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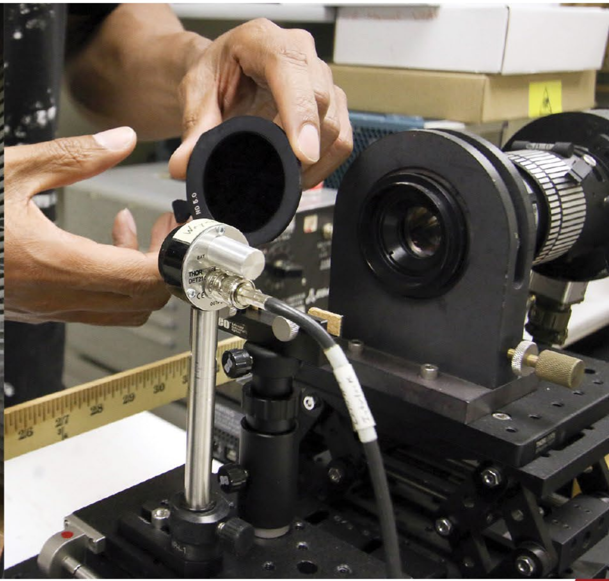

PDV Sensitivity

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PDV Sensitivity

- The main specification for system performance.
- Answers the question: Can I measure a target that returns X amount of light?
- Has been talked about many times before, with Daykin (2016) and Miller (2017) as two good examples.
- But… no community-wide, rigorous definition.
- The author thinks that we should talk about sensitivity much, much more… and that this would make our work better.
- I borrow from both Daykin and Miller here, as well as conversations with Mike Hanache and others.

Edward Daykin, "PDV/MPDV APPs Modeling Tools to Predict System Performance for Design and Experimentation", PDV Workshop 2016, Livermore, CA, June 6-9, 2016.
Edward Kirk Miller, Eric Larson, Kevin Lee, "Shot noise and fiber amplifier effects in photonic-Doppler velocimetry systems", SHOCK COMPRESSION OF CONDENSED MATTER - 2017: Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter, 9–14 July 2017.

Example Discussion

I'm doing an experiment with an expected minimum surface return of -60 dB and we are interested using a 1 ns analysis window. **Do you think that I will be successful?**

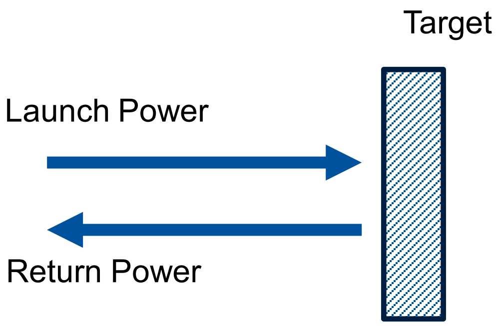
I just measured my system to have a sensitivity of 20 nW*ns. So if you launch 200 mW of power, you will see a -70 dB surface with an SNR of 10 dB… or a -60 dB surface with an SNR of 20 dB. **You should expect to be successful!**

Definition of PDV Sensitivity

- General definition: The signal required for a quality trace on the recording equipment. The lower the better.
- Suggest the following:
  - Minimum target return to achieve a SNR of 10 in the frequency domain.
- Two ways to define target return…

- **Relative Target Return** is [Return Power] / [Launch Power]
- Measured in dB.
- Used when defining performance of entire system -- both the launch-side and the return-side of the system.

- **Absolute Target Return** is simply Return Power.
- Measured in Watts.
- Used when defining performance of return-side of the system.



Calculating the Optimum Sensitivity: Some preliminaries

- Reminder that $SNR = \frac{P_{sig}}{N_{Noise}}$,
  - In a frequency bin of a particular width,
  - where both P and N are measured in electrical power in Watts into the oscilloscope.
- Noise comes from three places:
  - Optical ← Defines the theoretical limit of sensitivity.
  - Digitizer ← In practice, scope vertical can be adjusted such that digitizer noise is not limiting.
  - Detector ← In practice, always subdominant.
- An aside… All the equations for signal power and noise power are in the backup slides, but they are more suited for a lecture not a presentation. Here we will short cut through the math.

Calculating the Optimum Sensitivity

*Assumptions include intensity noise of laser is at shot noise limit, amplifiers have theoretical minimum ASE, Signal and LO polarizations are aligned.

- If optical noise is at the theoretical minimum* the PDV SNR is:

Scale factor... The inverse of the photon energy, 1.3e-19 J.

Units of energy. The amount of energy from the target that mixes with the LO light. **We suggest this is the natural unit for PDV sensitivity.**

$$SNR_{Optimal} = \frac{1}{h\nu} P_{sig} [AnalysisWindowLength]$$

Unitless number that happens to be the number of signal photons that mix with the LO light in the analysis window. Please see Miller et al.

$$[Sensitivity]_{Optimal} = 10h\nu = 1.3 \times 10^{-18}\ \mathrm{J} = 1.3\ \mathrm{nW\ ns}$$

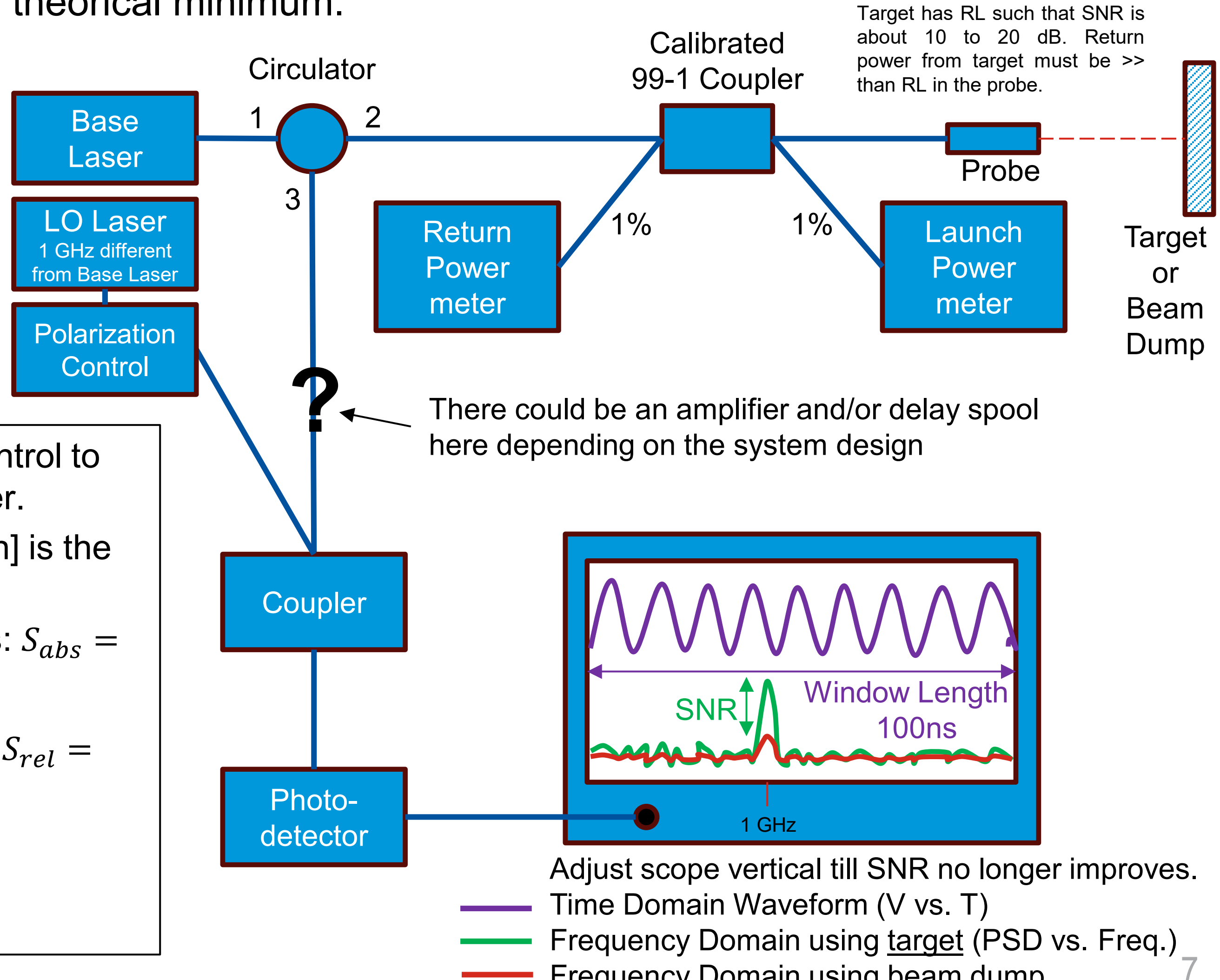
The natural units for PDV Sensitivity are nW ns.

The lower the sensitivity the better.

Measuring Sensitivity

- Measured sensitivity will always be higher than the optimum and will be affected by insertion loss, intensity fluctuations above the shot-noise limit, and amplified spontaneous emission greater than the theorical minimum.

Fine Print: Sensitivity should be fairly constant over the window lengths of typical interest to PDV (measured in ns). You should not expect it to be constant when going from ns to μs to ms.



- Adjust the polarization control to maximize the signal power.
- The ratio [Return]/[Launch] is the target return loss.
- The absolute sensitivity is: $S_{abs} = \frac{10}{SNR}[Return][Window]$
- The relative sensitivity is: $S_{rel} = \frac{10}{SNR}\frac{[Return]}{[Launch]}[Window]$

Some Equations…

- [Sensitivity] = (10/SNR) [Signal Power][Window Length]

- SNR = 10 [Signal Power][Window Length] / [Sensitivity]
- SNR = 10 [Launch Power][Target Return Ratio][Window Length] / [Sensitivity]

- [Launch Power Needed] = [SNR Needed][Sensitivity] / (10 [Target Return Ratio] [Window Length])

- [Minimum Detectable Target Return Ratio] = [Sensitivity] / ([Launch Power] [Window Length])

Practice

- You have a PDV system with a measured absolute sensitivity of 20 nW ns. You want to measure motion that has a bandwidth of 50 MHz (you want an analysis window of about 20 ns). You think the target return will be -60 dB. **What power do you need to launch to get an SNR of 100 (20 dB)?**
- Answer: = (100/10)(20 nW ns) / (20 ns) / 1e-6 = **10 mW**.
- Pro tip: Plan on having a healthy safety factor!

Relative vs. Absolute Sensitivity

- Relative sensitivity takes into account both the performance of the launch side of the interferometer and the return side.
- Absolute sensitivity takes into account the performance only on the return side.
- Both are useful.

Due diligence for every PDV experiment should be to calculate the expected SNR (at least roughly).

- At right, a version of the author’s spreadsheet to calculate both SNR and sensitivity from all the details of the system.

Experimenter: Younk

Date: September 17, 2024

Input Values	
Light	
Laser Wavelength (nm):	1550
Launch Power (dBm):	10
Target Return (dB):	60
Effective Insertion Loss (dB):	5
EDFA Gain (dB, 0 if none):	0
LO Light Power (dBm):	0
Adjust for misalignment polarization (0.5 for random):	0.5
Detector	
TIA (Ohms, 50 if no TIA):	2400
Responsivity (A/W):	0.64
Noise Equilivent Power (W/sqrt(Hz)):	1.00E-11
Digitizer	
Volts Full-scale (V):	0.5
ENOB:	6
Impeadence (Ohms):	50
Sample Rate (GHz):	50
Analysis Choices	
Number of points in window:	2048
Physical Quantities	
Electric Charge (C):	1.6022E-19
Plank's Constant (J/Hz):	6.63E-34
Speed of light (m/s):	2.9980E+08

Assumptions: LO intensity noise is at the shot noise limit. ASE from EDFAs is at theoritical minimum.

Calculated Values	
Light	
Photon Energy (J):	1.28E-19
Photon Energy (eV):	8.00E-01
Light Frequency (THz):	193.42
Doppler Shift (GHz/(km/s)):	1.2903E+00
Light Power from Target (dBm):	-55.00
Light Power from Target (nW):	3.16
Energy in window (pJ):	0.129526893
Number of photons in window:	1.01E+03
EDFA Gain (linear):	1.00E+00
LO Light (mW):	1
Analysis Choices	
Window Length (ns):	40.96
Frequency Bin (MHz):	24.41
Velocity Bin (m/s):	18.92
Signal on Scope	
Voltage (mV peak-to-peak):	7.73
Electrical Power (mW):	1.49E-04
Electrical Power (dBm):	-38.26
Detector	
Quantum Efficiency:	8.00E-01
Detector Noise Power in window (mW):	1.15E-07
Detector Noise Power in window (dBm):	-69.39
Digitizer	
Digitizer noise in window (mW):	4.96705E-08
Digitizer noise in window (dBm):	-73.04
Optical noise	
Optical noise in window (mW):	2.3069E-07
Optical noise in window (dBm):	-6.6370E+01
Totals	
Sum of noise (mW):	3.9556E-07
Sum of noise (dBm):	-6.4028E+01
SNR (Linear):	377
SNR (dB):	**25.8**
Sensitivity (nW ns):	3.43

We should periodically check the sensitivity of our PDV systems.

With a single check we can catch many issues:

- Seed laser getting weak.
- Additional insertion loss (a dirty connection).
- EDFA out of tune… too much pump light for the seed.
- Failing detector.
- Noisy digitizer front-end.
- Etc.

Summary

- The concept of PDV sensitive is not new.
- But we tend not to discuss sensitivity in a rigorous, quantified way. That should change.
- Indeed there is a natural definition, which is just the energy of light from the target within the analysis window that gives a SNR of 10 in the frequency domain.
- Systems designers, diagnostic engineers, and operators should use the language of sensitivity:
  - Absolute sensitivity: nW * ns
  - Launch power: mW or dBm
  - Relative surface return: dB
  - Relative sensitivity: dB * ns
- This will help us design better systems, choose the correct system for the job, maintain our systems, and tune our systems.

Backup Slides

Calculating Signal Levels and Noise in PDV systems

- Cannonical Equation for coherent detection, light intensity is:
  - $I(t) = I_{Sig} + I_{LO} + 2\sqrt{I_{Sig} I_{LO}} \cos(\omega_{Doppler} t)$
- AC voltage out of photodetector is:
  - $V_{pk-pk} = 4[TIA] A_R \sqrt{G I_{Sig} I_{LO}}$
- Average Power into scope:
  - $P_{sig} = 2 \frac{[TIA]^2}{R_{scope}} A_R^2 G I_S I_{LO}$
  - In dBm… $10\log(^{P_{sig}}/_{1\text{mW}})$

I denote light intensity (power) with the symbol I. (Electrical power into the scope I denote with P).

[TIA] is the gain in V/A of the transimpedance amplifier, use [TIA] = Rscope if not present. G is the effective gain of the optical amplifier, use G=1 if not present. Ar is the responsivity of the photodetector in A/W.

Rscope is the impedance of the scope input, typically 50 Ohms.

Assumes alignment of polarization of target and LO light.

Noise Power from Photodetector

- The key specification of the photodetector is Noise Equivalent Power.
  - This is the optical power on the detector averaged over 1 second where the SNR is one.
  - Has units of W/sqrt(Hz).
  - The noise power scales with the length of the analysis window.
- The Noise in one frequency bin is:

$$N_{Det} = [TIA]^2 A_R^2 [NEP]^2 \, R_{Scope}^{-1} [AnalysisWindowLength]^{-1}$$

Digitizer Noise

- The key specification of the photodetector is Equivalent Number of Bits (ENOB).
  - We assume a noise model where the rms voltage is 1/sqrt(12) of the Least Significant Bit*.
- The Noise in one frequency bin is:

$$N_{Dig} = \left(\frac{V_{FullScale}}{\sqrt{12} \cdot 2^{ENOB}}\right)^2 R_{Scope}^{-1} [NumPoints]^{-1}$$

*This is the assumption that leads to the ENOB = (SNR – 1.76)/6.02 formula.

Optical Noise

- The dominate optical noise is either intensity fluctuations of the LO laser (after the interferometer the LO is always much stronger than the signal) or amplified spontaneous emission from amplifiers after the interferometer.
- It is normally not too bad to assume the LO intensity noise is at the shot noise limit and that the ASE is at the theoretical minimum*.
- As shown in Miller et al., the noise in one frequency bin is:

$$N_{Optical} = [TIA]^2 e A_r P_{LO} R_{scope}^{-1} \eta G [AnalysisWindow]^{-1}$$

e is the electric charge and η is the QE of the photodetector. Note that $A_r = e\eta/h\nu$.

* This has a chance of be being true at MHz measurement frequencies that are typical of PDV. At lower measurement frequencies (longer integration times), the laser will not likely perform close to the shot noise limit.