Optical transmitter characteristics for GEPOF technical feasibility

Rubén Pérez-Aranda
rubenpda@kdpof.com

Supporters

- Frank Aldinger (Mitsubishi International)
- Yutaka Tanida (Mitsubishi Corporation)
- Y.Tsukamoto (Mitsubishi Rayon)
- Eric Chan (Boeing)
- Philippe Bolle (Skylaneoptics)
- 曹质文 / Mike Cao (Dongguan ipt Industrial Co,.LTD.)
- John Lambkin (Firecomms)
- Hugh Hennessy (Firecomms)
- Josef Faller (Homefibre)
- Manabu Kagami (Toyota R&D Labs)
- Bas Huiszoon (Genexis)
- Oscar Rechou (Casacom)
- Naoshi Serizawa (Yazaki)
- Thomas Lichtenegger (Avago Tech)

Agenda

- Objectives
- The optical transmitter ➤ main characteristics
- LED non-linear response and capacity penalties
- Conclusions

Disclaimer

- Technical characteristics provided in this presentation are limited to those directly affecting the optical link budget and, therefore, the Shannon's capacity analysis.
- Other characteristics, like the ones related to the physical semiconductor parameters, integration, manufacturing process, etc. are intentionally left outside of the sope of this presentation

Objectives

- This presentation provides technical characteristics of the optical transmitter used today for automotive applications as well as for consumer applications
  - This optical transmitter is a red LED, and it is the light emitter most widely used by the industry for POF communications
  - The red LED has been qualified for automotive applications, being demonstrated its reliability during the last +10 years
- The main objective of this presentation is to analyze the red LED from the perspective of the aspects that directly relates to the Shannon's capacity based technical feasibility assessment
- The results presented here will be used for Shannon's capacity analysis in [perezaranda_01_0514_shannoncap]

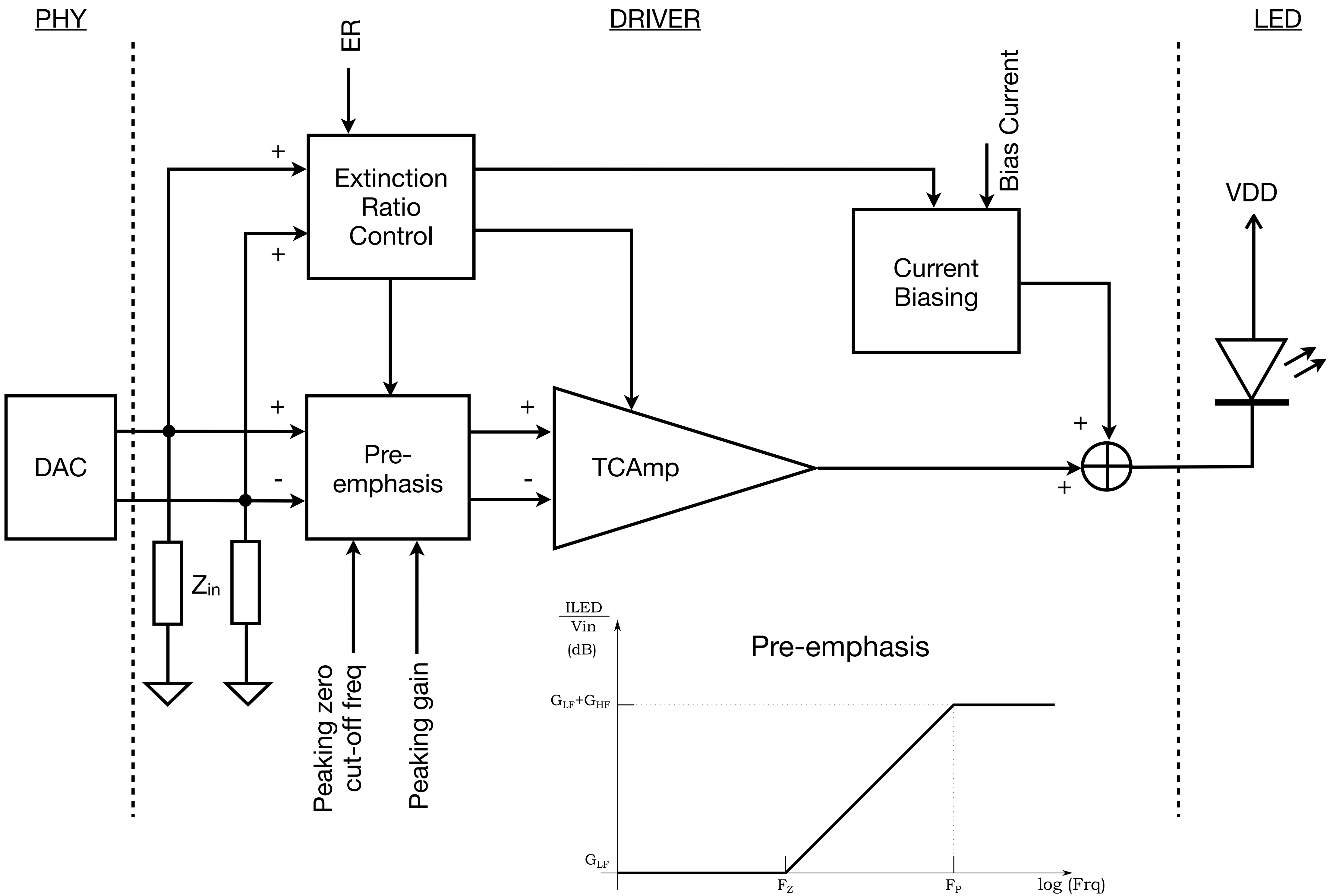
Knowledge Development

The optical transmitter ➤ main characteristics

The optical transmitter - architecture

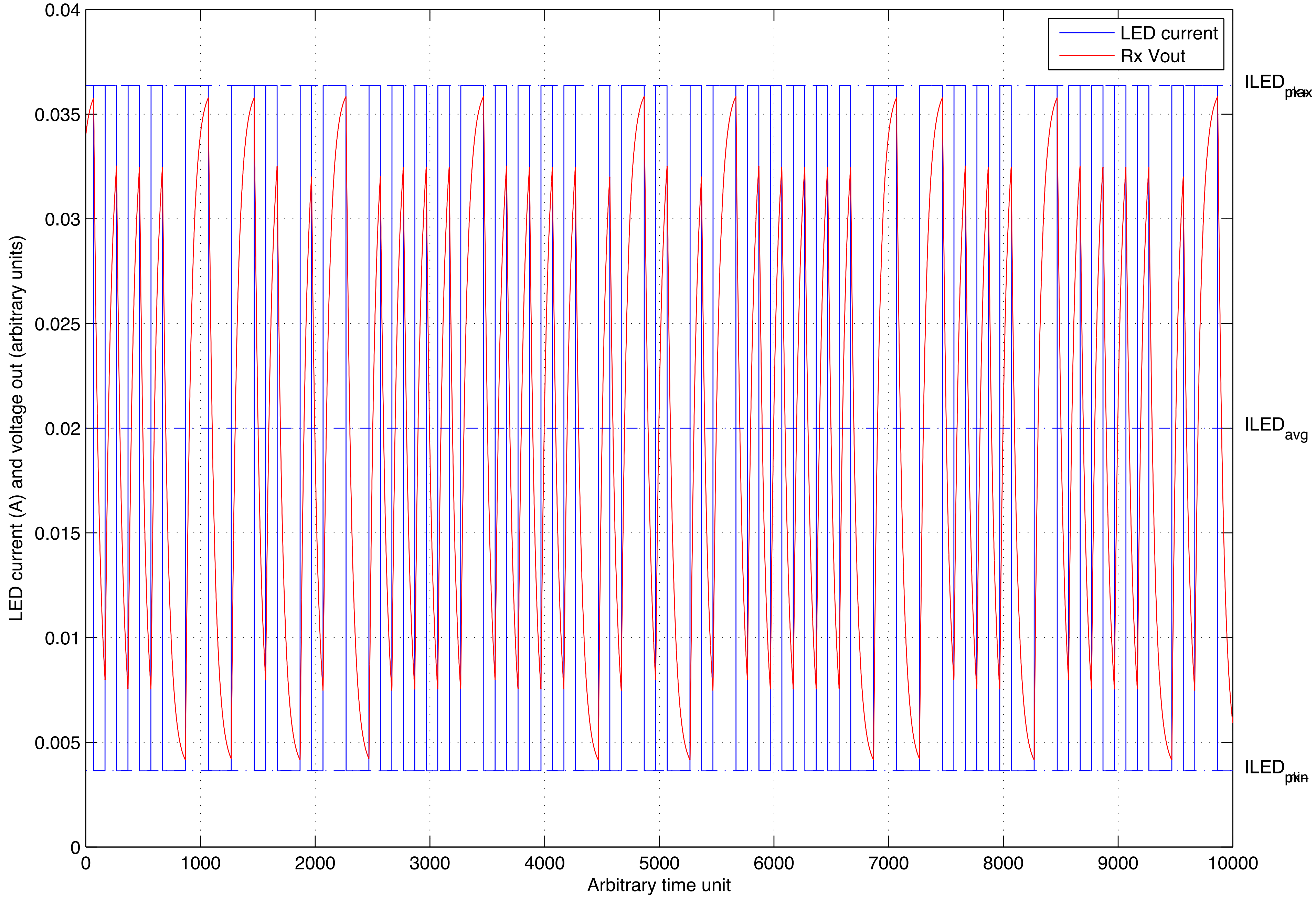
- The optical transmitter is composed by the current driver IC and the LED IC
- The red LED converts the electrical current into optical power
  - In general, the I-P characteristic of LED is not linear; this topic is covered later on
  - Electrical-to-electrical response is well approximated by a 1st order low pass system
  - Achievable -3dB bandwidth of LED itself is between 75 and 95 MHz, depending on the internal structure of LED
  - Wavelength center ~650 nm; wavelength width ~30 nm
- Typically, the driver is a trans-conductance amplifier in charge to convert the voltage communication signal from the PHY into the adequate current to drive the LED, providing:
  - Bias current control to ensure reliability of the LED
  - Extinction Ratio (ER) control, to avoid switching off the LED (optical power clipping) and ensure the quantum noise from PD is low
  - Typical target ER = 10 dBo
  - Typical process and temperature variation of ER < ±2 dBo
  - Frequency pre-emphasis, to enhance the bandwidth of the LED
  - Frequency pre-emphasis gain is limited based on reliability criteria ➤ max peak current

The optical transmitter - architecture

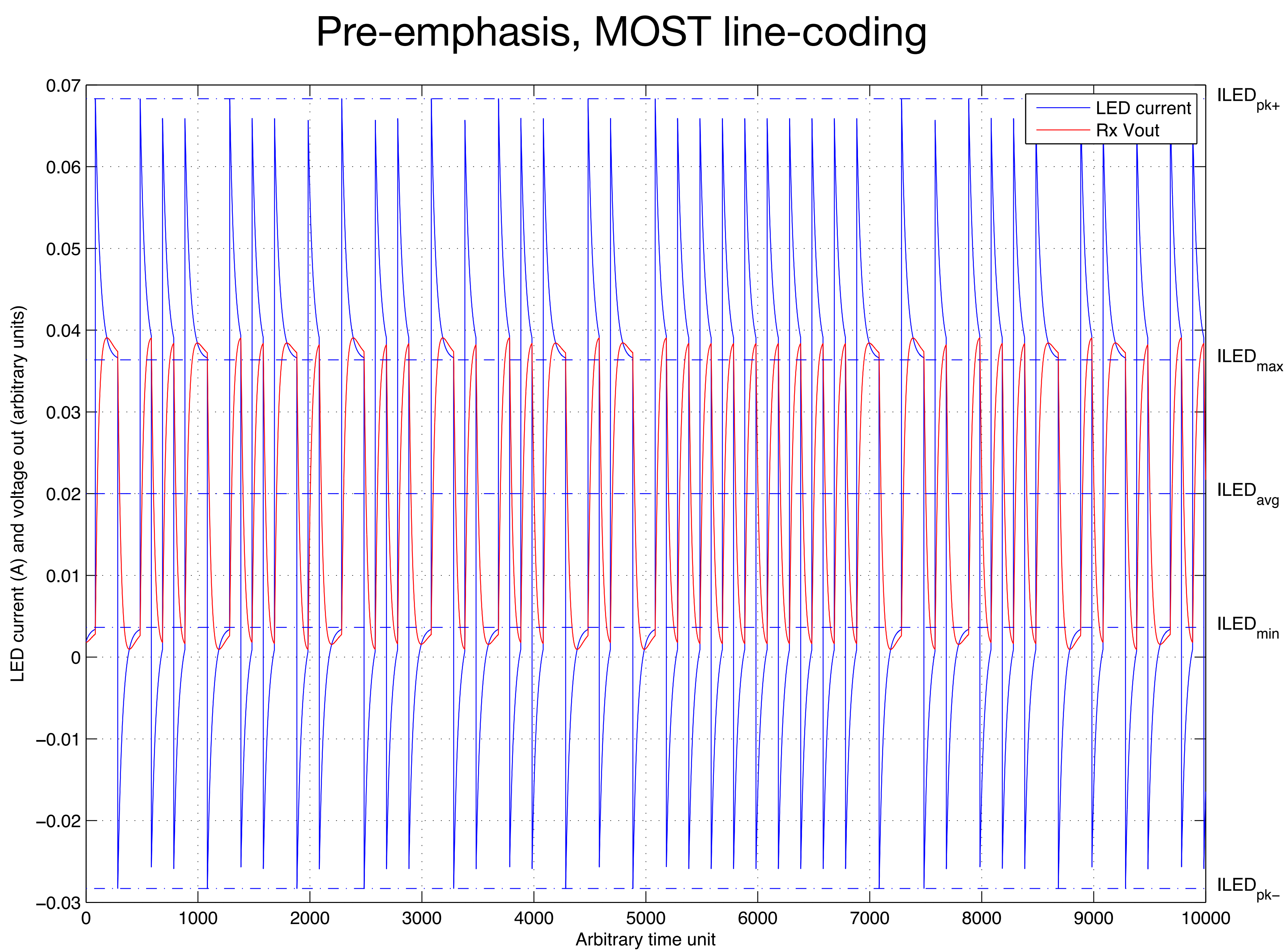


The optical transmitter - pre-emphasis

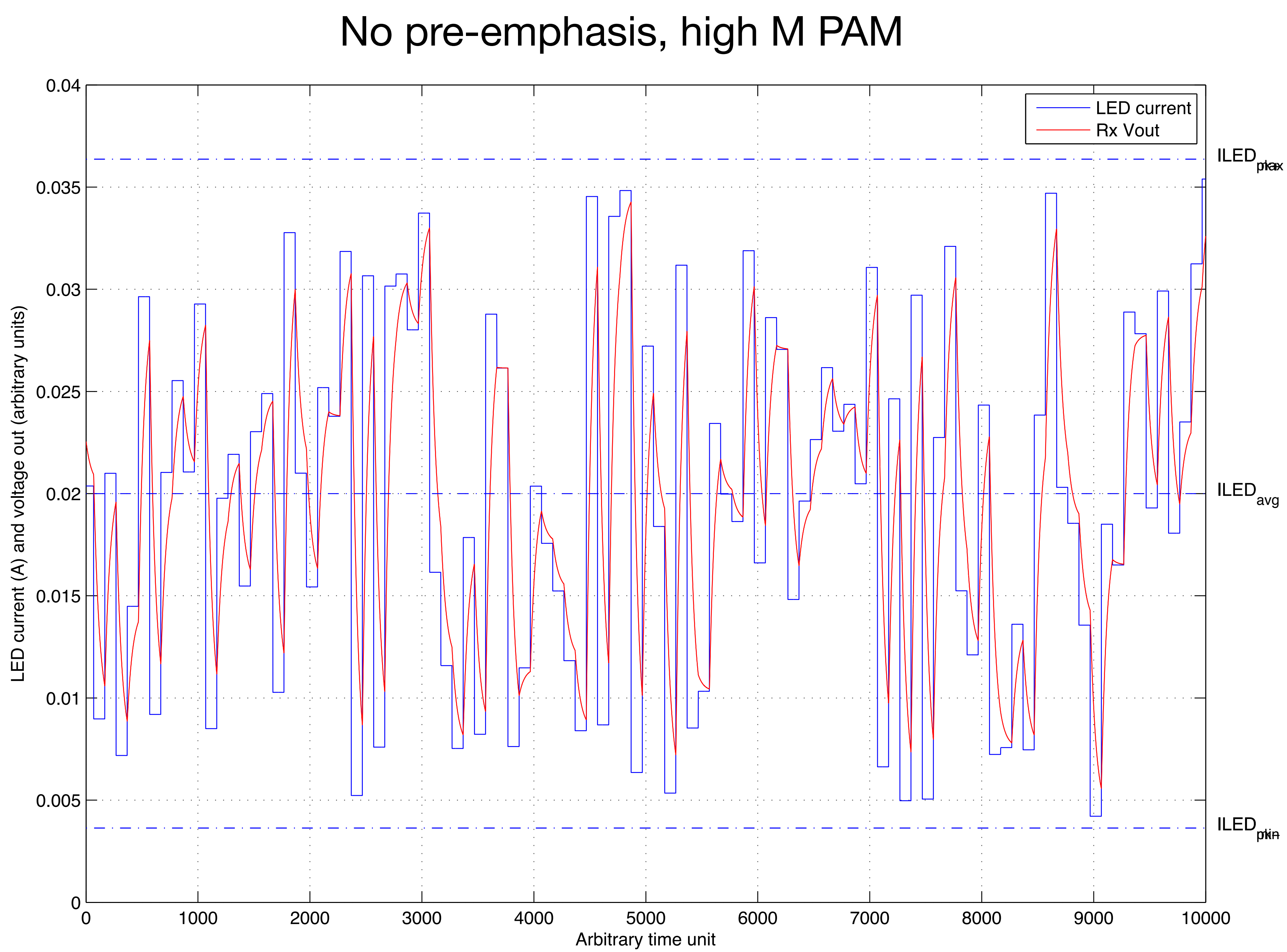
No pre-emphasis, MOST line-coding



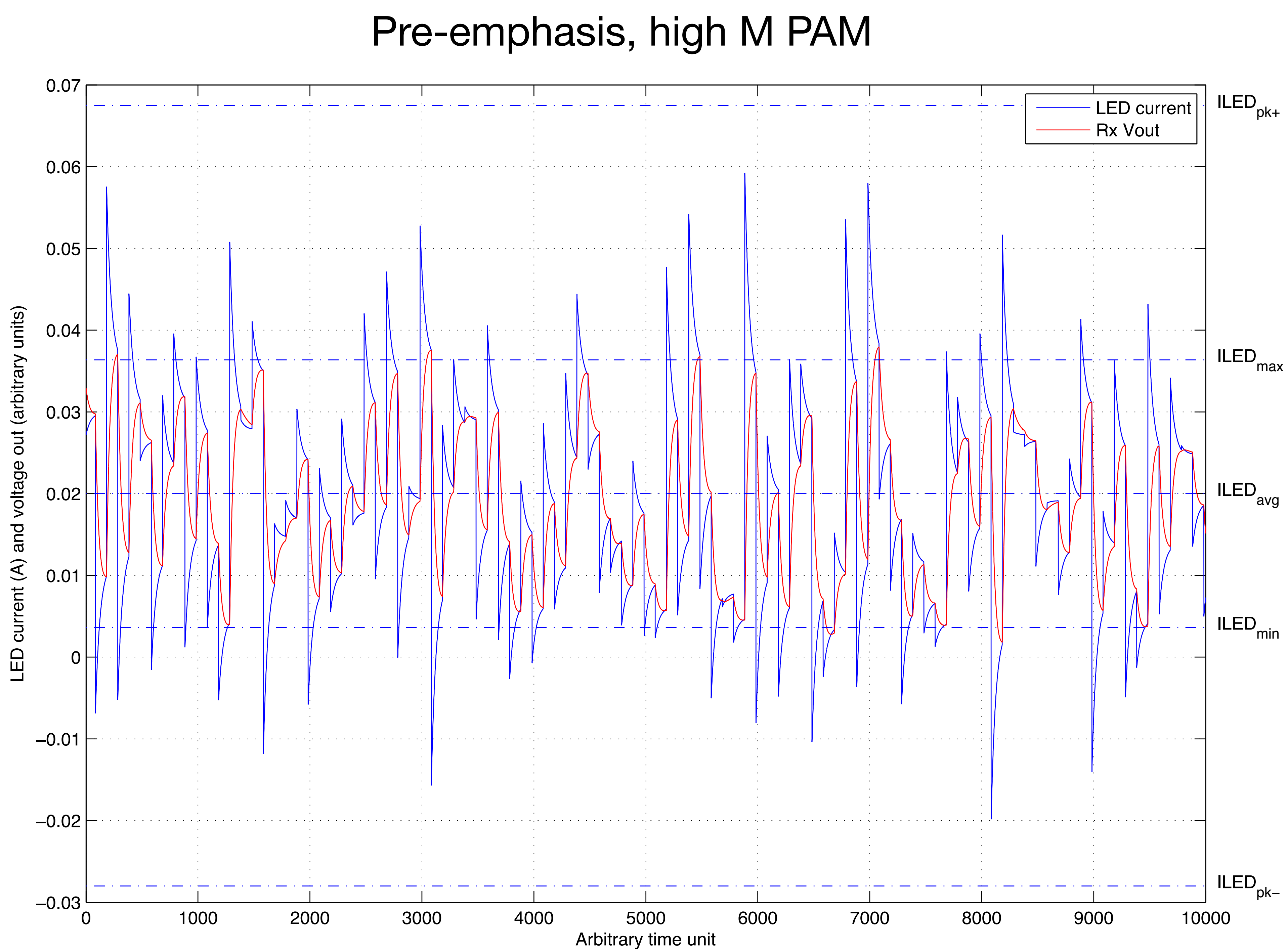
The optical transmitter - pre-emphasis



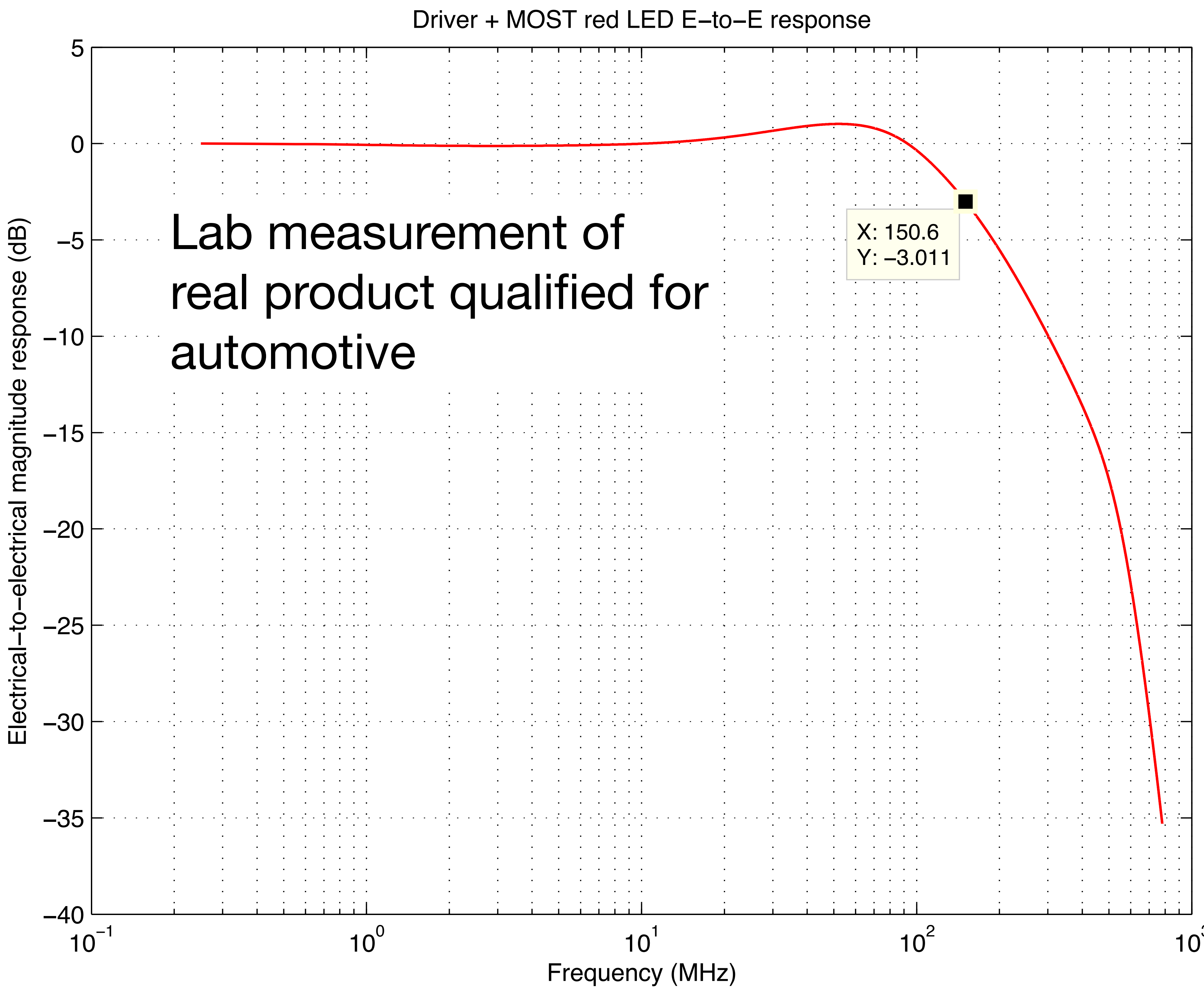
The optical transmitter - pre-emphasis



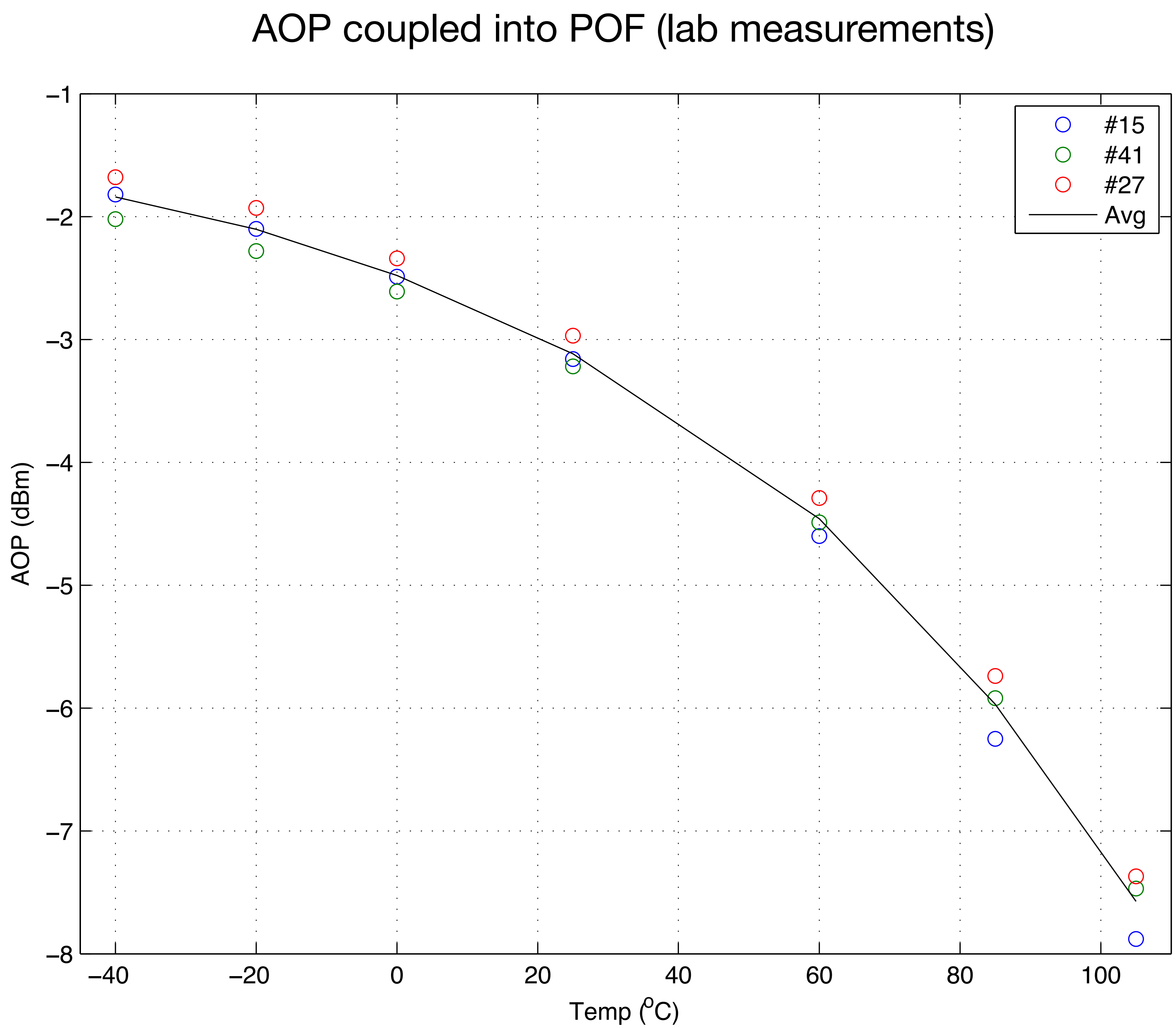
The optical transmitter - pre-emphasis



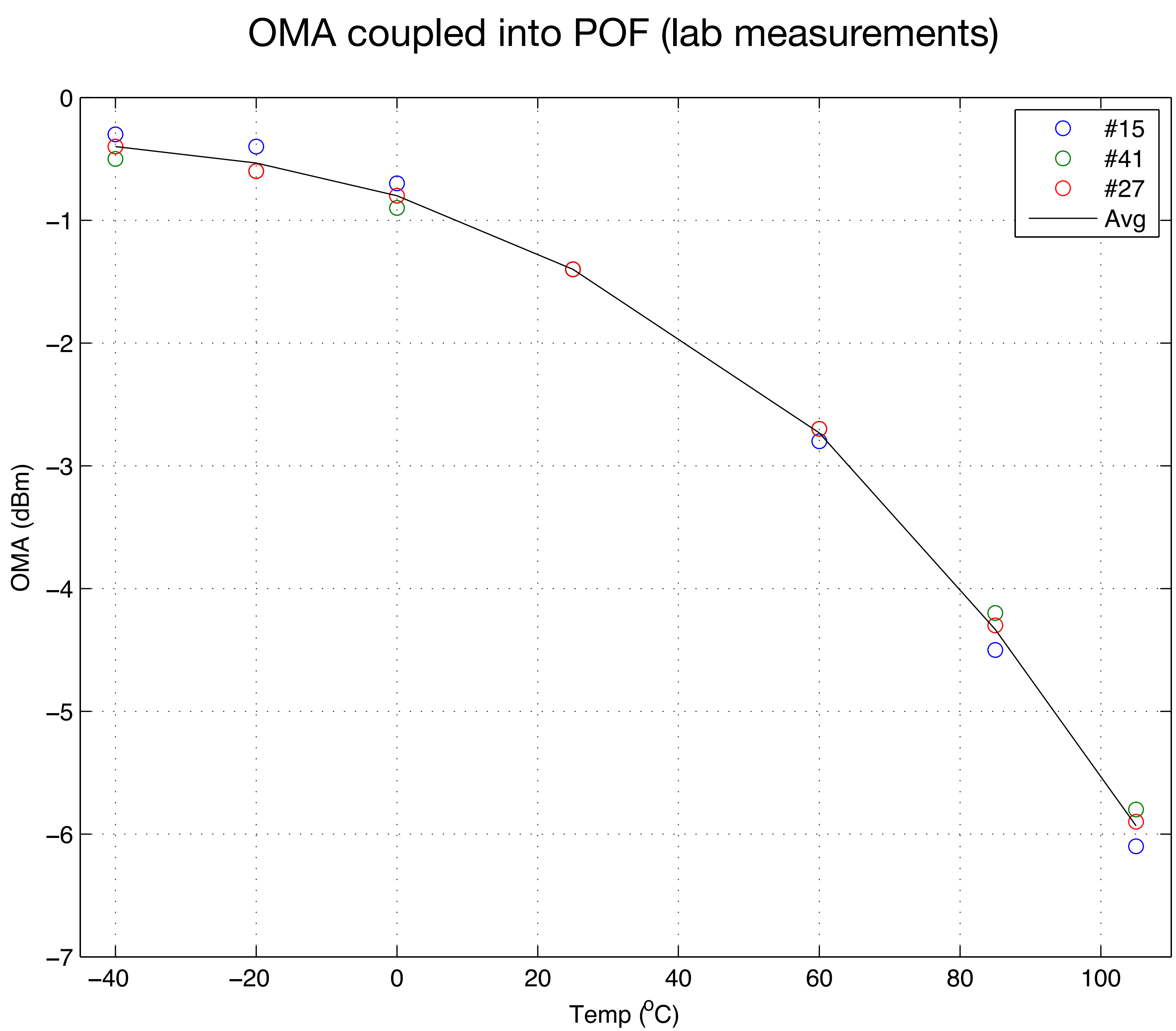
The optical transmitter - response



Performance with temperature

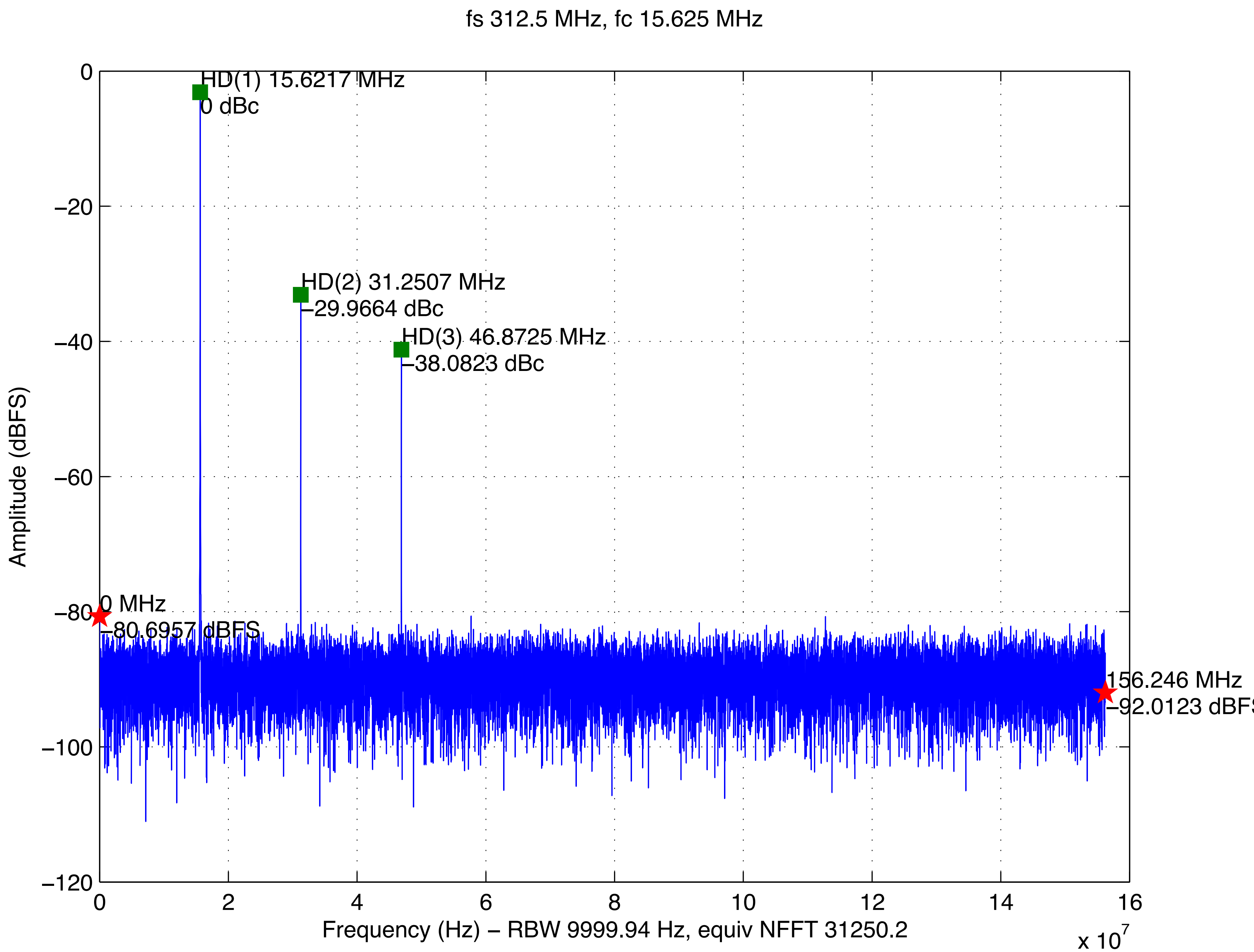


Performance with temperature



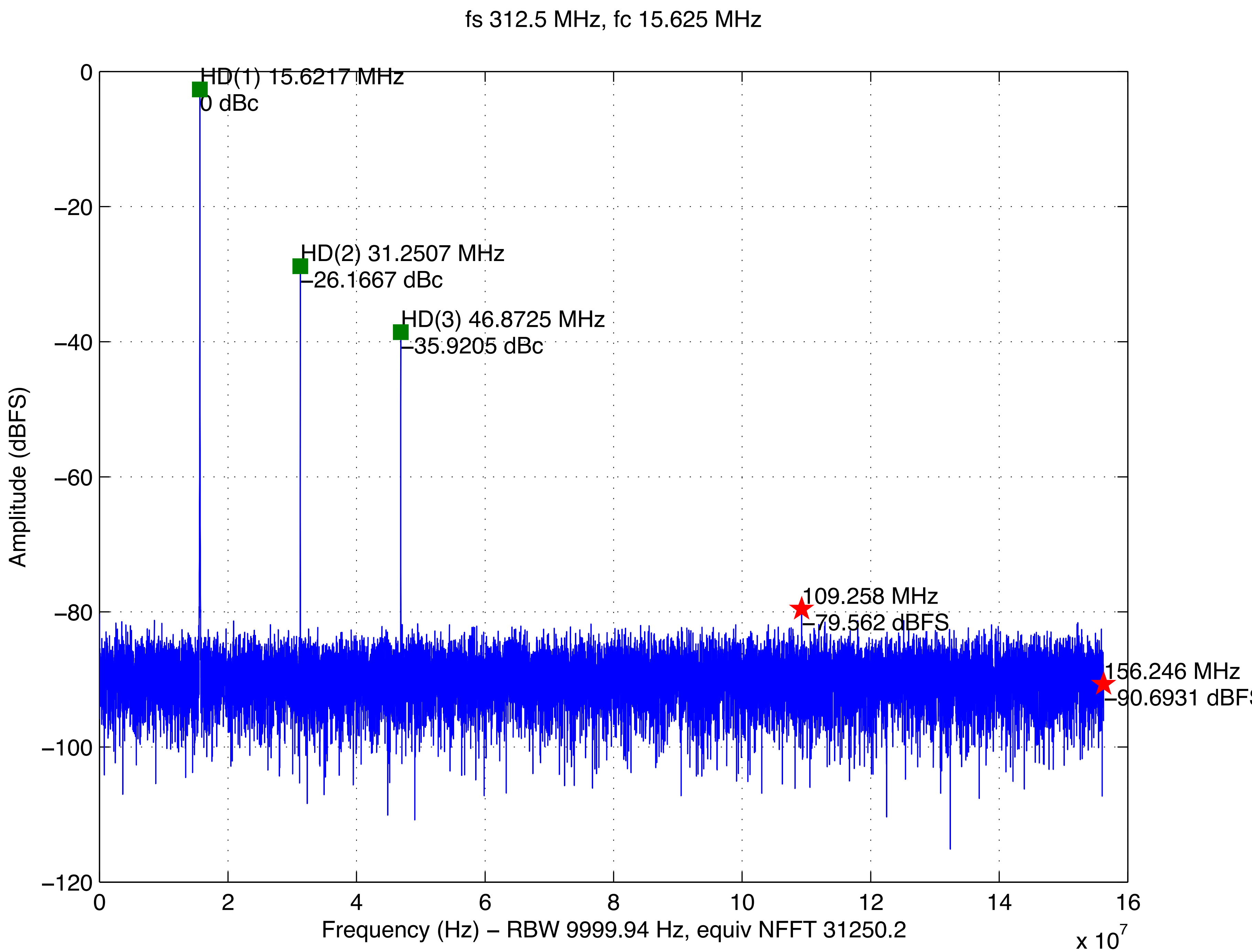
Non-linear response and capacity penalties

Non-linear distortion (-40 ºC, 15.6 MHz)



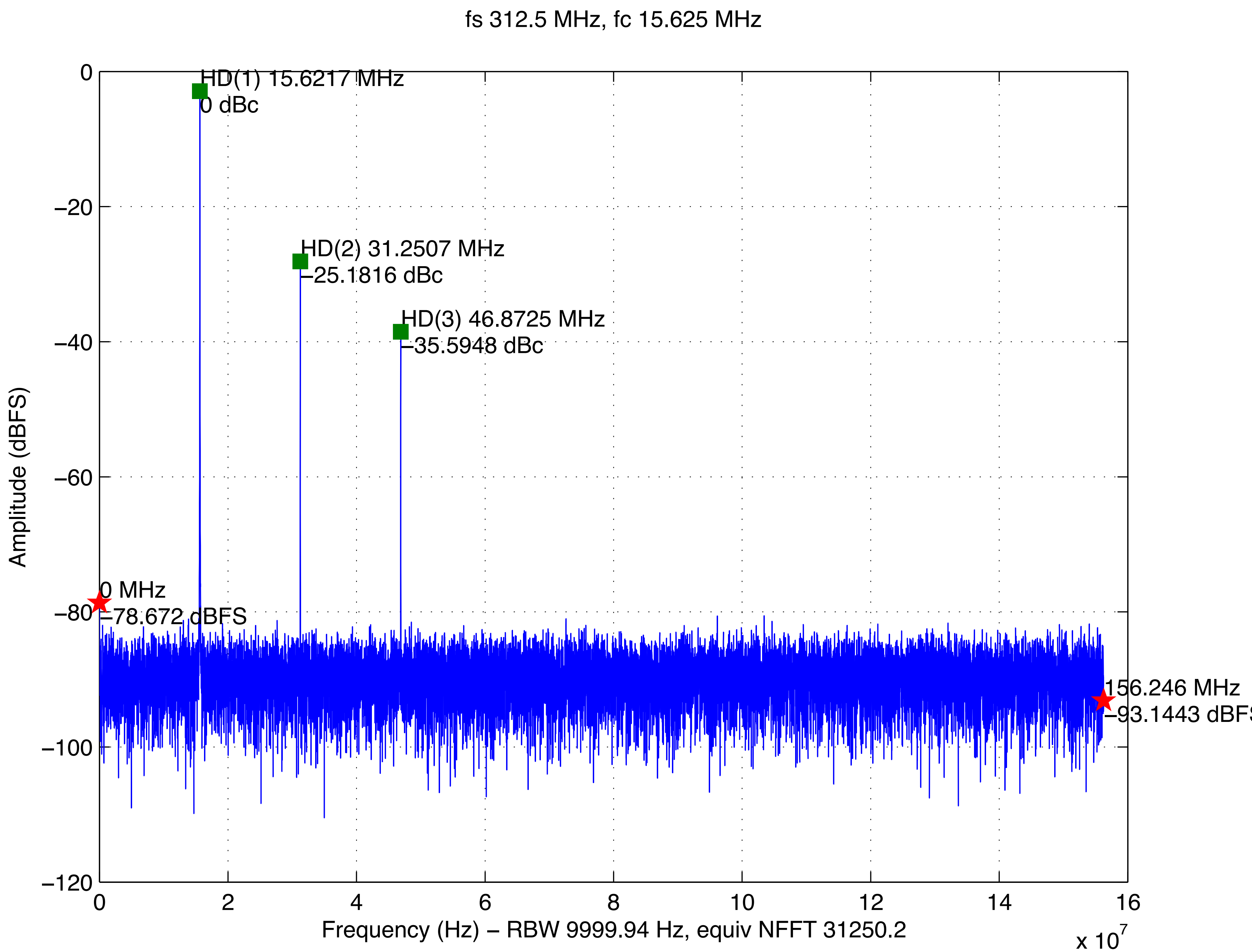
Lab. measurements of a real product

Non-linear distortion (+25 ºC, 15.6 MHz)



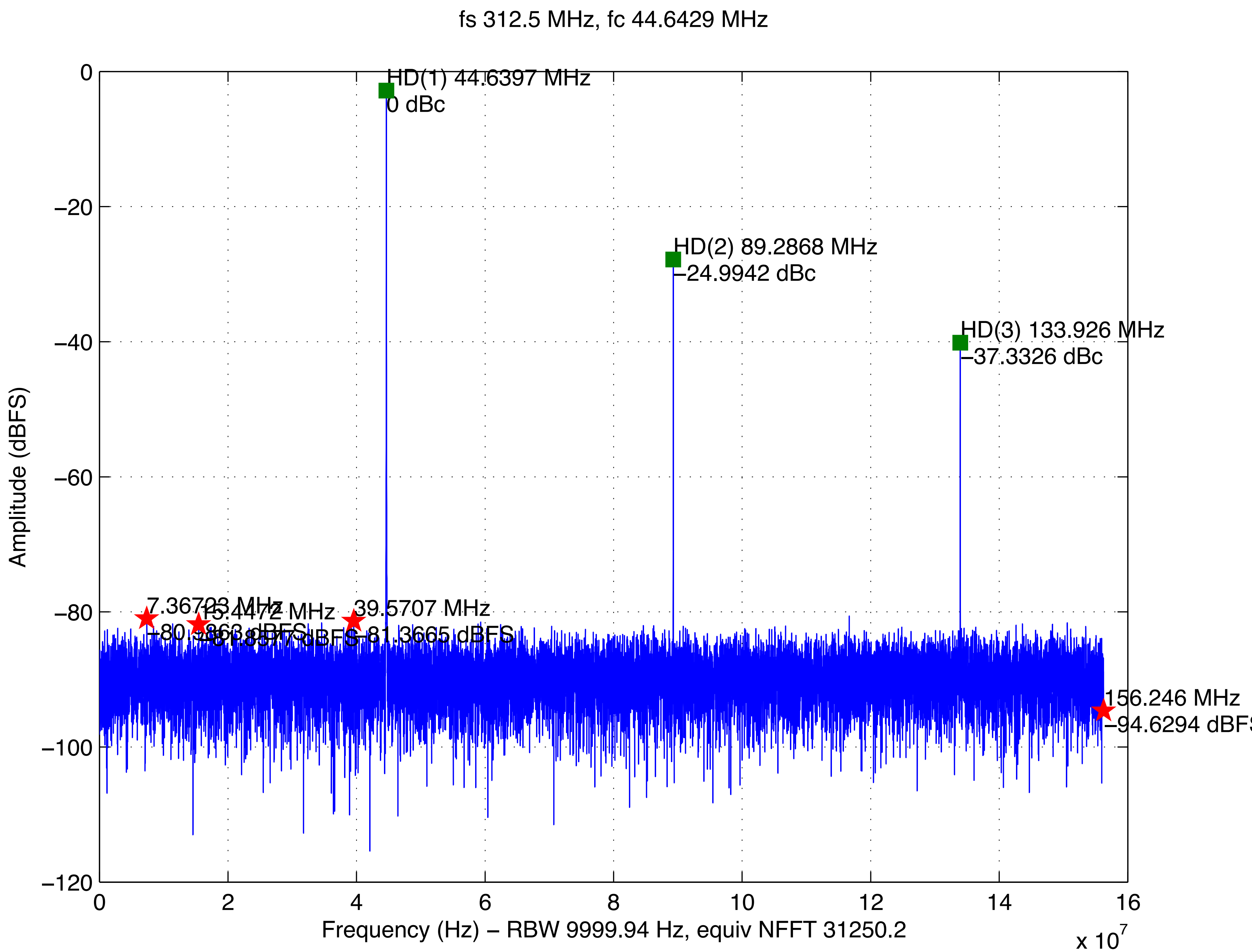
Lab. measurements of a real product

Non-linear distortion (+105 ºC, 15.6 MHz)



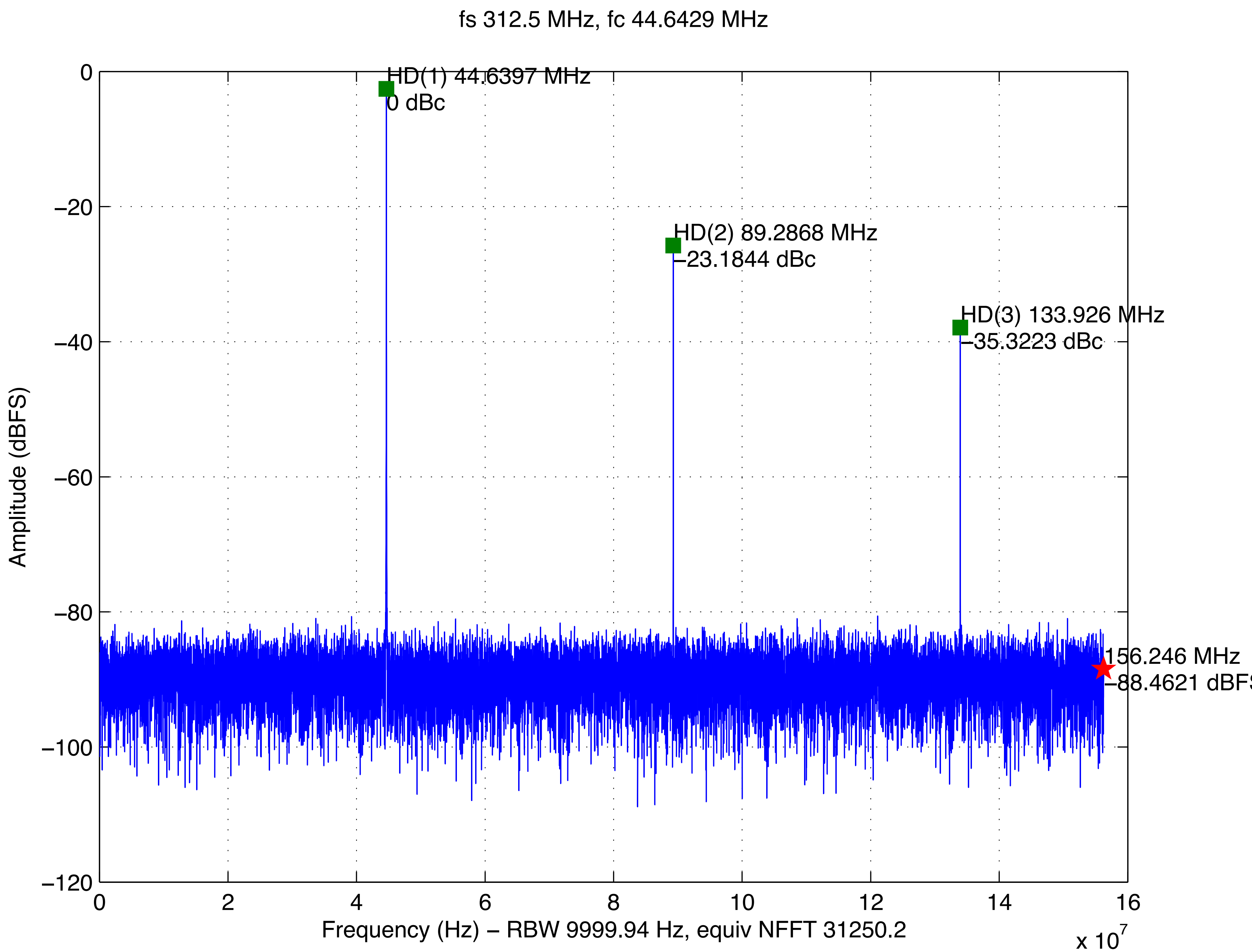
Lab. measurements of a real product

Non-linear distortion (-40 ºC, 44.6 MHz)



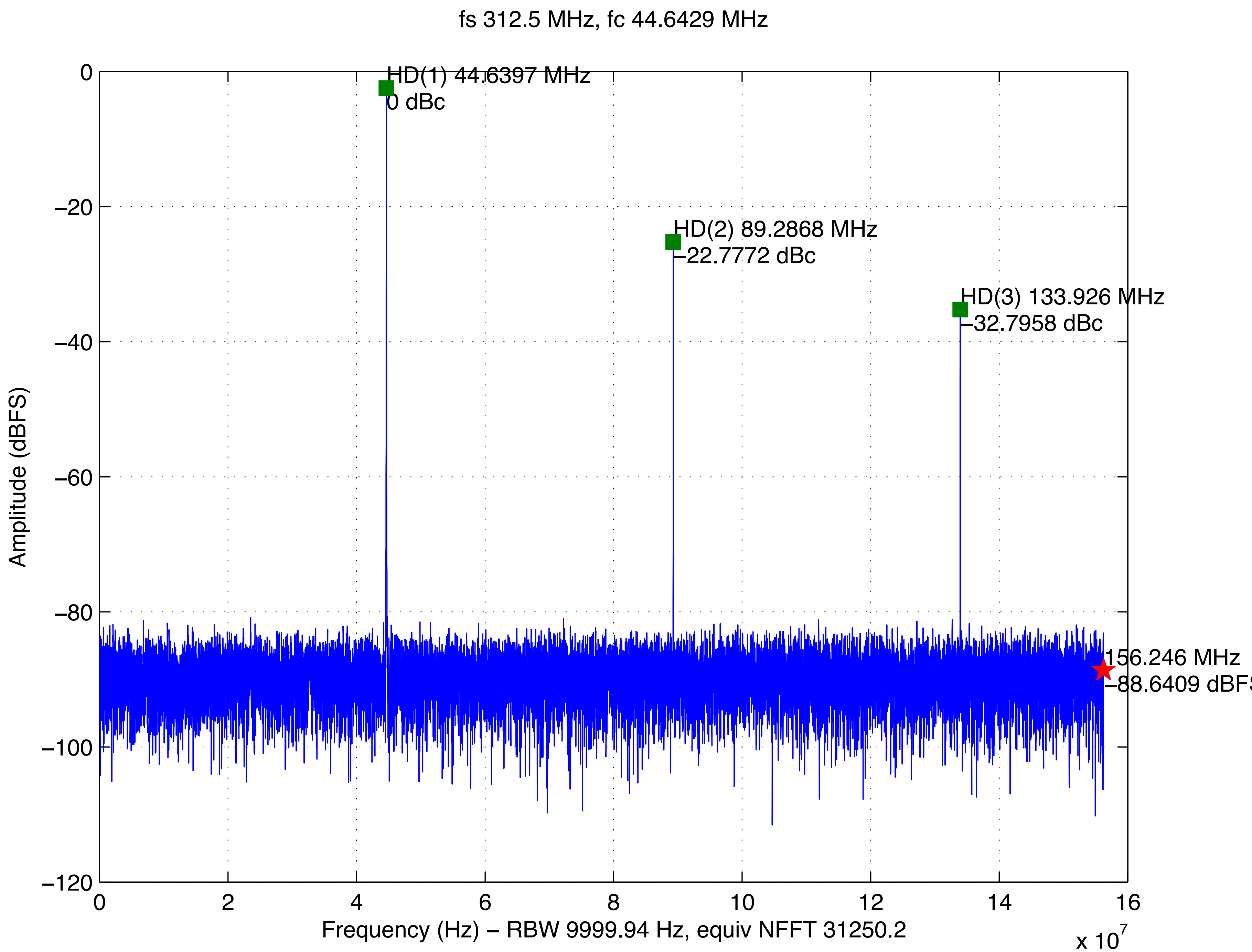
Lab. measurements of a real product

Non-linear distortion (+25 ºC, 44.6 MHz)



Lab. measurements of a real product

Non-linear distortion (+105 ºC, 44.6 MHz)



Lab. measurements of a real product

Non-linear distortion - preliminary conclusions

- Based on previous measurements we can do some conclusions:
  - The non-linear response of the LED depends on the temperature
  - The harmonic distortion measurement with input single tone depends on the frequency of the tone
- Based on this very basic measurements we could conclude that only low spectral efficiency modulation schemes would be feasible with the LED
- However, we are going to demonstrate that this conclusion is false, by analyzing the non-linear response in deeper detail
- The idea behind the following analysis is that the non-linear response of the LED can be adaptively compensated by the PHY in the same way the ISI is equalized in modern Ethernet PHYs to approach the channel capacity

Non-linear response - the Volterra model

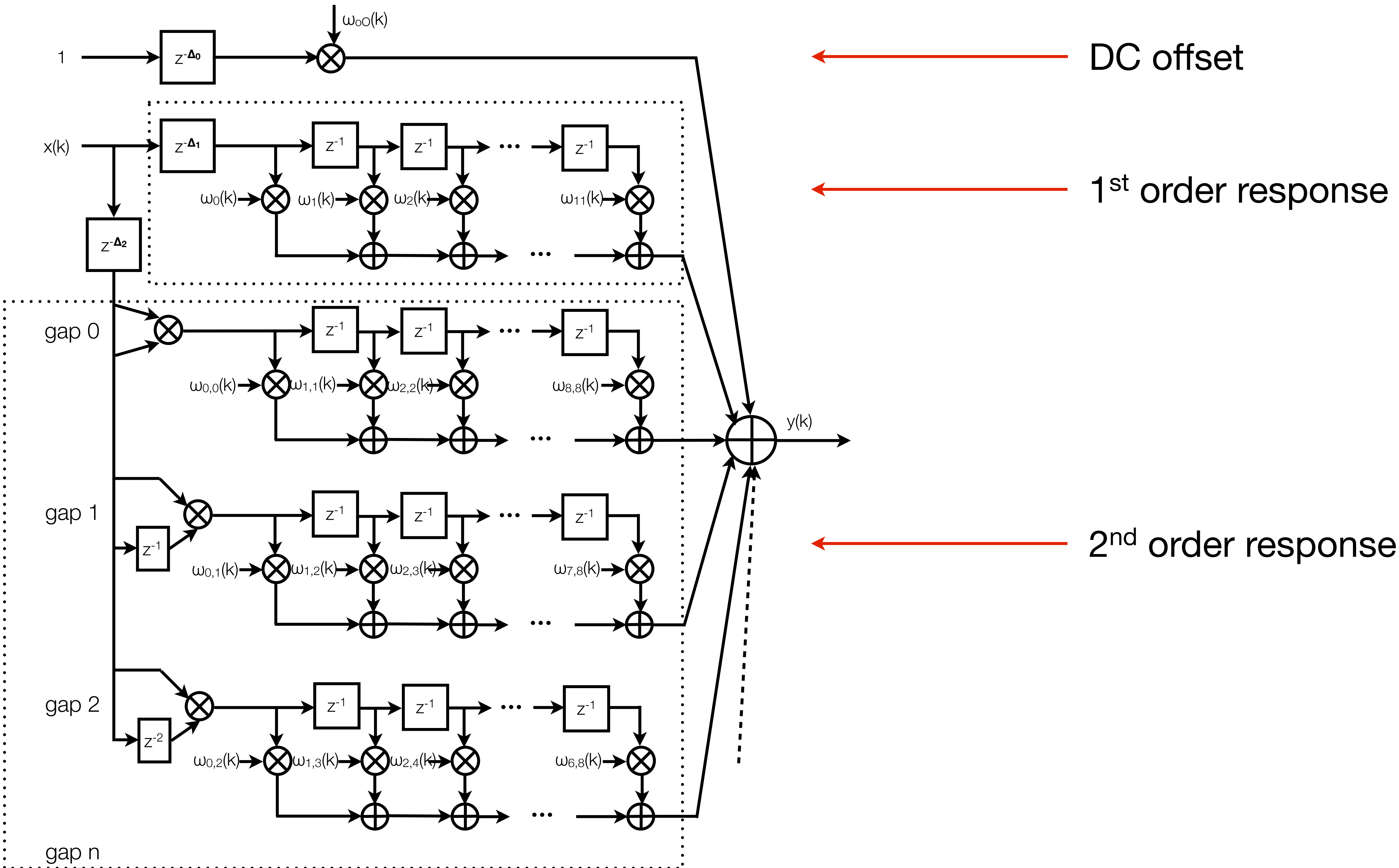
- In order to analyze the effect of LED HD in the communication system we need to develop a correct model for the non-linear response
- Truncated Volterra series expansion is selected to model the optical TX non-linear response
  - Volterra series expansion is a well known technique and it have been used by the industry in a wide range of engineering fields to model non-linear systems
  - It is attractive from the mathematical point of view ➤ linear combination of non-linear functions of the input signal
  - It fits a large class of non-linear systems
  - Well known adaptive filtering algorithms are suitable for Volterra series estimation

$$y(k) = w_{o0} + \sum_{l_1=0}^{L} w_{o1}(l_1)x(k-l_1) + \ldots$$ ← DC offset + linear filter

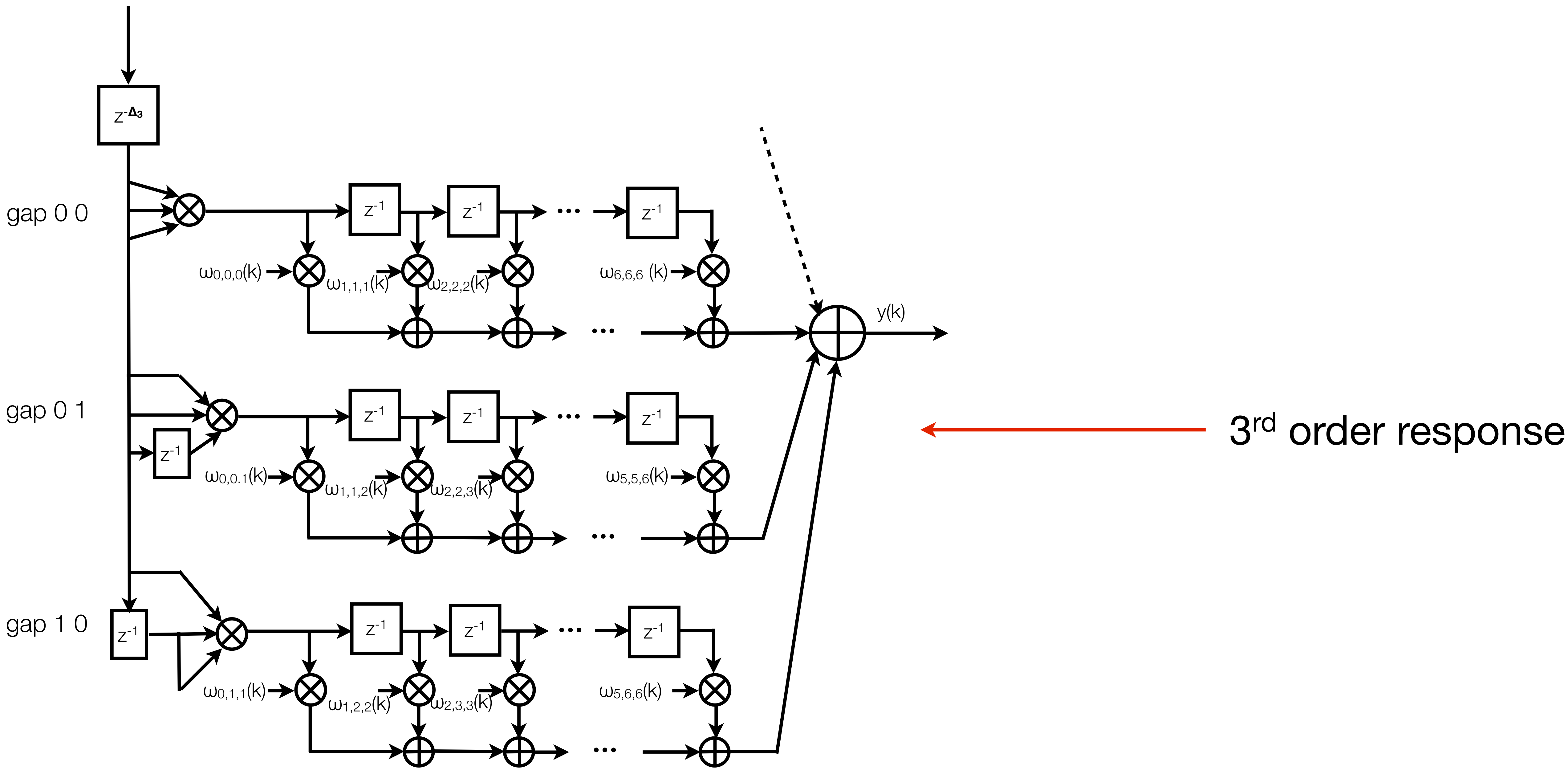
$$+\sum_{l_1=0}^{L}\sum_{l_2=0}^{L} w_{o2}(l_1,l_2)x(k-l_1)x(k-l_2) + \ldots$$ ← 2nd order convolution

$$+\sum_{l_1=0}^{L}\sum_{l_2=0}^{L}\cdots\sum_{l_p=0}^{L} w_{oP}(l_1,l_2,\ldots l_P)x(k-l_1)x(k-l_2)\ldots x(k-l_P)$$ ← Higher-order convolutions

Non-linear response - the Volterra model



Non-linear response - the Volterra model

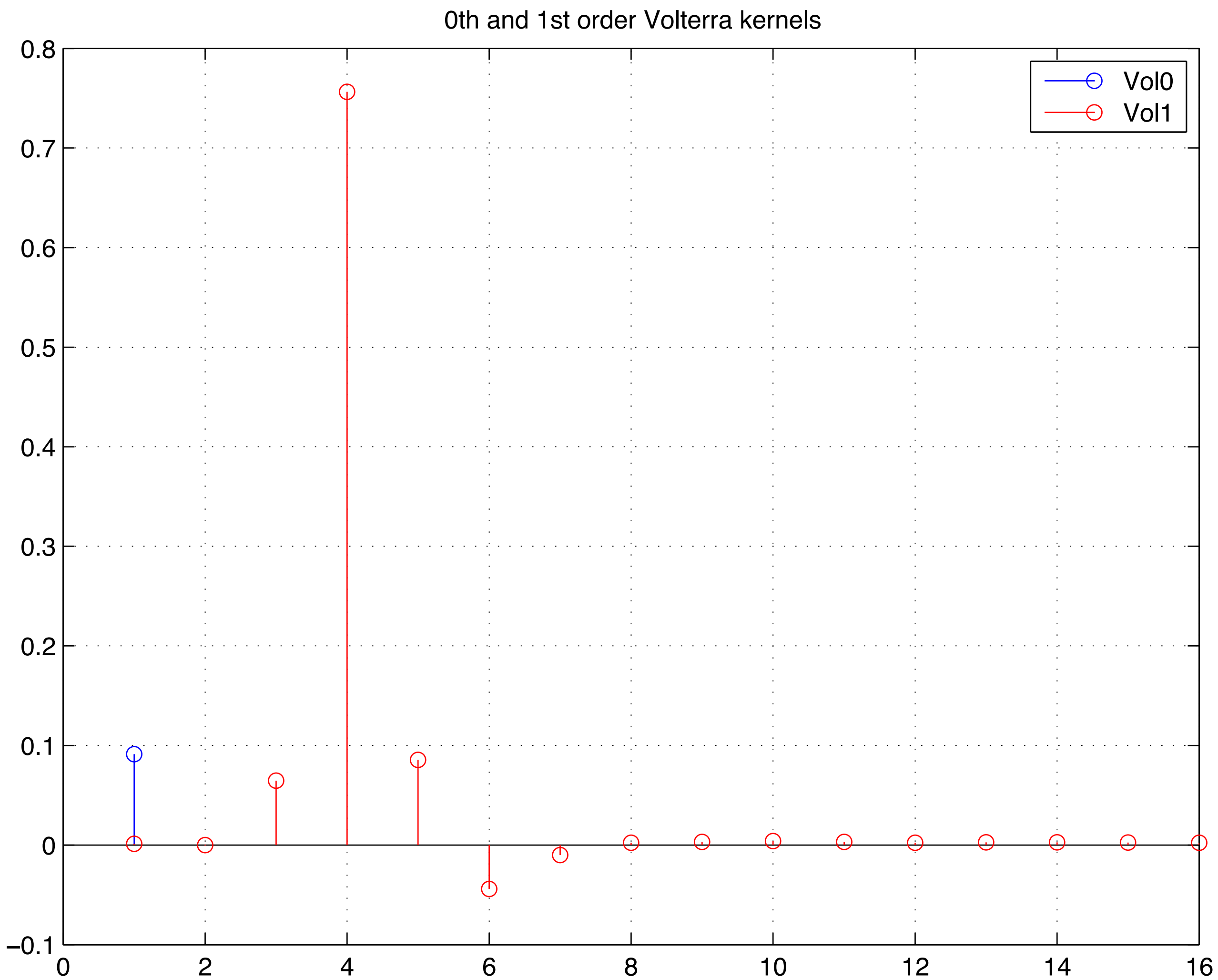


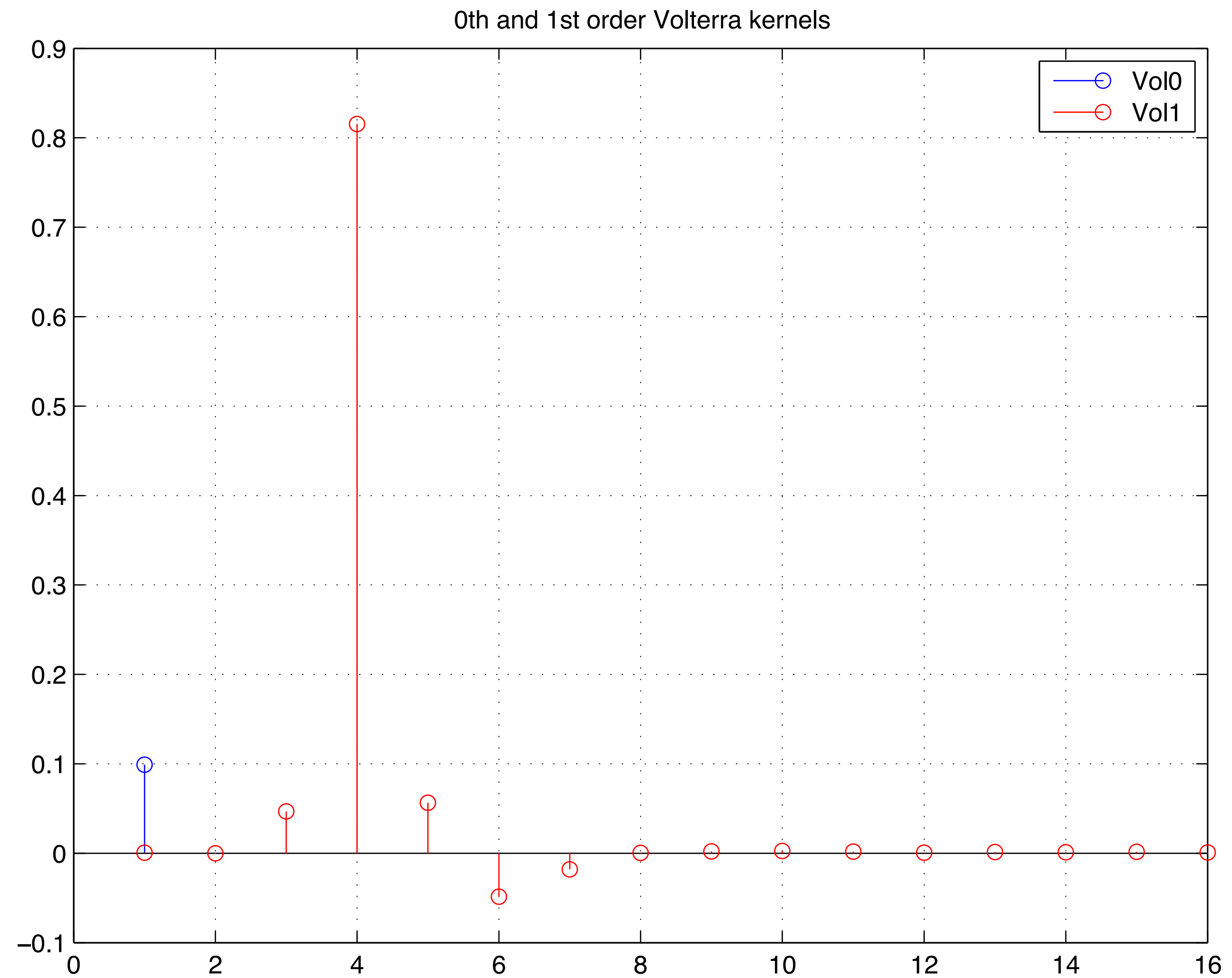
- The optical transmitter is well modeled by a 3rd order Volterra system.
- Higher order kernels are negligible

Non-linear response: Volterra DC and 1st order

-40 ºC

+105 ºC

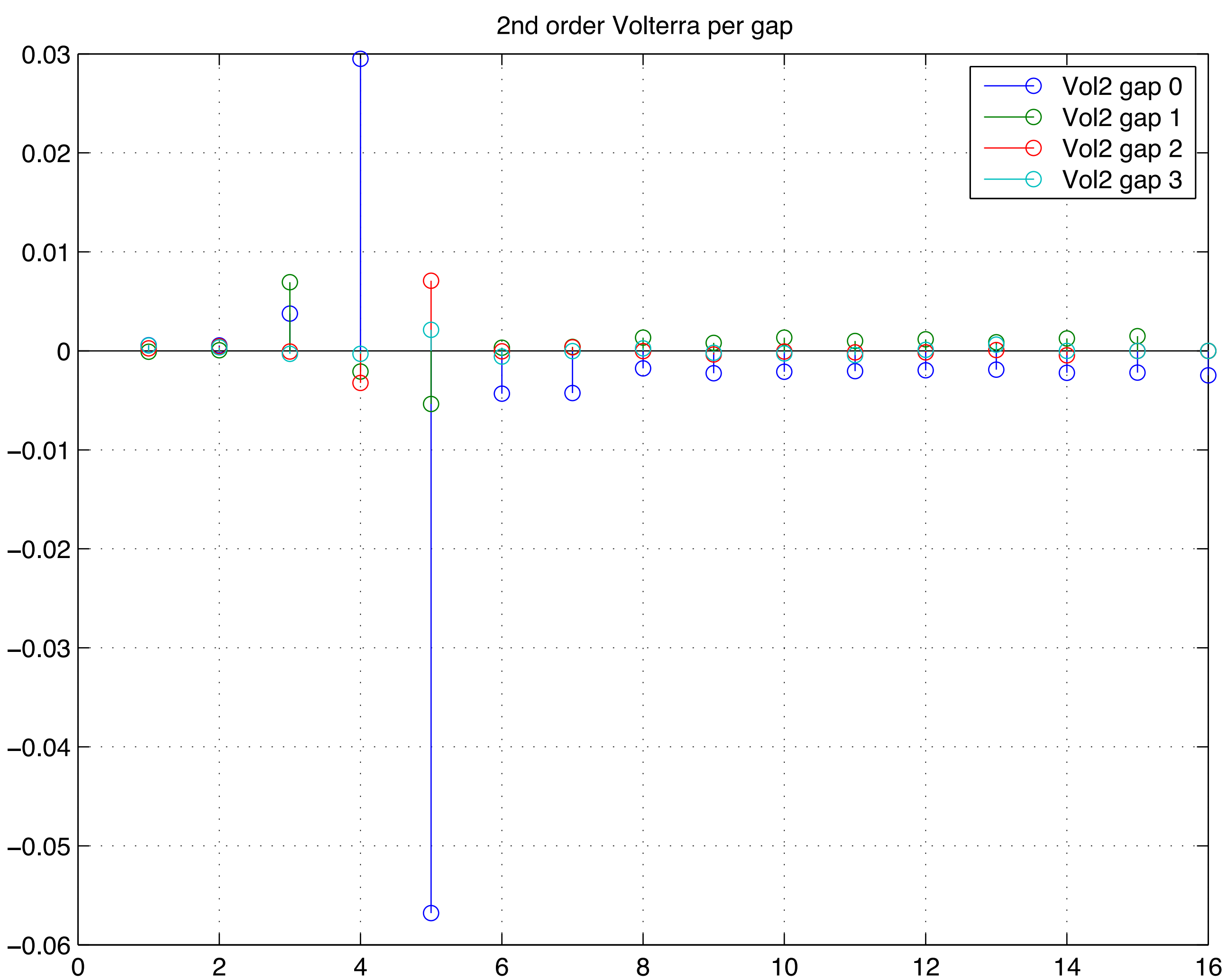


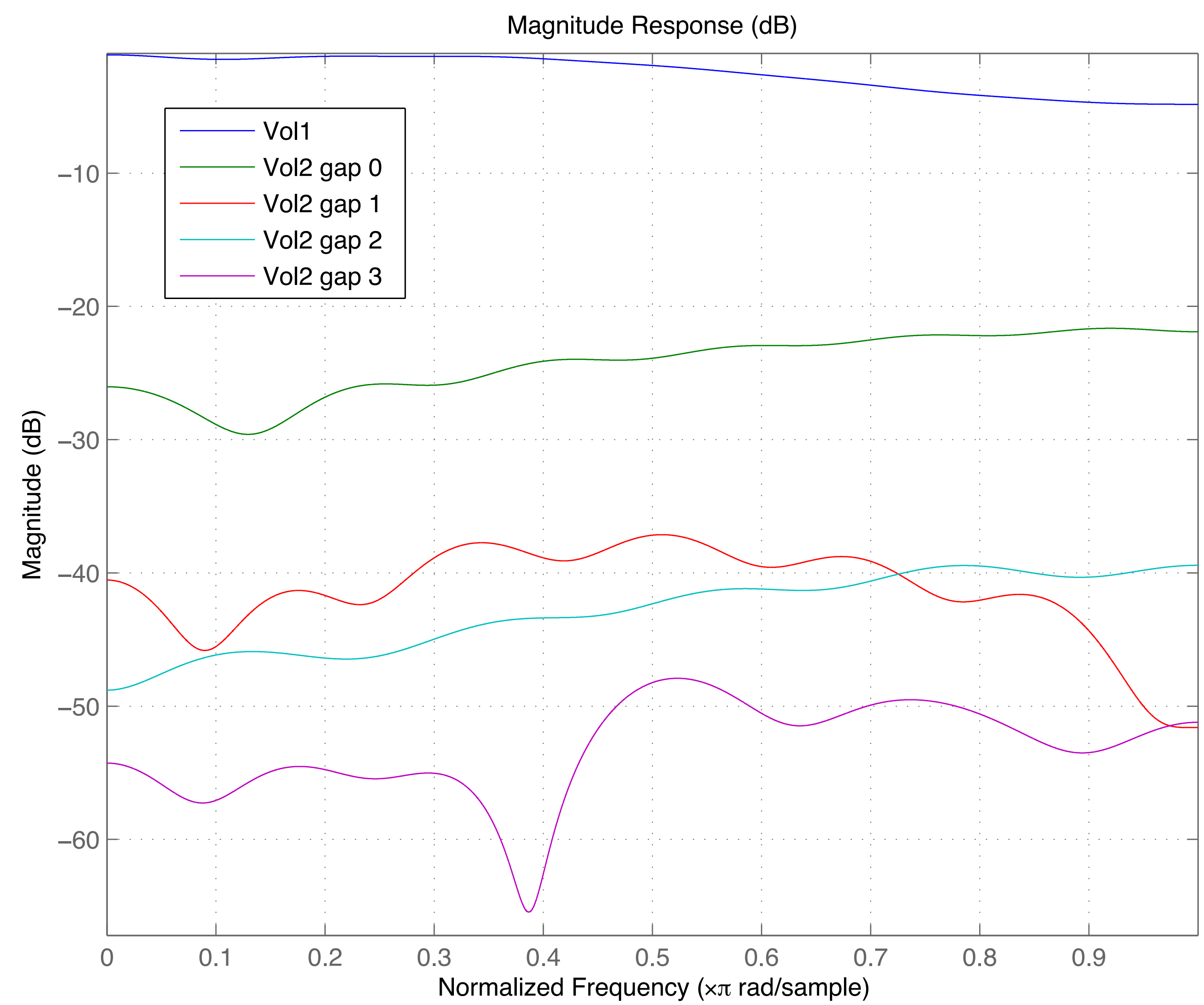


F_S = 312.5 MHz

Non-linear response: Volterra 2nd order

-40 ºC





F_S = 312.5 MHz

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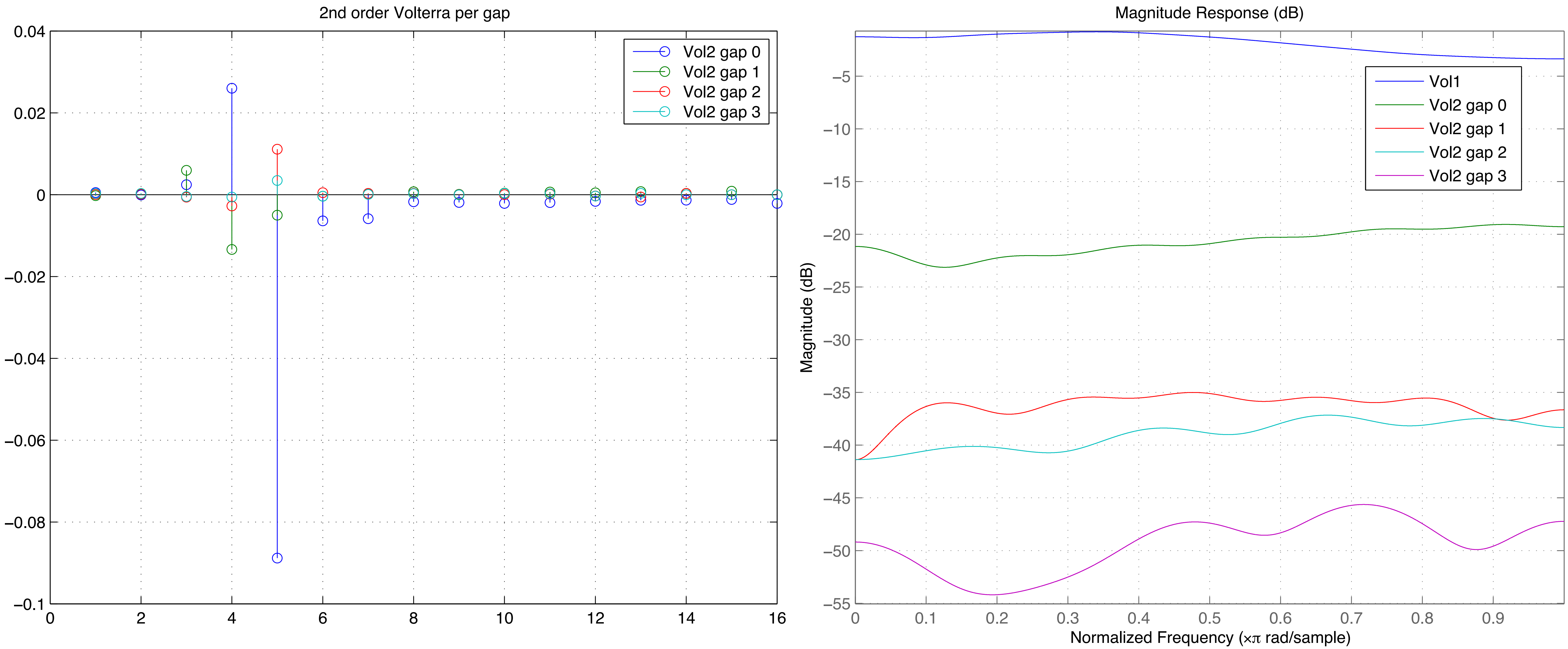
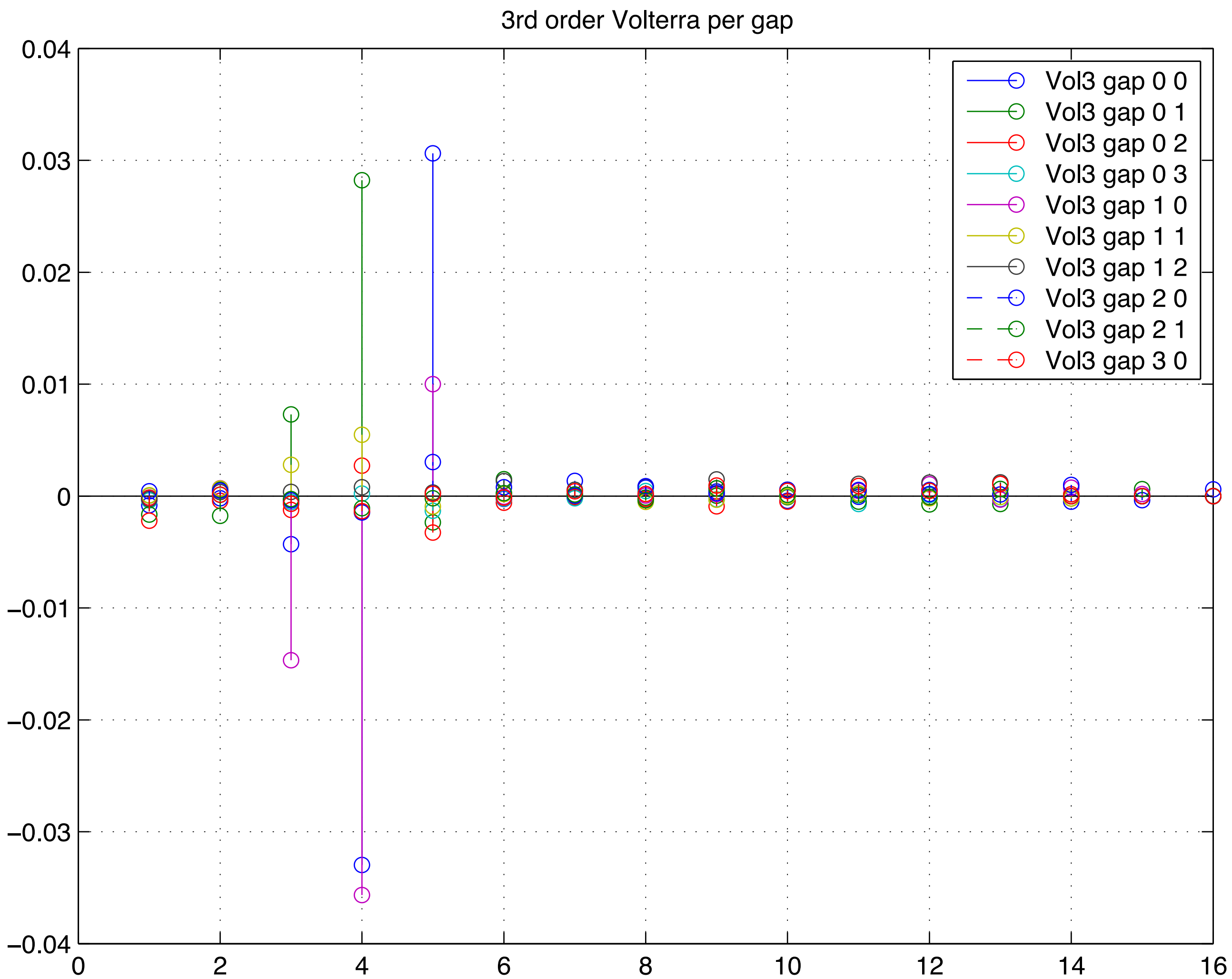
105 ºC

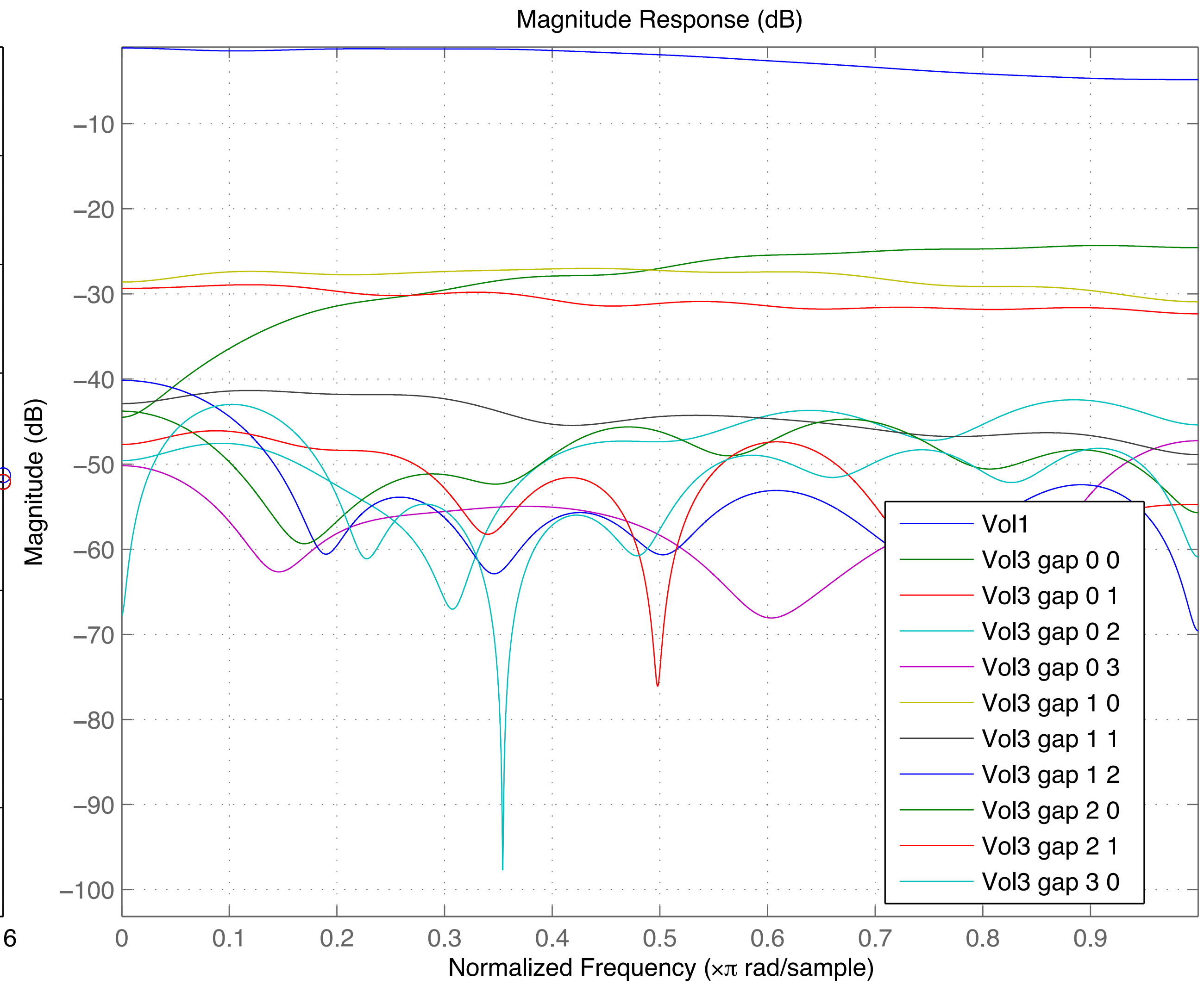


F_S = 312.5 MHz

Non-linear response: Volterra 3rd order

-40 ºC

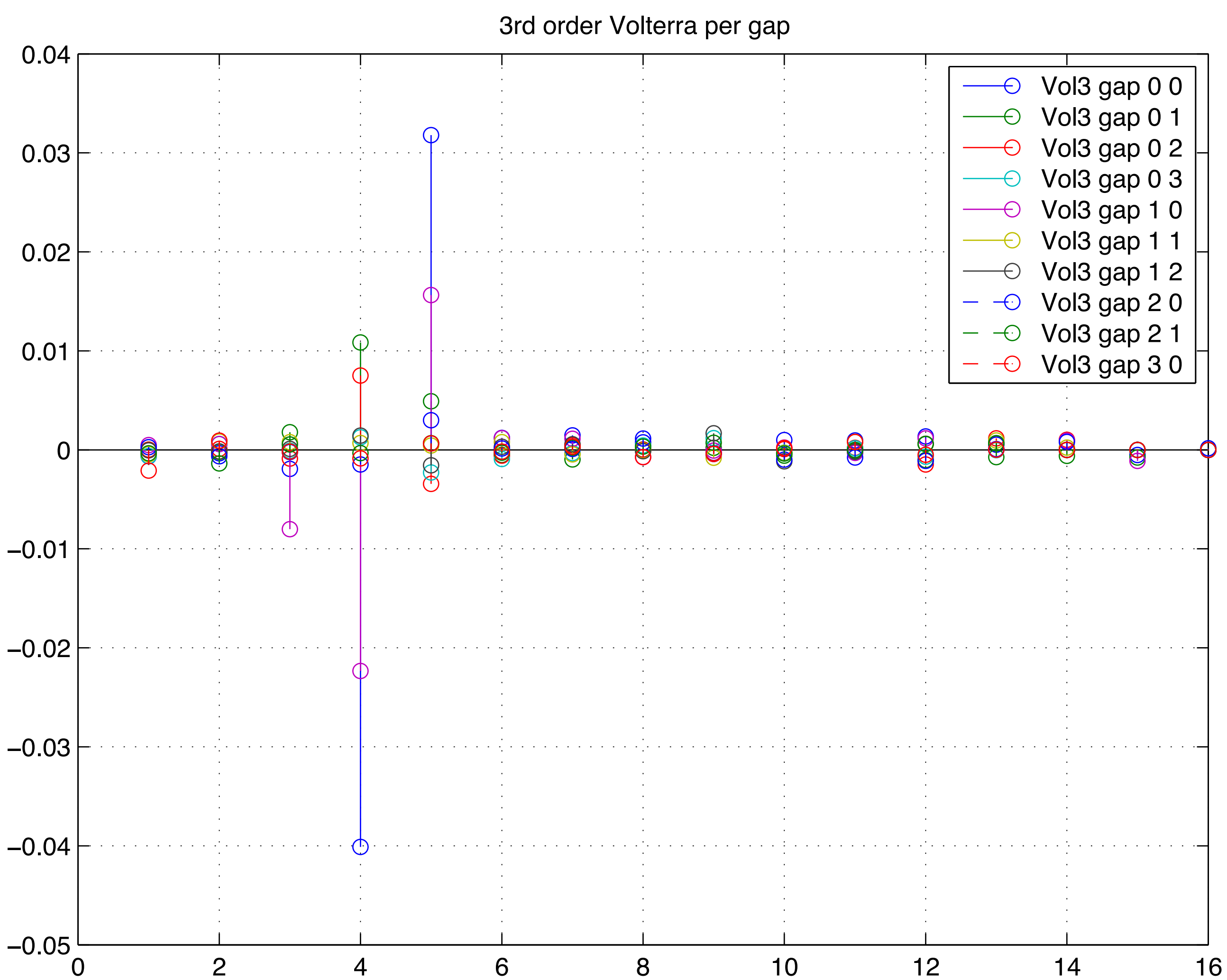


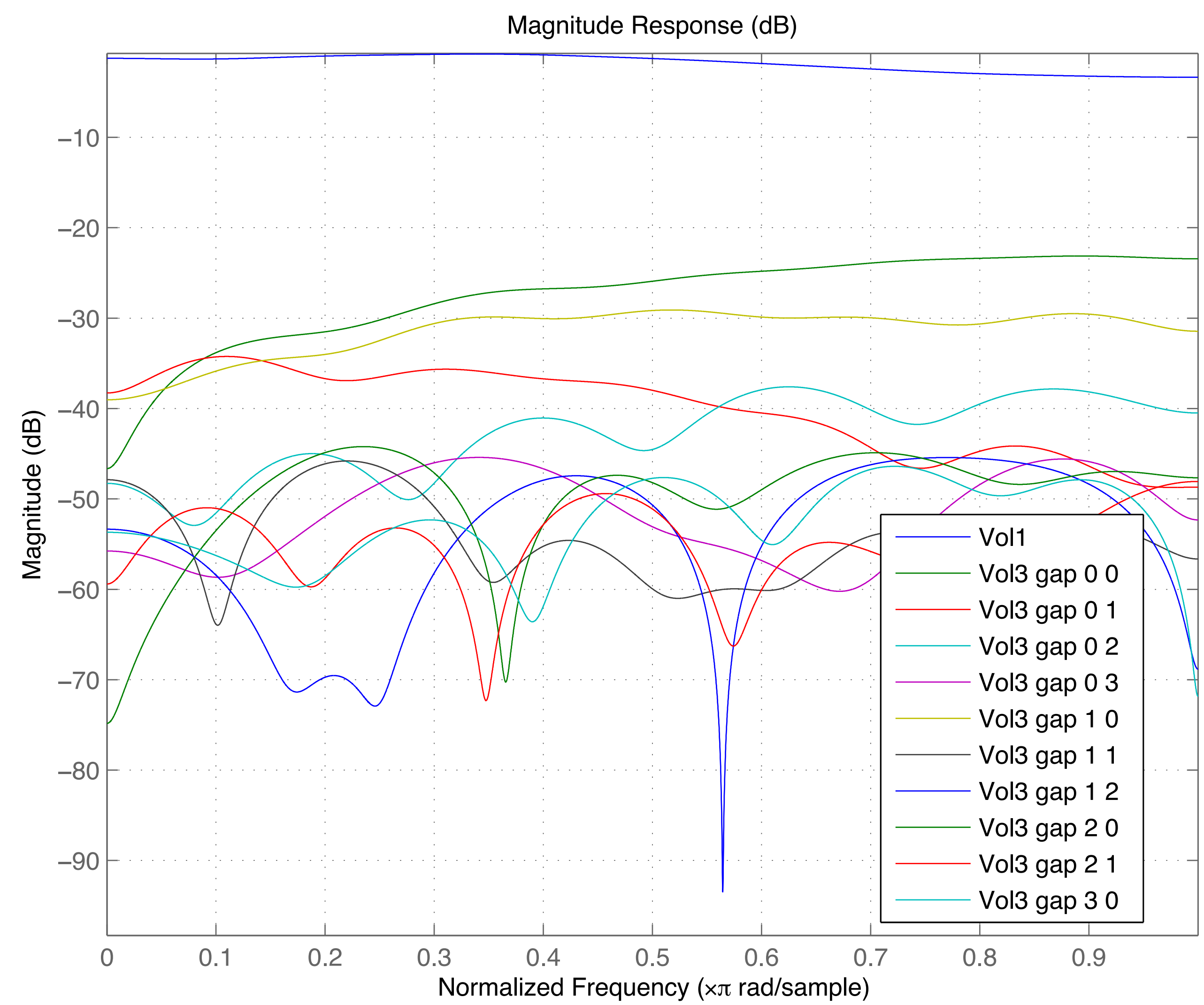


F_S = 312.5 MHz

Non-linear response: Volterra 3rd order

105 ºC



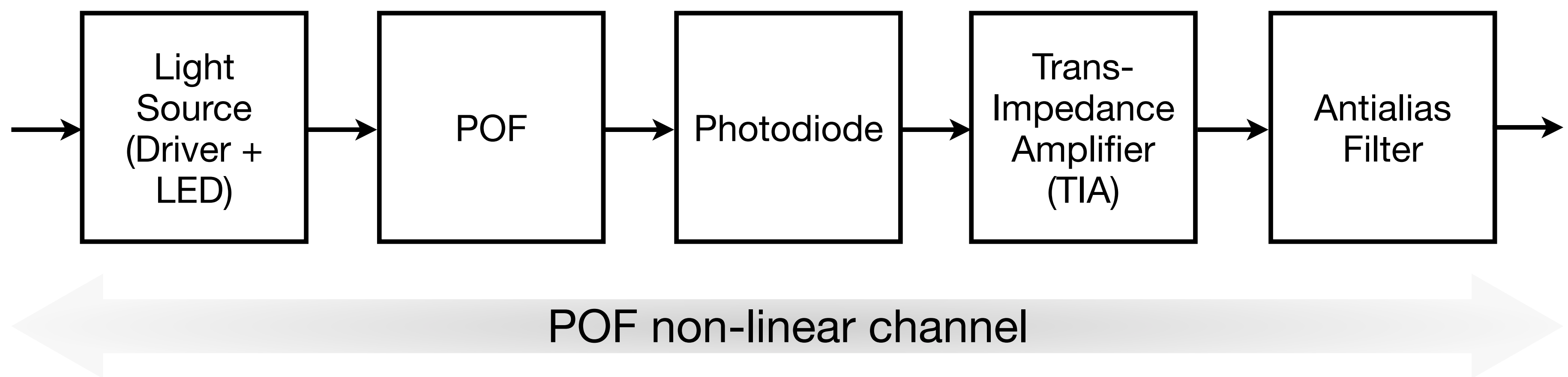


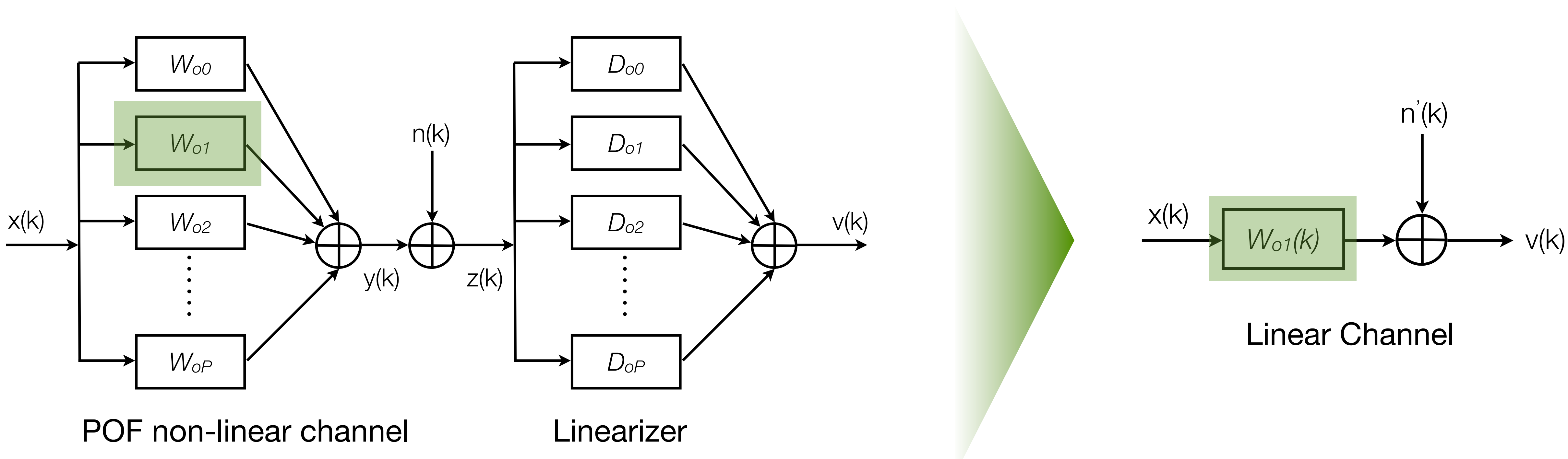
F_S = 312.5 MHz

Non-linear response: Volterra analysis

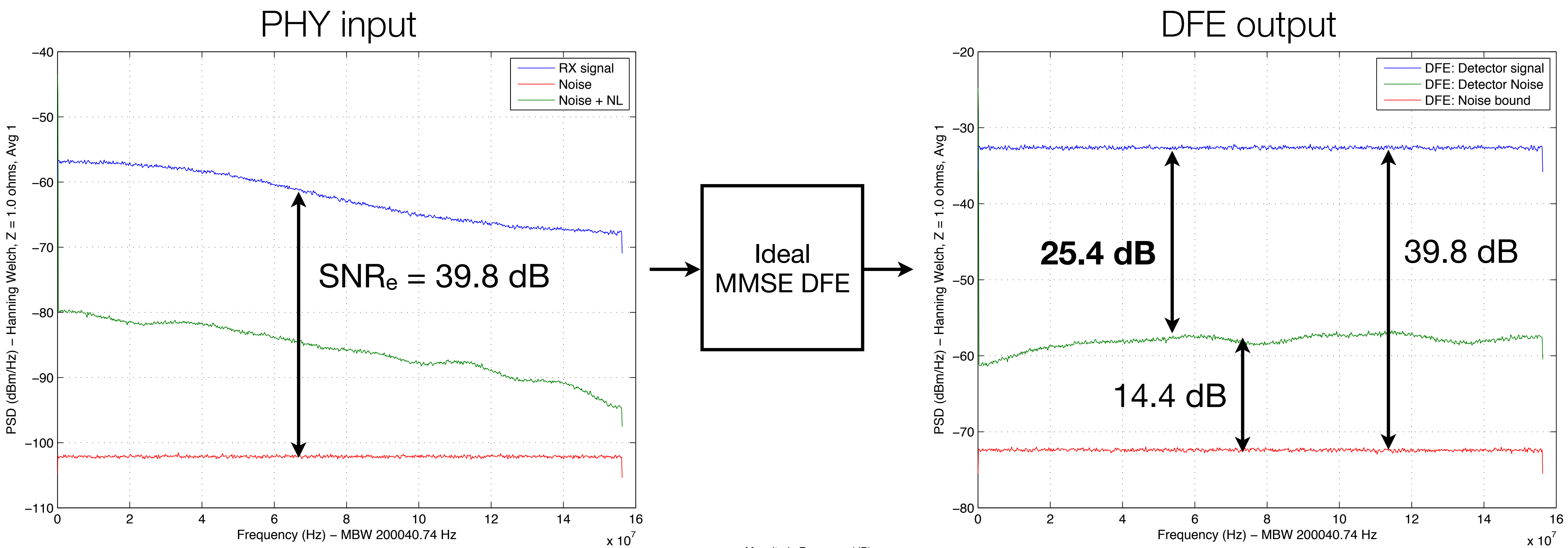
- Bandwidth of the optical TX increases with temperature, although impulse response could be considered approximately constant
- The magnitude of the 2nd and 3rd order Volterra kernels increases with temperature and frequency ➤ it confirms the basic single tone HD measurements
- It is important to note that most part of energy of 2nd and 3rd order responses is delayed respect to 1st order
  - We can conclude that optical TX cannot be modeled as a Wiener or a Hammerstein non-linear system
- The <u>morphology</u> of Volterra (2nd and 3rd) kernels basically does not change with temperature ➤ good from the implementation point of view

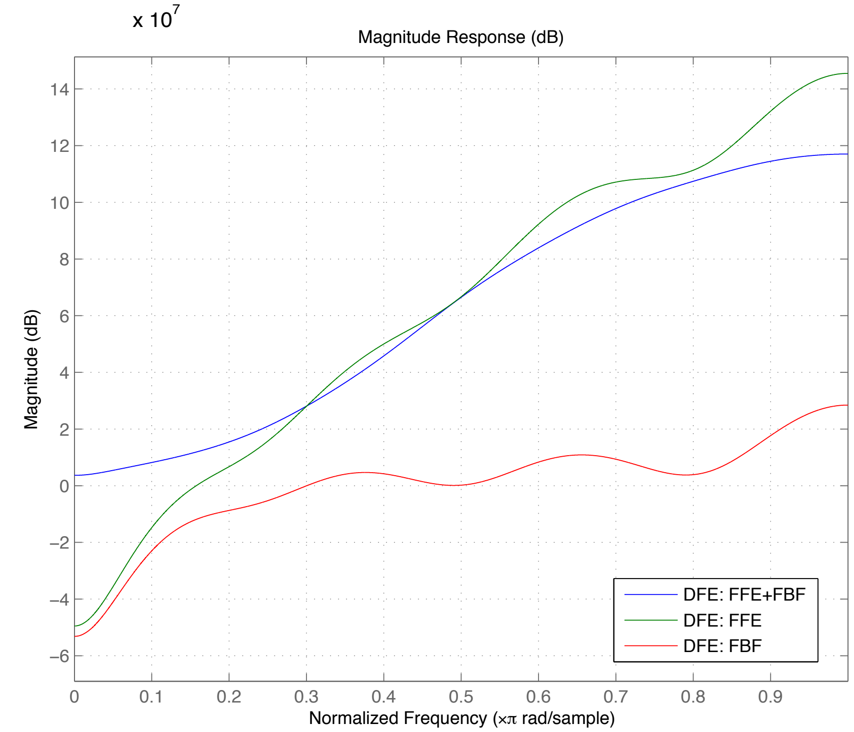
Capacity penalties - channel linearization





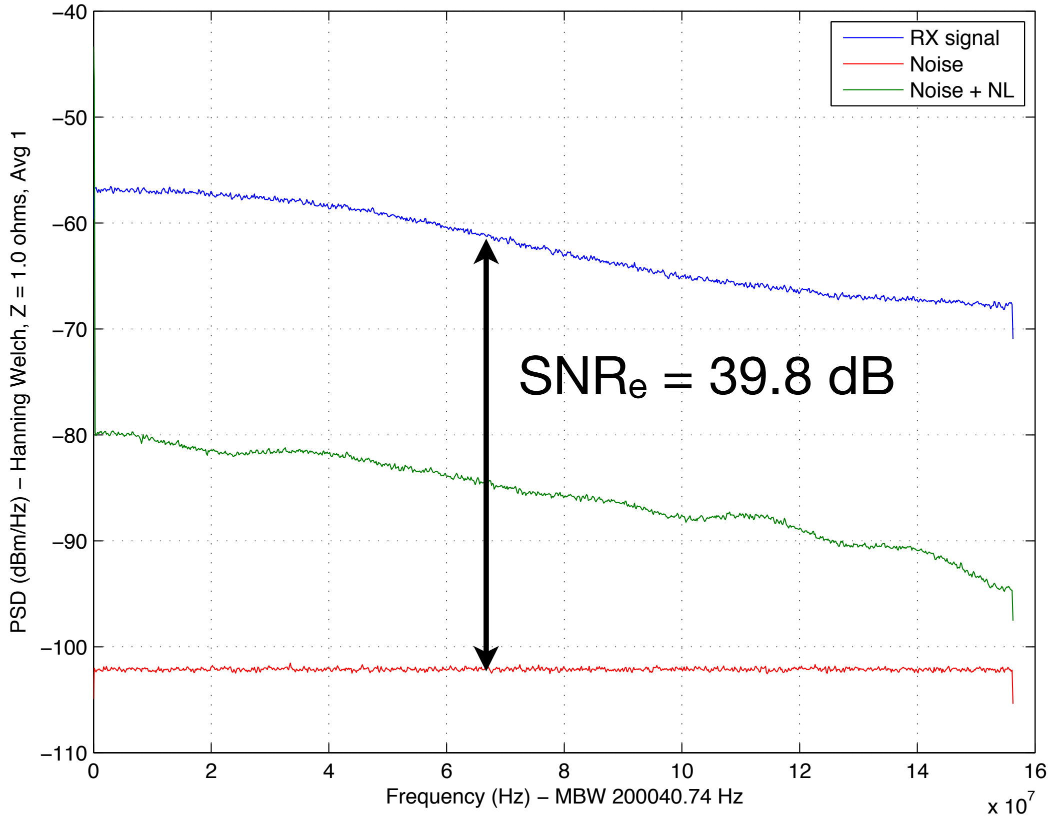
Capacity penalties - Linearizer is not implemented

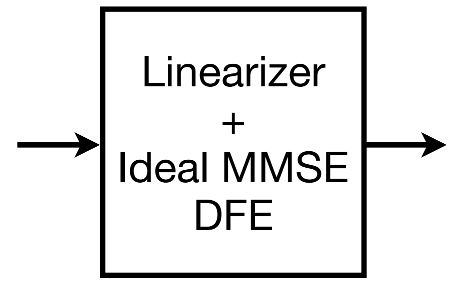




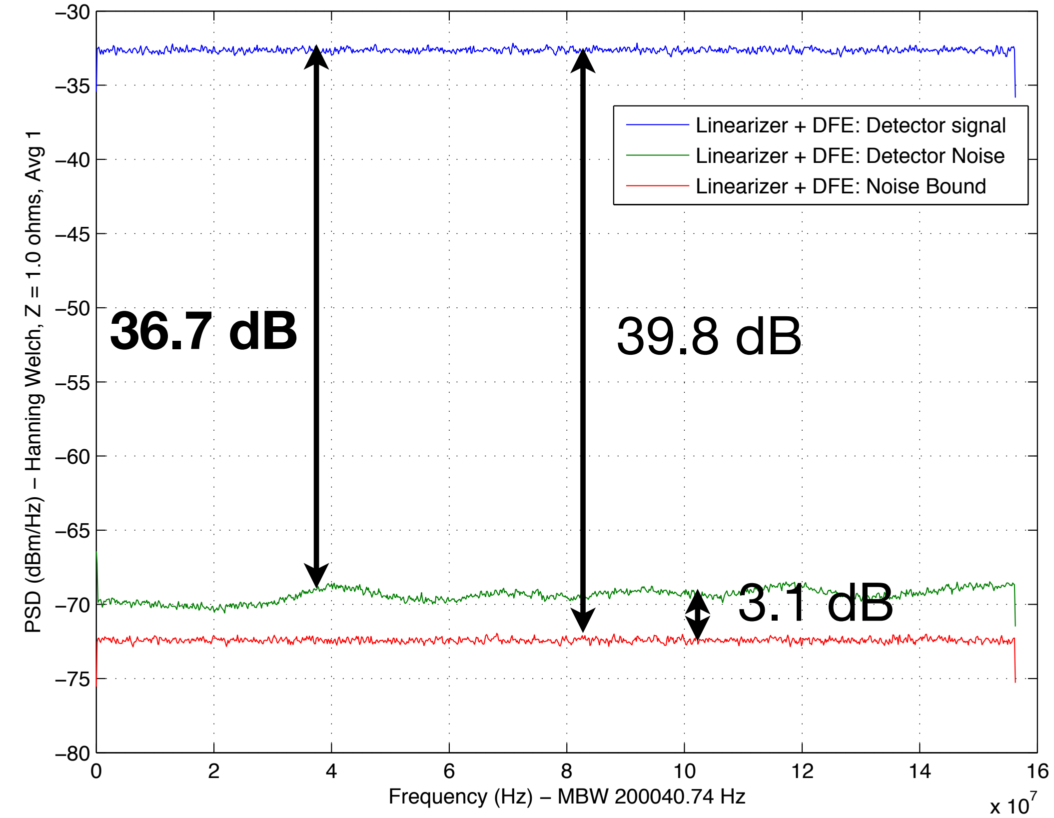
Capacity penalties - Linearizer is implemented

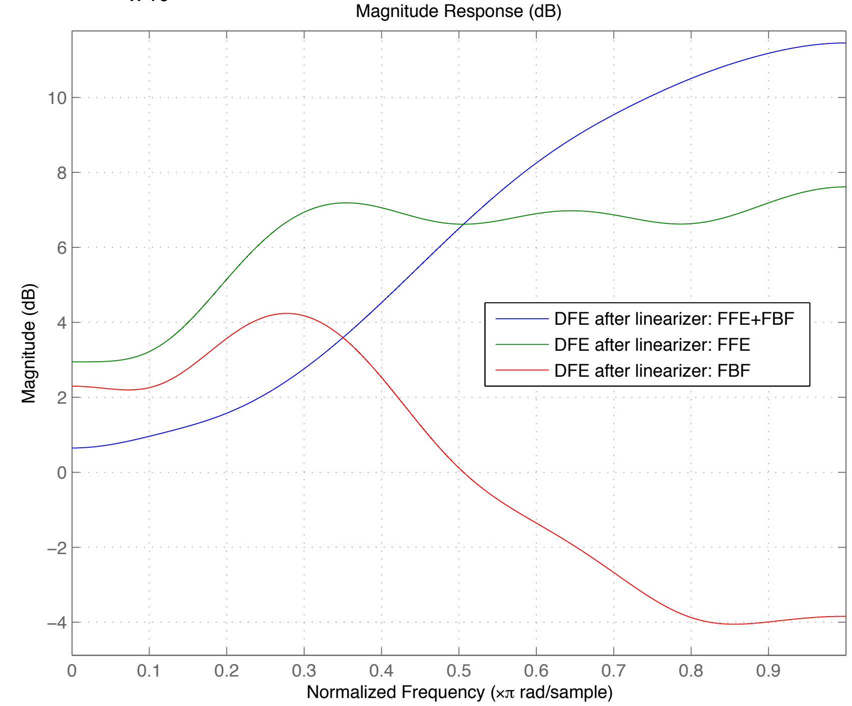
PHY input



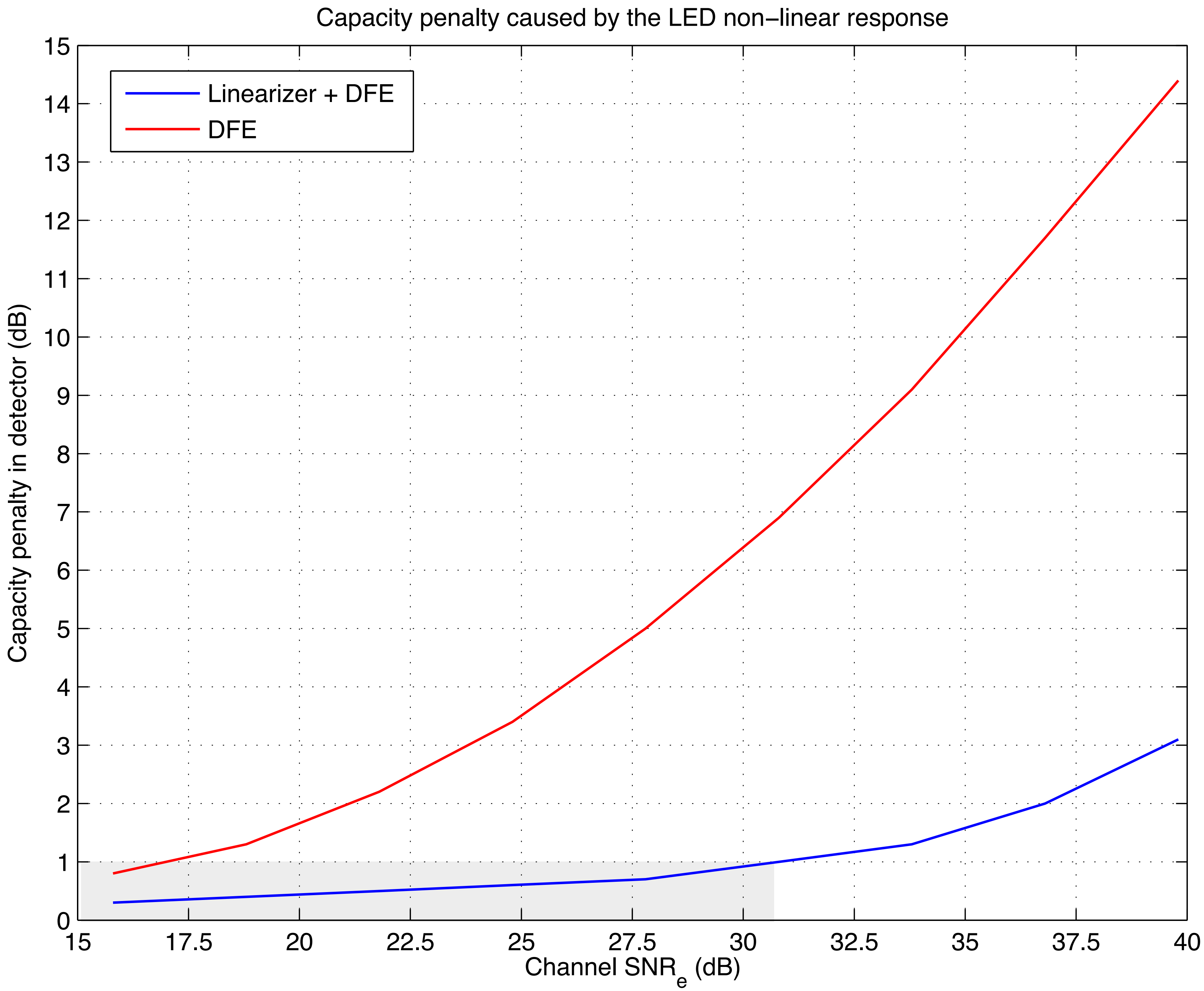


DFE output





Capacity penalties



Capacity loss < 1dB for SNR$_e$ < 30 dB

High spectral efficiency schemes are feasible

Conclusions

- Technical characteristics of the optical transmitter used today for automotive applications as well as for consumer applications have been presented
- The non-linear response of I-P characteristic of LED has been analyzed in detail, concluding that high spectral efficiency modulation schemes are also feasible with low capacity penalties, opening the use of LED beyond OOK schemes
- The results presented here will be used for Shannon's capacity analysis in [perezaranda_01_0514_shannoncap]

Questions?