Quantum noise measurements: challenges and tricks

Eugeniy Mikhailov

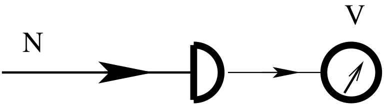
The College of William & Mary

July 31, 2007 mini-conference

Outline

Quantum noise

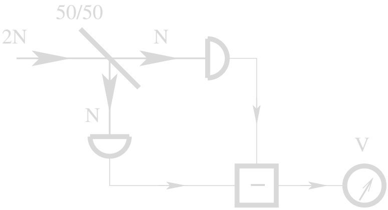
Simple photodetector



$V \sim N$

$\Delta V \sim \sqrt{N}$

Balanced photodetector

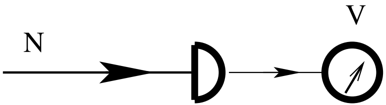


$V = 0$

$\Delta V \sim \sqrt{N}$

Quantum noise

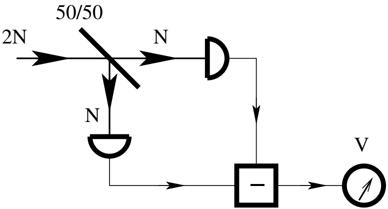
Simple photodetector



$$V \sim N$$

$$\Delta V \sim \sqrt{N}$$

Balanced photodetector



$$V = 0$$

$$\Delta V \sim \sqrt{N}$$

Coherent states of light: α

Quantum Mechanics
Properties:

- $\bar{N} = \langle\alpha|\hat{N}|\alpha\rangle = \langle\alpha|a^\dagger a|\alpha\rangle = \alpha^2$
- $\Delta N = \sqrt{\langle\alpha|\hat{N}^2 - \bar{N}^2|\alpha\rangle} = \alpha$

If $\alpha \to 0$

- $\Delta N = 1/2$

Classically

- Electric field $E = E_0 + \delta E$
- Intensity $I = E^2 = (E_0 + \delta E)^2 = E_0^2 + 2E_0\delta E + \delta E^2 \approx I_0 + 2\sqrt{I_0}\delta E$
  - $\bar{I} = I_0$
  - $\Delta I = 2\sqrt{I_0}\delta E$

Light and photodiodes

- In ideal world each photon generate an electron on a photodiode
- Photodiode measures intensity or photon number
- Photodiode output current (*i*) proportional to intensity (*I*)

So

$$i_o = \eta e \frac{I_0 Area}{\hbar\omega} = \eta e \frac{P}{\hbar\omega} = \eta 0.64[A/W]P$$

Shot-noise

$$\Delta i \sim \Delta I = \sqrt{2ei_o RBW}$$

More about Shot Noise

$$i_o = \eta 0.64[A/W]P$$

$$\Delta i \sim \Delta I = \sqrt{2 e i_o RBW}$$

Typical numbers:

- $P = 1mW$
- $\eta =$100 %
- $i_o = .64mA$

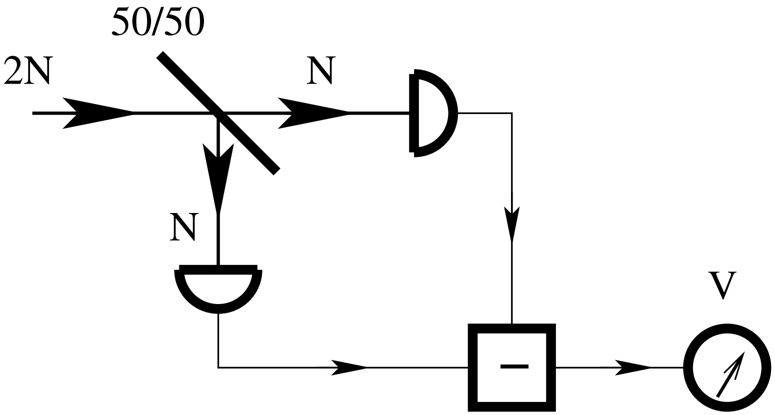
$\Delta i =$ 14 pA $/\sqrt{Hz}$

- Typical Scope RBW=20 MHz, $\Delta i =$ 64 nA
- We are aiming to RBW=100kHz, $\Delta i =$ 4.5 nA

We are trying to resolve tenth of the inch on the top of the Empire State Building.

Measurement: step 1 kill DC current offset

Relatively easy with balanced photodetector

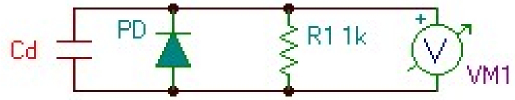


Watch out

- Matched quantum efficiency
- We need real 50/50 beam splitter

Measurement: step 2 transform current to voltage

Very simple: Load resistor



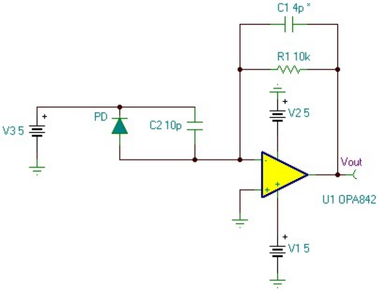
- Cut off frequency is still $f_c = 1/(RC_d)$
- Current transimpedance gain $\frac{R_f}{1+jR_fC_d\omega}$,

But Cd goes up as V goes up

- the more gain we have the weaker response at high frequencies

Measurement: step 2 improved transform current to voltage

Very simple: Load resistor

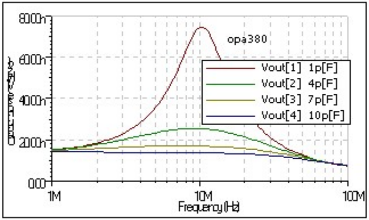


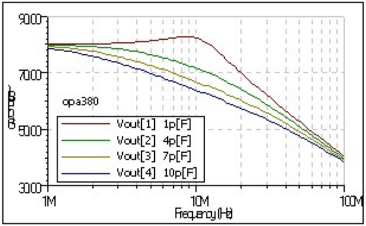
- Cut off frequency is still $f_c = 1/(RC_d)$
- Current transimpedance gain $\frac{R_f}{1+jR_fC_d\omega}$,
- $C_d = const$

Problems with amplifier

- Current transimpedance gain $\frac{R_f}{1+jR_fC_d\omega}$, drops with frequency
- Voltage gain = $\frac{Z_f}{Z_{in}} = jR_fC_d\omega$, grows with frequency

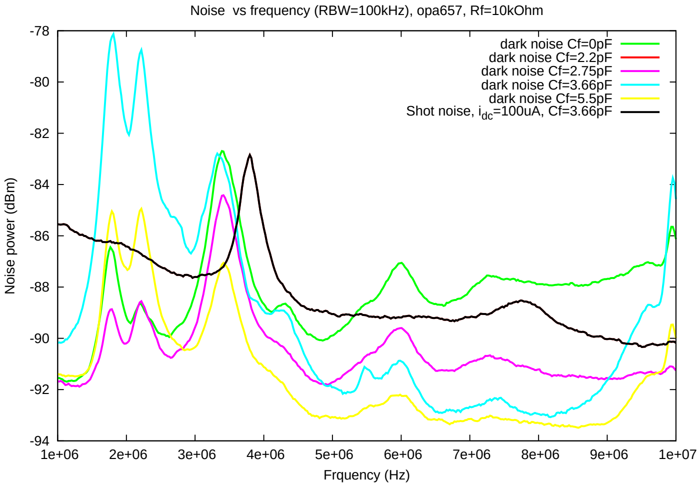
We need compensation: introducing C_f



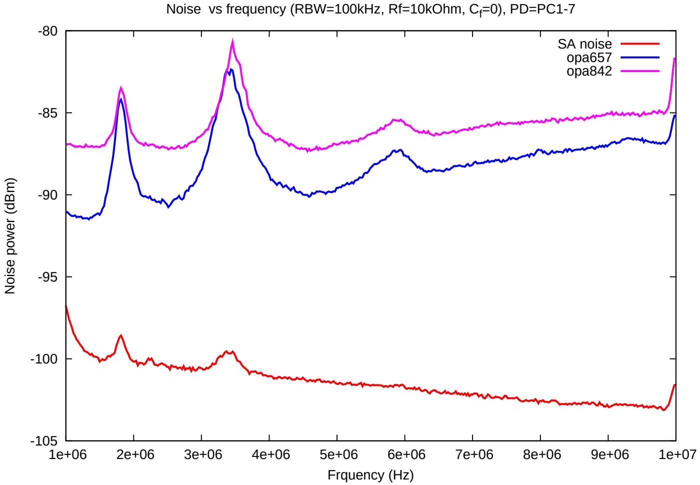


There is a price to pay: we decrease cut off frequency

Noise suppression with C_F



Dark noise with different OpAmps



Summary

- We leave in the fallen word full of noise
- Measuring quantum noise is hard
- Be prepared to scarify either SNR or bandwidth
- Careful choice of components is required

Good news

- We have 3-4 dB separation between quantum noise (our signal) and electronic noise

Bad news

- Perfect PD is still to be found, since QE is not great, just 84%