Compensation of TIA bandwidth limitation with FIR filters

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Electrical active filters

- TDM shared upstream channel requires two independent signal paths to assure proper 1G and 10G data stream recovery
- Signal path switching is not possible without violating the layering rules for the Ethernet stack
- Signal needs to be identified at the PMD layer, processed accordingly and then fed to the proper CDR module for clock/data recovery
- The recovered data stream (reshaped, timed, recovered) is then forwarded to the proper MAC stack (IEEE 802.3ah for 1 Gbit/s signal, future IEEE 802.3av for 10 Gbit/s signal)
- Several approaches are possible:
    - one Rx block, optimized for 10 Gbit/s, with a signal splitter in electrical domain (I);
    - two independent Rx blocks, signal split in the optical domain, optimized for the given data rate (II);

Dual rate PMD – motivation [2]

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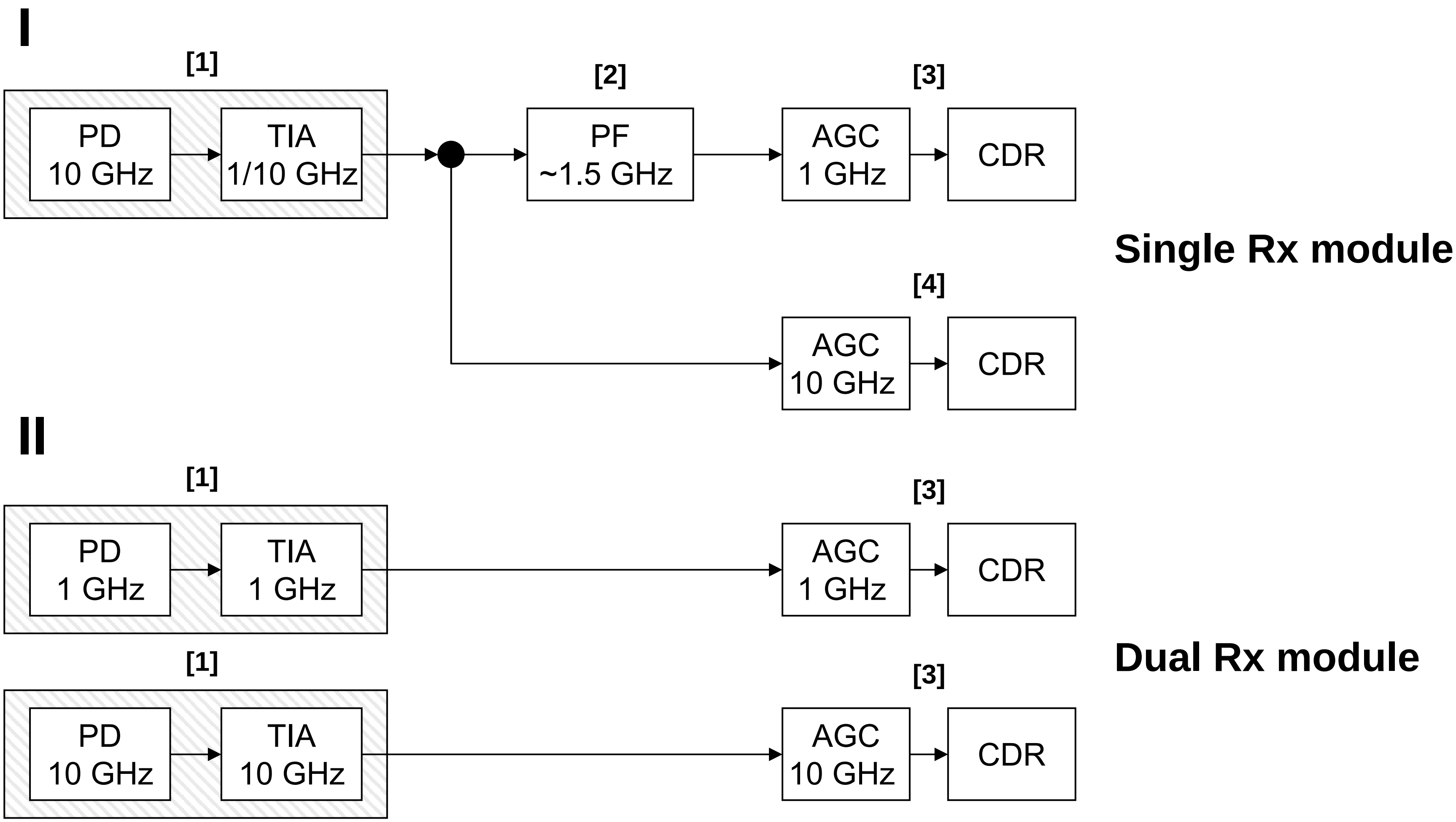
Possible dual rate PMD structures



Dual rate PMD – motivation [3]

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Technical hurdles with configuration I

- 10 Gbit/s receiver has sensitivity penalty at 1 Gbit/s data rate
  - 1 Gbit/s systems will suffer from additional penalty which is not accounted for in IEEE 802.3ah specifications
  - Backward compatibility problems – some of the 1 Gbit/s systems will not work correctly once migrated to 1G/10G environment
- 1G/10G TIA required – it was argued that such a structure **is** inherently technically challenging (see presentation of Ad Hoc on Dual Rate PMD from March 2007)
  - Requires gain adjustment to compensate for decreased 10 Gbit/s receiver sensitivity at 1 Gbit/s data rate
  - How can I be achieved if only MAC client layer knows the data rate of the incoming burst ?

Dual rate PMD – motivation [4]

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Technical hurdles with configuration II

- Requires signal splitting in the optical domain – 3 dB signal power is lost
  - Can be compensated using SOA based pre-amp
  - Additional noise source in the system
  - 10 Gbit/s SOA is required – significant module cost element
- Provides two independent signal pathways
  - Both Rx and TIA modules in each path are optimized for the given data rate
  - What happens in the 10 Gbit/s signal path when 1 Gbit/s signal is received and vice versa ?
- 1 Gbit/s birst mode receiver block will be unused once 802.3ah equipment migrates to 10 Gbit/s data rate

Dual rate PMD – motivation [5]

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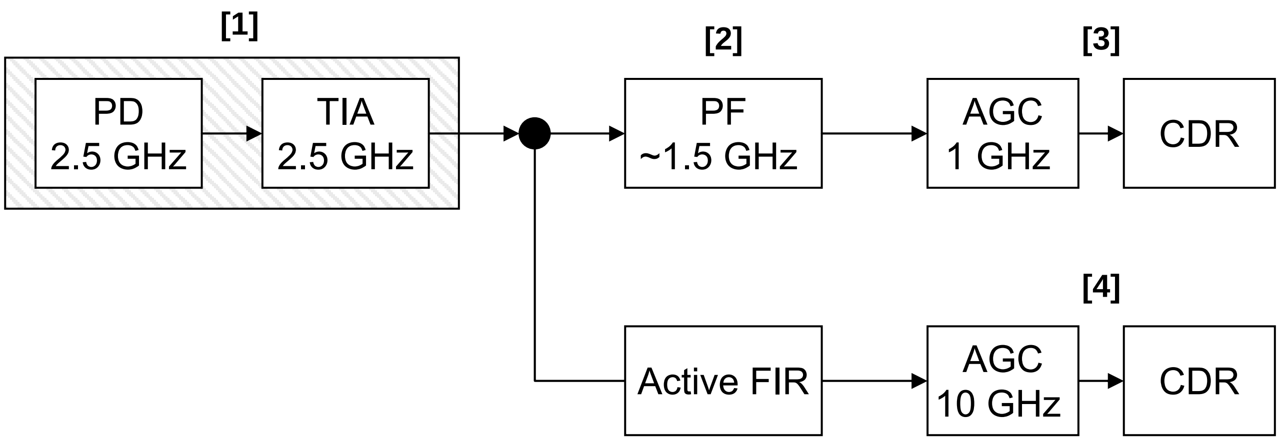
Intermediate solution



Single Rx module

- Use 2.5 Gbit/s qualified Rx/TIA module,
- 1 Gbit/s signal path: remove higher frequency components from the signal and use 1 Gbit/s compliant AGC and CDR modules
- 10 Gbit/s signal path: recover 10 Gbit/s signal received by 2.5 Gbit/s capable Rx (adds ISI-like effect to the opriginal 10 Gbit/s signal), using active FIR filters manufactured in CMOS technology. Once receivered, amplify using 10 GHz **AGC** (*TIA)* postamp and feed to 10 GHz capable CDR/AGC modules

Compensation of TIA bandwidth limitation with FIR filters

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Primer on FIR filters

Electrical compensator filters
Introduction

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Electrical active filters

- Known for long to compensate distortion in electrical systems (communication systems, data storage, speech, …)

- Recently, focus has been on high speed such filters for compensation of dispersion impairments in legacy, long haul optical links for data rates ≥ 10 Gbit/s.

- Measurement results show that such filters also optimize channel by compensating electrical device distortion; optimization of system noise bandwidth was also verified to improve channel OSNR penalty.

- Initial prototypes implemented in high-speed III-V semiconductor processes (GaAs, InP), but recent progress on integration technology makes possible implementation on low-cost CMOS.

Structure of a Finite Impulse Response (FIR) filter.

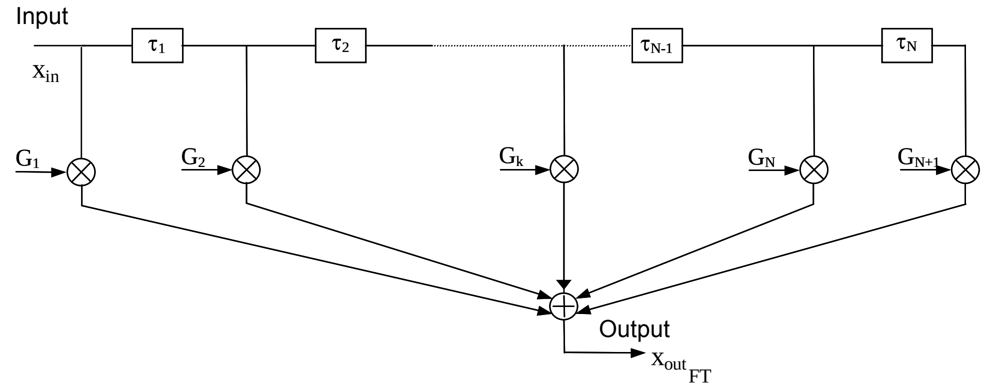
- Structure I is not realizable (zero delay from multipliers to output sum node).

- Tap delay:
- **(II)** $\tau_k = \tau_{ik} + \tau_{ok}$
- **(III)** $\tau_k = \tau_{ik} - \tau_{ok}$

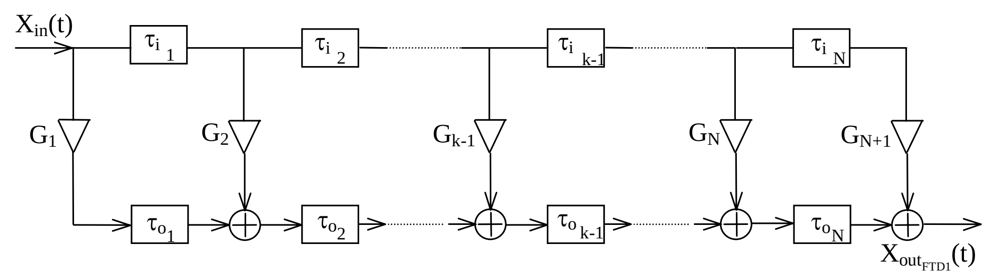
- Structure III preferred since large delay values are an issue in microwave monolithic designs.

$$H(f) = \sum_{k=1}^{N} G_k \exp(-j2\pi f(k-1)\tau)$$

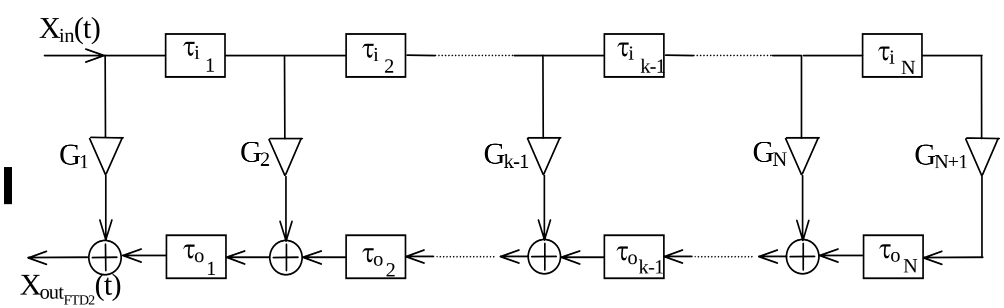
I



II



III



Electrical compensator filters
Electronics of 10Gbps filter prototype (FLT10G) implemented for dispersion compensation (adjustable)

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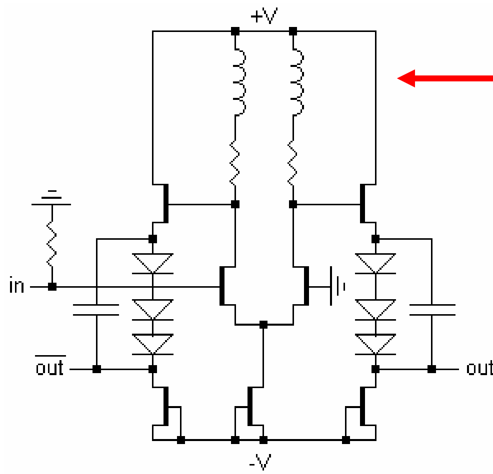

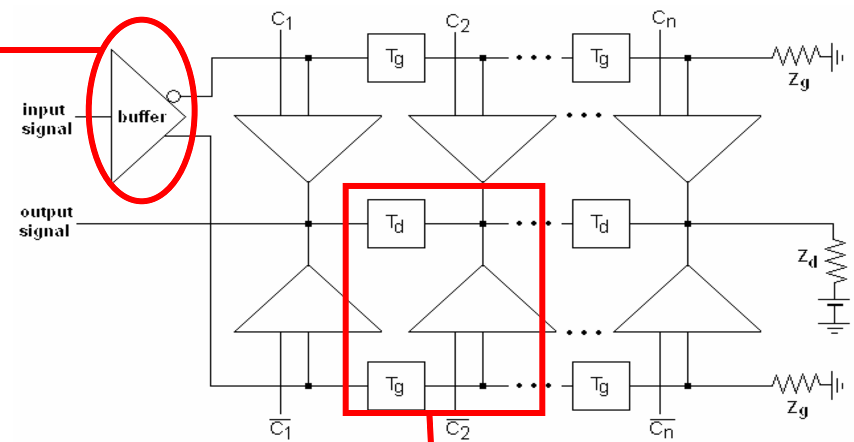

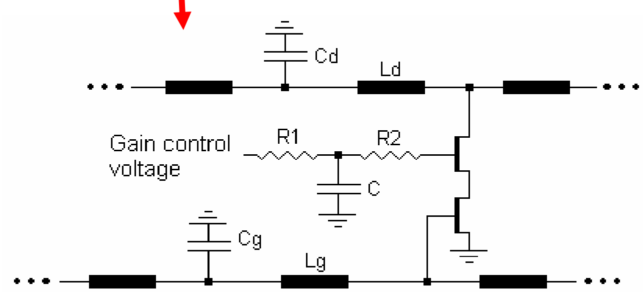

- Filter allows positive and negative coefficients.

- The cascode was selected for the adjustable G_n gain coefficient.

- An external circuitry acts on the control voltages to activate the cells and synthesize the optimized transfer function.

Electrical compensator filter (FLT10G) developed 10 Gbit/s FIR filter prototype

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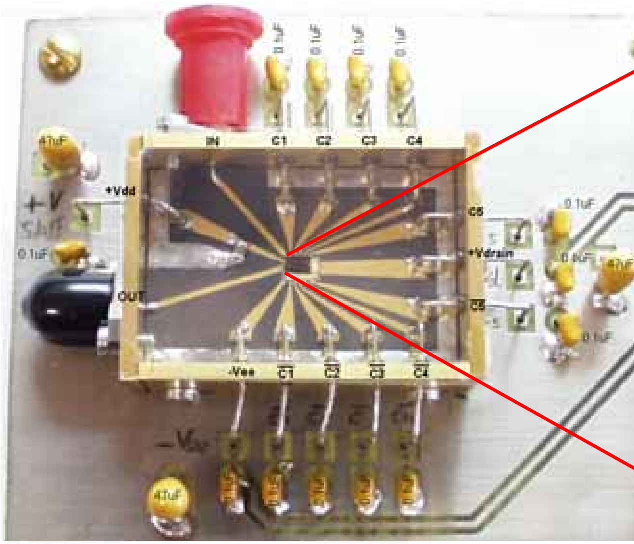
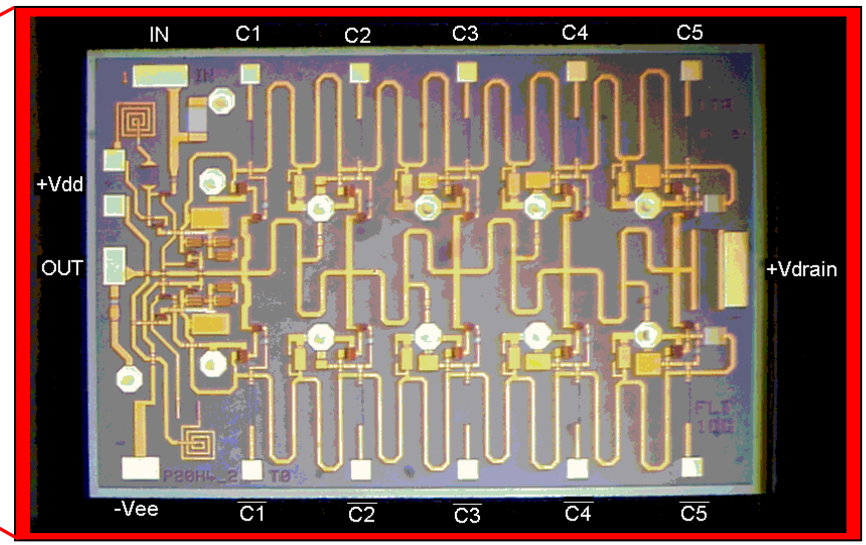


Assembled filter



Internal filter structure

Parameters of the FIR filter prototype

- Technology: 0.2um gate length
- Power consumption: < 300mW (with discrete, external components)
- Chip size: 3x2 mm

Electrical compensator filters
Measured results for the 10Gbit/s FIR filter prototype (FLT10G) – frequency domain characterization

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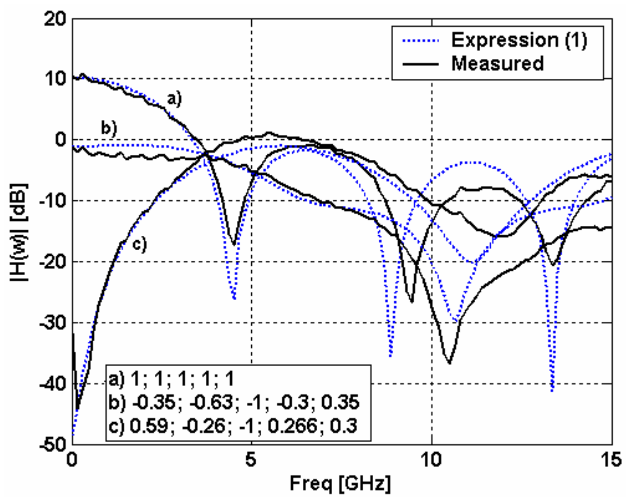
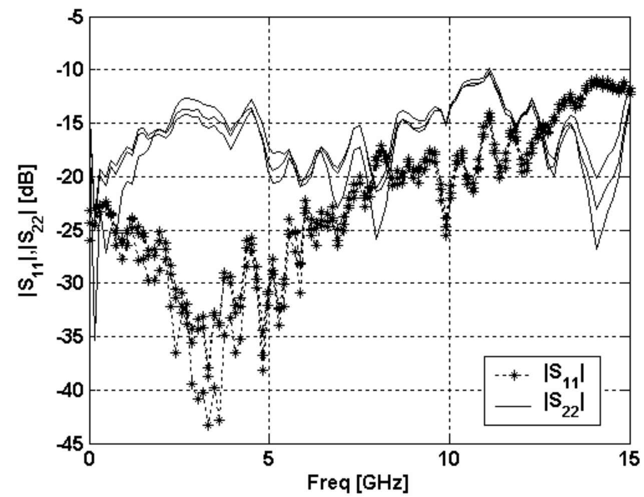


Comparison of filter prototype and ideal filter



$$H(f) = \sum_{k=0}^{4} G_k \exp(-j2\pi f k\tau)$$

- ➢ The filter prototype can synthesize transfer functions of the low-pass and high-pass type with good approximation to the ideal theoretical filter.

- ➢ Very good input and output matching is measured independent of synthesized transfer function

Electrical compensator filters
Measured results for the 10 Gbit/s FIR filter prototype (FLT10G) – distortion compensation

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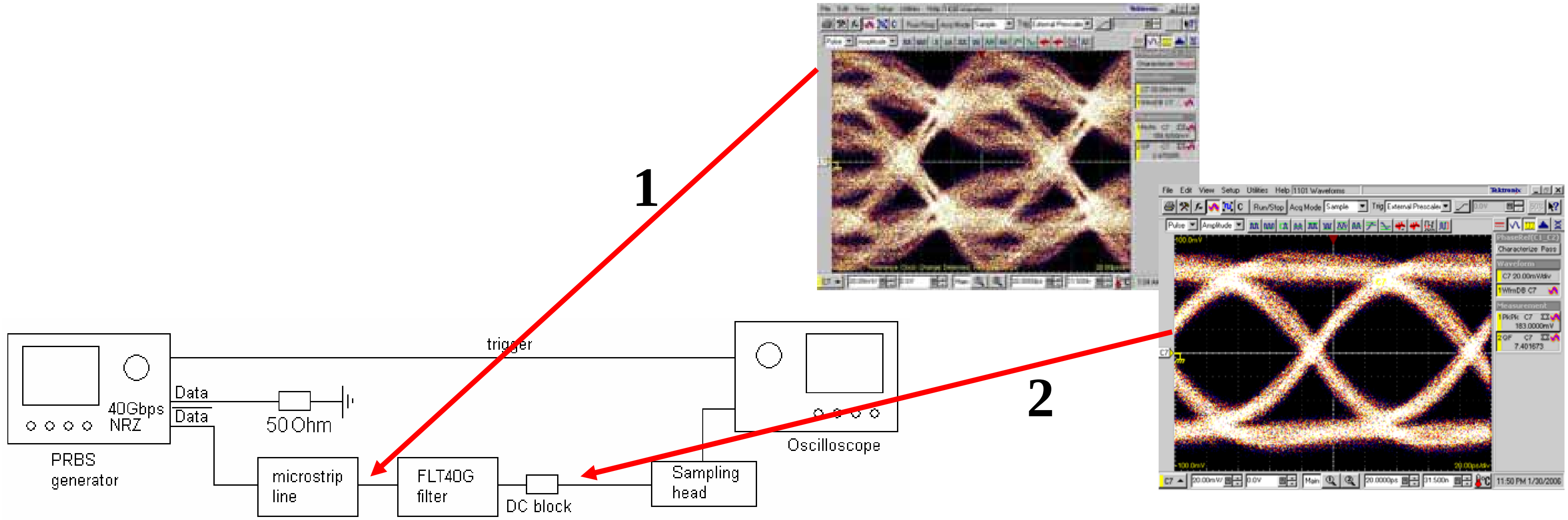
- A dispersive microstrip line was included in series with electrical filter.
- The microstrip degrades the signal due to group delay dependence with frequency (1).
- Compensation of a 2720 ps/nm dispersive line using the prototype filter is possible (2)
- The filter is capable of compensating the phase distortion of the line: it synthesizes a transfer function that approximates a 160km SSMF span.



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System simulation

Compensation of TIA bandwidth limitation with FIR filters – system model

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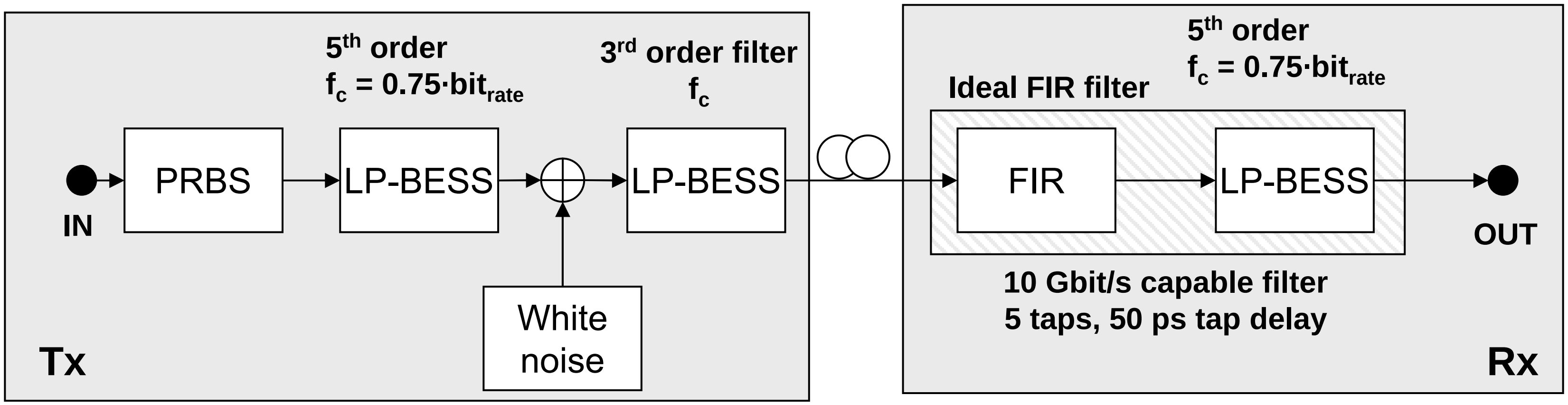

➢ "PRBS" block – and ideal NRZ rectangular signal generator, followed by a 5th order Low Pass (LP) Bessel filter, with -3dB cut-off of 7.5 GHz to "smooth" the signal,

➢ white optical noise in transmission channel accounted for,

➢ 2nd LP-BESS filter is the 5th order LP Bessel filter, with -3dB cut-off frequency f_c to emulate detector and amplifier bandwidth limitation.

➢ "FIR" block - an ideal FIR filter in series with 5th order LP Bessel filter with cut-off frequency of 10 GHz, approximates FLT10G, the implemented filter for compensation of dispersion in long-haul 10 Gbit/s optical systems .

Ideal filter, equivalent to FLT10G, f_c = 1.5 GHz
No optical noise in the signal channel

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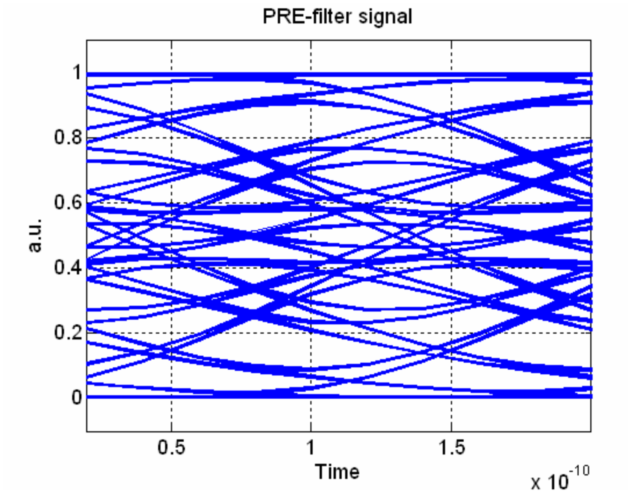
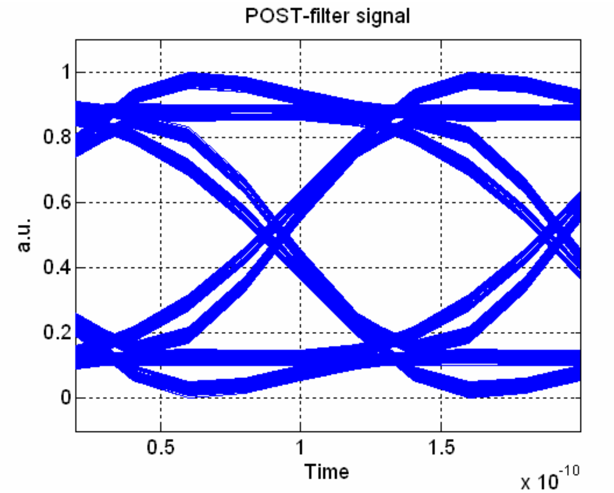
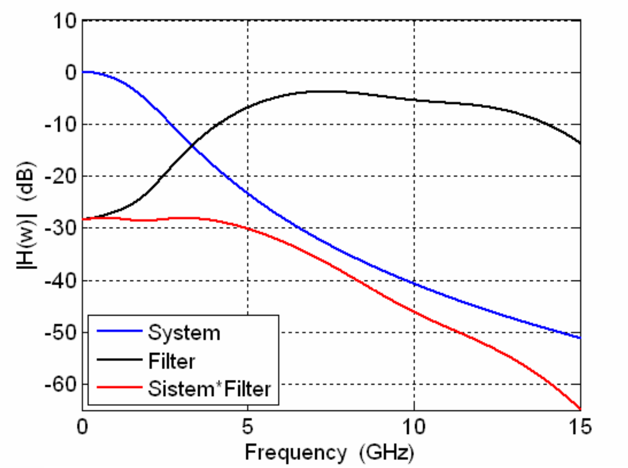
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.

Best result of 500 iterations of the optimization routine.

Optimum normalized filter coefficients [C1..C5] equal to

-0.1215 -0.0614 0.3847 -0.3363 0.0961

FIR filter details:

Tap count: 5

Tap delay: 50 ps

Compensation of TIA bandwidth limitation with FIR filters – FIR optimization process

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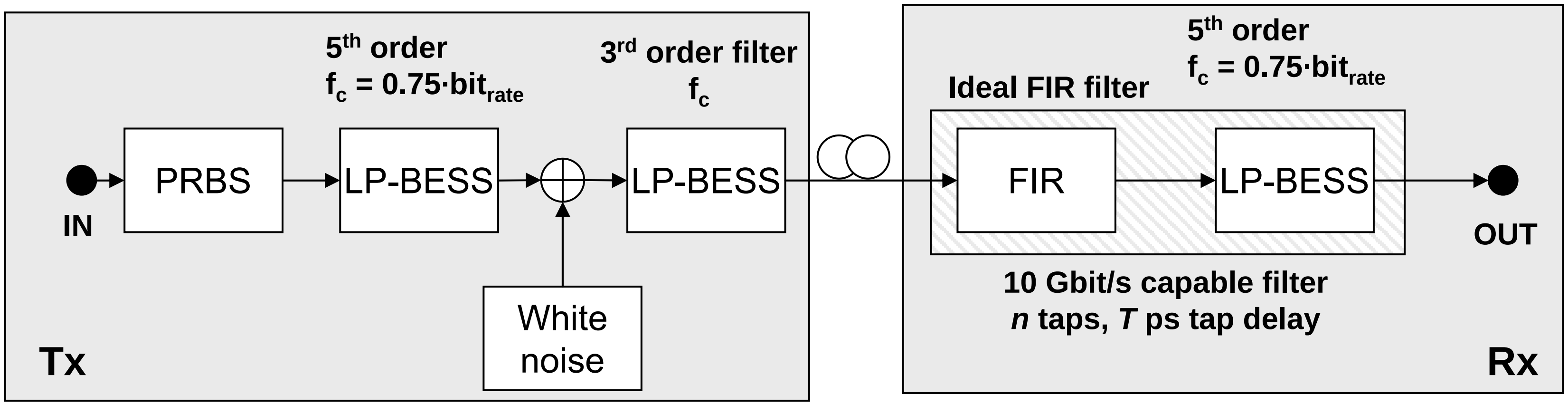

- “PRBS” block, 2^{nd} LP-BESS – the same blocks and functionality as in the previous model
- “FIR” block - an ideal FIR filter in series with 5^{th} order LP Bessel filter with cut-off frequency of 10 GHz, number of taps and tap delay as indicated below,
- Optimization step: for each tap delay [30..150] ps – step 10ps, coefficients considered [5..10] – step 1, 200 interactions limit per specific case of (delay, coefficient). Simplex multivariable optimization process was utilized.

Optimized ideal filter, f_c = 1.5 GHz
No optical noise in the signal channel

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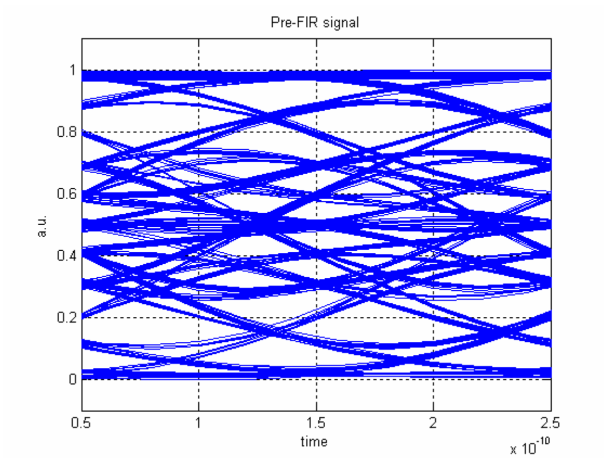
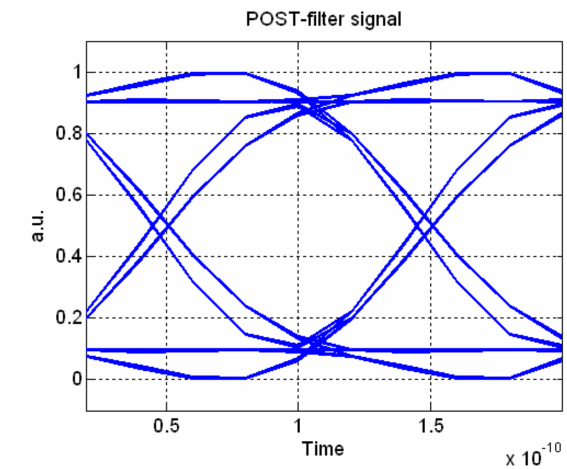
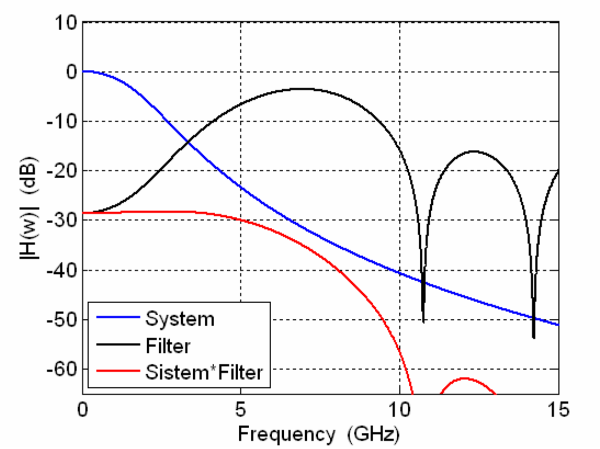
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.
Best result of 200 iterations of the optimization routine.
Optimum normalized filter coefficients [C1..C7] equal to
-9.667759e-002 2.349434e-001 9.158423e-002 -2.735487e-001 -4.471889e-002 1.919084e-001 -6.661873e-002

FIR filter details:
Tap count: 7
Tap delay: 40 ps

Optimized ideal filter, f_c = 1.5 GHz
20 dB OSNR

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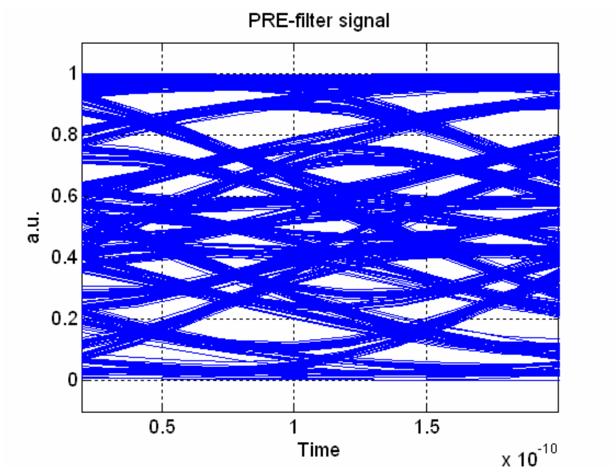
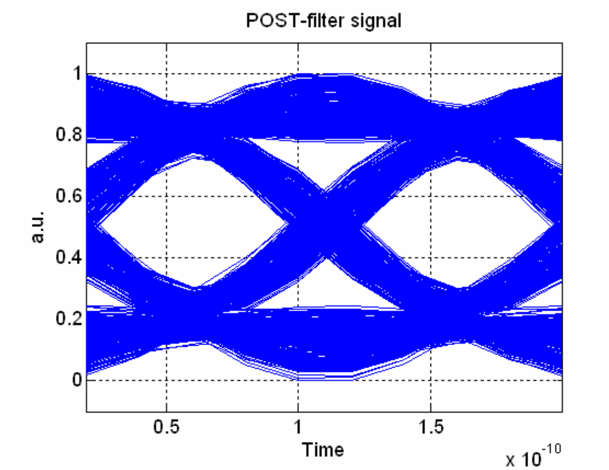
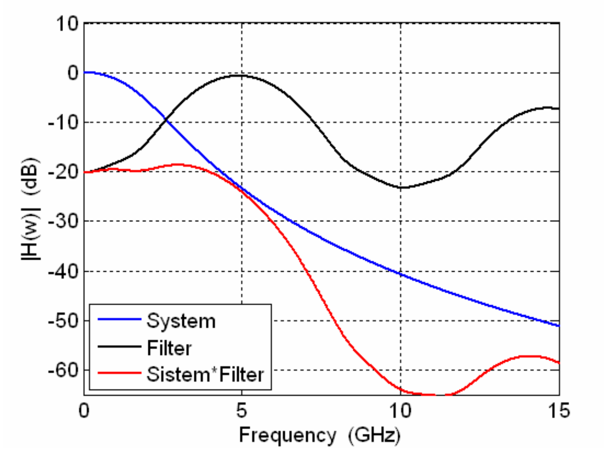
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.
Best result of 200 iterations of the optimization routine.
Optimum normalized filter coefficients [C1..C6] equal to
1.972066e-003 -4.764727e-002 3.610430e-001 -
3.541380e-001 1.857001e-001 -4.949961e-002

FIR filter details:
Tap count: 6
Tap delay: 100 ps

Optimized ideal filter, f_c = 1.5 GHz
30 dB OSNR

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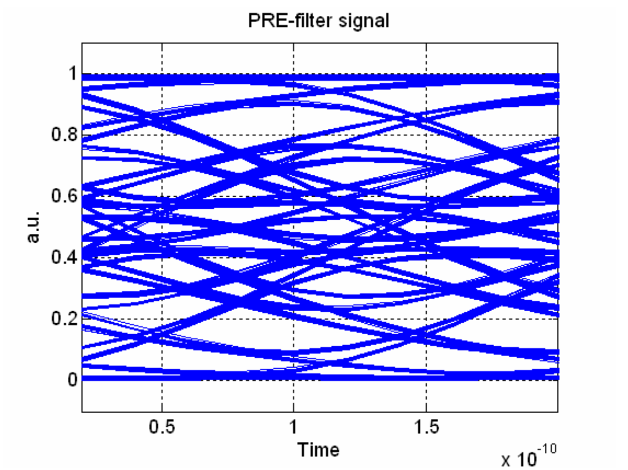
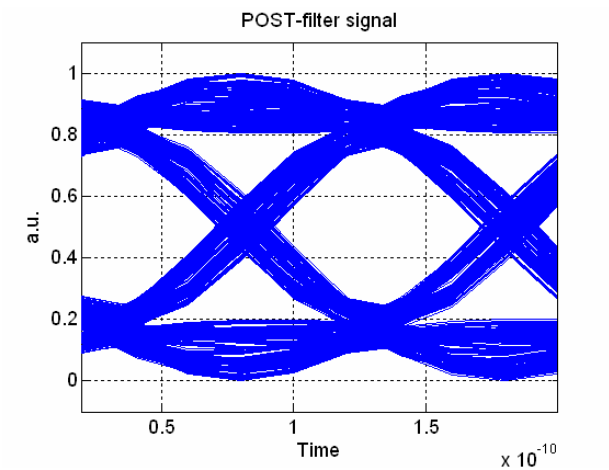
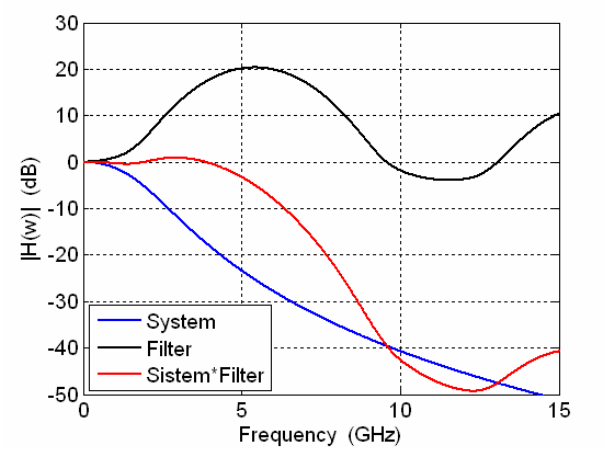
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.

Best result of 200 iterations of the optimization routine. Optimum normalized filter coefficients [C1..C6] equal to 3.716038e-002 -4.617673e-001 3.980980e+000 -4.310592e+000 2.224569e+000 -4.703503e-001

FIR filter details:

Tap count: 6

Tap delay: 90 ps

Optimized ideal filter, f_c = 1.0 GHz
No optical noise in the signal channel

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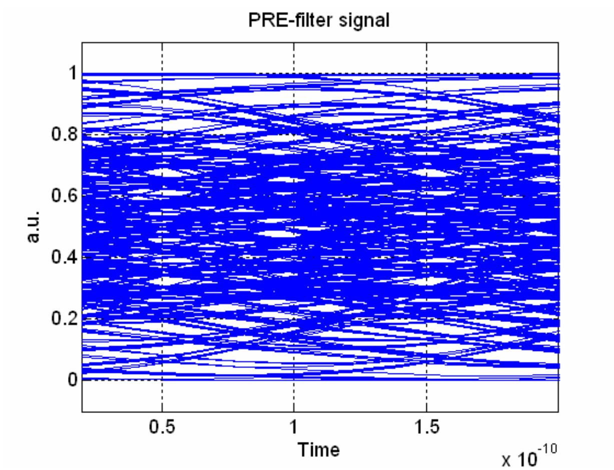
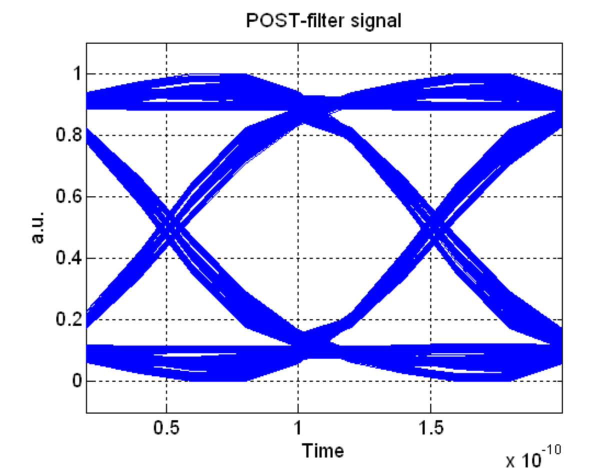
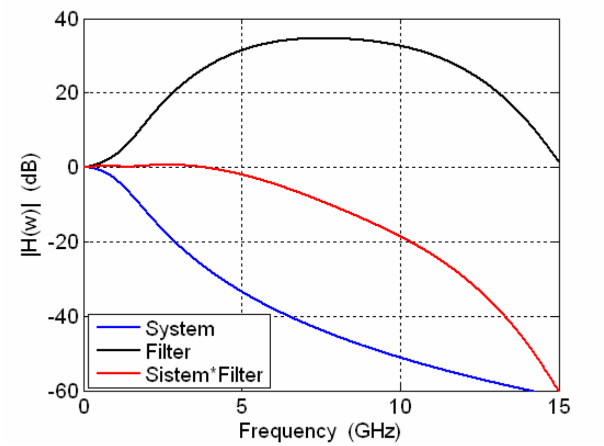
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.

Best result of 200 iterations of the optimization routine.

Optimum normalized filter coefficients [C1..C6] equal to

-3.235037e+000 2.113696e+001 -2.992065e+001

1.419941e+001 2.161409e-001 -1.396818e+000

FIR filter details:

Tap count: 6

Tap delay: 60 ps

Optimized ideal filter, f_c = 1.0 GHz
30 dB OSNR

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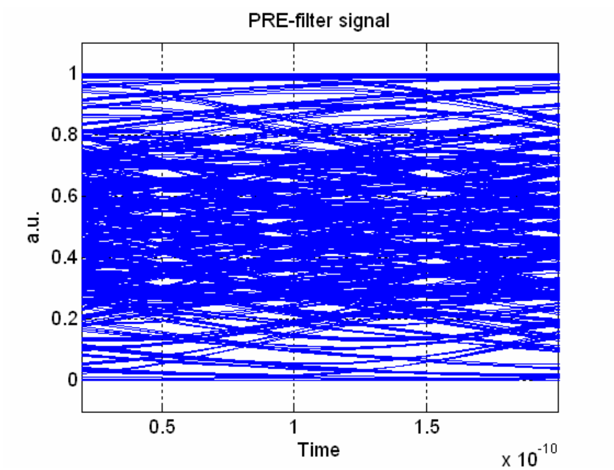
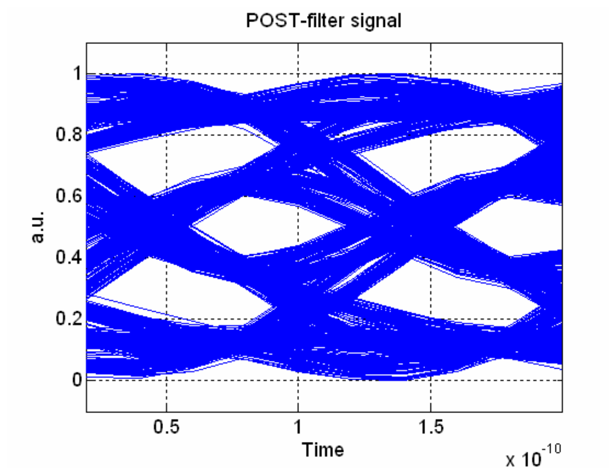
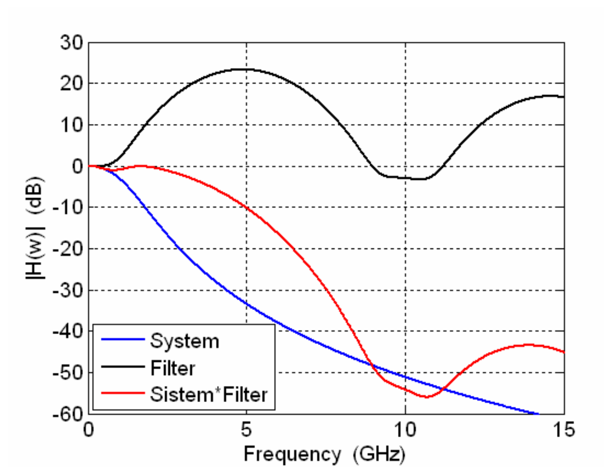
Before FIR filter



After FIR filter



Signal spectra



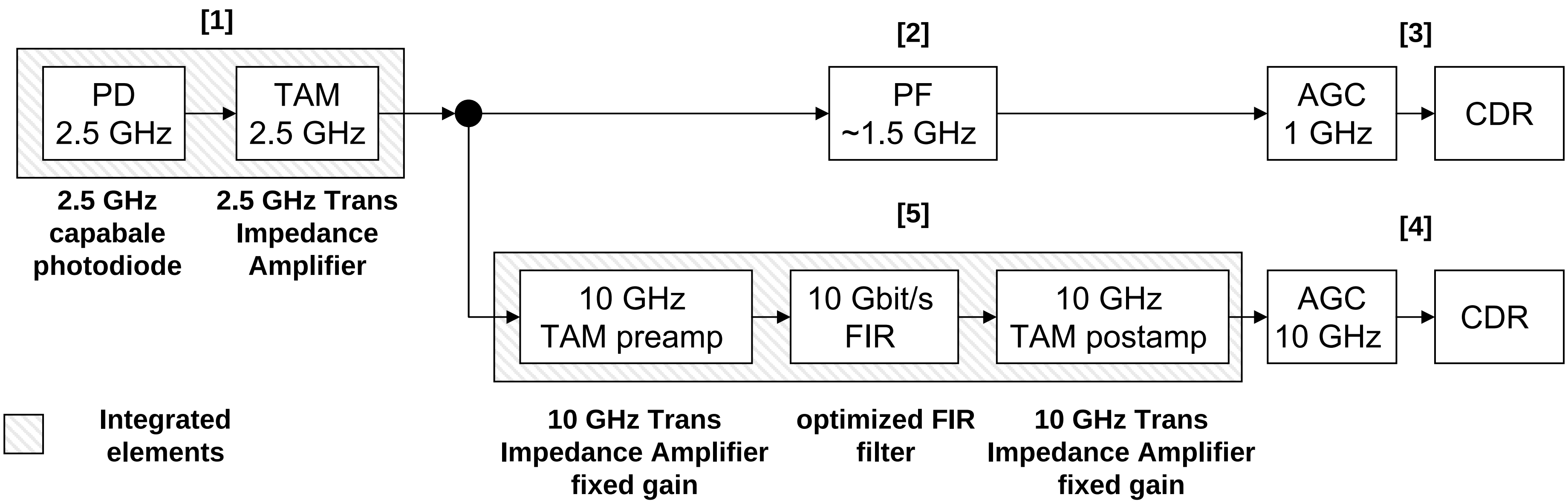
Signal before and after a FIR filter.
Best result of 200 iterations of the optimization routine.
Optimum normalized filter coefficients [C1..C5] equal to 1.585076e-001 -1.519647e+000 6.279686e+000 -5.890403e+000 1.971856e+000

FIR filter details:
Tap count: 5
Tap delay: 100 ps
No pre/post amp

Compensation of TIA bandwidth limitation with FIR filters

Alternative dual rate PMD

Considered dual rate PMD structure



[1] – 2.5 Gbit/s receiver module (2.5 Gbit/s qualified PD and Trans Impedance Amplifier – TAM)

[2] – Passive Filter (PF) adjusting the signal spectrum from 2.5 GHz to 1.5 GHz

[3] – 1 Gbit/s capable AGC and CDR modules (IEEE 802.3ah compliant)

[4] – 10 Gbit/s capable AGC and CDR modules – specification defined by IEEE 802.3av Task Force

[5] – integrated FIR filter with fixed coefficients and pre/post TAM amplifiers with fixed gain – retrieves the 10 Gbit/s signal from 2.5 GHz optimized signal path

Optimized ideal filter, equivalent to FLT10G, f_c = 2.5 GHz
No optical noise in the signal channel

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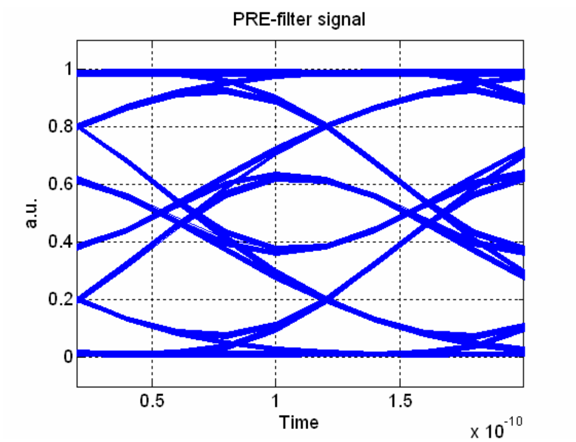
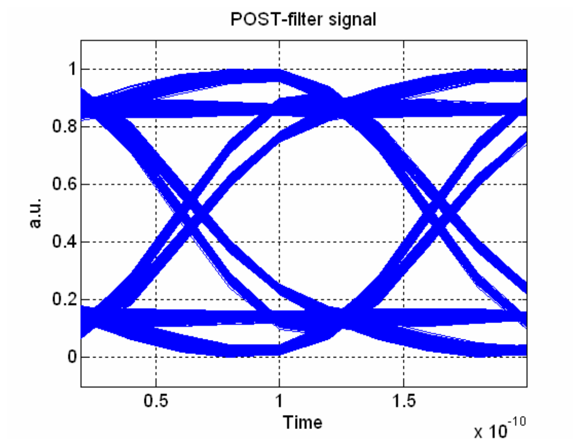
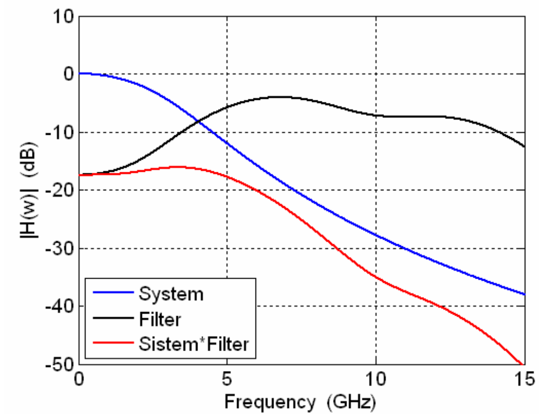
Before FIR filter



After FIR filter



Signal spectra



Signal before and after a FIR filter.

Best result of 200 iterations of the optimization routine.
Optimum normalized filter coefficients [C1..C5] equal to
-0.0864 0.1053 0.3490 -0.3465 0.1128

FIR filter details:

Tap count: 5
Tap delay: 50 ps
No pre/post amp

Conclusions

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- presented results are for simulation only – currently we will start laboratory tests for FIR filtered 1G/10G signals
    - application of a single 2.5 Gbit/s capable receiver seems like a reasonable alternative for 2 receiver system and splitting signal in optical domain.
    - 1 Gbit/s signal path uses a PF to shape the signal spectrum and remove any high frequency components
    - 10 Gbit/s signal path uses an active FIR filter to recover the original signal and open the eye diagram
    - FIR filter will recover the 1 Gbit/s signal – the 10 Gbit/s CDR will not lock then to the incoming bit stream ...
- the signal amplitude after FIR filter block is very low – approximately -40 dB
    - pre-amplification can be useful to maximize the dynamic range of the FIR filter
    - the prototype filter has the input voltage range of ± 200 mV – a pre-amp would have to limit the output voltage to this range (**specific for this particular FIR filter implementation**)
    - post-amplification is required to assure proper signal voltage to be fed to AGC block and the following CDR

Future work

- lab experiments with the FIR filter prototype
- G / 10 G signal tests with the dual rate PMD structure (discrete components)
- no burst mode receiver available – we will have to work with no AGC block then
- provide more realistic simulation results accounting for electrical noise sources