- Electroabsorption Modulators absorb light according to the electric field across the device
- Static Response: the ratio of the output light intensity over the input light intensity expressed as a function of the externally applied bias voltage
- The static response can be used to determine the maximum achievable extinction ratio – Extinction Ratio: P(“0”)/P(“1”) – which can have a significant effect on system performance
- The static response depends on input light wavelength and device temperature

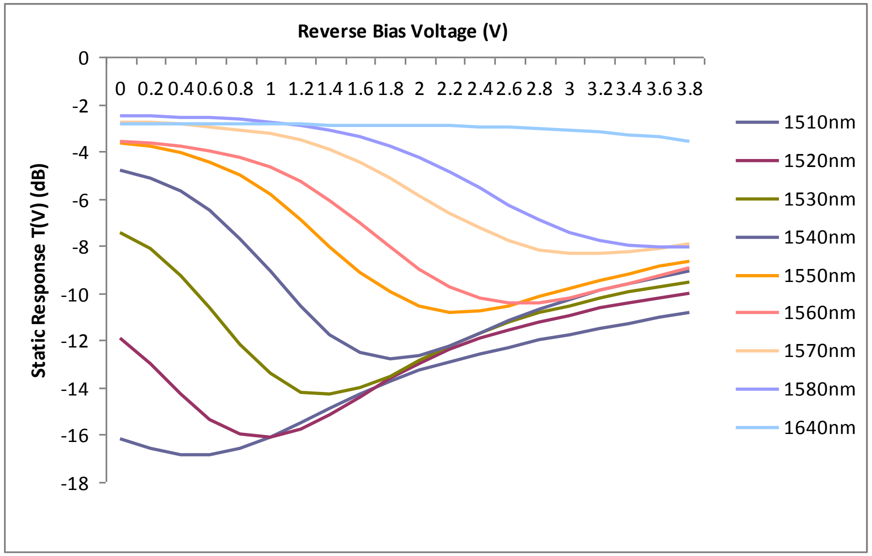


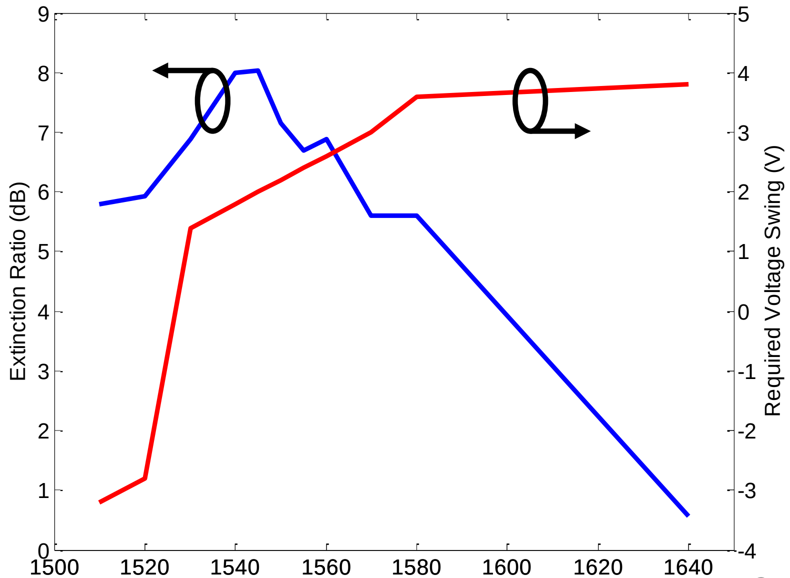




Static Response and Wavelength

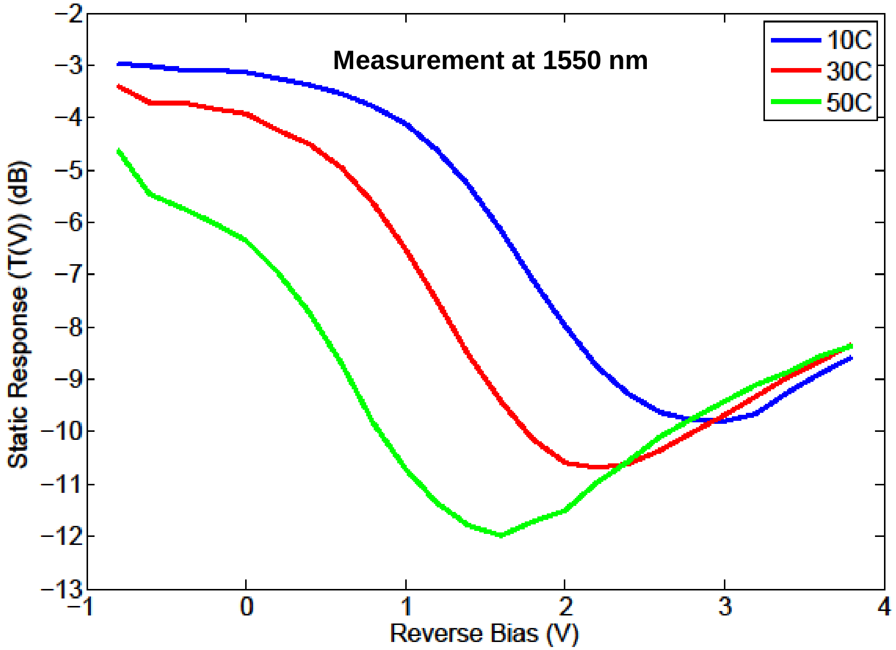
- Important trends with increasing wavelength:
  - Insertion loss decreases
  - Static response minimum moves to higher voltage
- Maximum achievable extinction ratio shows a maximum at ~1545 nm:
  - Hence proper laser can be selected
- Required voltage swing to achieve maximum extinction ratio is ~2V at 1545nm





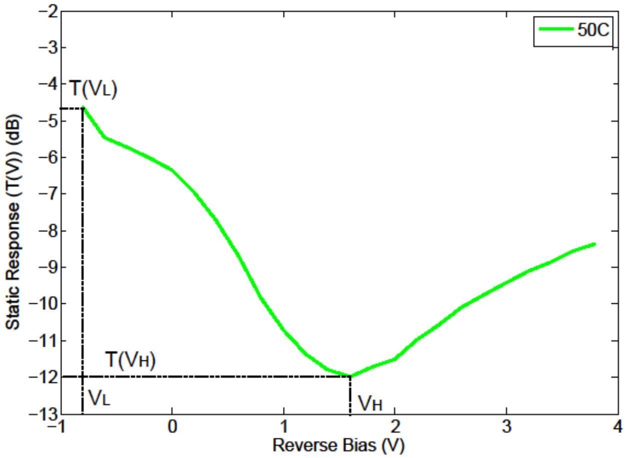
Static Response and Temperature

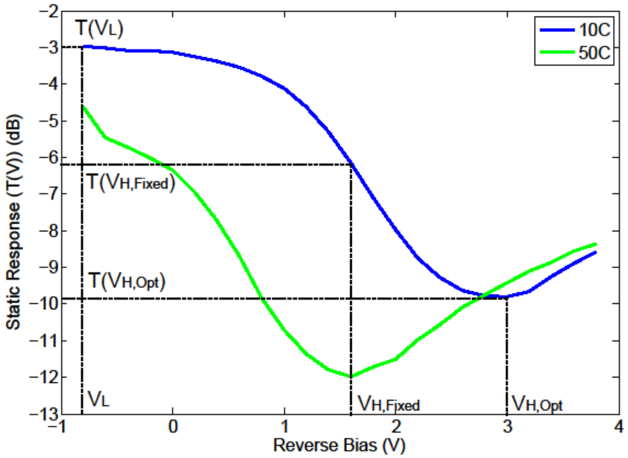
- Increasing temperature leads to:
  - Increase of insertion loss
  - Decrease of the reverse bias voltage level at which the static response minimum occurs
  - Slight increase of the maximum extinction ratio



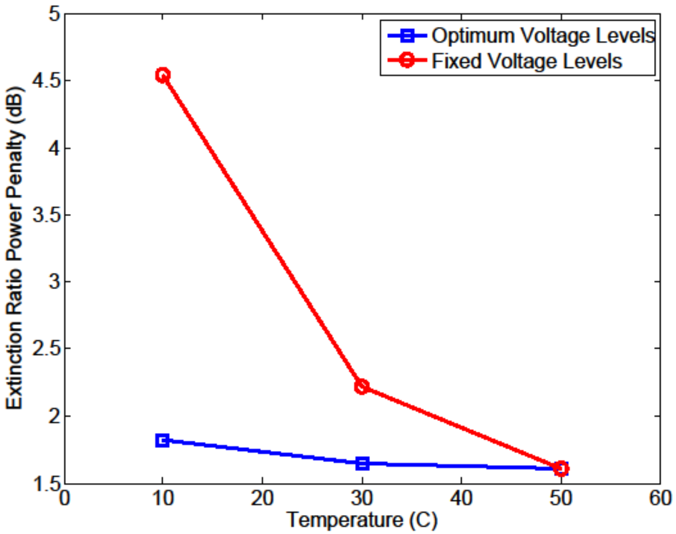
- Device is temperature-sensitive
- In commercial applications use of TEC is an appropriate solution
- Not in our application – mass and power increase

Extinction Ratio Power Penalty Vs. Temperature



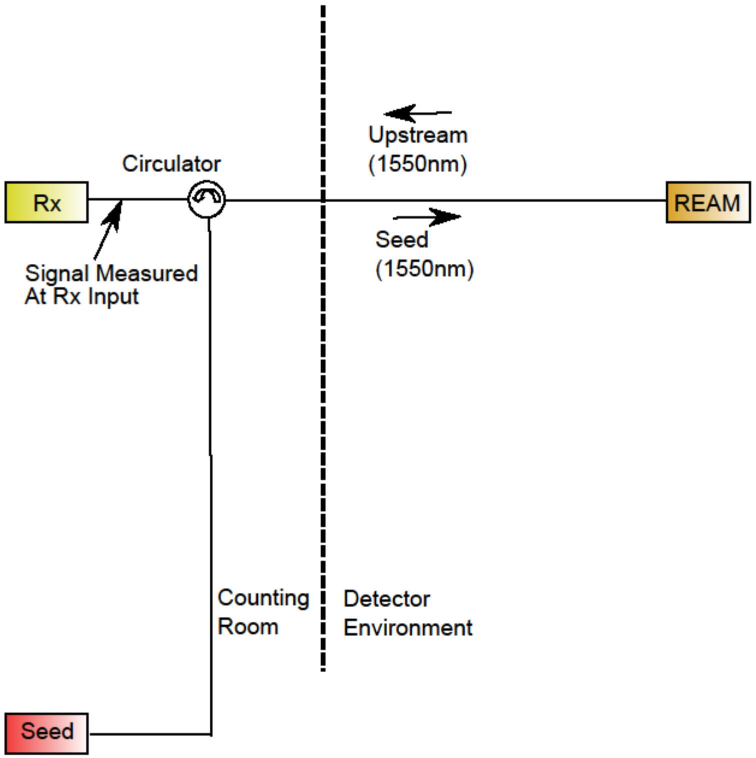


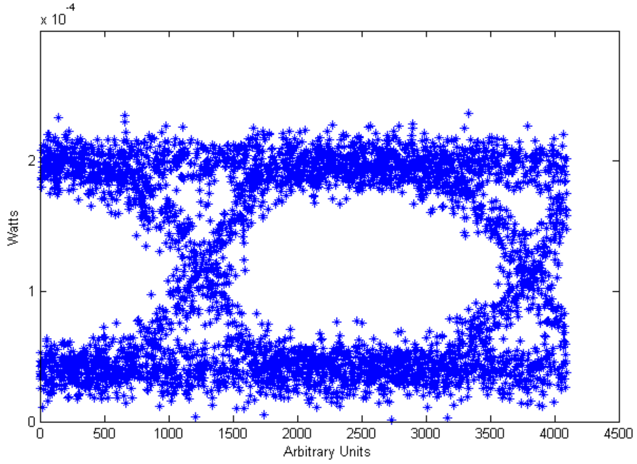
- The extinction ratio power penalty was calculated for two cases:
  - When optimum modulation voltage levels are used at different temperatures (i.e. there is a voltage adaptation mechanism)
  - When fixed modulation voltage levels are used at different temperatures (i.e. no adaptation mechanism)
- There is a significant increase in the extinction ratio power penalty for high temperature variation
- Temperature variations of the order of ~5^{o}C can be easily accommodated



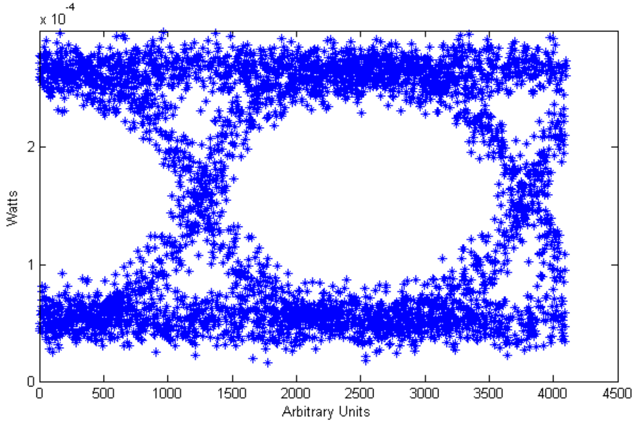
Dynamic Measurements at 1545nm – Eye Diagrams at 10Gbps

$Q=(I_1 - I_0)/(\sigma_1+\sigma_0)$



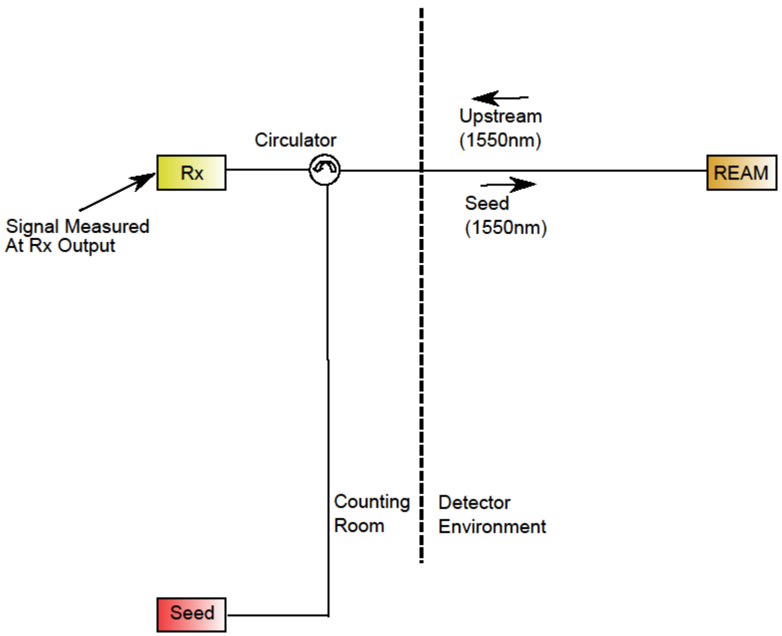


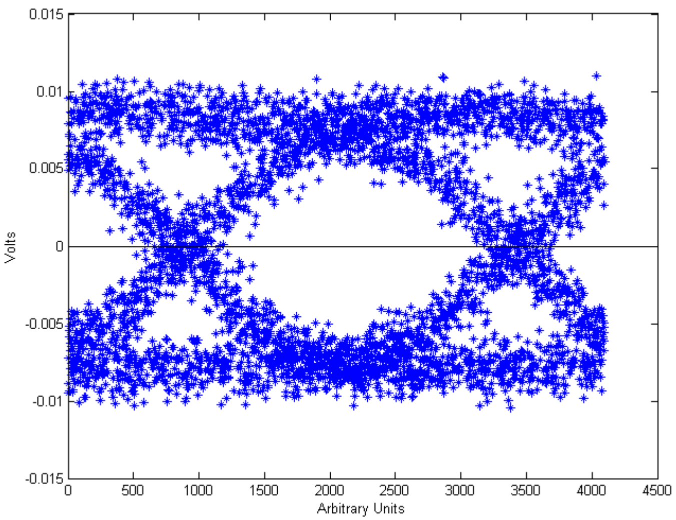
Optical eye diagram, Q=7 (received power=-9.3dBm, equivalent BER=10^{-12})



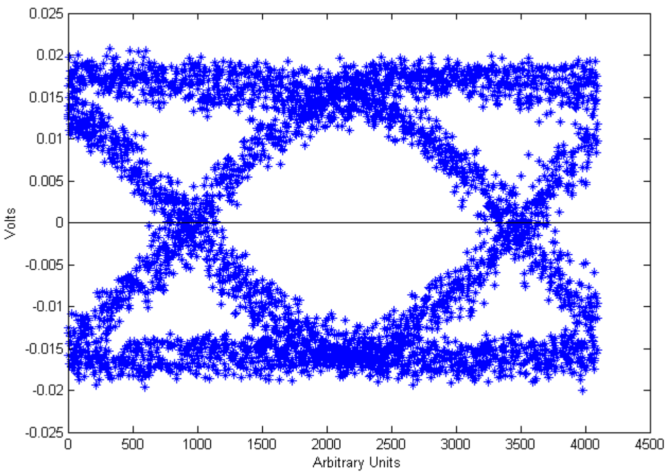
Optical eye diagram, Q=9 (received power=-7.9dBm, equivalent BER=10^{-20})

Dynamic Measurements at 1545nm – Eye Diagrams at 10Gbps





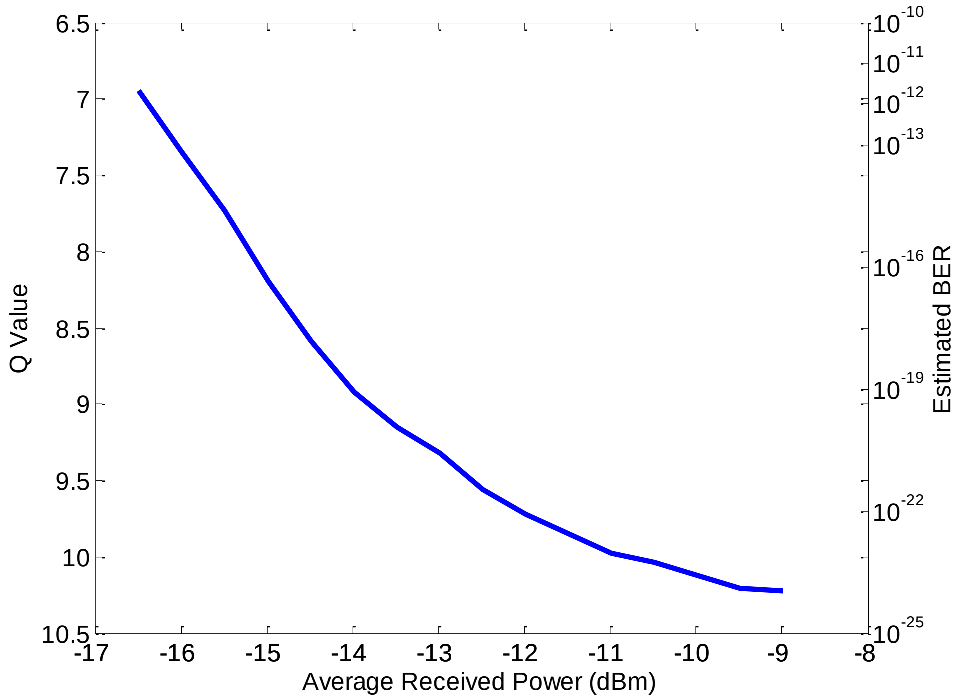
Electrical eye diagram, Q=7 (received power=-16.4dBm, equivalent BER=10^{-12})



Electrical eye diagram, Q=9 (received power=-13.5dBm, equivalent BER=10^{-20})

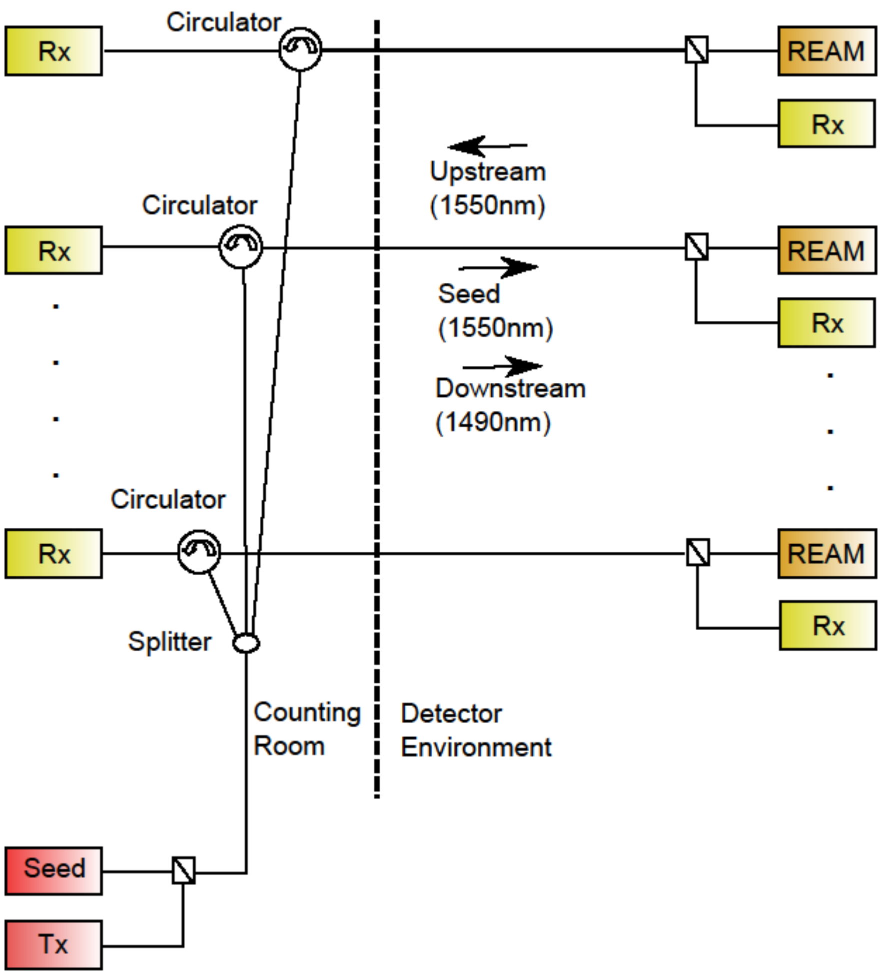
Dynamic Measurements at 1545 nm – Estimated BER Vs Average Power

- The required average power to achieve BER=10^{-12} is P_{rec}=-16.4dBm (launched power: -6.6dBm)
- Using a 10dBm DFB laser would allow us achieving a 1:16 splitting ratio (possibly even 1:32, depending on Rx)

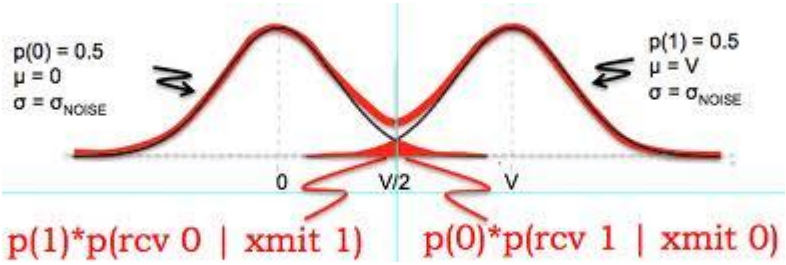


Conclusion

- A new architecture for bidirectional data transfer in the HL-LHC has been presented
- Use of Reflective Electroabsorption Modulators – possible advantages in terms of radiation hardness and power consumption – at the front-end
- Efficient use of resources
- 10Gbps transmission has been experimentally verified
- Radiation hardness tests to be carried out in the near future (order for samples has been already placed)
- Simultaneous operation of REAM as a Tx and Rx to be investigated



Backup slide - Main theme of presentation



We would like to have maximum "distance" between "0" and "1", affected by => received power, extinction ratio

We would also like to minimize noise standard deviation, affected by => thermal noise, relative intensity noise, reflection-induced noise

Backup slide - Sources of power penalty

- Discussed in this presentation:
  - Extinction Ratio
  - Reflections
  - Relative Intensity Noise
- Not discussed in this presentation:
  - Dispersion (not source of major power penalty)
  - Chirping (not source of major power penalty)
  - Modal Noise (irrelevant)
  - Mode partition noise (irrelevant)

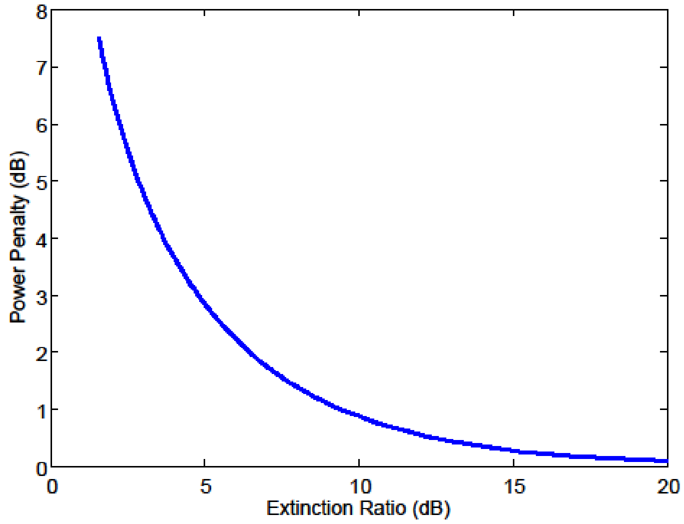
Backup slide - Link budget calculations

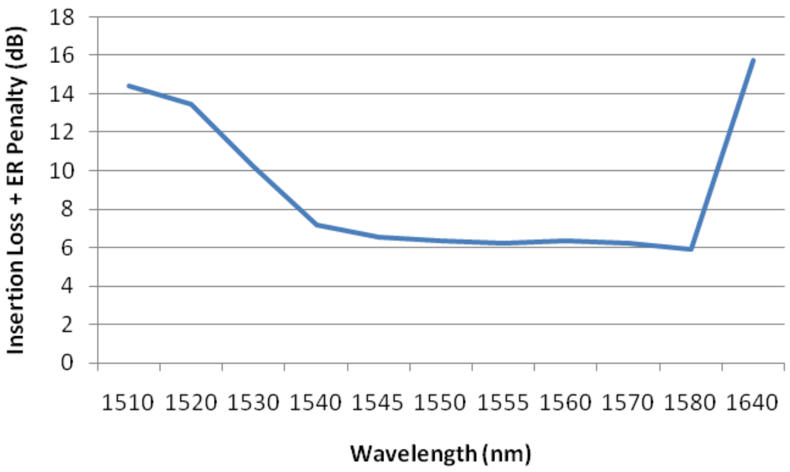
Upstream Link Budget Calculations	
Quantity	Value
Seeding Source Power	7 dBm
Receiver Sensitivity	-19 dBm
Overall Fiber Loss	0.4 dB
Connector Loss	2 dB
Splitting Loss	1+10log(N)
Filter Loss	1.5 dB
Circulator Losses	1.5 dB
REAM Insertion Loss	3.5 dB< $\alpha_{REAM,ins}$ <5 dB
Power Penalties – Upstream	$\alpha_{Pen,US}$
Power Margin	19.6 – 10log(N) – $\alpha_{REAM,ins}$ – $\alpha_{Pen,US}$

Downstream Link Budget Calculations	
Quantity	Value
Transmitter Power	0 dBm
Receiver Sensitivity	-25 dBm
Overall Fiber Loss	0.2 dBm
Connector Loss	2 dB
Splitting Loss	1+10log(N)
Filter Loss	0.75 dB
Circulator Losses	0.75 dB
Power Penalties – Downstream	$\alpha_{Pen,DS}$
Power Margin	20.3 – 10log(N) – $\alpha_{Pen,US}$

Backup Slide: Extinction ratio power penalty and choice of optimum wavelength

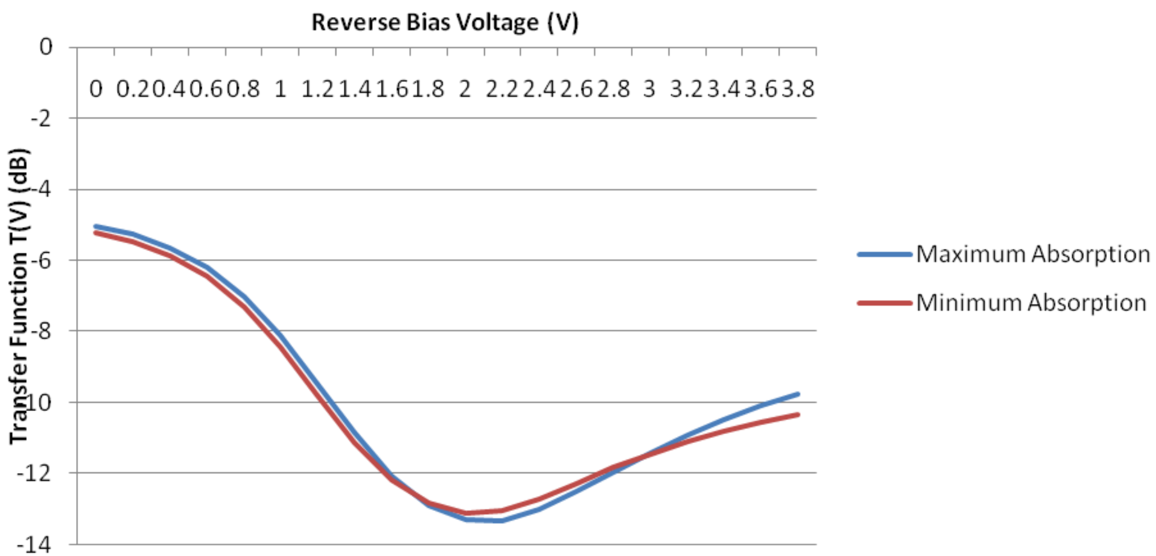
- There is a relatively wide wavelength region where the overall power penalty caused by the imperfect extinction ratio and the insertion loss is stable
- 1545 nm has been judged to be a good compromise between low required voltage swing and optimum overall power penalty





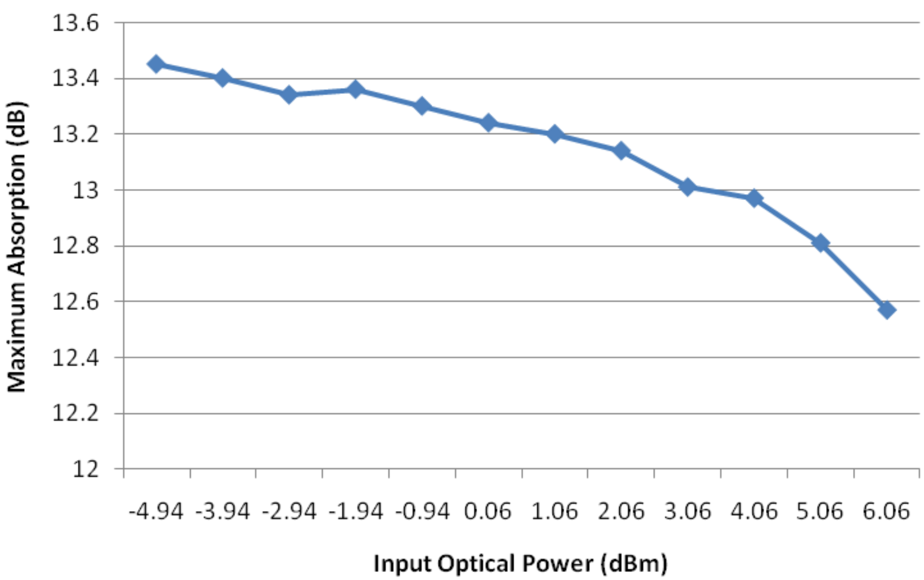
Backup slide - Static response and polarization

- Polarization sensitivity at 1545 nm has been measured
- Maximum extinction ratio difference 1 dB (ignored in the rest of the document)



Backup slide - Saturation/Optical input power and maximum absorption

- Maximum absorption variation <1dB
- Input optical power dynamic range (>10dB) much higher than the required



Backup slide - Noise Measurements

- Optical head thermal noise (BW=30GHz): 10.50uW
- Electrical head thermal noise (BW=20GHz): 260uV
- Electrical head + 10G PIN Diode: 780.5uV
- PIN diode induced thermal noise: 735.8uV
- Equivalent optical thermal noise:2.9uW
- Overall “Conversion efficiency” (measured by comparing optical and electrical noise): ~265V/W
- Implied receiver sensitivity (Q=7): -14dBm
- Tunable laser relative intensity noise: ~ -146dB/Hz
- Insertion of REAM between tunable laser and scope **did not** lead to noise increase (no shot noise added+no reflection-induced performance degradation)

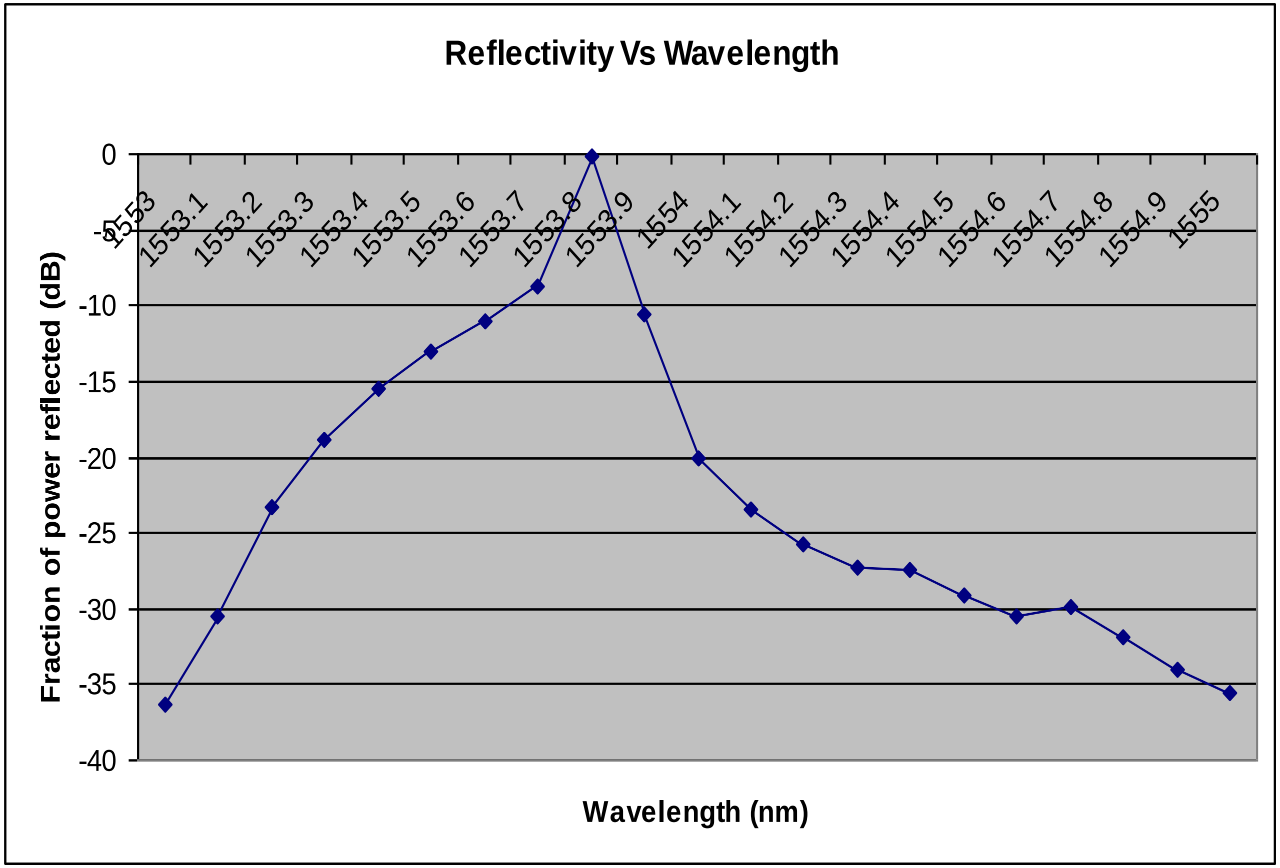
Backup slide - Impact of Relative Intensity Noise

- For Q=9, RIN=145dB/Hz, RIN power penaly ~0.1dB (negligible)

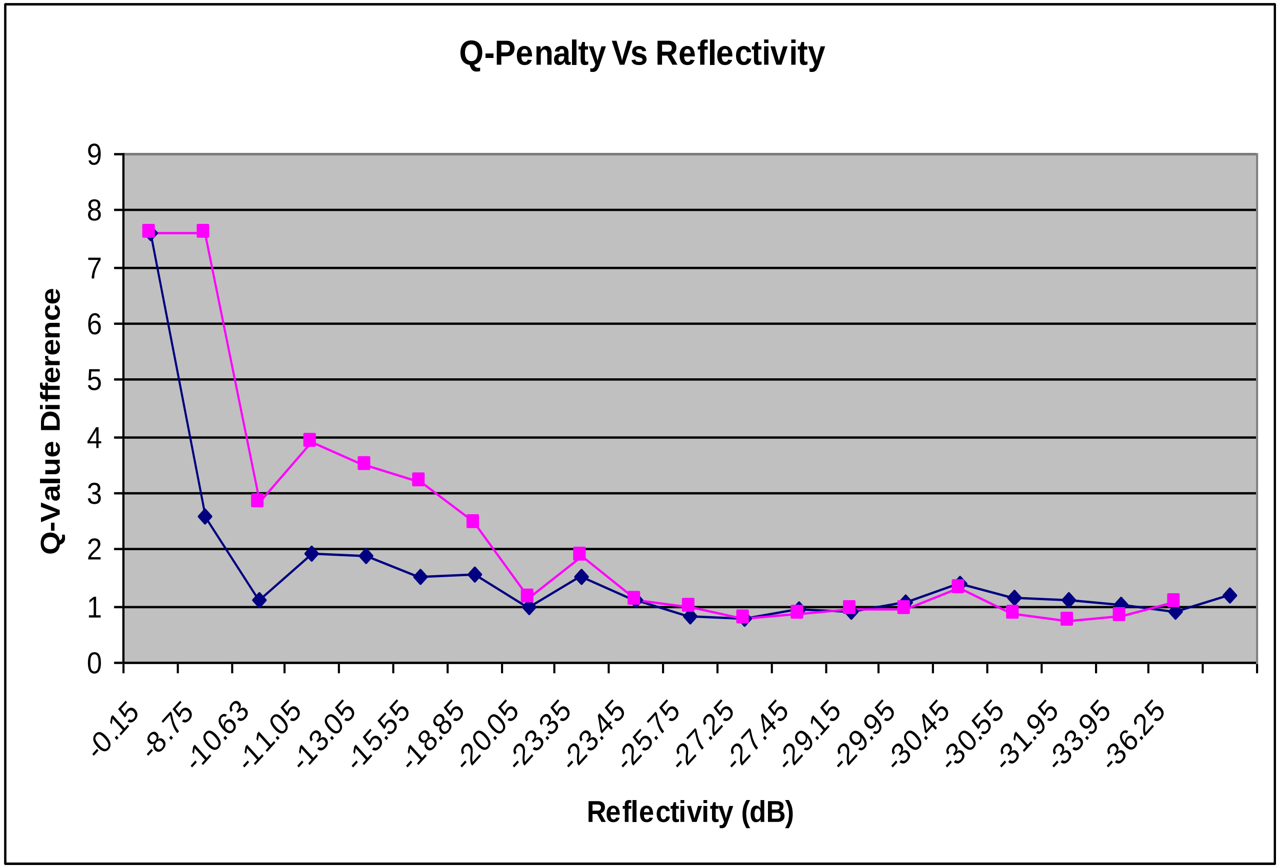
Backup slide - Impact of reflections

- Can affect system performance through the following mechanisms:
  - Beating of signal and reflections at the receiver
  - Cavity formation
  - Disturbance of laser diode operation

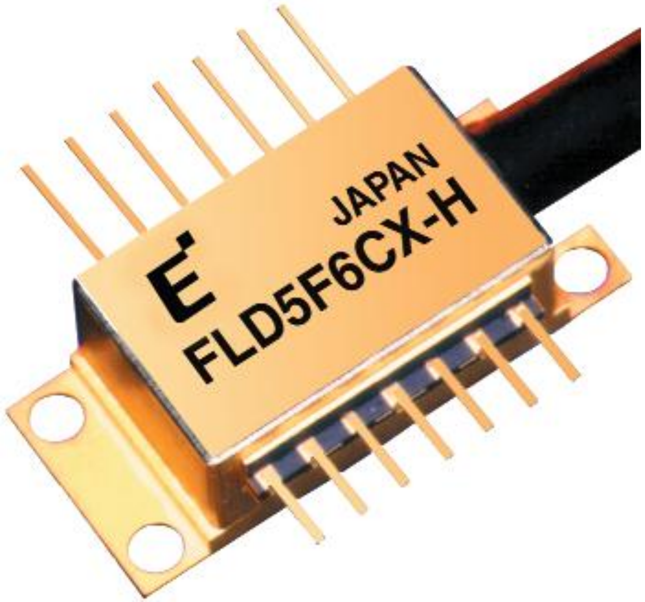
Backup slide - Impact of reflections Bragg grating reflectivity vs wavelength



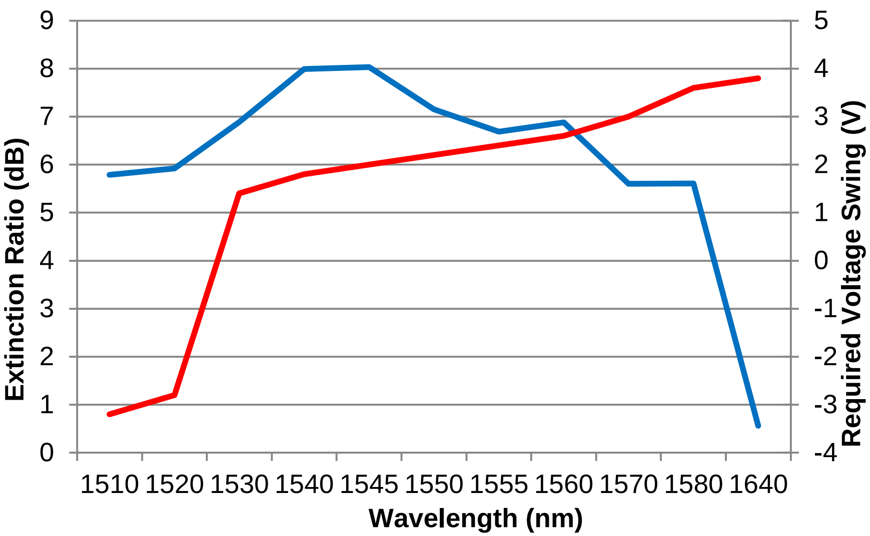
Backup slide - Impact of Reflections



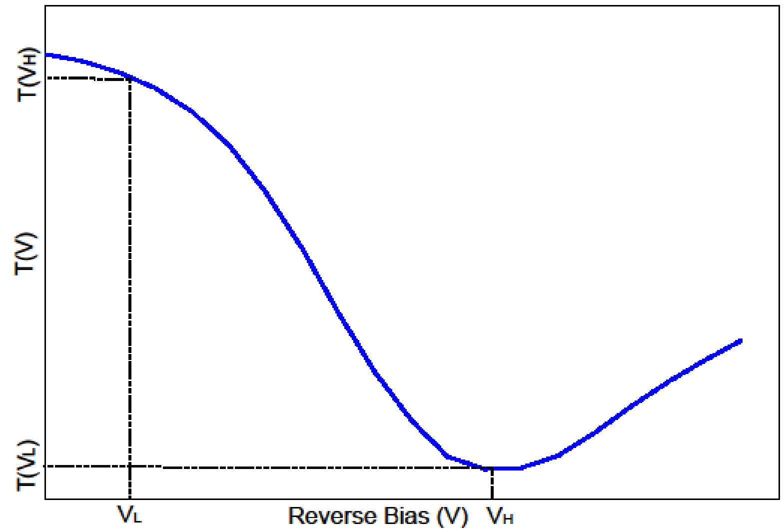
- Laser diode depicted: 3cm(length)x1.5cm(width)
- Circulator depicted: 5.5mm(diameter)x80mm(length)



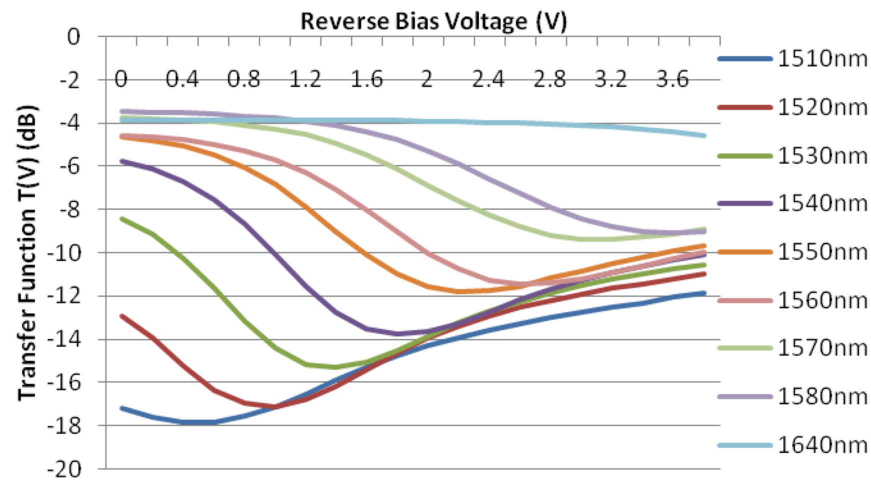
Graphs



Extinction Ratio (dB)
Required Voltage Swing (V)
Wavelength (nm)
1510 1520 1530 1540 1545 1550 1555 1560 1570 1580 1640



T(VH)
T(V)
T(VL)
VL
Reverse Bias (V)
VH



Reverse Bias Voltage (V)
Transfer Function T(V) (dB)
1510nm
1520nm
1530nm
1540nm
1550nm
1560nm
1570nm
1580nm
1640nm