Applying the IBIS-AMI Redriver Framework to Electrical-Optical-Electrical Links

Tripp Worrell — MathWorks

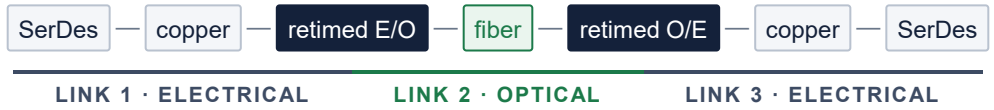
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What I Want to Cover

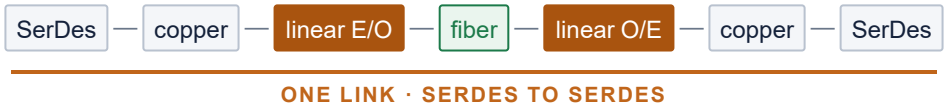
1. Optical modules used to contain a retimer. Linear drive removes it.
2. Four optical effects that now reach the SerDes Rx
3. The IBIS solution: **a redriver**
4. Init and GetWave when the modulator is nonlinear
5. Future considerations

Traditional Optics Was Three Links. Linear Drive Is One.



Retimed module — THREE links

- A retimer at each end of the fiber recovers the clock and regenerates the signal
- Two electrical links and one optical link, in series
- Three budgets, each verified independently
- Optical impairments **stay inside the optical link**

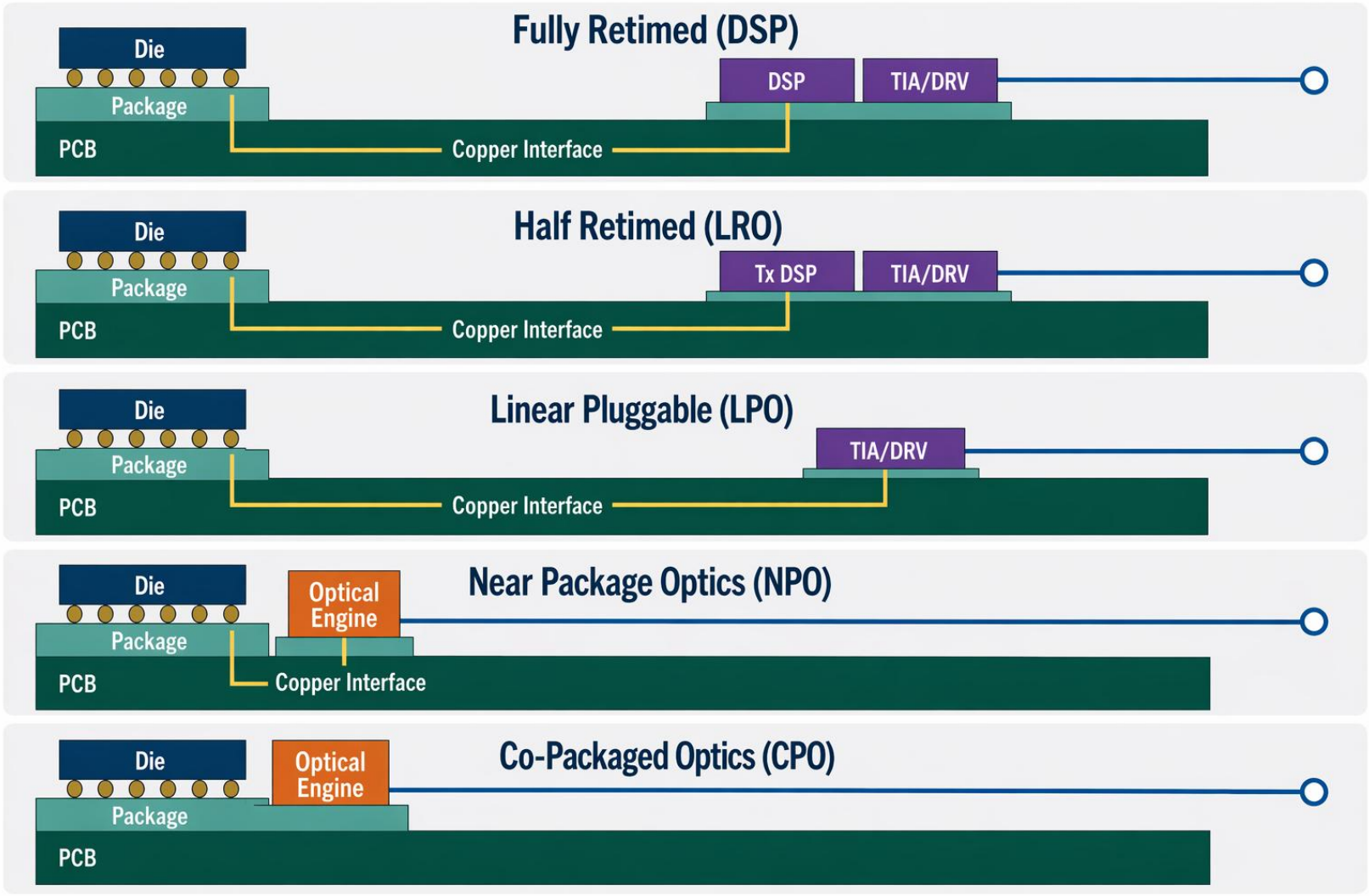


Linear module — ONE link

- No clock recovery anywhere between the two SerDes
- The SerDes Rx equalizes **through** the optical portion
- One budget, one simulation
- Optical impairments **reach the SerDes Rx**

> Electrical and optical design could be treated as separate disciplines because the retimer kept them apart. They are now one system.

Removing the Retimer: DSP → LRO → LPO → NPO → CPO



What Changes for the Model Maker

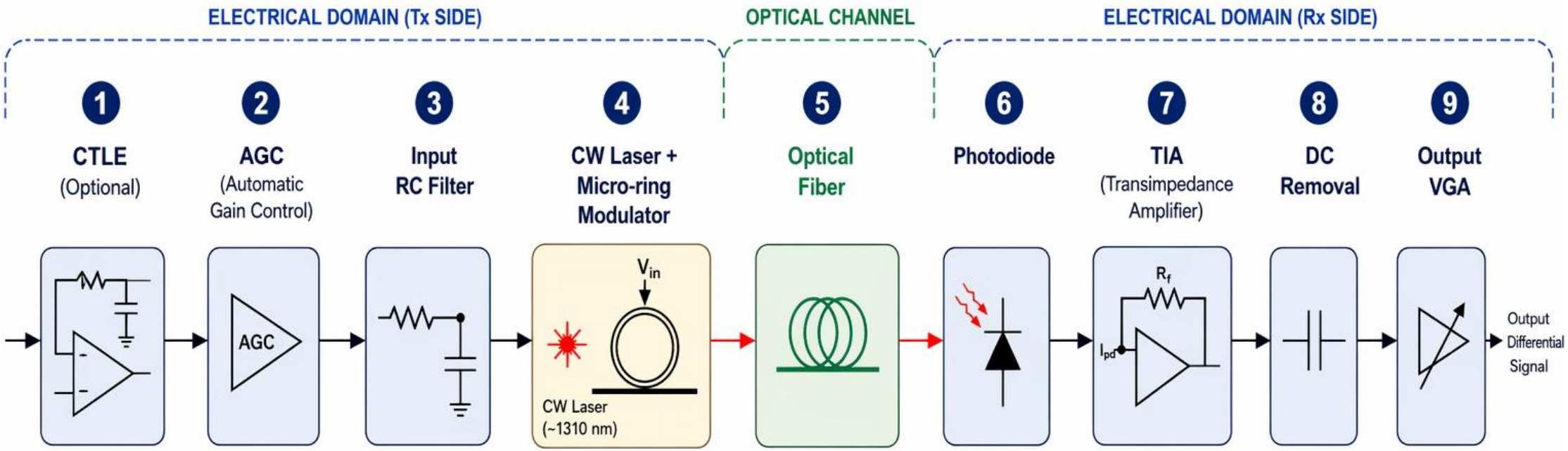
1. The optical module is now a **redriver**, not an endpoint
2. Optical impairments now reach the **SerDes Rx**, which may or may not have been designed for them
3. Link margin depends on **several suppliers at once**

   Electrical: the SerDes Tx, the SerDes Rx · **Optical:** the optical transmitter, the optical receiver, and the installed fiber and connectors — and the optical transmitter and receiver need not come from the same vendor

The two domains cannot be simulated separately. The equalizer and the optical nonlinearity **interact**.

> Few engineers have deep experience in both domains. A shared system-level model is how the two are brought together.

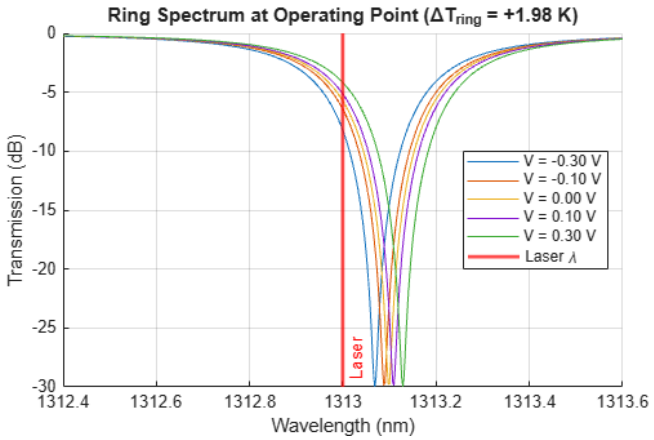
The EOE Signal Chain

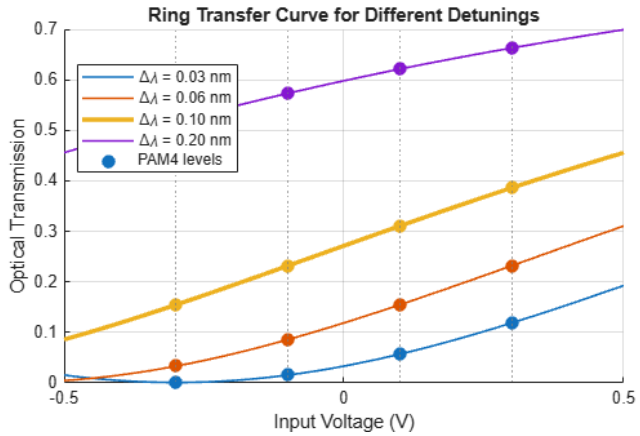


Effect 1: The Modulator Has a Narrow Linear Window

1 CTLE · 2 AGC · 3 Input RC · **4 Laser + ring** · 5 Fiber · 6 Photodiode · 7 TIA · 8 DC block · 9 Output VGA

ELECTRICAL | OPTICAL PORTION | ELECTRICAL





EACH CURVE ON THE RIGHT IS A DIFFERENT DETUNING — THE LASER-TO-NOTCH GAP

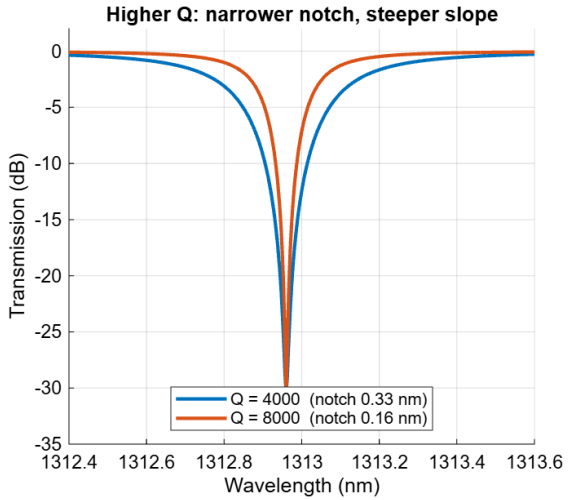
LASER POSITION	OPTICAL SWING	LEVEL SPACING
Close to resonance	small	strongly unequal
At the steepest point	**largest**	**nearly even**
Far from resonance	small	less even

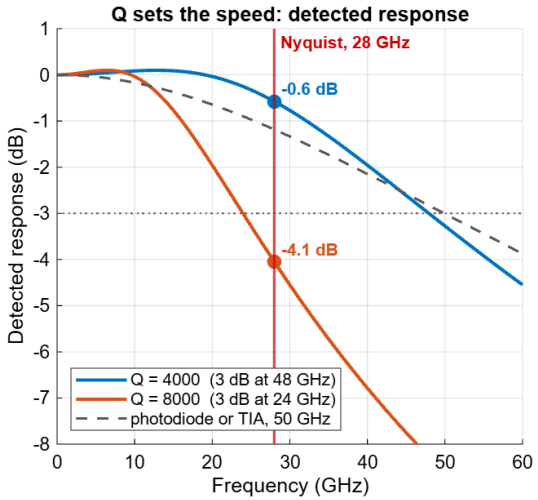
- Voltage does not scale the signal — it **slides the notch** under a laser line that stays where it is.
- The notch's **slope** has a place where it is both **steepest and straightest**: largest swing, most even levels.
- Nearer to resonance, **two things degrade at once** — the swing shrinks, and the low levels end up close together while the high ones stay spread apart.

Effect 2: Photon Lifetime Ties Bandwidth to Efficiency

1 CTLE · 2 AGC · 3 Input RC · **4 Laser + ring** · 5 Fiber · 6 Photodiode · 7 TIA · 8 DC block · 9 Output VGA

ELECTRICAL | OPTICAL PORTION | ELECTRICAL





Q	NOTCH	LIGHT OUT PER VOLT	BANDWIDTH
4000	wide, gentle slope	less light	48 GHz
8000	narrow, steep slope	more light	24 GHz

Twice the slope for the same drive, and half the bandwidth. **One parameter sets both.**

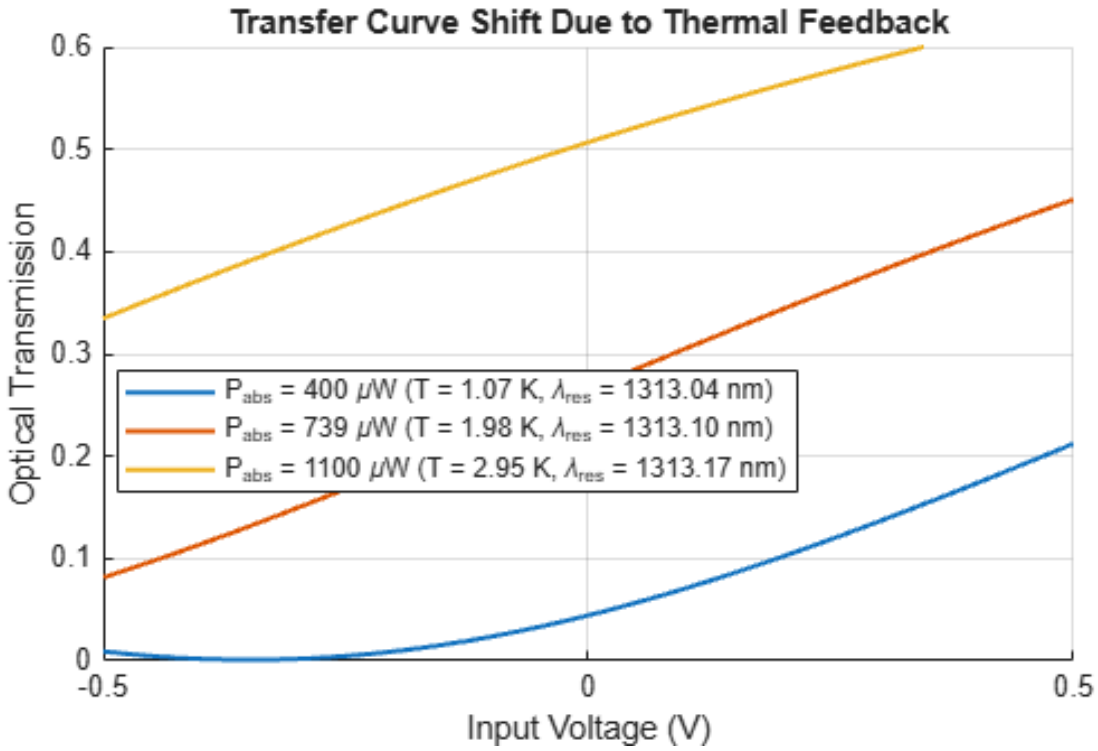
- Light entering the ring takes time to build up and to leak out. That storage time **is** the bandwidth limit.
- **Choosing Q:** keep the ring above the rest of the budget. The photodiode and the amplifier are 50 GHz each. At Q = 4000 the ring is 48 GHz, only **0.6 dB down at Nyquist**.
- At Q = 8000 it is 24 GHz — below Nyquist for 56 GBaud, 4 dB down there, and the **tightest limit in the link**.
- So that extra light costs strong intersymbol interference, an eye already closed at the modulator output, and the whole recovery burden on the SerDes equalizer — which costs signal-to-noise ratio.

Effect 3: The Ring Heats Itself

1 CTLE · 2 AGC · 3 Input RC · **4 Laser + ring** · 5 Fiber · 6 Photodiode · 7 TIA · 8 DC block · 9 Output VGA

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- Absorption is strongest when the notch sits **on** the laser. About three quarters of the light reaching the ring becomes **heat**
- Heat moves the resonance **one way only**, to longer wavelength — here by 40 % of the notch width
- Cold, the notch sits just short of the laser. Self-heating carries it **through** and parks it on the far slope: the heating **creates** the operating point
- Past the crossing the loop **corrects itself** — hotter → further from the laser → more light through → less absorbed
- Still **data dependent**: what was recently sent sets where on the slope it sits

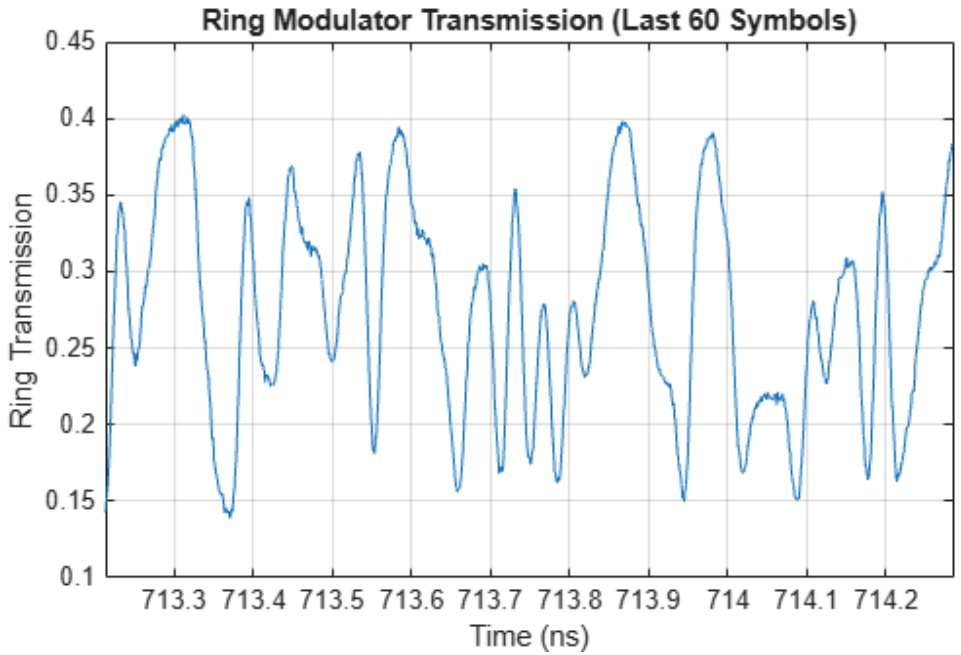


Effect 4: Light Does Not Speak IBIS-AMI

1 CTLE · 2 AGC · 3 Input RC · 4 Laser + ring · 5 Fiber · 6 Photodiode · 7 TIA · 8 DC block · 9 Output VGA

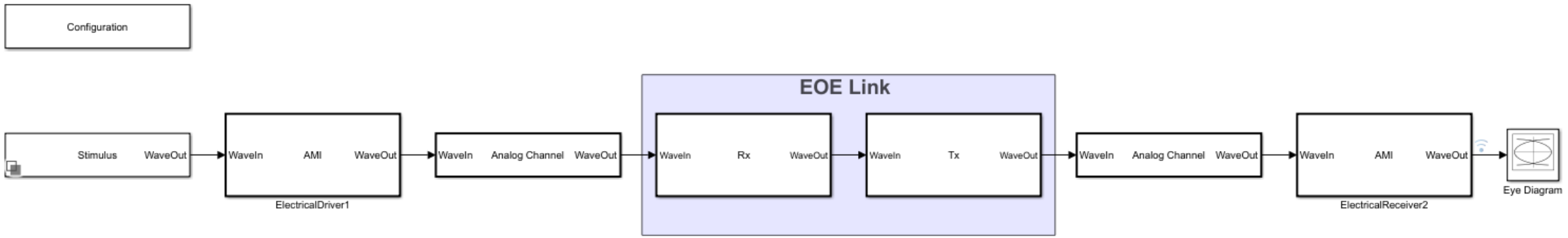
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- An AMI model receives a **differential voltage** and returns a differential voltage
- Optical power is **not a voltage at all**. It cannot go negative — as the plot shows, it never comes near zero.
- What carries the information is the ratio between levels, not the swing about a mean. Rescaling this waveform, or removing its mean prematurely, **destroys the signal**.
- The sign cannot be recovered later. A photodiode turns light into current, and a transimpedance amplifier turns current into voltage — both **single-ended**. Removing the direct-current level is what returns the waveform to **differential**.



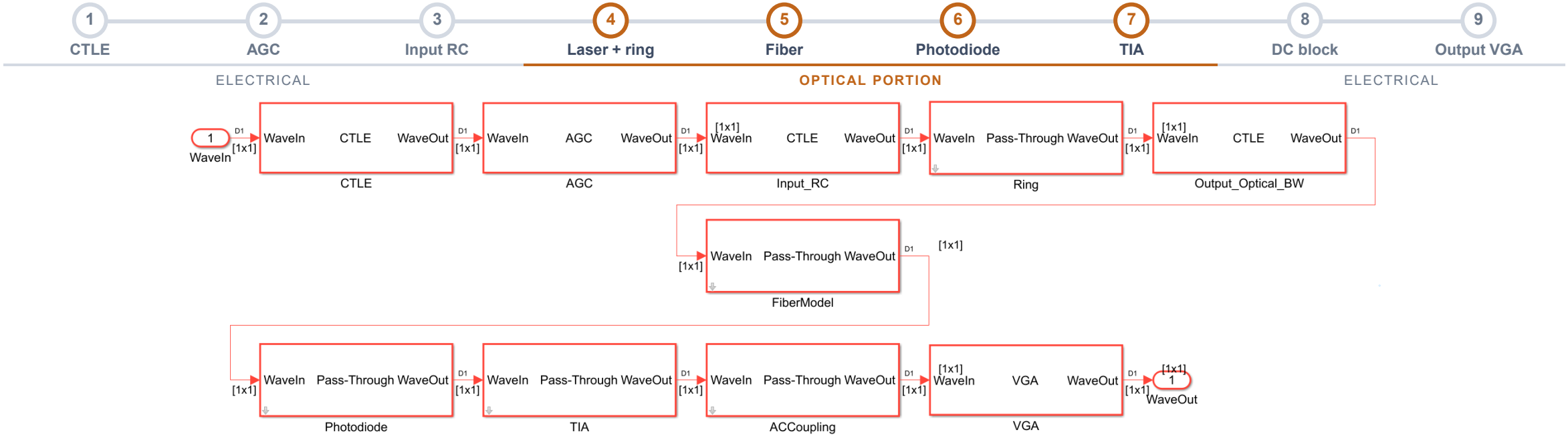
The IBIS Solution: This Is a Redriver

> IBIS 8.0, §10: a **redriver** is a repeater that sits between two channels and re-conditions the signal **without recovering the clock**.



- That definition describes a linear optical module: same position in the topology, same interface, no clock recovery
- Both ends of this simulation are **compiled IBIS-AMI models**
- The redriver in the middle is running **live in the modeling environment**, where it is still being developed — it can be compiled and handed to another tool at any point
- **No extension to the standard, no new API, no new parameter type.**

Inside the EOE Redriver



- Equalizer, gain control and output amplifier: **standard SerDes equalization blocks**
- The two bandwidth limits are **pole and zero filters** — one pole at the modulator input, a pole pair and a zero for the ring

- The optical portion holds the **laser, ring modulator, optical power combiner and thermal network**, with the thermal feedback loop closed inside it
- From outside: one input waveform, one output waveform
- The whole optical path sits in the **receiver half** here — a modeler is free to divide it differently

Init and GetWave With a Nonlinear Modulator

Init

One impulse response. Linear and time-invariant assumed. Produces the statistical result, and a starting point for downstream adaptation.

GetWave

Sample by sample. No linearity assumption.

- A ring modulator is nonlinear and time-varying, so strictly it does not satisfy Init's assumptions
- A downstream receiver **can** adapt without help from Init — but it takes longer to settle
- A reasonable linear approximation gives it a much better starting point: **faster convergence, shorter simulations**

> So Init returns the best linear approximation available: the slope of the modulator's transfer curve at its operating point.

What the Linear Approximation Carries, and What It Drops

Init carries

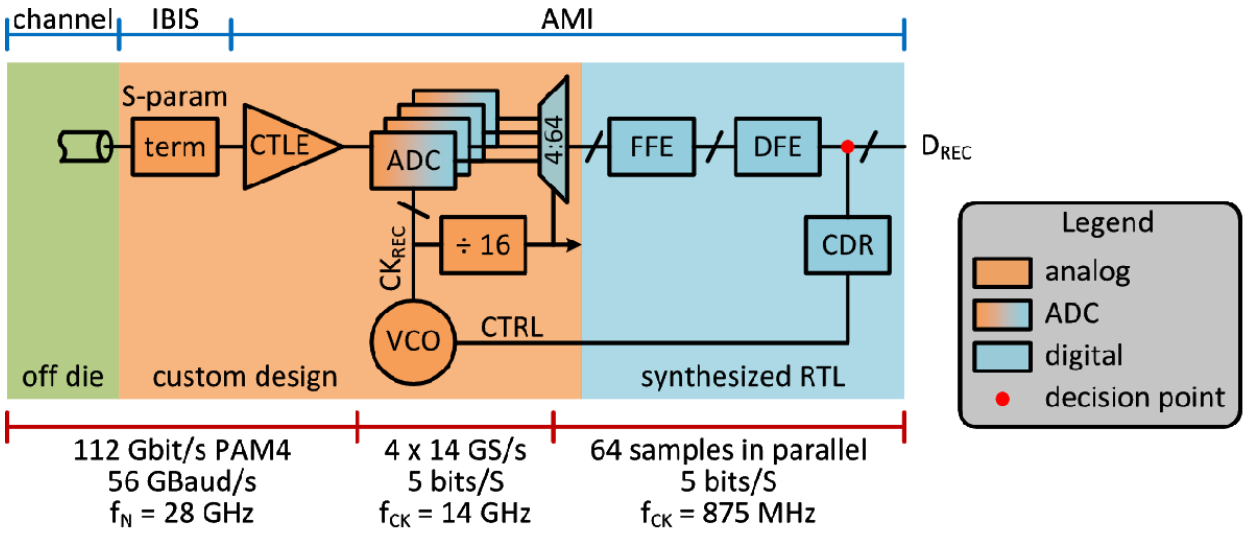
- All four bandwidth limits: **100, 48, 50, 50 GHz**
- End-to-end linear gain: drive volts → output volts
- Fiber loss (0.175 dB)

Init drops

- Ring nonlinearity → **no PAM4 level compression**
- Thermal drift — time-varying by definition
- Direct-current removal — data-dependent settling
- **Laser frequency noise**, which the ring turns into amplitude noise — along with shot noise and amplifier noise
- Pattern-dependent heating

Init is optimistic. Use it for adaptation. Do not use it for your margin number.

The SerDes Rx: ADC Plus DSP

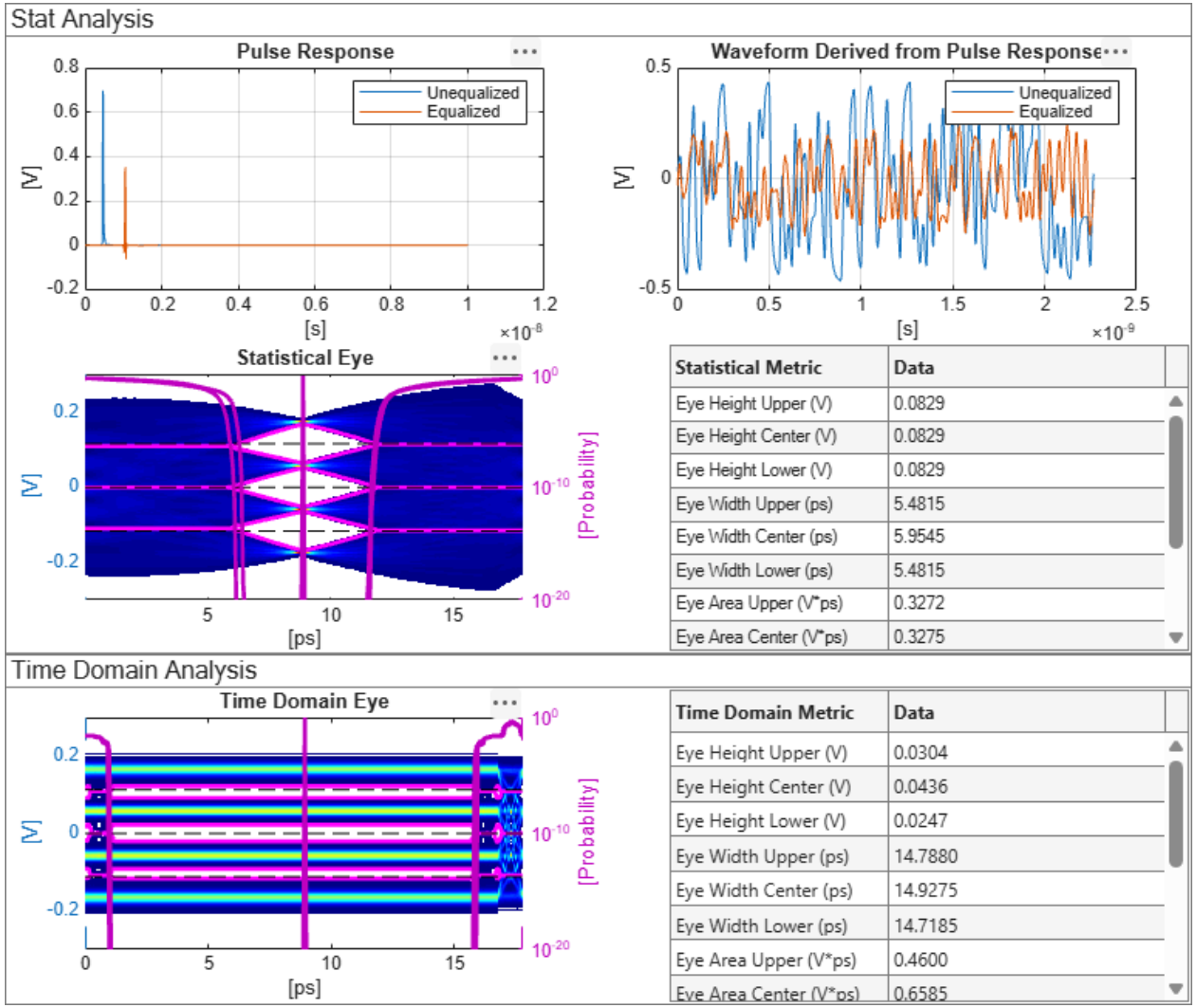


- **Analog front end:** three equalizer stages — mid-band zero, main, noise filter — then a variable gain amplifier and a saturating amplifier
- **Conversion:** four time-interleaved analog-to-digital converters, 64-wide demultiplexer
- **Digital equalization:** 21-tap feed-forward filter, one decision-feedback tap
- **Clock recovery:** baud-rate phase detector

IBIS-AMI is written for a **slicer-based** receiver, which has a node just before the decision sampler where an equalized analog waveform can be observed. An ADC-based receiver **has no such node** — the converter is in the way. A bridge reconstructs a virtual one by holding each equalized sample for a full symbol.

> So the eye is built from **one sample per symbol**: read **eye height** and the resulting **symbol error rate**, not eye width.

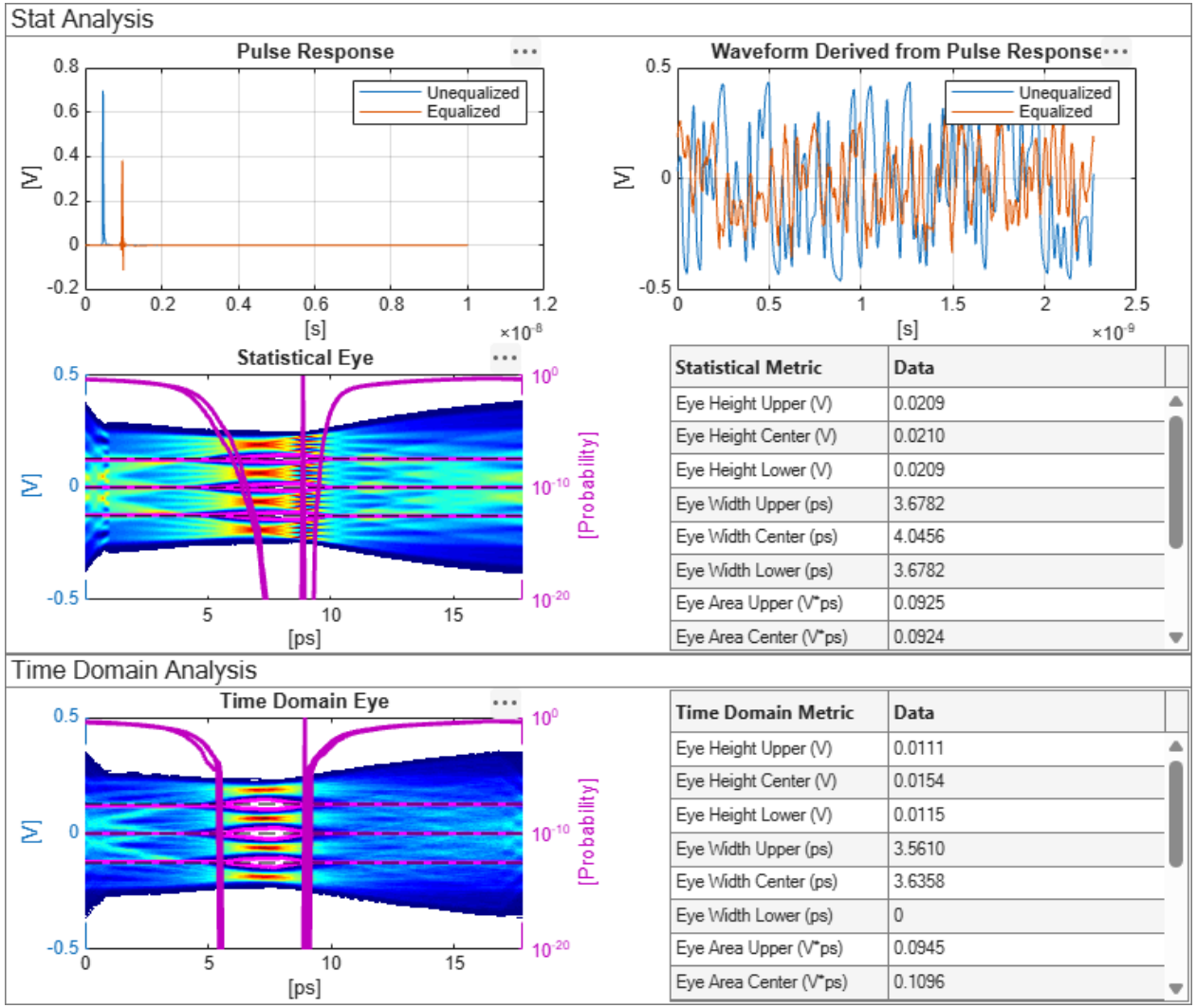
Results: Zero Symbol Errors, and Init Twice the Eye Height



EYE HEIGHT (V)	UPPER	CENTER	LOWER
Init	**0.0829**	**0.0829**	**0.0829**
GetWave	**0.0304**	**0.0436**	**0.0247**

- **GetWave: 43.6 mV center eye, and not one symbol error** across the whole run
- That eye is open only because of the receiver equalization: the **21-tap filter and one DFE tap**. Without them there is no eye at all.
- **Init estimates 82.9 mV** — about twice the measured height, on the same receiver and the same channel.
- Init carries only the **linear** part of the optical path: the four bandwidth limits, the end-to-end gain, the fiber loss. **None of the nonlinearity.**
- In copper that omission is small. Here it is not: **the modulator's linear window is narrow, and its position moves with the data.** So Init starts adaptation; **the margin comes from GetWave.**

Trying Another Standard's Receiver on the Same Optical Link



SERDES MODELS REPLACED WITH PCIE GEN 6. OPTICAL PORTION UNCHANGED. BOTH ROWS GETWAVE.

EYE HEIGHT (V)	UPPER	CENTER	LOWER	SER
ADC + digital EQ	**0.0304**	**0.0436**	**0.0247**	**0**
Analog CTLE + DFE	**0.0111**	**0.0154**	**0.0115**	**0.055**

- ADC-based DSP receiver replaced with a **PCIe Gen 6 model** at both ends — CTLE, 16-tap DFE, CDR. Optical portion unchanged.
- **The channel's signature is unchanged** — center eye tallest, outer eyes squeezed — whichever SerDes model sits at the ends.
- The PCIe receiver **opens an eye at about a third of the height**, and still makes symbol errors.
- **Equalization from another standard, tried against EOE impairments** — any SerDes model can be substituted and the link re-run.

What Is Next

1 Decompose the optical portion into separate models



Three cascaded redrivers, one per supplier — **already legal in IBIS**. Open question: the waveform between two optical models is **optical power**, not a zero-mean differential voltage. A tool that scales or removes the mean between repeater stages would corrupt it.

2 Simulation length

Thermal settling takes about **100 million symbols** at this rate; wavelength-control loops in a real module are slower still. A long IBIS-AMI run today is about **1 million symbols** — a hundred times short. Observing thermal drift is a simulation-time and methodology problem.

Takeaways

1. Optical and electrical design were separate because the retimer kept them apart. Linear drive makes them **one system** — and the SerDes receiver now decides whether the link works.
2. The optical portion adds four unfamiliar effects. Each one resembles something from electrical design. None of them behaves the same way.
3. **A linear optical module is an IBIS redriver.** The framework fits without extension.
4. Put the best linear approximation in **Init**. Take margin from **GetWave**.
5. Open work: **decomposition across suppliers, and simulation length**

> Thank you — questions welcome
>
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