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The Limits of Multiplexing

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What are the limits to multiplexing?

- Physical limits to frequency multiplexing – Dynamic Range
  - Digitizer Effective Number of Bits (ENOB)
  - Signal-to-Noise Ratio (SNR)
  - MPDV Dynamic Range
  - Sources of noise due to optical amplification
- Physical limits to time multiplexing – Coherency
  - Degradation of beat signal visibility due to laser coherence and fiber-optic affects
  - Some preliminary laboratory measurements
- Practical constraints to large channel count experiments
  - The 'little things': fibers, connectors, polishing, cleaning
  - Data Assurance Methods and Tools: Transmissions & Optical Back Reflection (OBR) measurements
  - Cross-talk in many point experiments (discussion)

Frequency Multiplexing – How Deep can we go?

Sources that limit frequency Multiplexing

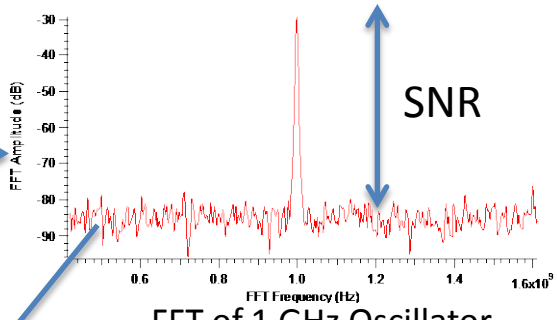
- Recording. Digitizer Effective Number of Bits limitation.
- Detection. Photo-diode noise floor limits … SNR (see Rutkowski Report, will not discuss today).
- Optical. Optical amplifier noise can limit SNR

Frequency Multiplexing – Digitizer Effective Bits & SNR

Oscillator (sine wave) Electrical or optically generated

Digitizer

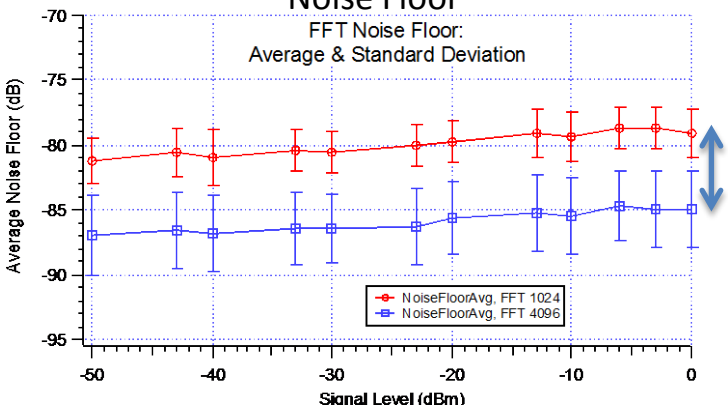
FFT



FFT of 1 GHz Oscillator

Noise Floor

Noise Floor is a function of FFT window length = N



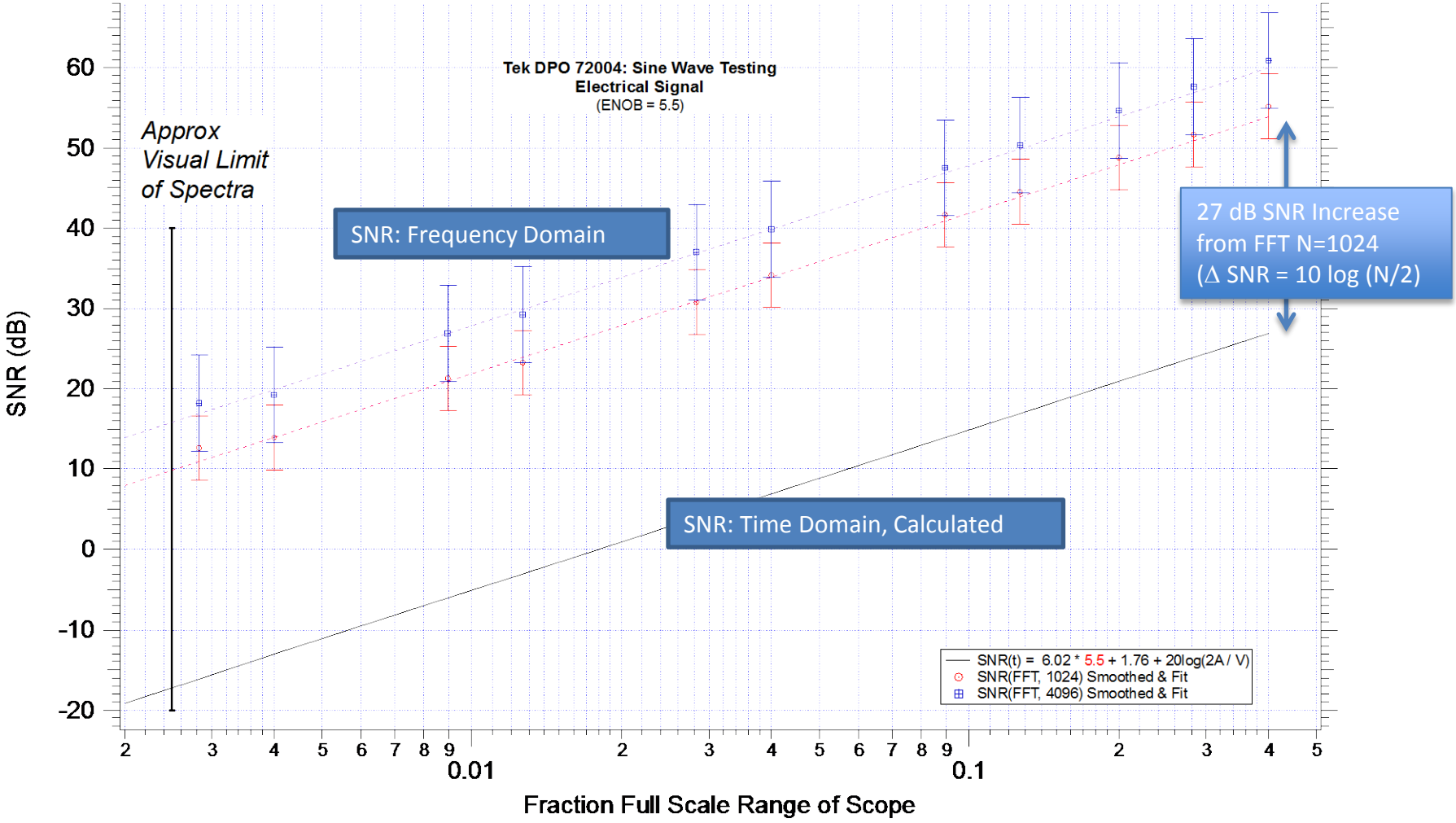
N varied x4 (6 dB)

$$SNR = 6.02\,E + 1.76 + 20 \log (2A/V)\ dB$$

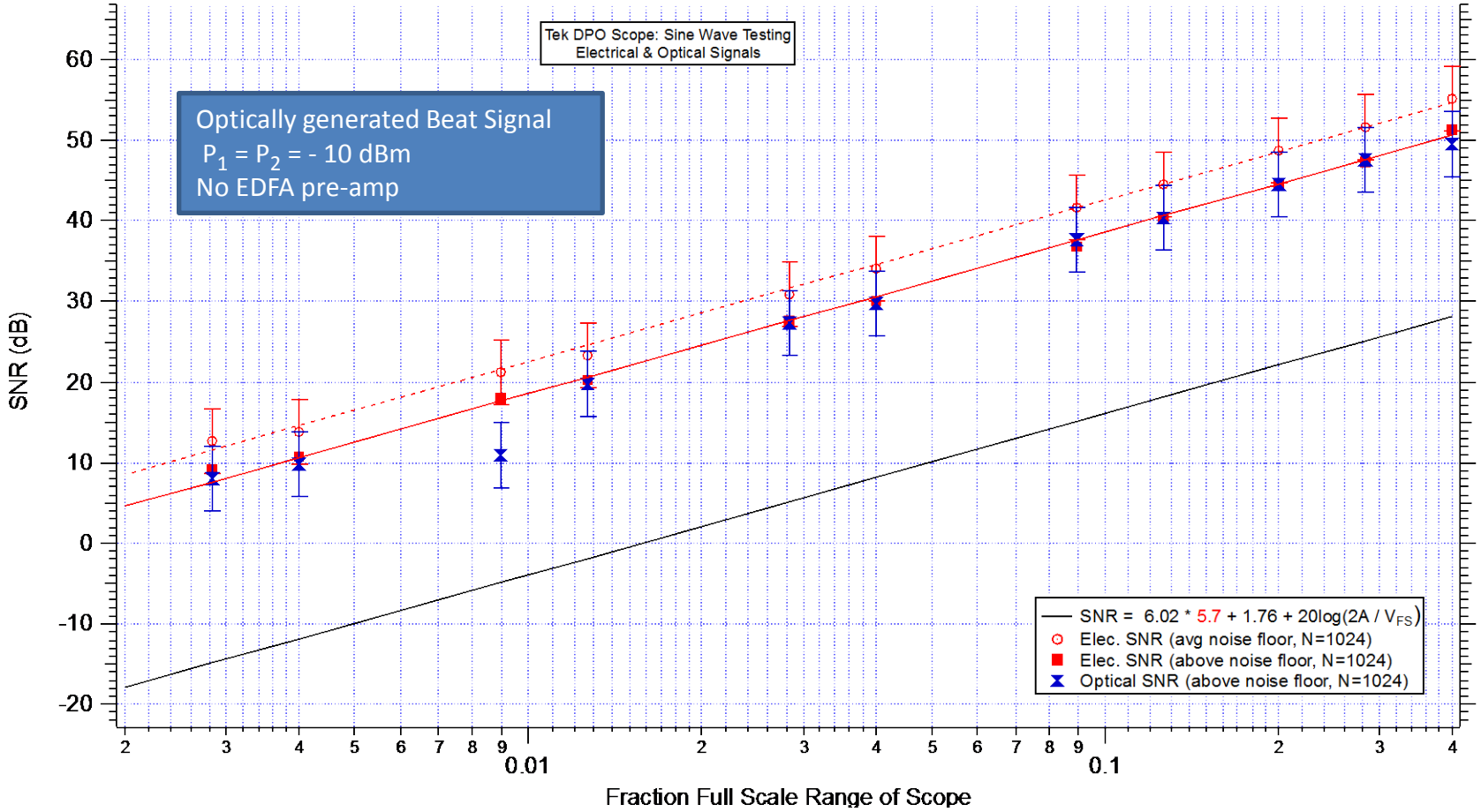
E = effective bits for digitizer, V = full scale range, A = RMS amplitude of applied signal

See Wiley Encyclopedia of Electrical and Electronics Engineering, Vol. 18, J. Blair

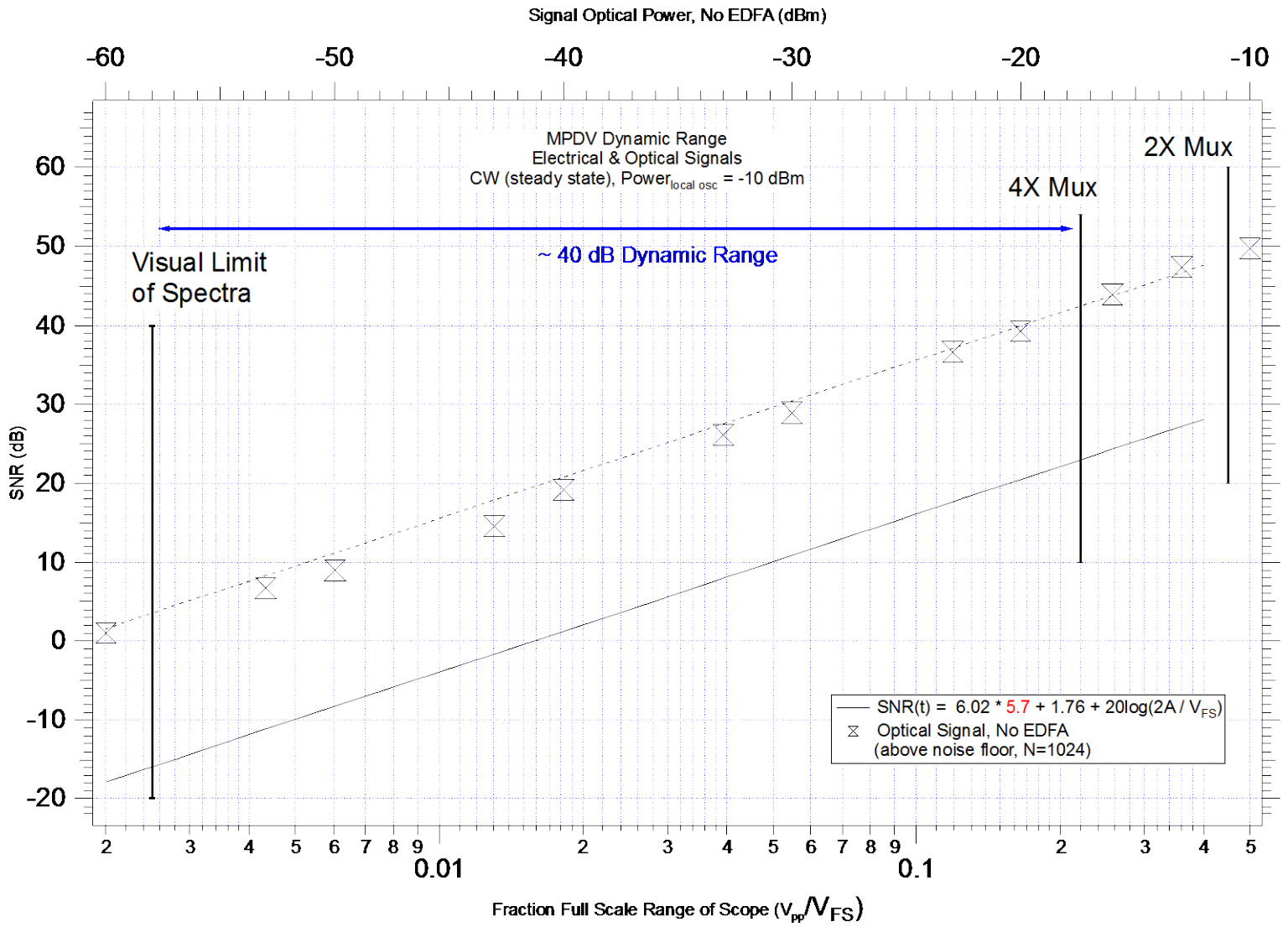
Limits of Frequency Multiplexing – Digitizer SNR



Limits of Frequency Multiplexing – SNR for Electrically vs. Optically Generated Signals



Limits of Frequency Multiplexing – MPDV Dynamic Range



Limits of Frequency Multiplexing – Noise from Optical Amplification

1. Use of Erbium Doped Fiber Pre-Amp generates amplified spontaneous emission (ASE) which beats with signal and local oscillator. G=Gain
2. ASE affects on SNR:
   - Local Oscillator (LO) – ASE
   - Signal - ASE
   - ASE – ASE (we usually neglect)

Signal Power (time averaged)

$$I_{sig}^2 = 2\eta^2 G I_s I_{LO}\ ,\ where\ I_{sig} = \frac{eP_s}{h\nu_s}$$

Noise Power Spectral Density

$$\sigma_{LO-ASE}^2 = 4\eta^2 I_{LO} I_{ASE} \frac{B_e}{B_o}$$

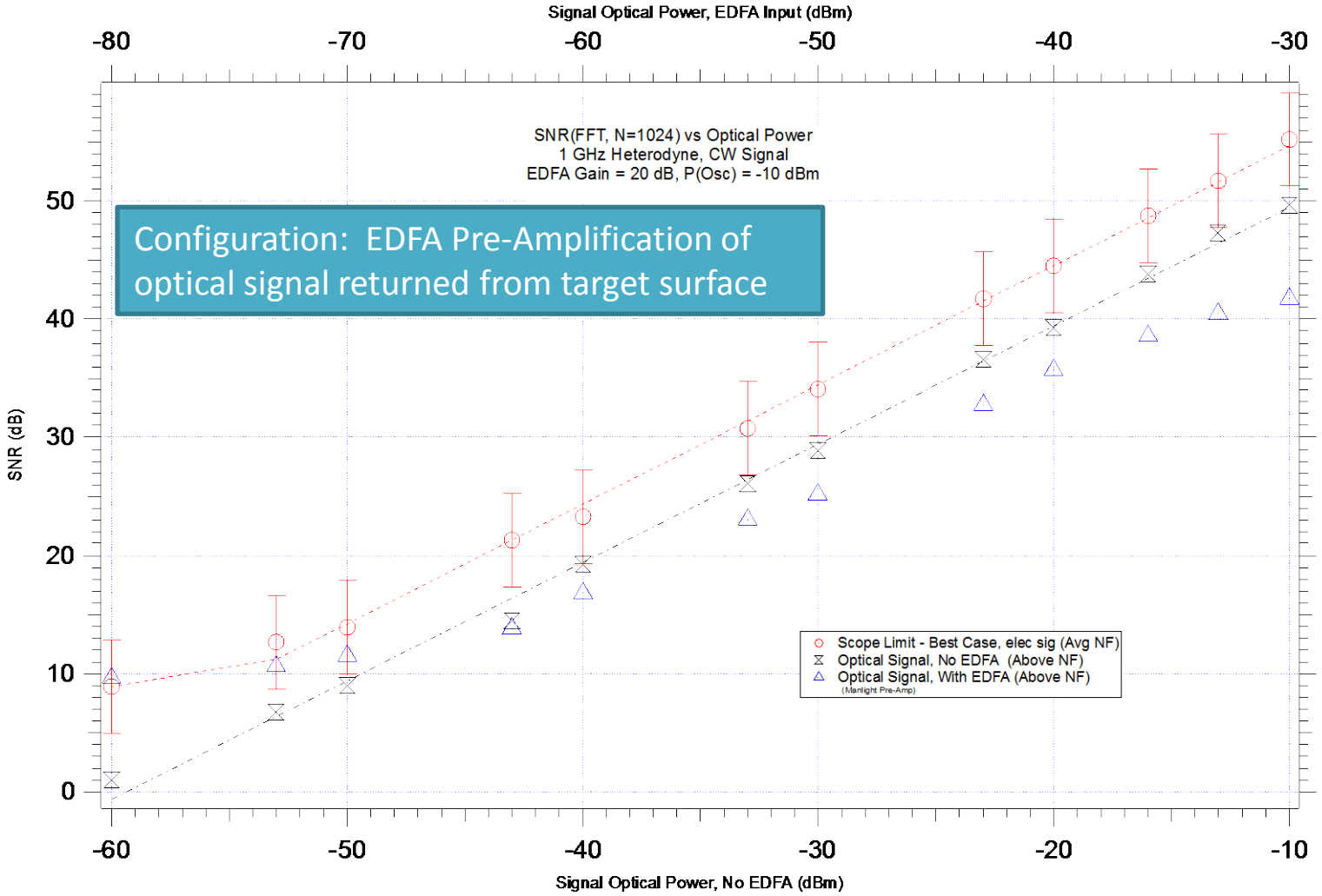
$$\sigma_{s-ASE}^2 = 4\eta^2 G I_s I_{ASE} \frac{B_e}{B_o}$$

LO – ASE noise usually dominates for typical conditions

Example: LO-ASE Noise ≈ Miteq Noise Floor when

- Pre-amp, Gain ~ 23 dB
- ASE filtered, 200 GHz bandpass
- Power (local osc) ~ 100 microwatts

Limits of Frequency Multiplexing – EDFA Affects on SNR



Time Multiplexing: How Deep can we go?

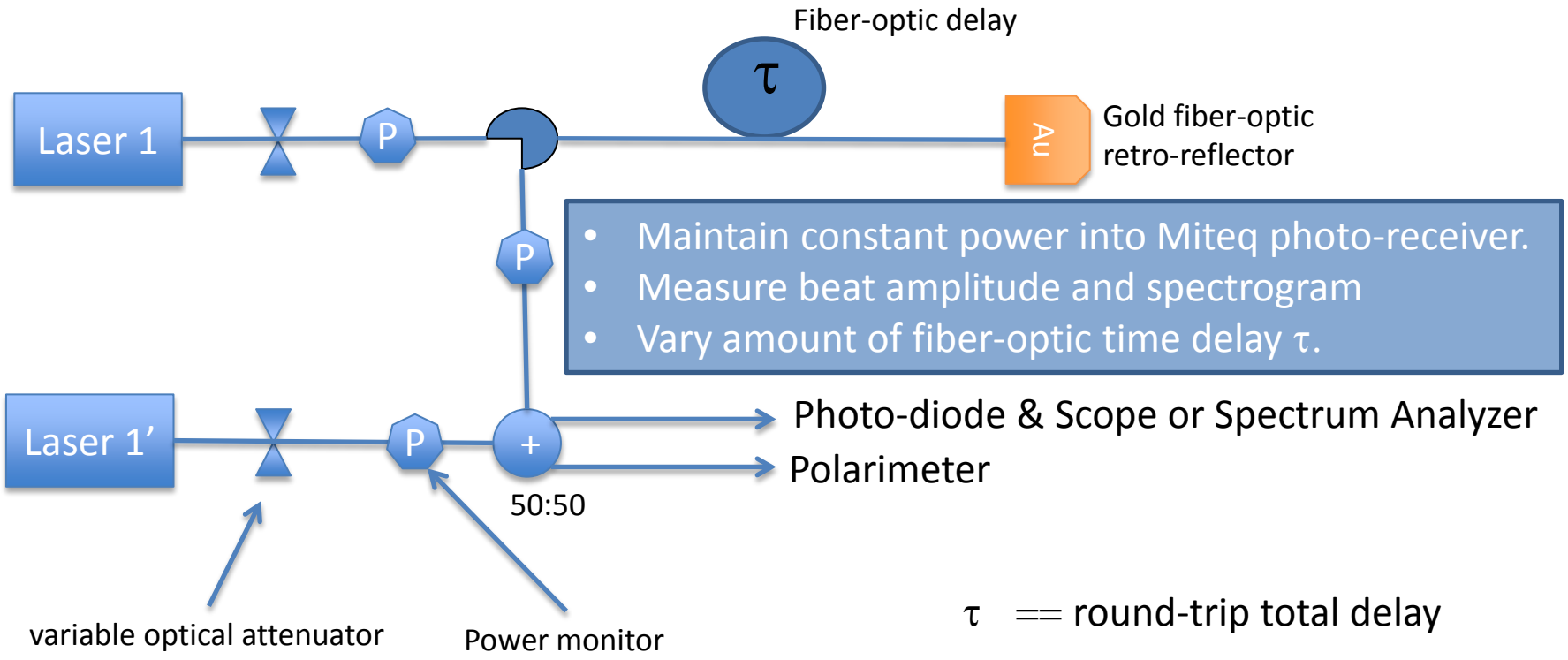
$$I(\tau) = I_1 + I_2 + 2\sqrt{I_1 I_2}\ V(\tau)\ \cos\phi$$

V(τ) == Fringe Visibility
0 < V(τ) < 1

- Visibility is a function of laser linewidth $\Delta\nu$ (or equivalently temporal coherence).
- Temporal coherence characterized by coherence time $\tau_c \sim \alpha*(1/\Delta\nu)$ or equivalently coherence length $\ell_c = c\ \tau_c / n$

  α is multiplicative constant dependent on spectral line-shape (e.g. Gaussian, Lorentzian etc.)
- Example: $\Delta\nu = 15$ kHz linewidth, n=1.47 and $\alpha = 1$, then $\ell_c = 13.6$ km
- Linewidth is also degraded in fiber due to polarization mode dispersion (PMD)

Time Multiplexing: Laboratory Measurements



Work in Progress

- No measureable effect (V_{rms}) for $\tau < 350$ μs (70 km). Visibility and DOP ≈ 1, but amplitude modulations consistent with polarization fluctuations evident for delays $\tau > \tau_{c.}$

Limits of Multiplexing – Practical Consideration

Eight is the new one … statistics will catch up with you. Many more fibers and connectors.

- QA is necessary, automation is desirable
  - ✓ fibers, connectors, polishing, cleaning.

See Talk by Carlos Perez
Lessons Re-Learned

- MPDV Data Assurance: Methods and Tools.
  - ✓ Fiber Transmissions measurements
  - ✓ Optical Back Reflection (OBR) measurements
  - ✓ LUNA measurements

See Talk by Mike Pena
Tools to Characterize MPDV

- Cost and Risk
  - ✓ Data risk … how many eggs in the basket?

Special Case for Off-Line Discussions:
Many channels (> 100) in geometries conducive to cross-talk … what to do?