DesignCon 2023
WHERE THE CHIP MEETS THE BOARD

Simulation and Analysis of Electrical/Optical Communication Links Using Free Software

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Abstract

Copper and electrical channels have dominated the computer and data center ecosystem for years, with optical communications relegated to long-haul communications. The demise of copper has been predicted for years as speeds continue to increase unabated – a demise that has not materialized. Cracks are forming in copper's dominance, however, as reach has diminished and power has soared, portending more optical integration into previously all-electrical systems.

Since signal integrity involves the analysis of the transmission and reception of signals throughout the entire link, optical components can complicate traditional analysis techniques. Much of this complication comes from optical modulators that are often unfamiliar to signal integrity engineers.

This paper serves as a small tutorial on how optical modulators and receivers can be integrated into signal integrity analysis.

Biography

Pete Pupalaikis is a signal integrity engineer with Nubis Communications. Prior to Nubis, he worked for twenty-five years at Teledyne LeCroy designing high speed measurements instruments. He is the author of the book "S-parameters for Signal Integrity" and is an IEEE Fellow.

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Introduction

COPPER AND ELECTRICAL CHANNELS have dominated the computer and data center ecosystem for years, with optical communications relegated to long-haul communications. The demise of copper has been predicted for years as speeds continue to increase unabated – a demise that has not materialized. Cracks are forming in copper's dominance, however, as reach has diminished and power has soared, foretelling more optical integration into previously all-electrical systems.

Since signal integrity involves the analysis of the transmission and reception of signals throughout the entire link, optical components can complicate traditional analysis techniques. Much of this complication comes from optical modulators that are often unfamiliar to signal integrity engineers.

This paper serves as a small tutorial on how optical modulators and receivers can be integrated into signal integrity analysis when the entire electical-optical path (in the case of the transmitter) and the entire optical-electrical path (in the case of the receiver) must be considered.

Consult [1] for a more in-depth discussion.

Optical Modulators

Mach-Zehnder Modulators

- General principle
- The segmented model

Ring Modulators

- General principle
- Tilt model

Packaging Challenges

- Present the different OIF type pictures.
- Issue of driver/TIA mounted directly on the PIC
- Issues of crosstalk between the driver and TIA

Power Delivery Challenges

As an expert in power integrity instructs, "usually one can optimize the signal integrity or the power integrity, but not both". In copackaged optics (CPO) this cannot be any truer. The typical problem can be summarized as follows:

- In CPO, the communications bandwidth density is very high (on the order of $10\,\mathrm{Gb/s/mm^2}$).

- Depending on the speed of each electrical channel (usually $100-200\,\mathrm{Gb/s}$ pulse amplitude modulation (PAM) at two bits per symbol (i.e. PAM-4)), most of the area is taken up by ground and signal to form the differential pairs necessary just for communication.
- This leaves relatively small area for power and ground pads.

Despite the small pad pitches employed (as low as $400\,\mu m$), this does not leave many pads for power and ground. This small size and number of pads in CPO leads to specific power delivery network (PDN) challenges that must be analyzed. The PDN consists of:

- series resistance, causing current times resistance (IR) drops on the voltage rails, and
- series inductance, leading to resonances in the impedance of the network.

While more pads means more of this in parallel, leading to lower inductance and resistance, often there are limitations to the amount that this resistance and inductance can be reduced. Furthermore, portions of the delivery network might pass through wire bonds, which are particularly inductive. Finally, while inductance is typically mitigated by on-package and/or on-die decoupling capacitors, in CPO, this decoupling might not be possible or might be severely reduced due to real estate limitations.

Power Delivery Analysis

The typical way to analyze power delivery is in three steps:

1. Calculate the direct current (DC) resistance of each pad in an optical module and use this information to calculate the effective series resistance (ESR) for power domains based on the parallel combinations of the pads. In other words, if a given pad has a DC resistance of R, usually on the order of tens of milliohms, and there are P pads in parallel, the ESR at DC of the power domain is calculated as
$$ESR_{DC} = \left(\frac{P}{R}\right)^{-1}.$$
2. Calculate the frequency dependent impedance of the power domain by determining the transfer characteristic of voltage drop vs. current draw. Many would know that this is, in fact, the Z-parameters of the power domain.
3. Apply known transient current waveforms to the frequency dependent impedance to obtain transient voltage waveforms on the voltage rail. Transient voltage waveforms can be analyzed for time- and frequency-domain behavior such as peak-peak and rms voltage ripple along with spectral content.

A typical analysis is shown in figure 1. In figure 1, a single voltage rail is shown passing through a connector and a substrate to a die mounted on the top of the substrate (all other rails are removed for simplicity).

While an entire paper could be devoted to this topic, here are some basic comments:

- The analysis was performed using the *SignalIntegrity* software found at https://github.com/ TeledyneLeCroy/ SignalIntegrity.
- The transient waveform is supplied by a subproject named TAVDDH.si through the current source with reference designator AVDDH_CS.

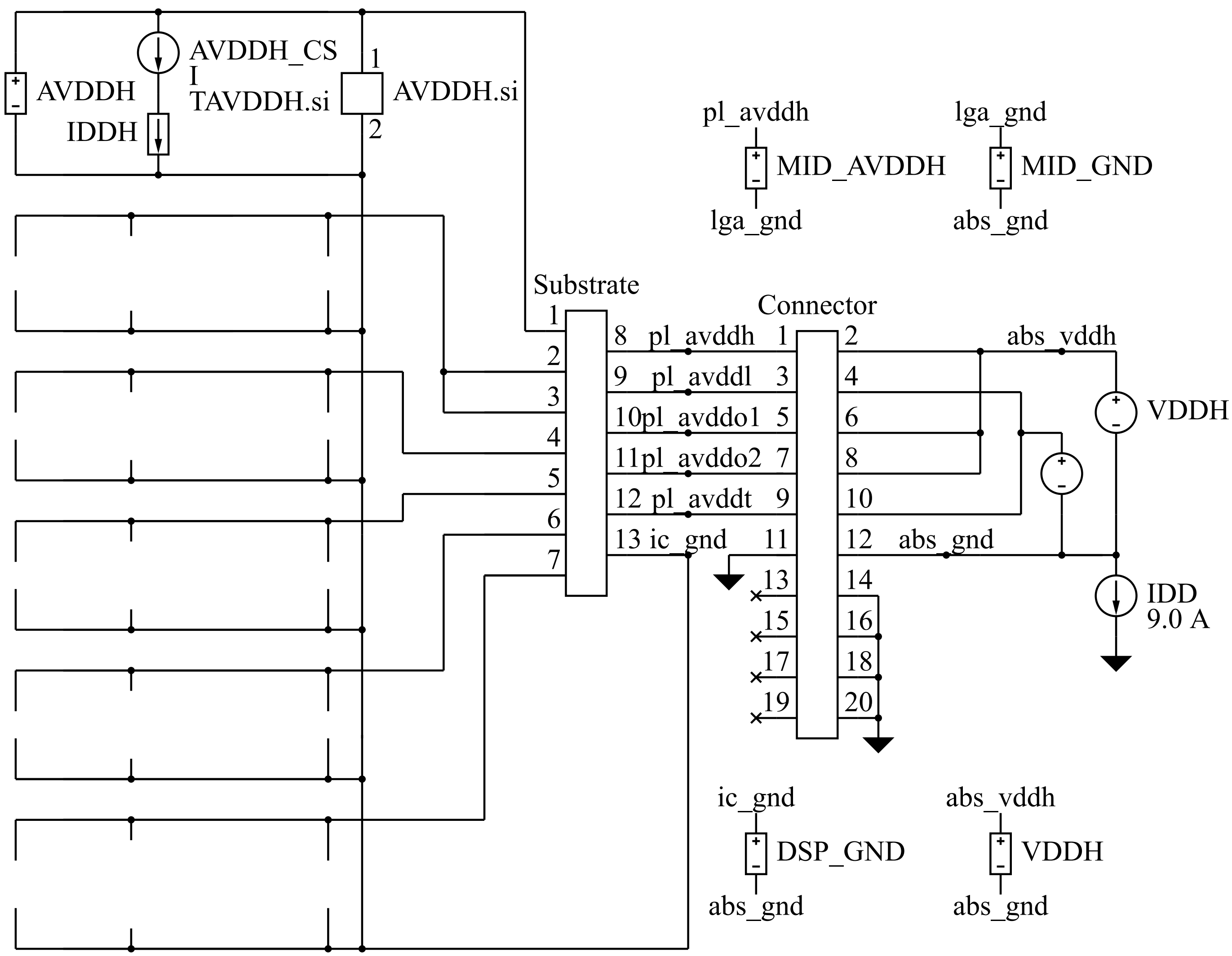

Figure 1: Typical PDN analysis

- The on-die decoupling capacitance is supplied by the subproject AVDDH.si.
- The transient current is measured by the current probe named IDDH and the differential transient voltage[1] is measured by the differential voltage probe named AVDDH.
- In this simulation, transfer parameters are generated which, when convolved with the the transient current source, produce the differential voltage. As mentioned previously, these are the Z-parameters and, when plotted in the frequency domain, reflect the frequency dependent impedance of the PDN.
- The substrate s-parameters are generated from Ansys SiWave, a commercial package from Ansys.
- The connector utilizes a simple transmission line model consisting of distributed $40\,\mathrm{m}\Omega$ series resistance, $50\,\mu\Omega/\sqrt{\mathrm{Hz}}$ skin-effect resistance, $4\,\mathrm{nH}$ inductance, and $200\,\mathrm{fF}$ capacitance. This model was fit to an s-parameter extraction of the connector pin.[2] Many connector pins are utilized in parallel.

[1] It is differential because it is measured with respect to reference ground at the IC die.

[2] This fit was performed in the *SignalIntegrity* tool by varying the transmission line parameters until a good fit was obtained to the s-parameter model.

References

[1] P. J. Pupalaikis, *S-Parameters for Signal Integrity*. Cambridge University Press, 2020.