Introduction to Analyzing Noise in Photodiode Amplifiers

Presented By: S.E Nickols for the staff of Gen-Probe

Nick's Background.

- **<u>Experience:</u>** **Over 20 years of electronics/systems design , design analysis, design verification , product certification, manufacturing transfer, and vendor management. Have recent experience with medical device development. Have had involvement with design control, risk management and regulatory issues. (class II and III)**
- **<u>Industries:</u>** **Scientific, Semiconductor, and Medical.**
- **<u>Interests:</u>** **Projects requiring a multidisciplinary approach to solve a customer's problem.**
- **<u>Approach:</u>** **Team player. Quality Oriented. Process oriented. Customer oriented.**
- **<u>What I Bring to table:</u>** **Aside from technical skill and experience, "hind sight", a can do attitude, flexible, strong adaptation skills, open minded, here to make you money.**

Presentation Contents

- Photodiode Review
- Photo Detector Basics
- Noise Concepts Review
- Photodiode and Amplifier Noise Theory
- Bandwidth and Stability Calculations
- Transimpedance Amplifier Theoretical Noise Calculations
- Transimpedance Amplifier Tina Spice Analysis
- Transimpedance Measurement Example

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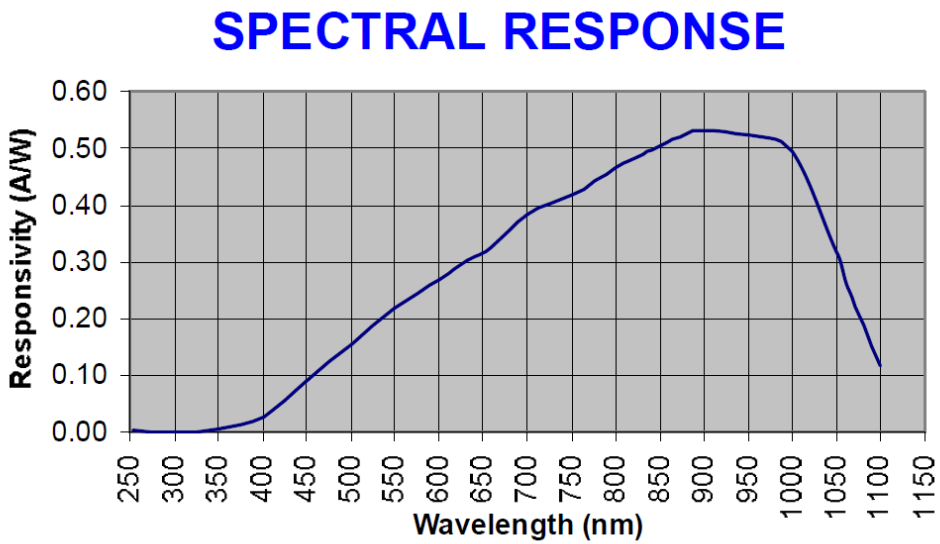
Photodiode Review

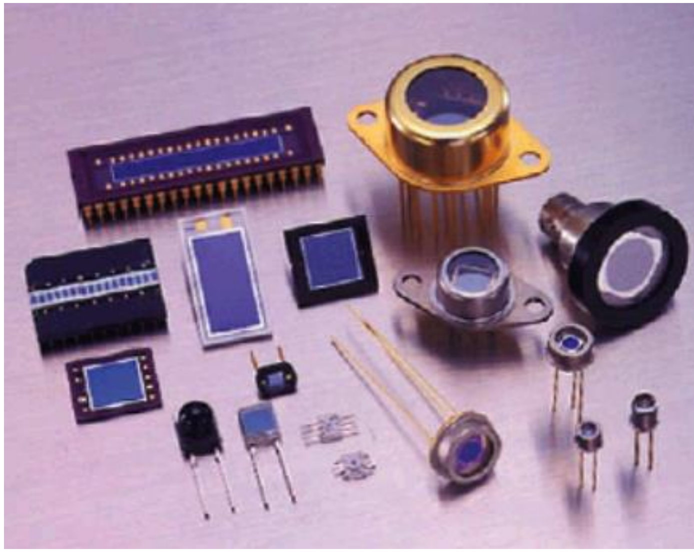
Introduction

- Photodiodes convert light into current or voltage.

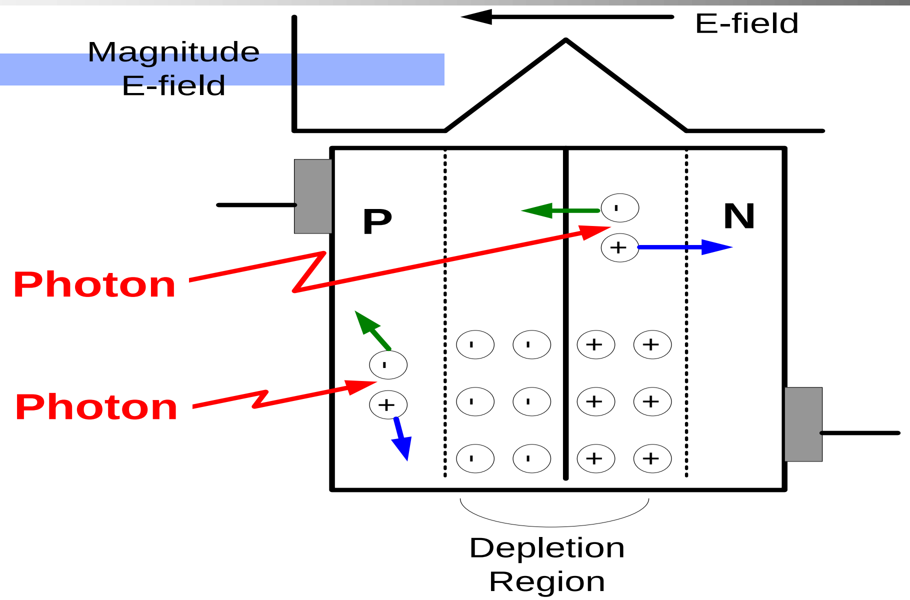
Commonly Used Photodiode types:

- PN photodiode – more wavelength selective (Solar cell)
- PIN photodiode – wide spectral range (less selective) Most widely used.
- APD (Avalanche photodiode) – sensitive to low light, fast





Basic Photodiode Physics



<u>Principle of Operation:</u>

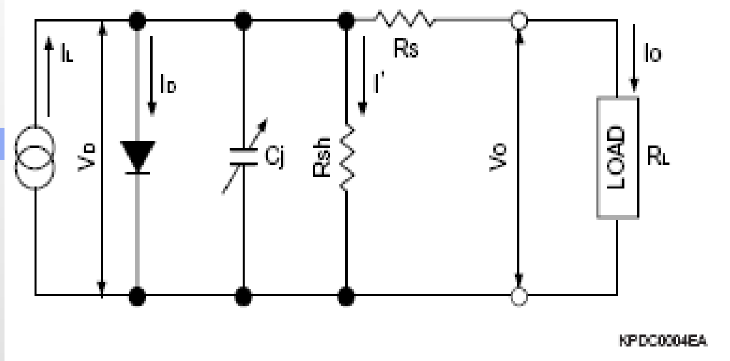
. - The P-layer material at the active surface and the N material at the substrate form a PN junction which operates as a photoelectric converter.

- When light strikes a photodiode, the electron within the crystal structure becomes stimulated. If the light energy is greater than the band gap energy Eg, the electrons are pulled up into the conduction band, leaving holes in their place in the valence band.

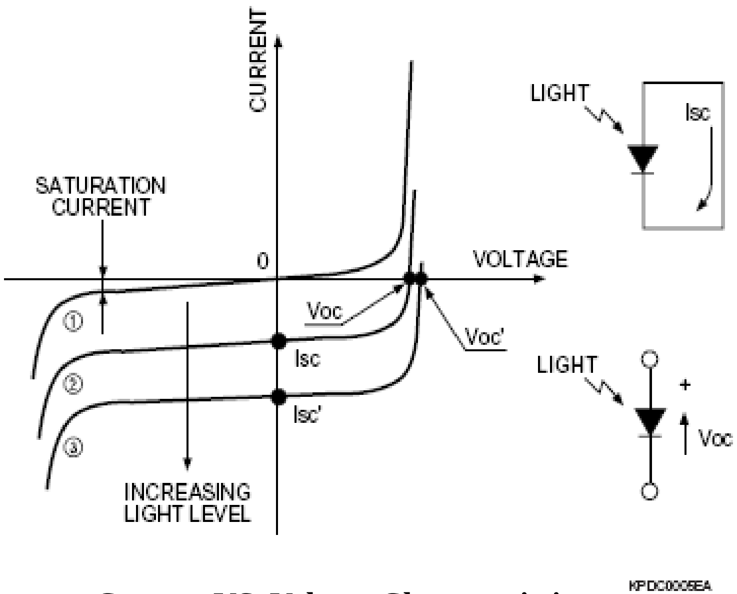
- These electron-hole pairs occur throughout the P-layer, depletion layer and N-layer materials. In the depletion layer the electric field accelerates these electrons toward the N-layer and the holes toward the P-layer.

- This results in a positive charge in the P-layer and a negative charge in the N-layer. If an external circuit is connected between the P- and N-layers, electrons will flow away from the N-layer, and holes will flow away from the P-layer toward the opposite respective electrodes.

Photodiode Circuit Model Basics



Photodiode Equivalent Circuit



Current VS. Voltage Characteristics

$I_L = r_\phi \phi_e$

r_ϕ is the diode's flux responsivity

ϕ_e is the radiant flux energy in Watts

I_D : Diode Current

C_j : Junction capacitance

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{\phi_B}}}$$

C_{j0} is the photodiode capacitance at zero bia

ϕ_B is the built-in voltage of the diode junctio

V_R is the reverse bias voltage

R_{sh} : Shunt resistance

R_s : Series resistance

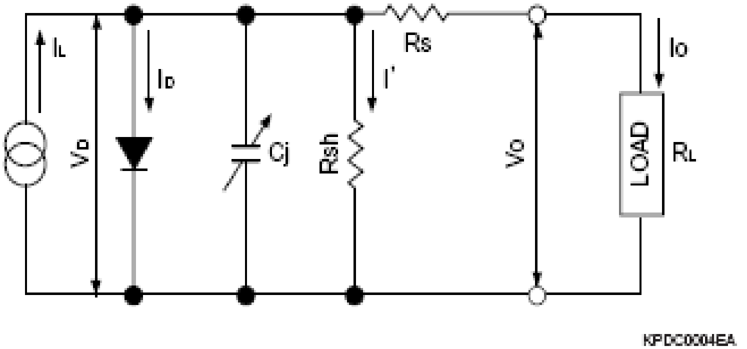
I' : Shunt resistance current

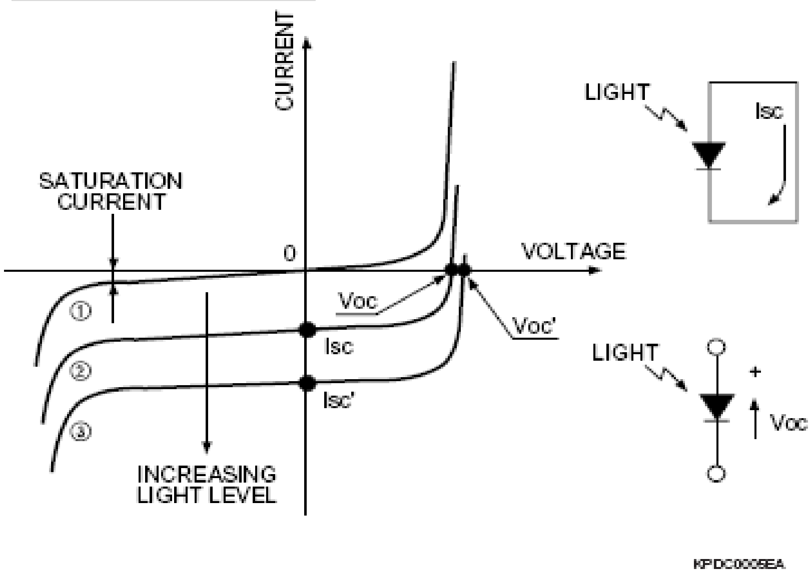
V_D : Diode Voltage

I_o : Output current

V_o : Output voltage

Photodiode Basics Continued





Current VS. Voltage Characteristics

Use left equivalent circuit, the output current is given as :

$$I_o := I_L - I_D - I' = I_L - I_S\left(e^{\frac{eV_D}{kT}} - 1\right) - I'$$

I_S : Photodiode reverse saturation curren

e: electron charge

k: Boltzmann's constant

T: Absolute temperature of the photodiod

The open circuit voltage V_{oc} is the output voltage when I_o equals 0. Thus Voc becomes:

$$V_{oc} := \frac{kT}{c} \ln\left(\frac{I_L - I'}{I_S} + 1\right)$$

Photo Diode Properties

Key Properties

The most important properties of photodiodes are:

- **The *responsivity,* i.e., the photocurrent divided by optical power – related to the quantum efficiency, dependent on the wavelength where *h v* is the photon energy, *η* is the quantum efficiency, and *e* the elementary charge. For example, a photodiode with 90% quantum efficiency at a wavelength of 800 nm, the responsivity would be ≈ 0.58 A/W The *quantum efficiency* of a photodiode is the fraction of the incident (or absorbed) photons which contribute to the photocurrent.**

$$R = \eta \frac{e}{h\nu}$$

- **The *active area,* i.e., the light-sensitive area**
- **The *maximum allowed photocurrent* (usually limited by saturation)**
- **The *dark current* (in photoconductive mode, important for the detection of low light levels)**
- **The speed, i.e. *response time*, related to the rise and fall time, often influenced by the capacitance.**
- **Notes:**

Higher photocurrents are actually desirable for suppression of shot noise and thermal noise. Larger active areas (with diameters up to the order of 1 cm) allow for handling of larger beams and for much higher photocurrents, but at the expense of lower speed

The quantum efficiency of a photodiode can be very high – in some cases more than 95% – but varies significantly with wavelength. Apart from a high internal efficiency, a high quantum efficiency requires the suppression of reflections e.g. with an anti-reflection coating.

Semiconductor Materials

Commonly used photodiode materials are:

•***Silicon (Si):*** **low dark current, high speed, good sensitivity between roughly 400 and 1000 nm (best around 800–900 nm) .**
•***Germanium (Ge):*** **high dark current, slow speed due to large parasitic capacity, good sensitivity between roughly 900 and 1600 nm (best around 1400–1500 nm) .**
•***Indium Gallium Arsenide Phosphide (InGaAsP):*** **expensive, low dark current, high speed, good sensitivity roughly between 1000 and 1350 nm (best around 1100–1300 nm) .**
•***Indium Gallium Arsenide (InGaAs):*** **expensive, low dark current, high speed, good sensitivity roughly between 900 and 1700 nm (best around 1300–1600 nm) The indicated wavelength ranges can sometimes be substantially exceeded by models with extended spectral response.**

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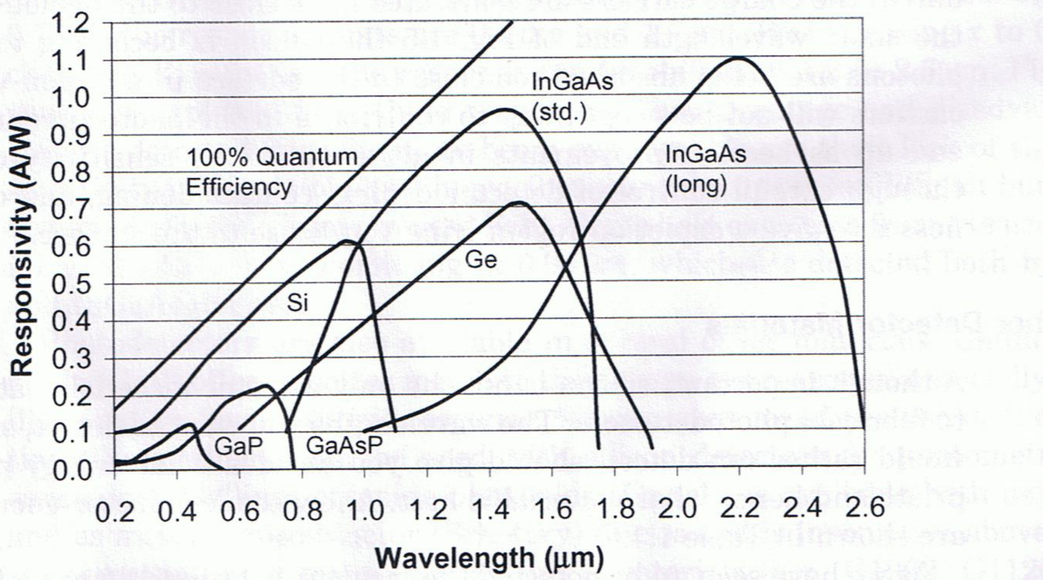


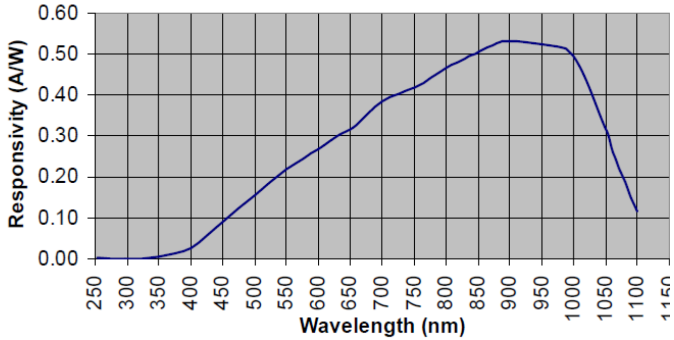
Example Photodiode: "Advanced Photonix" PDB-C158

ABSOLUTE MAXIMUM RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	PARAMETER	MIN	MAX	UNITS
V_{BR}	Reverse Voltage		50	V
T_{STG}	Storage Temperature	-40	+100	°C
T_O	Operating Temperature	-40	+80	°C
T_S	Soldering Temperature*		+260	°C

* 1/16 inch from case for 3 seconds max.

SPECTRAL RESPONSE



ELECTRO-OPTICAL CHARACTERISTICS RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
I_{SC}	Short Circuit Current	H = 100 fc, 2850 K	100	145		μA
I_D	Dark Current	V_R = 10 V		2	30	nA
R_{SH}	Shunt Resistance	V_R = 10 mV	100	150		MΩ
C_J	Junction Capacitance	V_R = 10 V, f = 1 MHz		10	25	pF
λrange	Spectral Application Range	Spot Scan	400		1100	nm
V_{BR}	Breakdown Voltage	I = 10 μA	30	75		V
NEP	Noise Equivalent Power	V_R = 10V @ λ = Peak		4.4×10^{-14}		W/ $\sqrt{\text{Hz}}$
t_r	Response Time	RL = 1KΩ, V_R = 10 V		50		nS

**Response time of 10% to 90% is specified at 660nm wavelength light.

Cj is not specified at Vr=0V.

Calling the manufacturer for this information, Cj=70pF for Vr=0V

PIN Diode Structure

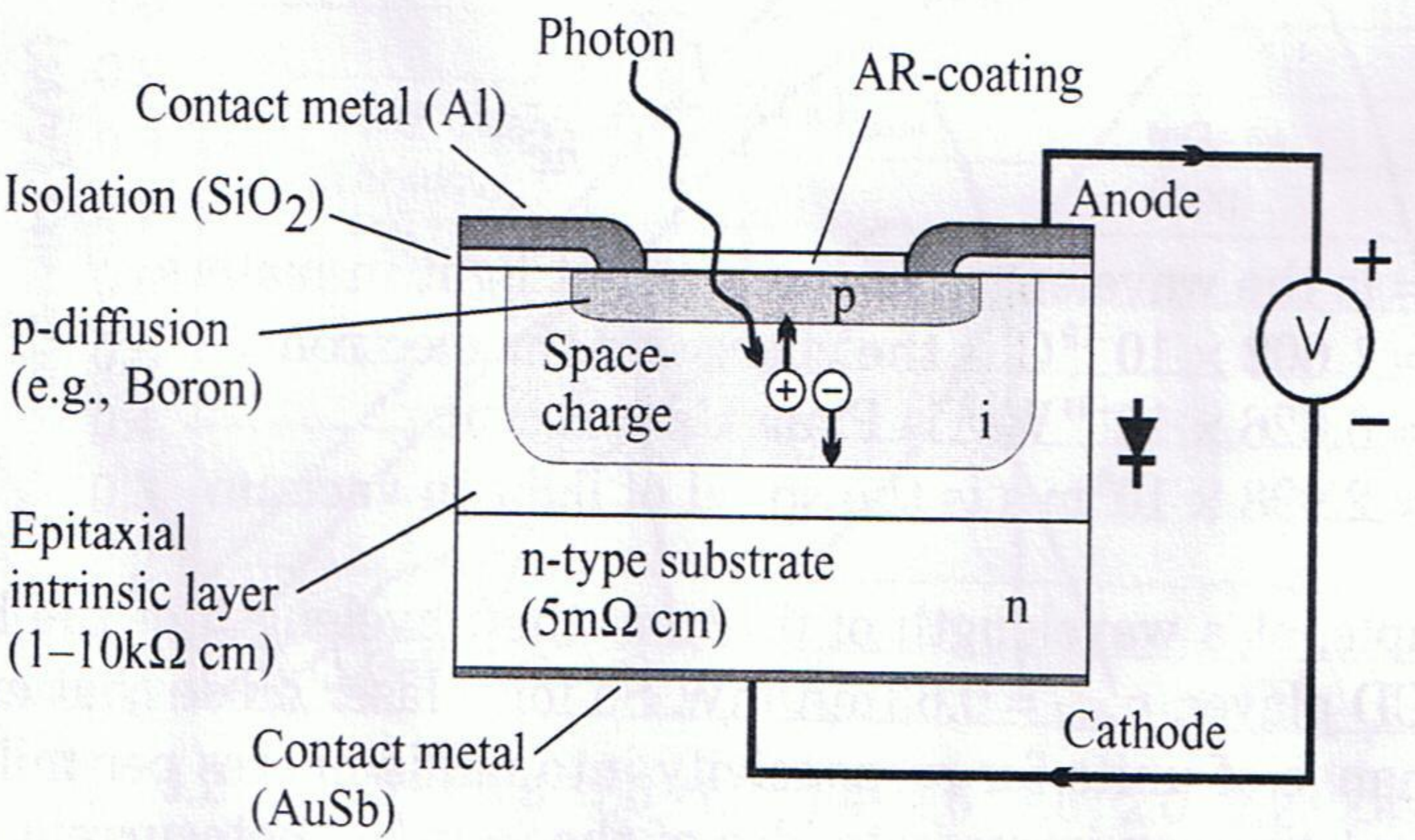


Photo Detector Basics

Basic Photodetector Circuit

Simple?

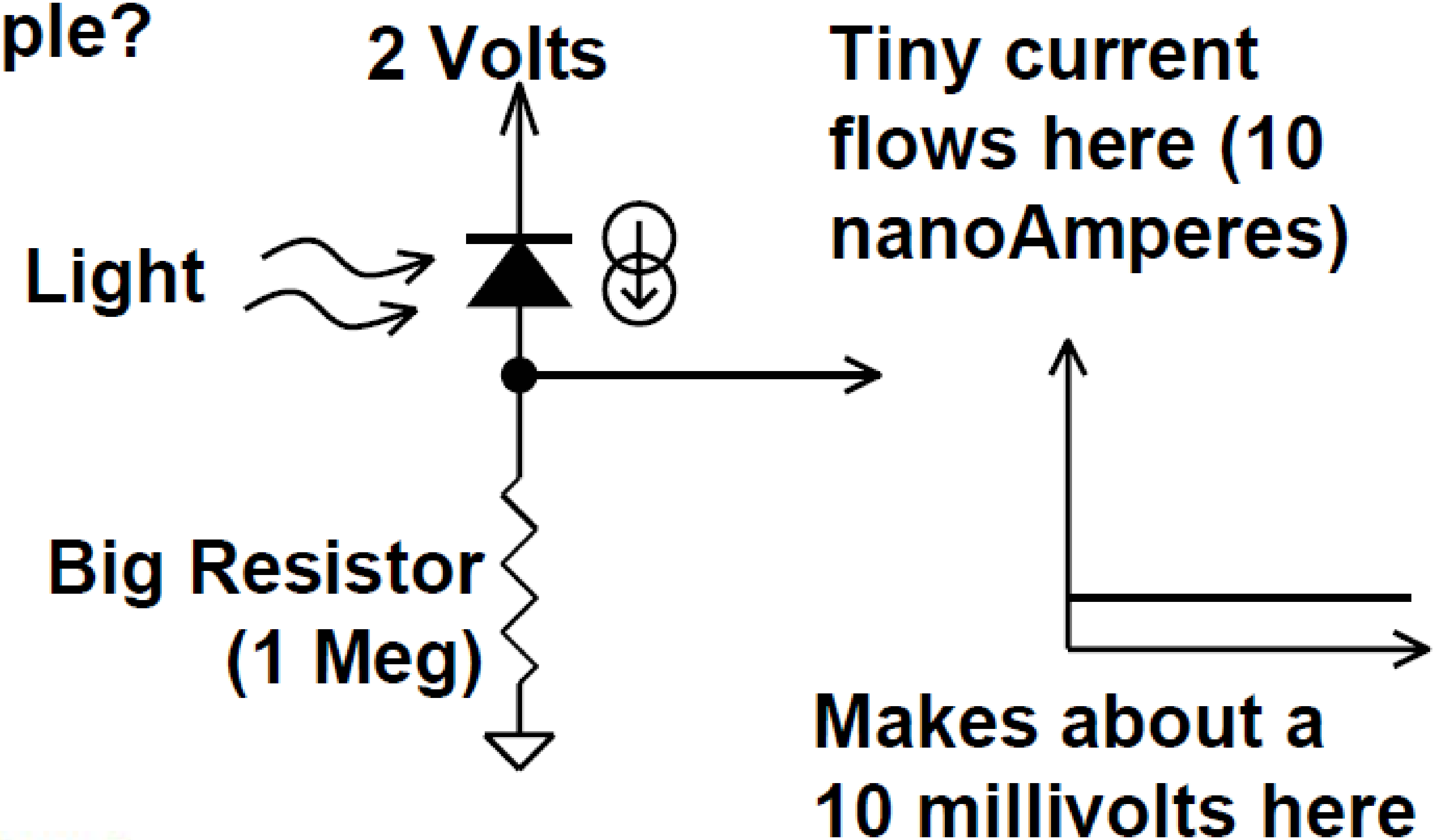
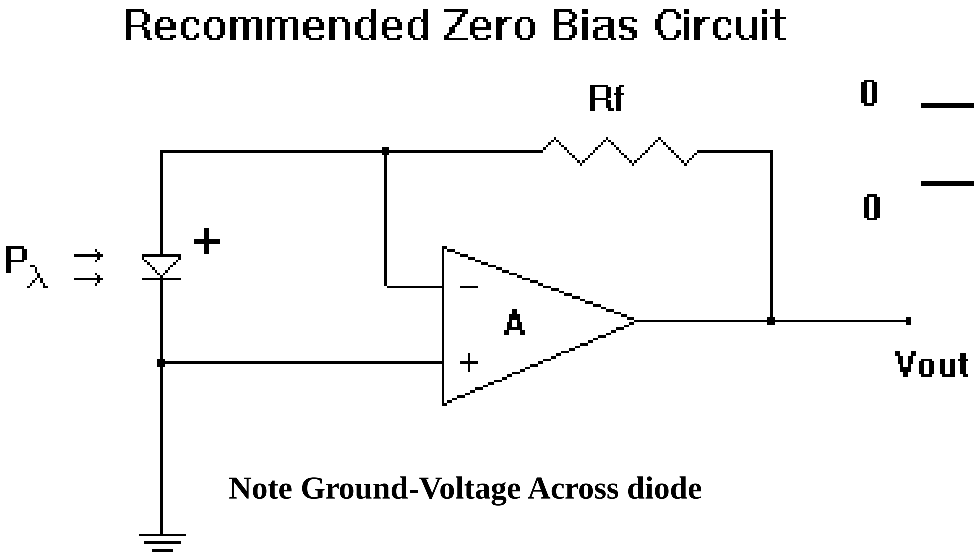
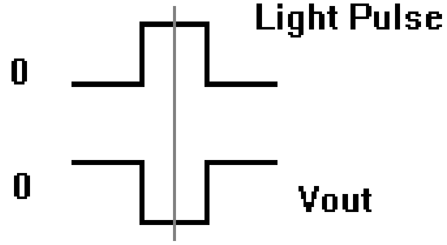


Photo Voltaic Mode Amplifier





Note Ground-Voltage Across diode

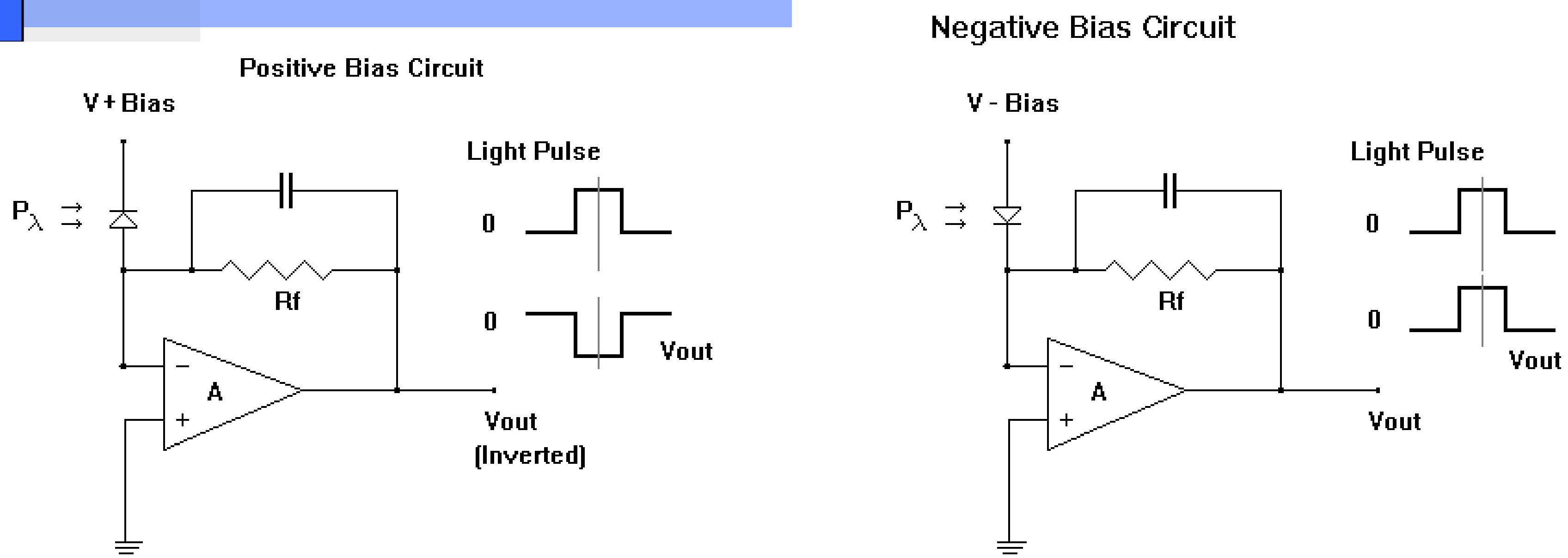
Photo Voltaic Mode Amplifier

Use Photovoltaic Mode:

- Where precision is more important then speed.

The lack of dark current removes an entire error term. The lower noise makes smaller measurements possible. The linear output makes calculations trivial.

Photo Conductive Mode



+/- 10V, there is voltage across the diode.

Photo Conductive Mode Amplifier

Use Photoconductive Mode:

- **Where speed is more important then precision.**

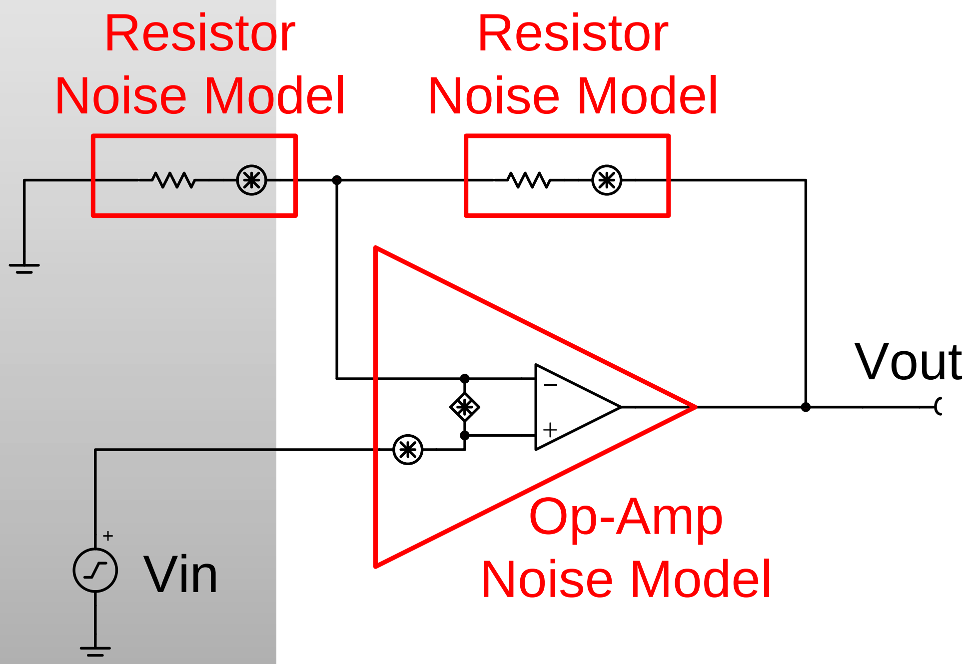
  The voltage across the diode lowers it's capacitance. This allows faster amplifiers:

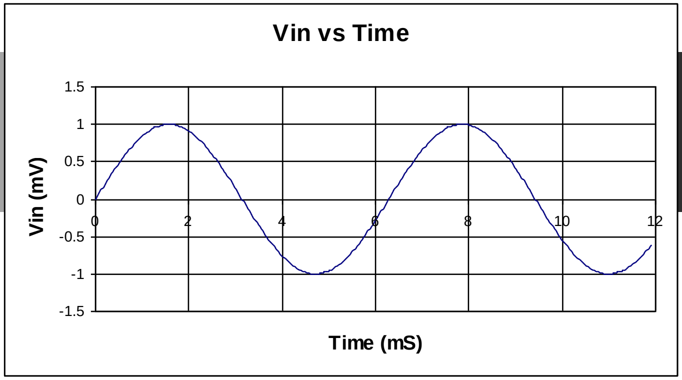
- **Less capacitance allows a faster amplifier while maintaining stability.**

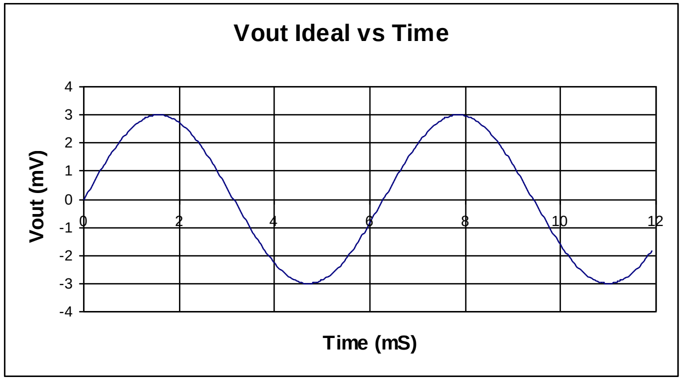
Noise Review

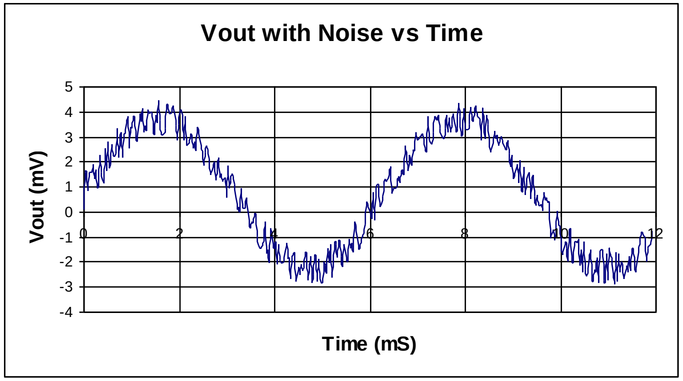
Intrinsic Noise

- Error Source
- Generated by circuit itself (not pickup)
- Calculate, Simulate, and Measure

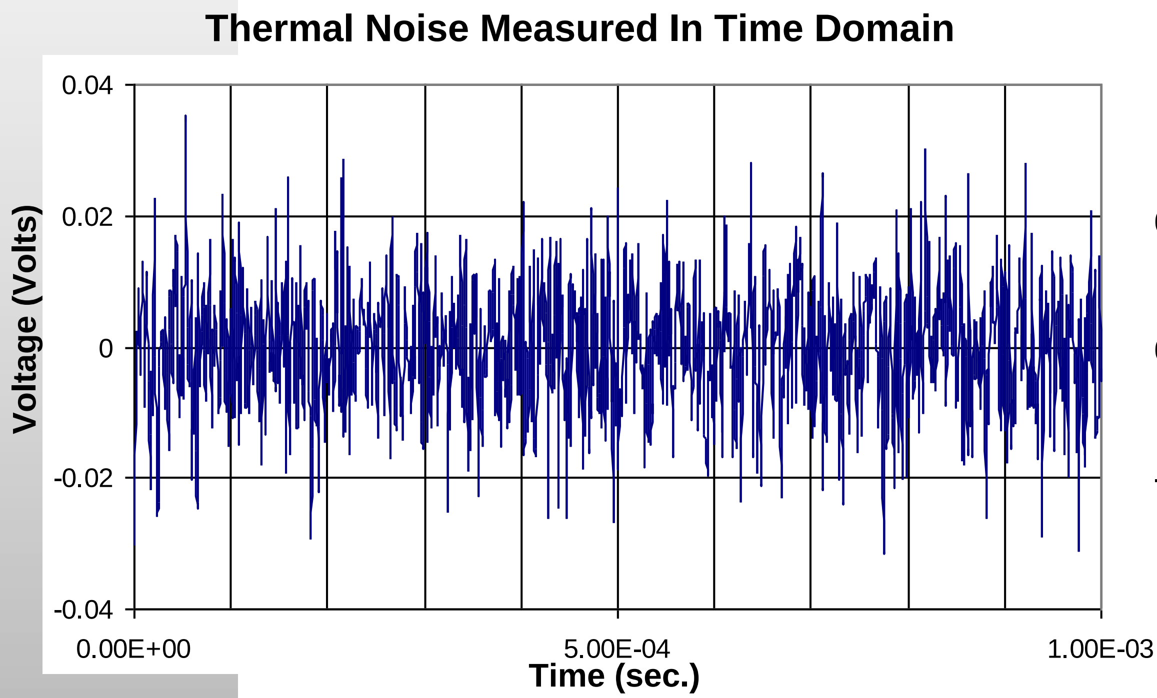


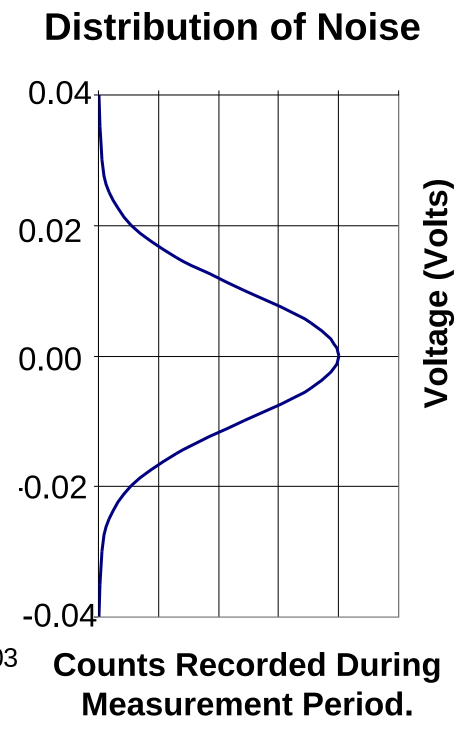






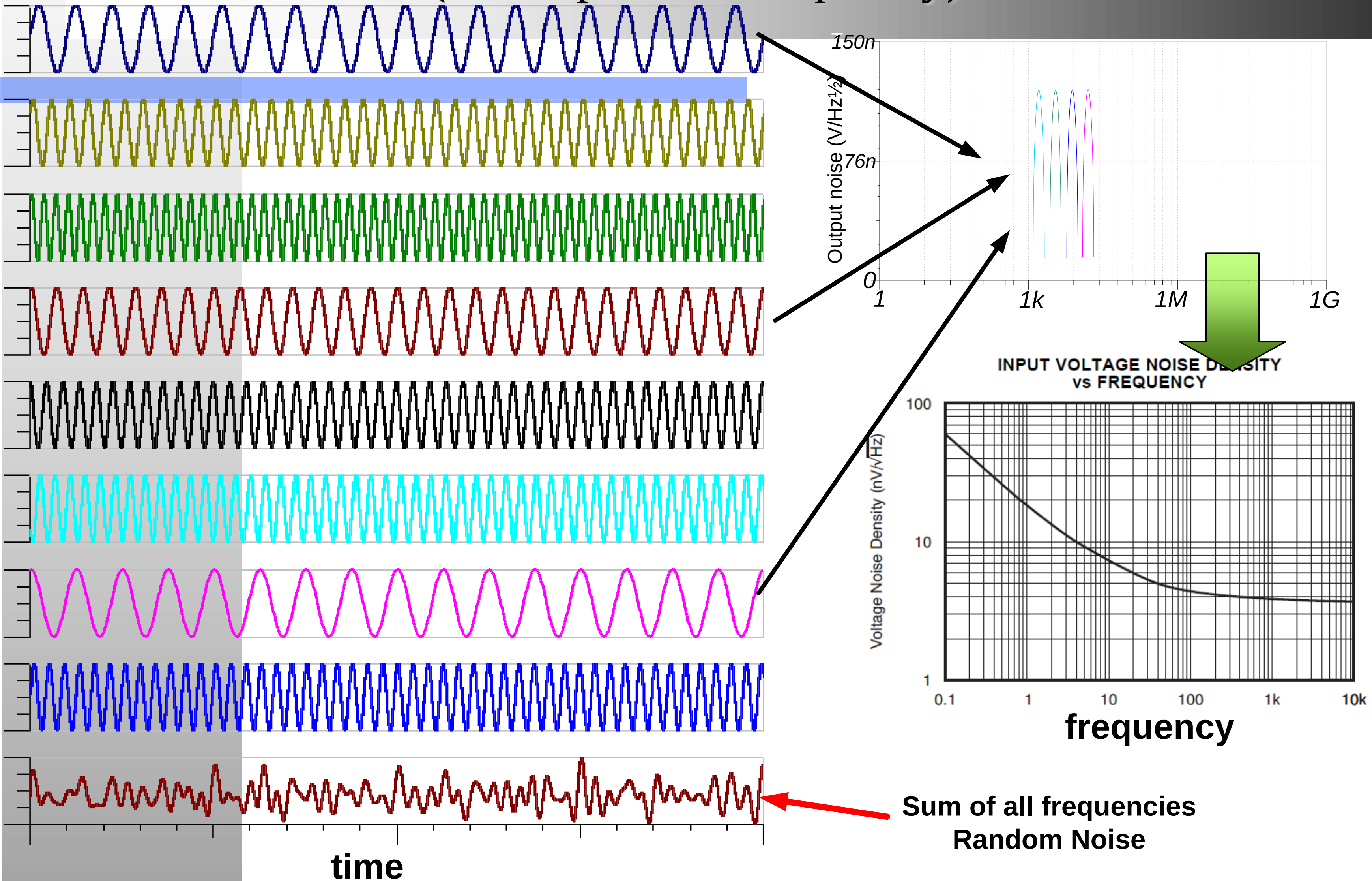
Time Domain – White noise normal distribution



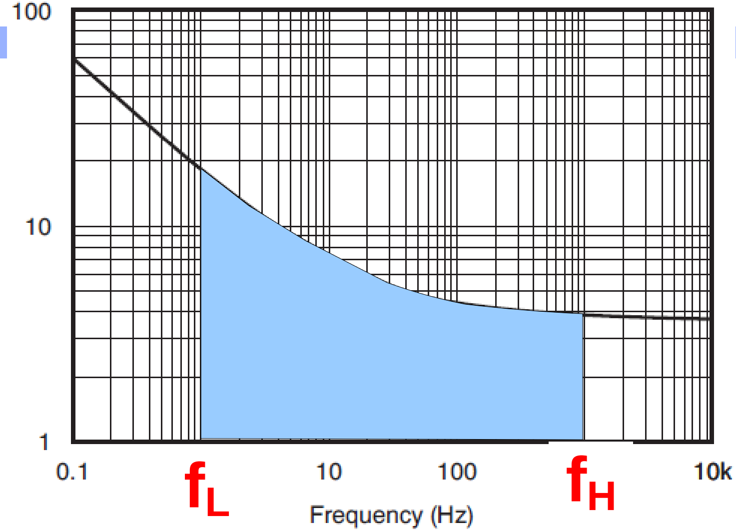


What is Spectral Density?

(Noise per unit frequency)

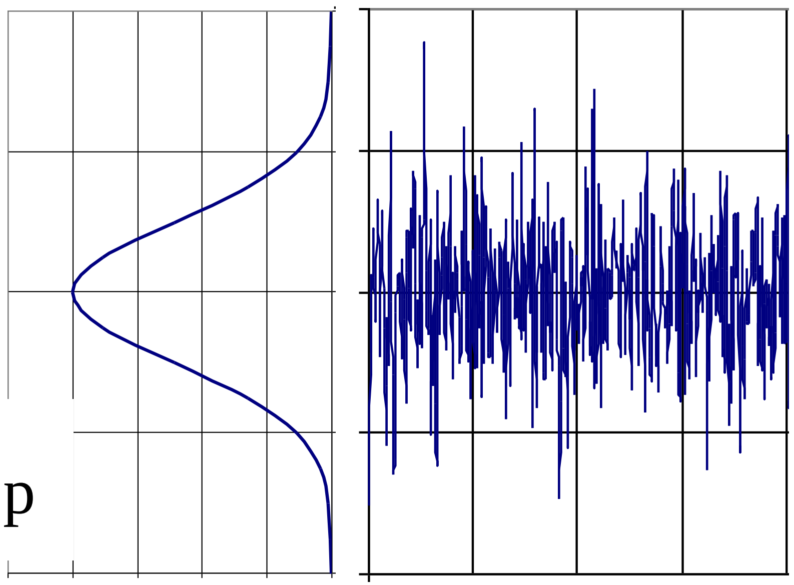


Convert Spectral Density to RMS
Convert RMS to Peak-to-Peak



$$\sqrt{\int_{f_L}^{f_H} e_n^{\;2}\, df} = E_{rms}$$

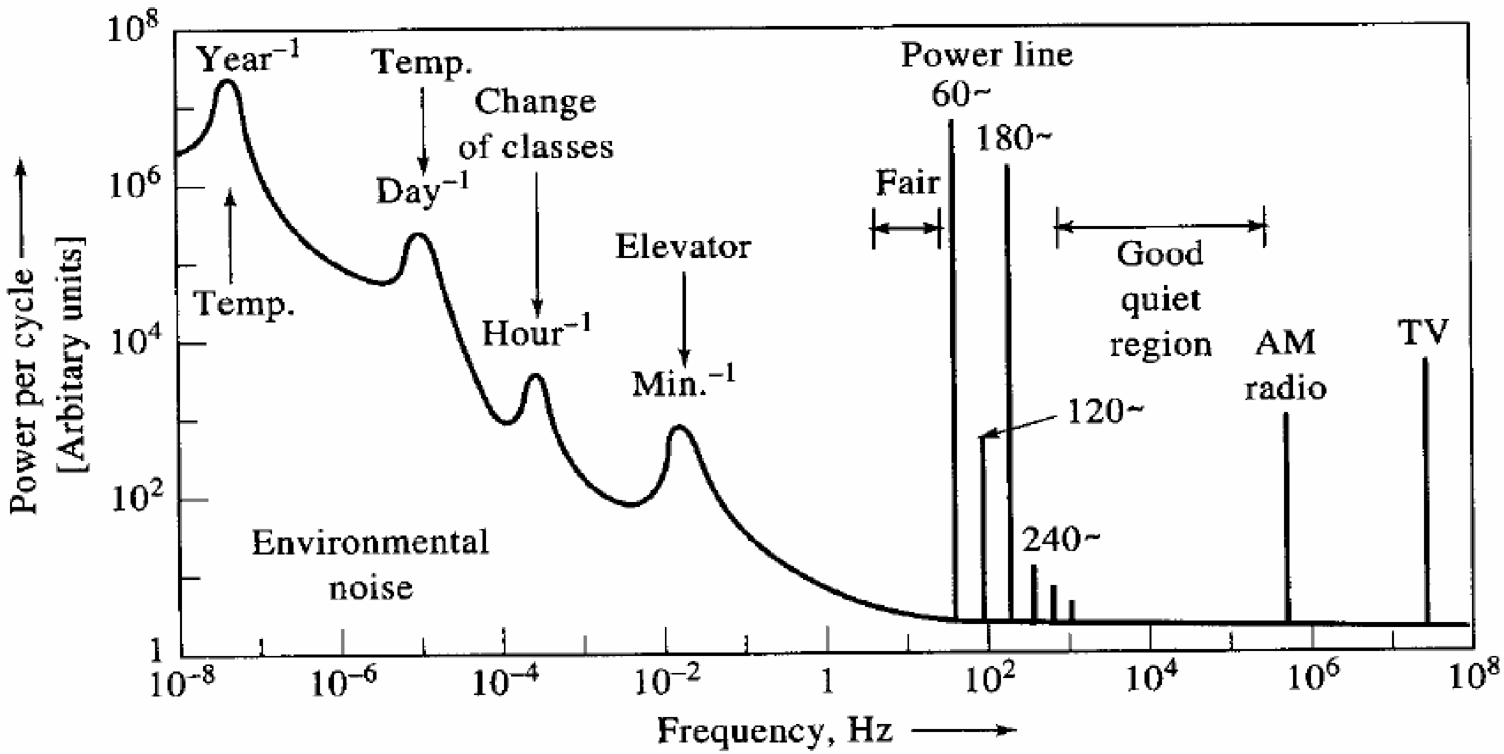
$$6 \cdot E_{rms} = E_{pp}$$



Photodiode vs. Photo Amplifier Noise?

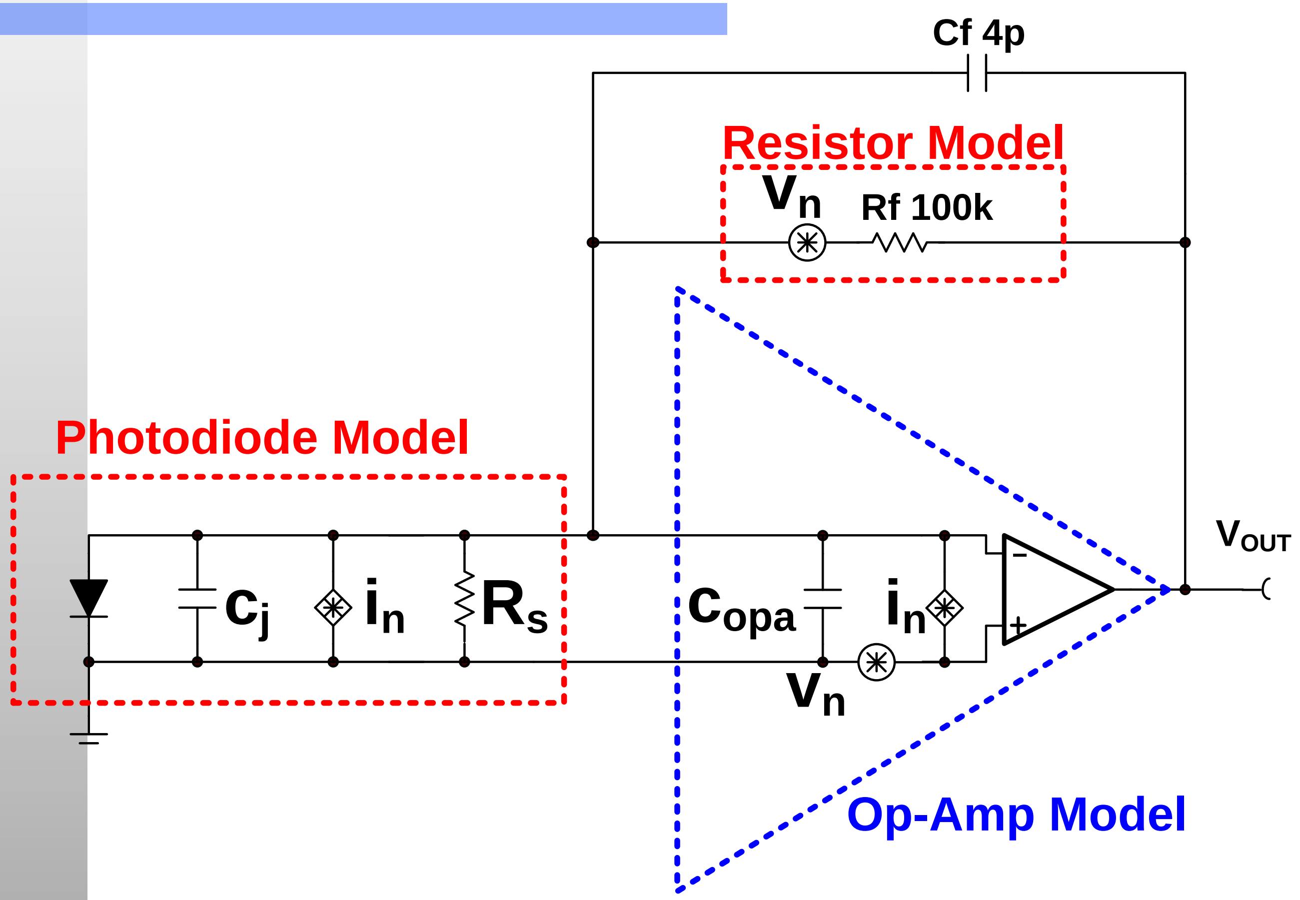
- Noise is a key parameter in photodiode design
  - Wide bandwidth (integrate more noise)
  - Low signal levels (noise more critical)
- Photodiode amplifier noise is more complex
  - Parasitic capacitance and sensor capacitance
  - Poles and zeros
  - Gain peaking

Sources of Noise



Photodiode Amplifier Noise Theory

Photo-Diode Amp Noise Model



Photodiode Noise

Thermal (Johnson Noise)

$$i_j = \sqrt{\frac{4k_b \cdot T_n}{R_{sh}}}$$

Shot noise (dark)

$$i_{sD} = \sqrt{2q \cdot I_D}$$

Shot noise (w. Light)

$$i_{sL} = \sqrt{2q \cdot I_L}$$

Total Diode Current Noise

$$i_n = \sqrt{i_j^2 + i_{sD}^2 + i_{sL}^2}$$

k_b Boltzmann constant $1.38*10^{-23}$ J/K

q Electron Charge $1.6*10^{-19}$ C

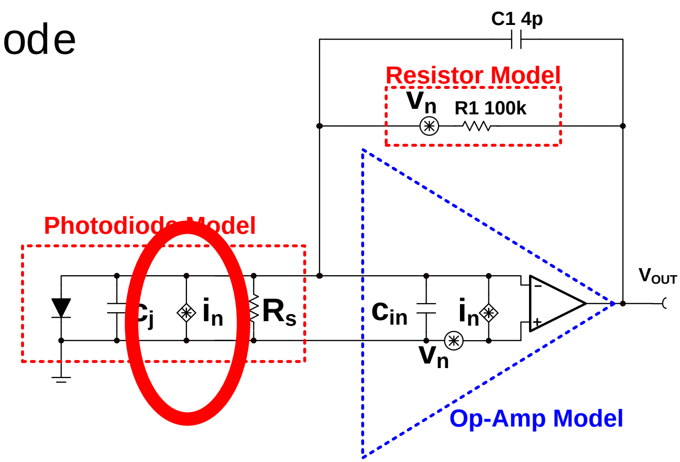
T_n Temperature in Kelvin (25C)

f_p Transconductance bandwidth

R_{sh} Shunt Resistance in photodiode

I_D Dark Current in photodiode

I_L Photo current in photodiode

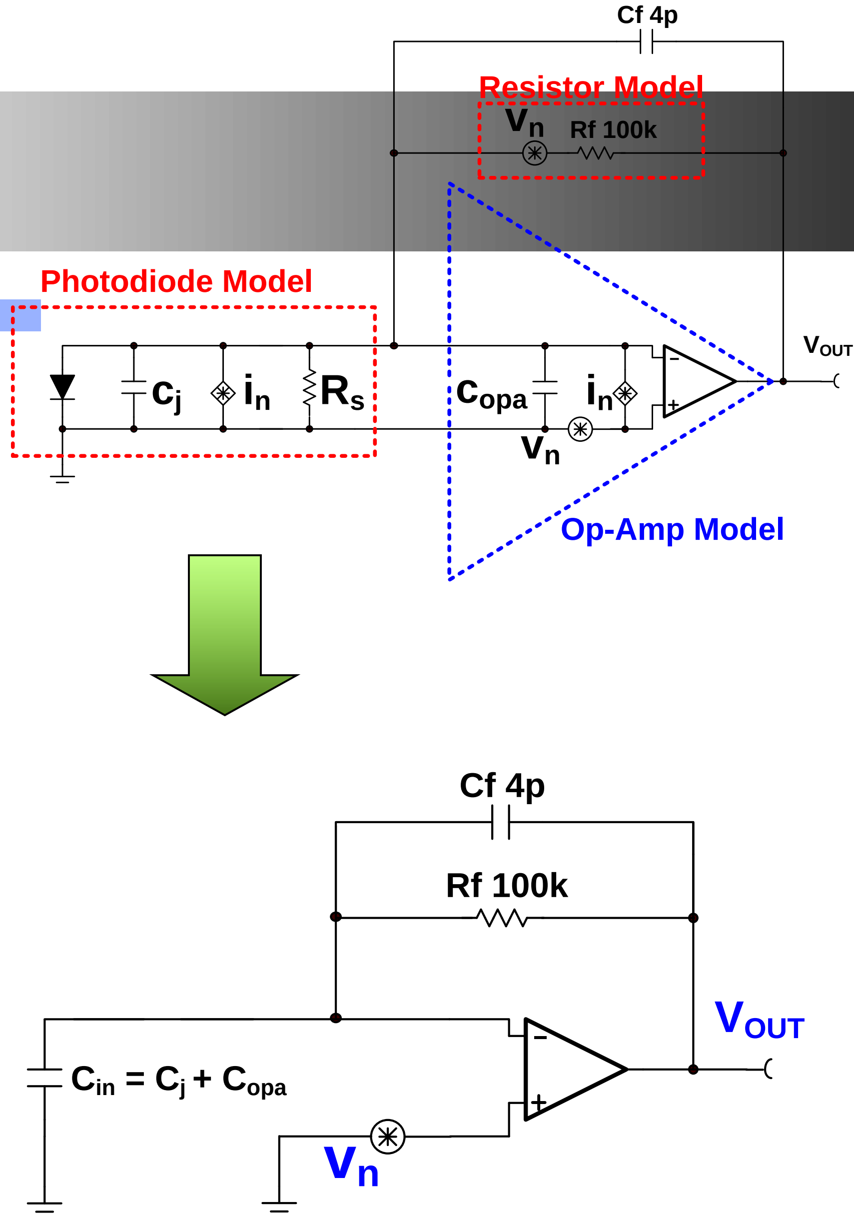


Noise Gain

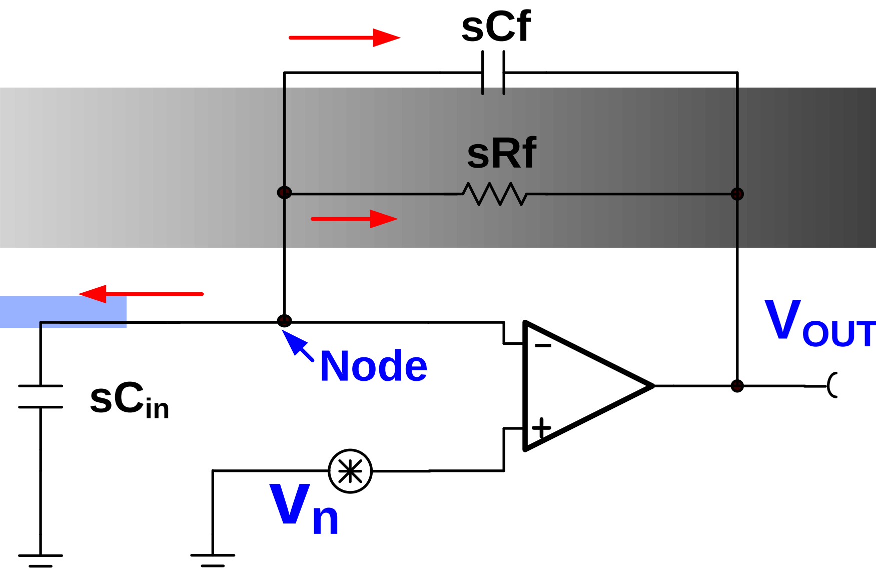
Simplify the model to compute Noise Gain

$$\text{Noise\_Gain} = \frac{V_{out}}{V_n}$$

Gain seen by the noise voltage source.



Noise Gain



Nodal Analysis on transimpedance amp

$$\frac{V_n}{\frac{1}{s \cdot C_{in}}} + \frac{\left(V_n - V_{out}\right)}{R_f} + \frac{V_n - V_{out}}{\frac{1}{s \cdot C_f}} = 0$$

Solve for noise gain Vout / Vn

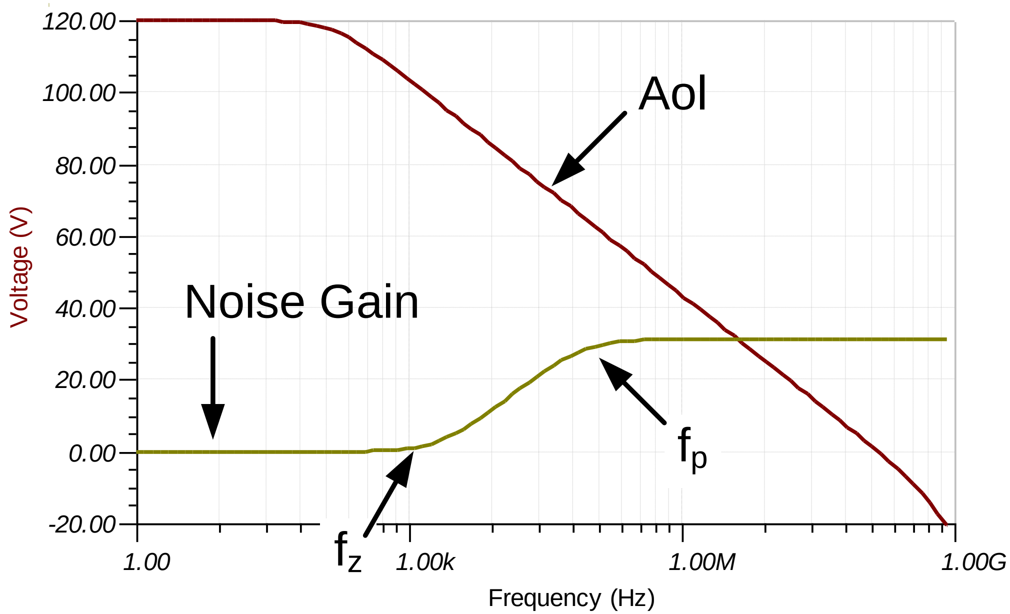
$$\frac{V_{out}}{V_n} = \frac{R_f \cdot \left(C_f + C_{in}\right) \cdot s + 1}{C_f \cdot R_f \cdot s + 1}$$

The numerator contains a**Zero**

$$f_z = \frac{1}{2\pi\ R_f \cdot \left(C_f + C_{in}\right)}$$

The denominator contains a**Pole**

$$f_p = \frac{1}{2\pi\ R_f \cdot C_f}$$



Noise Gain

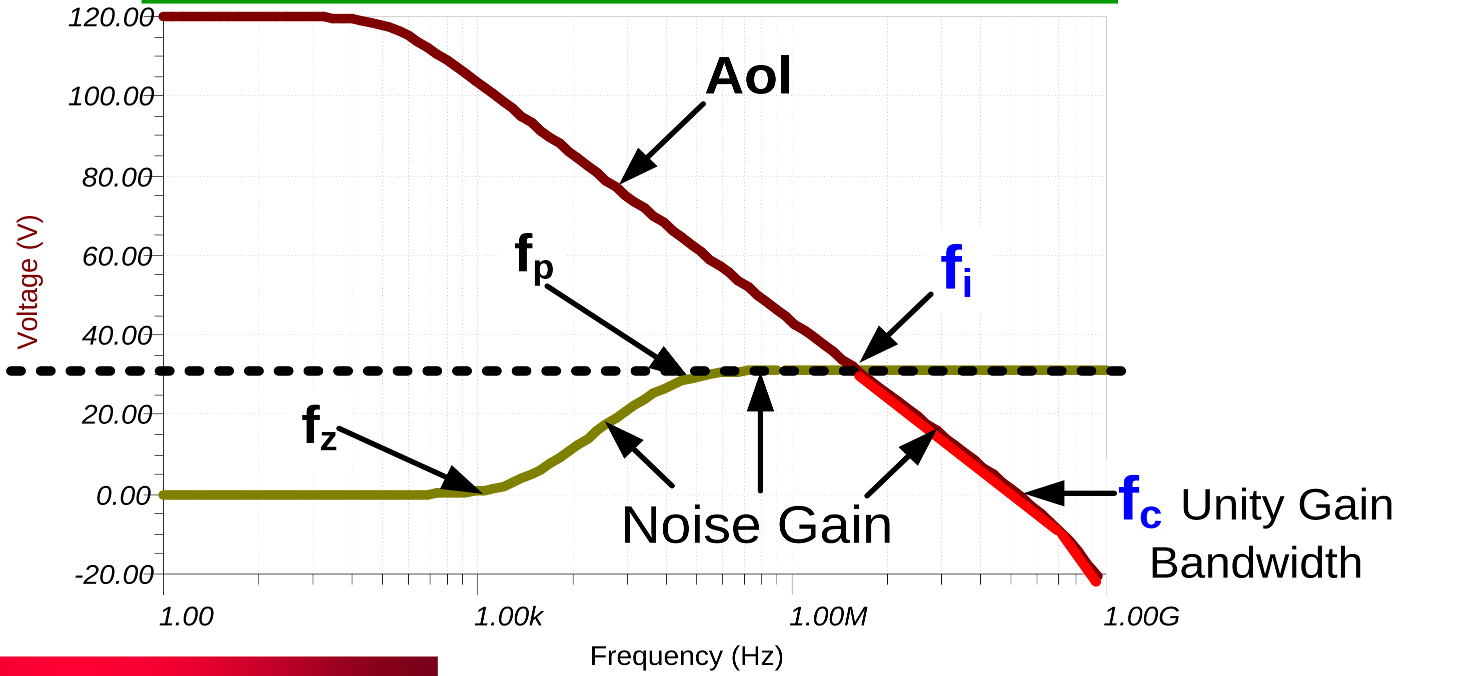
$$f_i = \frac{C_f}{C_i + C_f} \cdot f_c$$ Intersection of the noise gain curve with the Aol Curve

f_c Unity Gain Bandwidth from Op-Amp Data Sheet

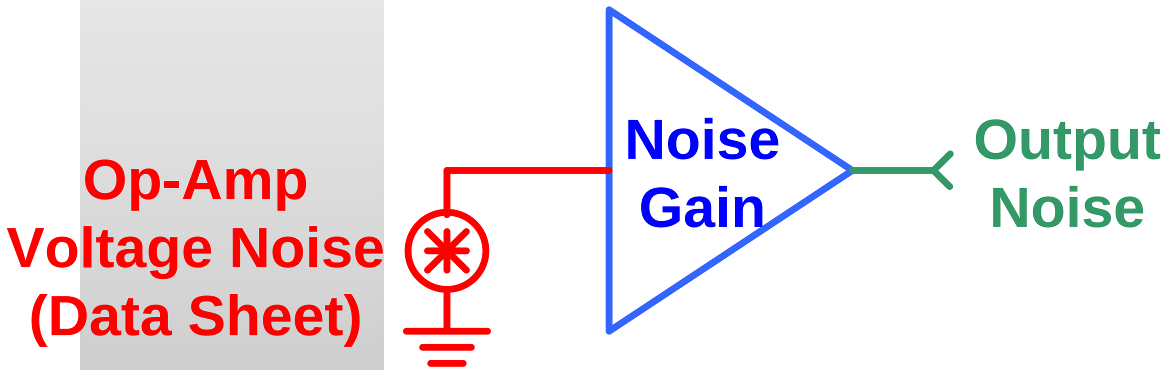
$$GPM = 1 + \frac{C_{in}}{C_f}$$ Gain Peak Magnitude

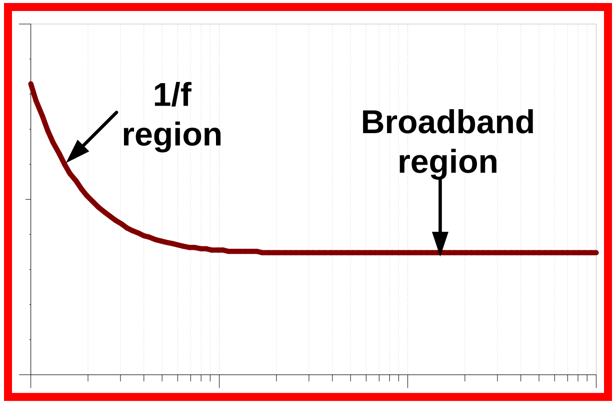
Gain Peak Magnitude

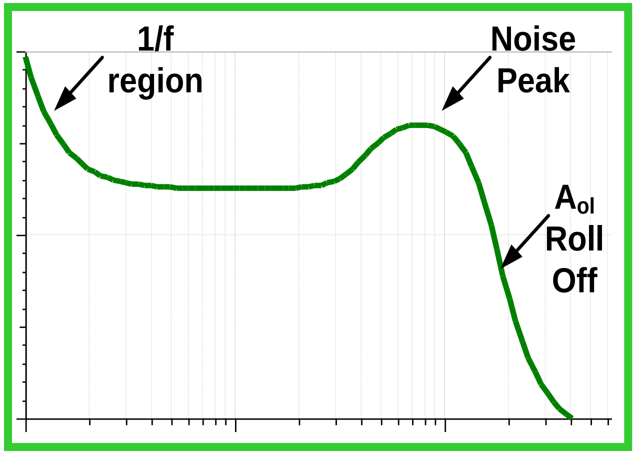
$1+ C_{in} / C_f$



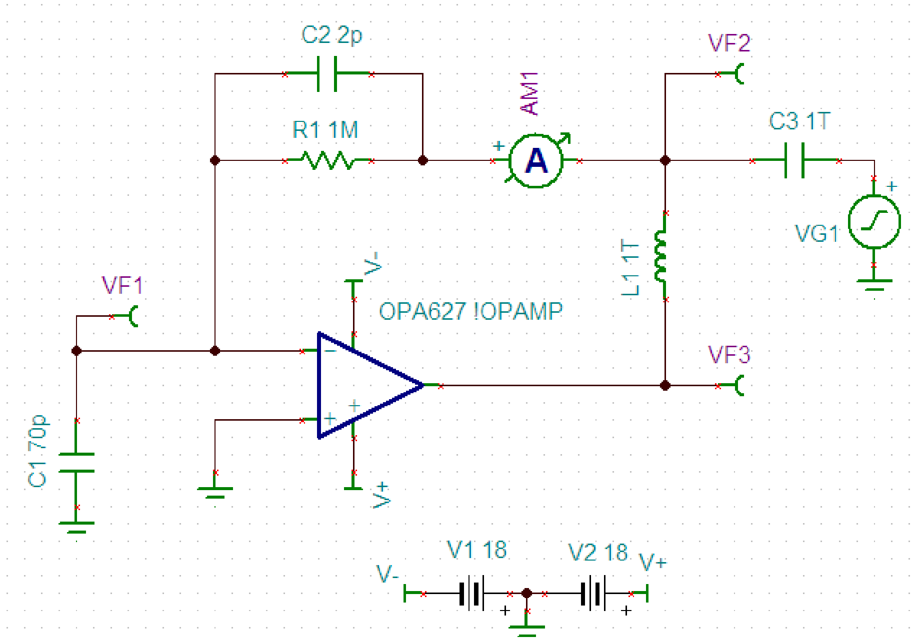
Noise Gain


Op-Amp
Voltage Noise
(Data Sheet)
Noise
Gain
Output
Noise

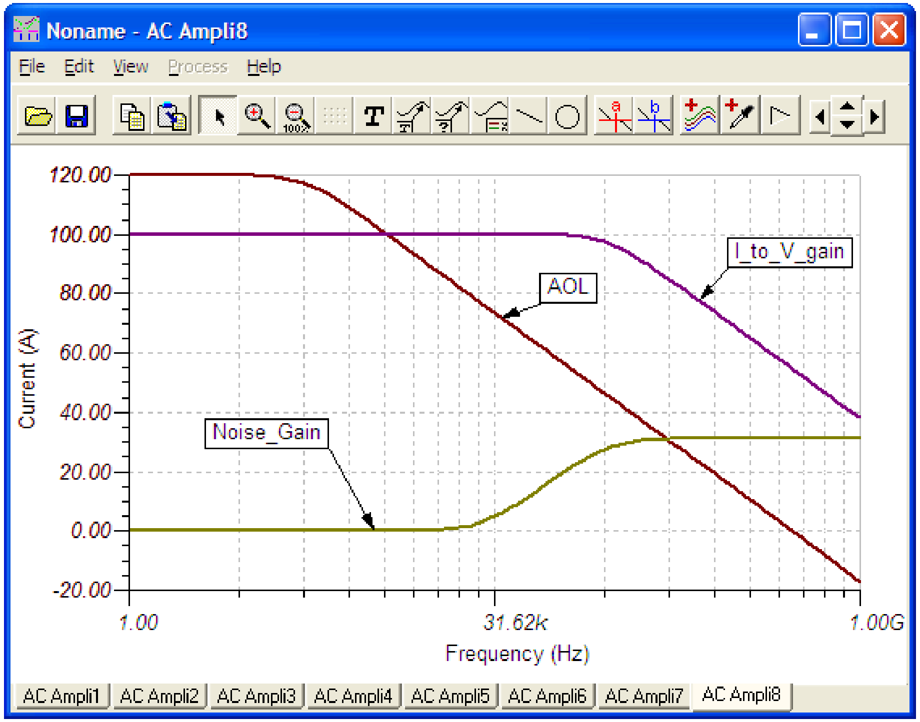

1/f
region
Broadband
region


1/f
region
Noise
Peak
A_{ol}
Roll
Off

Simulating Noise Gain and Noise Bandwidth



- **Break the loop to measure Aol, 1/B, and I to V Gain**



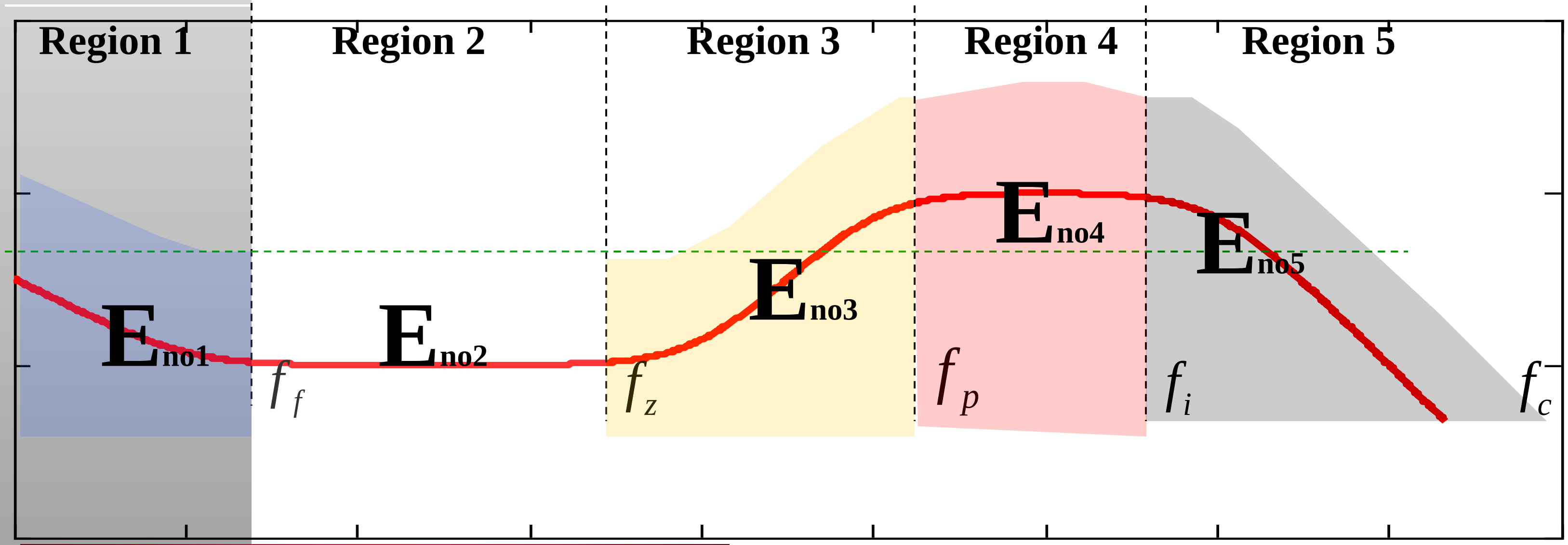
$$A_{ol} = \frac{VF3}{VF1}$$

$$Noise\_Gain = \frac{1}{\beta} = \frac{VF2}{VF1}$$

$$I\_to\_V\_Gain = \frac{VF3}{AM1}$$

Voltage Noise eni , eno and Eno

$$e_{no} = A_n \cdot e_{ni} = \frac{\left(1 + \frac{s}{\omega_z}\right) \cdot \sqrt{1 + \frac{\omega_f}{s}}}{\left(1 + \frac{s}{\omega_p}\right) \cdot \left(1 + \frac{s}{\omega_i}\right)}$$



Voltage Noise e_{ni} , e_{no} and E_{no}

Region 1 noise:

$$E_{noe1}^{\ \ 2} = \int_{f_L}^{f_f} \frac{e_{nif}^{\ \ 2} \cdot f_f}{f} d_f = e_{nif}^{\ \ 2} f_f \ln \frac{f_f}{f_L}$$

Region 2 noise:

$$E_{noe2}^{\ \ 2} = \int_{f_f}^{f_z} e_{nif}^{\ \ 2} d_f = e_{nif}^{\ \ 2} \left(f_z - f_f \right)$$

Region 3 noise:

$$E_{noe3}^{\ \ 2} = \int_{f_z}^{f_p} \frac{e_{nif}^{\ \ 2} \cdot f^2}{f_z^{\ 2}} d_f = \left(\frac{e_{nif}}{f_z} \right)^2 \frac{f_p^{\ 3} - f_z^{\ 3}}{3}$$

Region 4 noise:

$$E_{noe4}^{\ \ 2} = \int_{f_p}^{f_i} \left(\frac{e_{nif}}{\beta} \right)^2 d_f = \left(e_{nif} \cdot \frac{C_i + C_f}{C_f} \right)^2 \left(f_i - f_p \right)$$

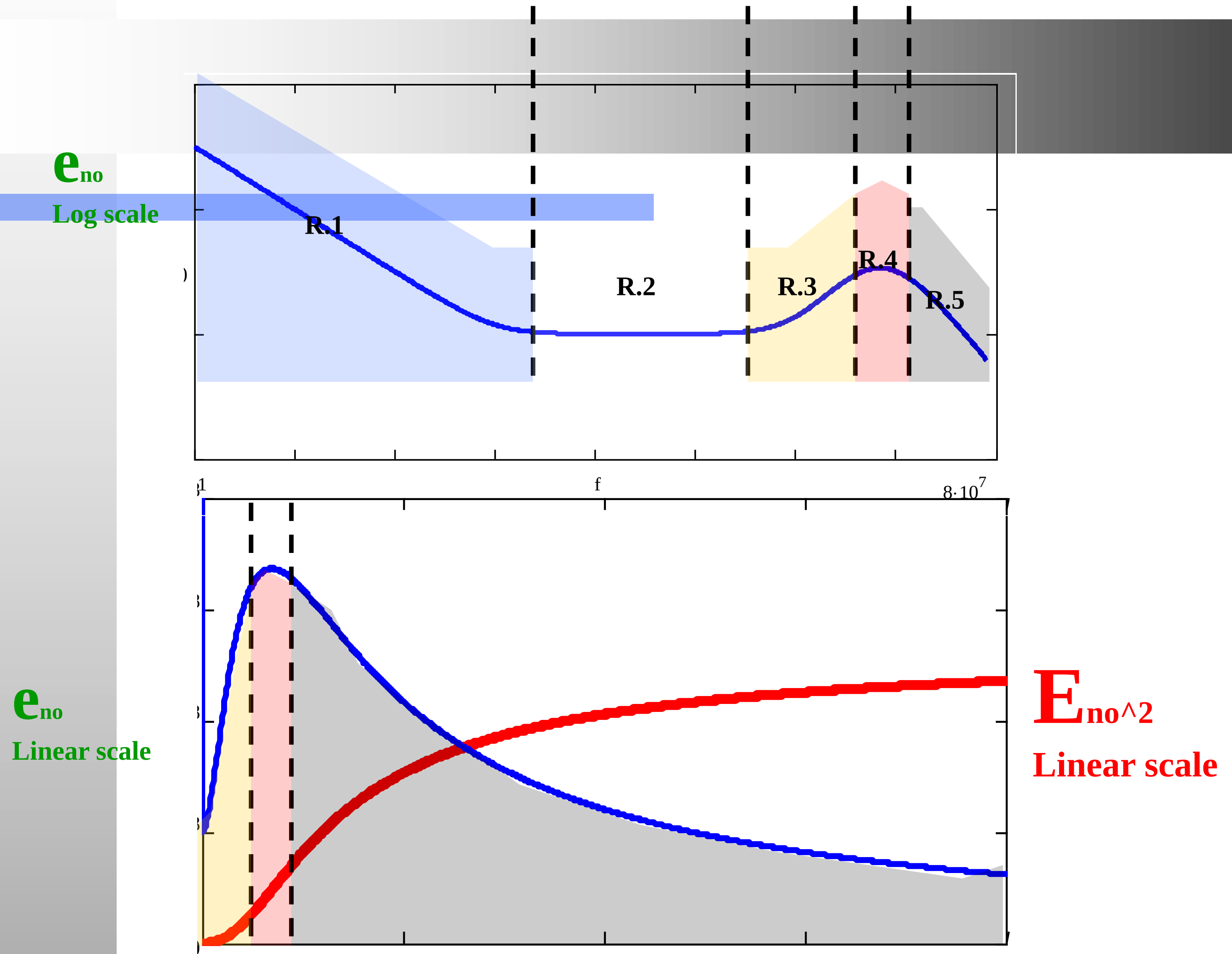
Region 5 noise:

$$E_{noe5}^{\ \ 2} = \int_{f_i}^{\infty} \left(\frac{e_{nif} f_c}{f} \right)^2 d_f = \frac{\left(e_{nif} f_c \right)^2}{f_i}$$

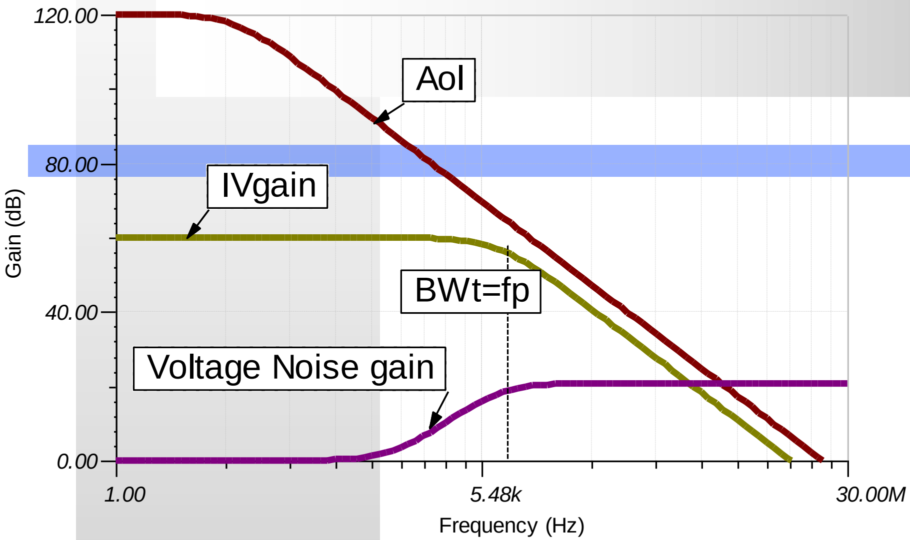
Total voltage noise:

$$E_{noe}^{\ \ 2} = E_{noe1}^{\ \ 2} + E_{noe2}^{\ \ 2} + E_{noe3}^{\ \ 2} + E_{noe4}^{\ \ 2} + E_{noe5}^{\ \ 2}$$

Voltage Noise eni , eno and Eno



Resistor Noise and Current Noise



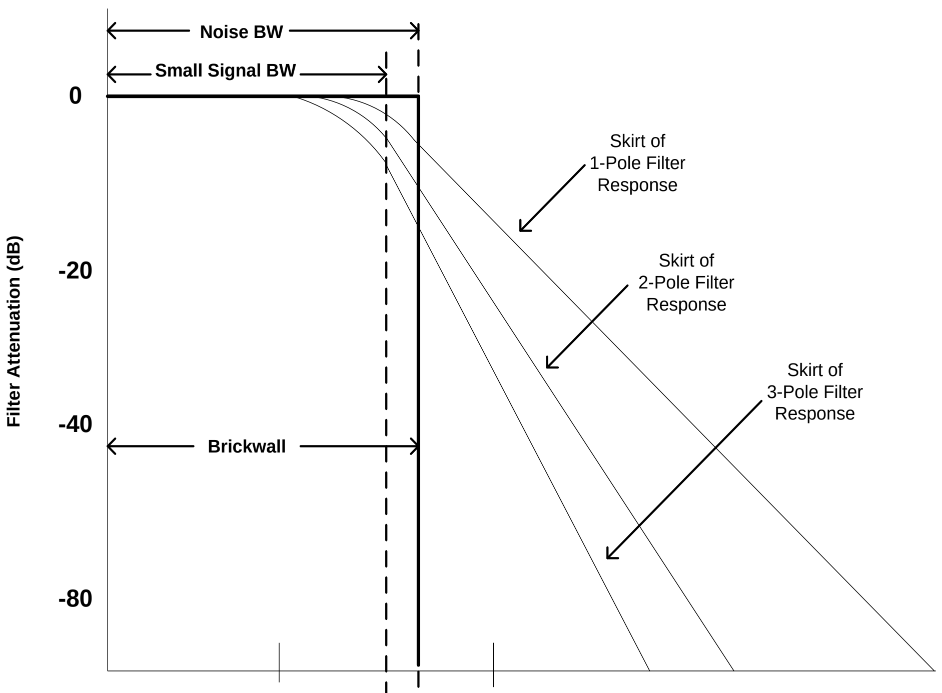
Current noise and resistor noise are limited by the transimpedance (I-V gain) bandwidth

Poles	Kn
1	1.57
2	1.22
3	1.16

$$BW_n = K_n \cdot f_p$$

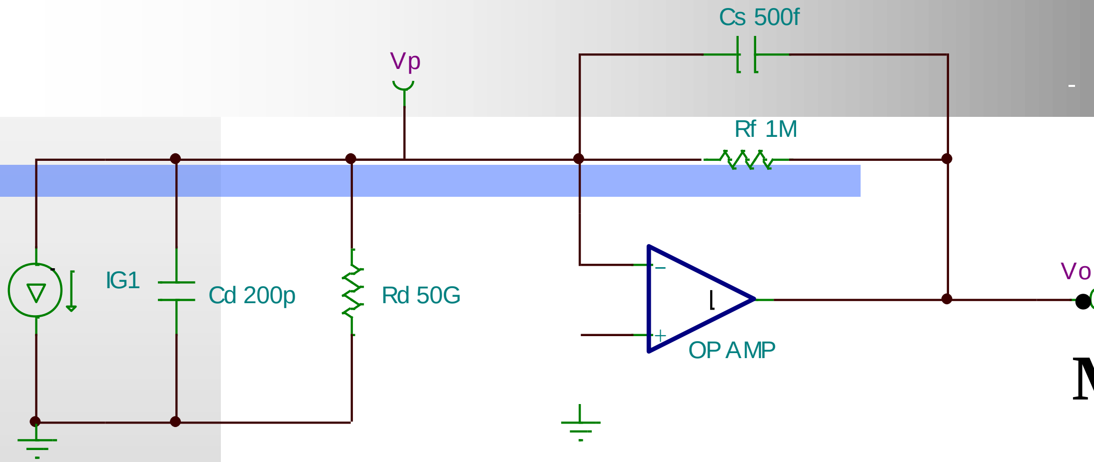
$$E_{noR} = \sqrt{4K \cdot T \cdot R_f \cdot BW_n}$$

$$E_{no1} = i_{ni} \cdot R_f \cdot BW_n$$



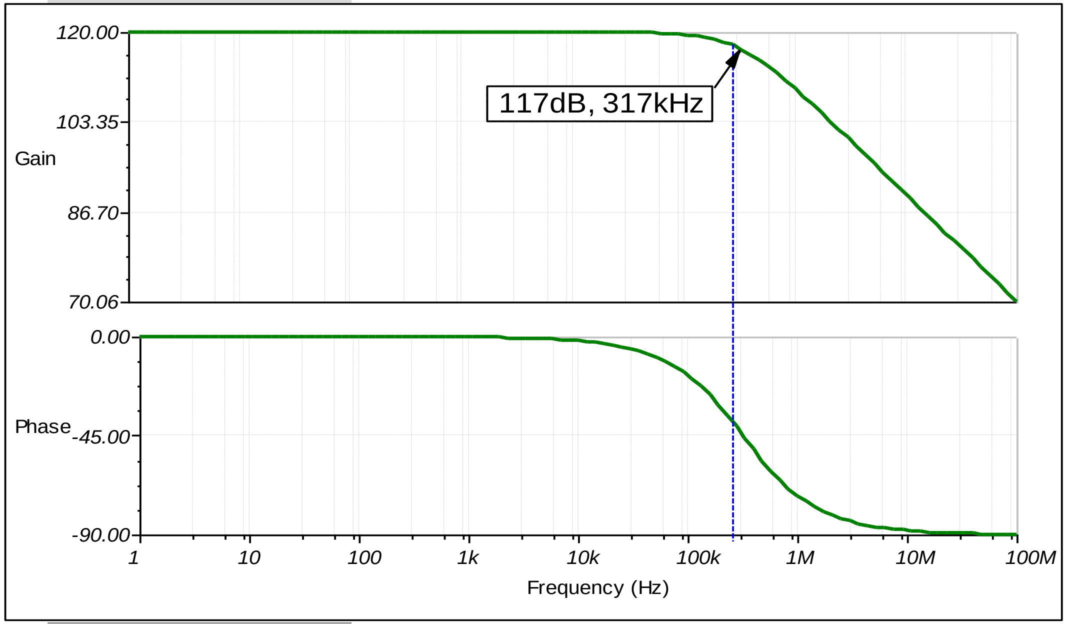
Bandwidth and Stability

Parasitic Capacitance Limits the Bandwidth

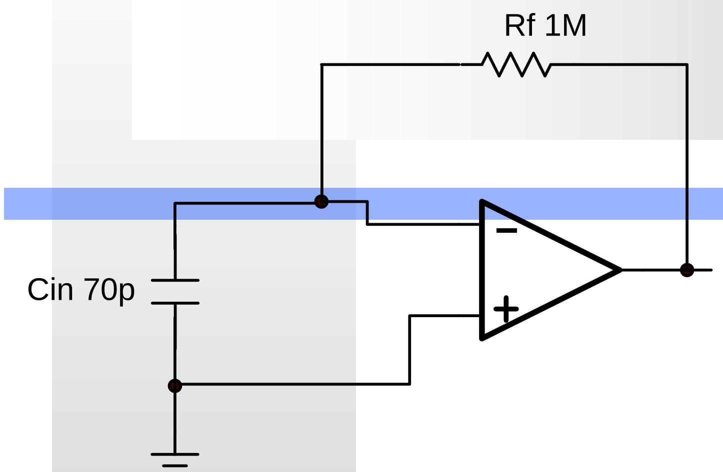


$$f_p = \frac{1}{2\pi\ R_f \cdot C_f} = 318\text{kHz}$$

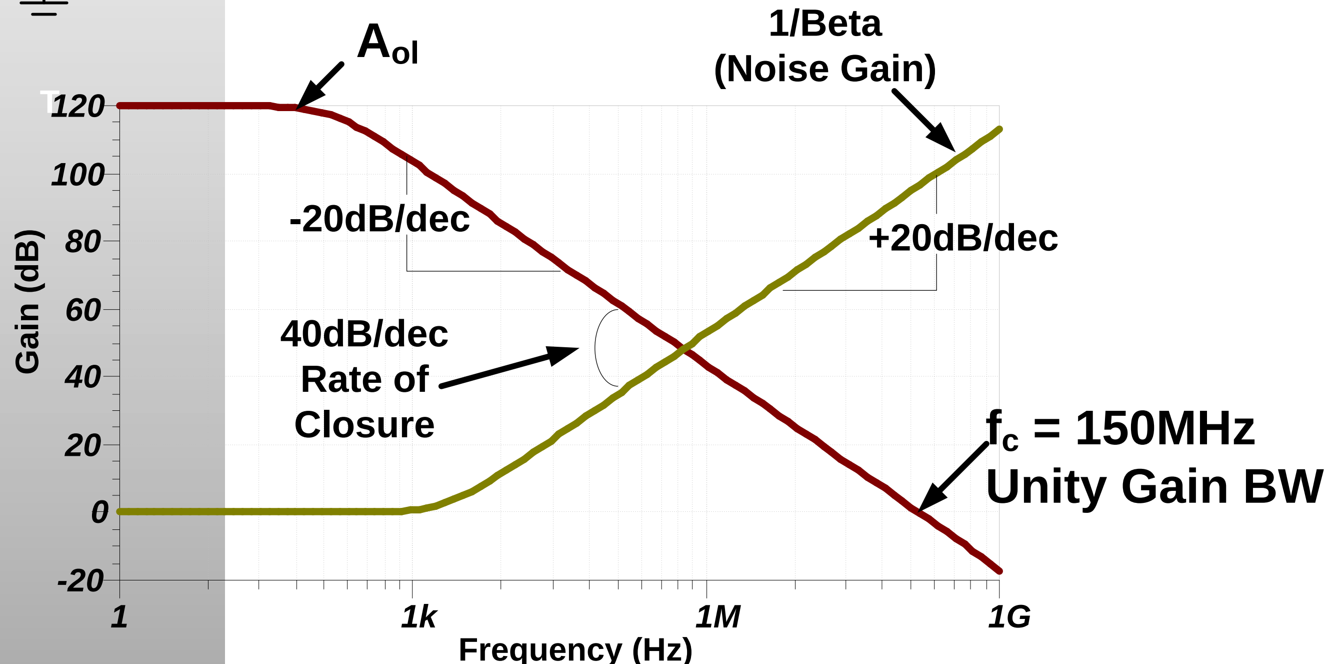
- Max bandwidth with Min Cf
- Low Cf may be unstable
- Wide BW increases noise
- As shown Cf=Cs (stray cap)



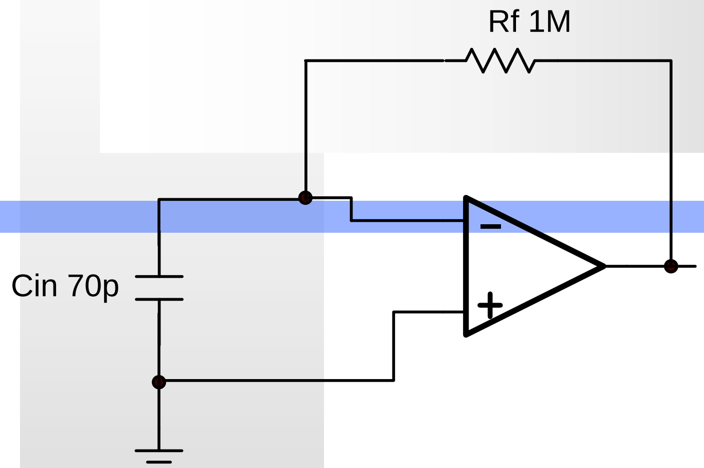
Feedback Capacitance Required for Stability



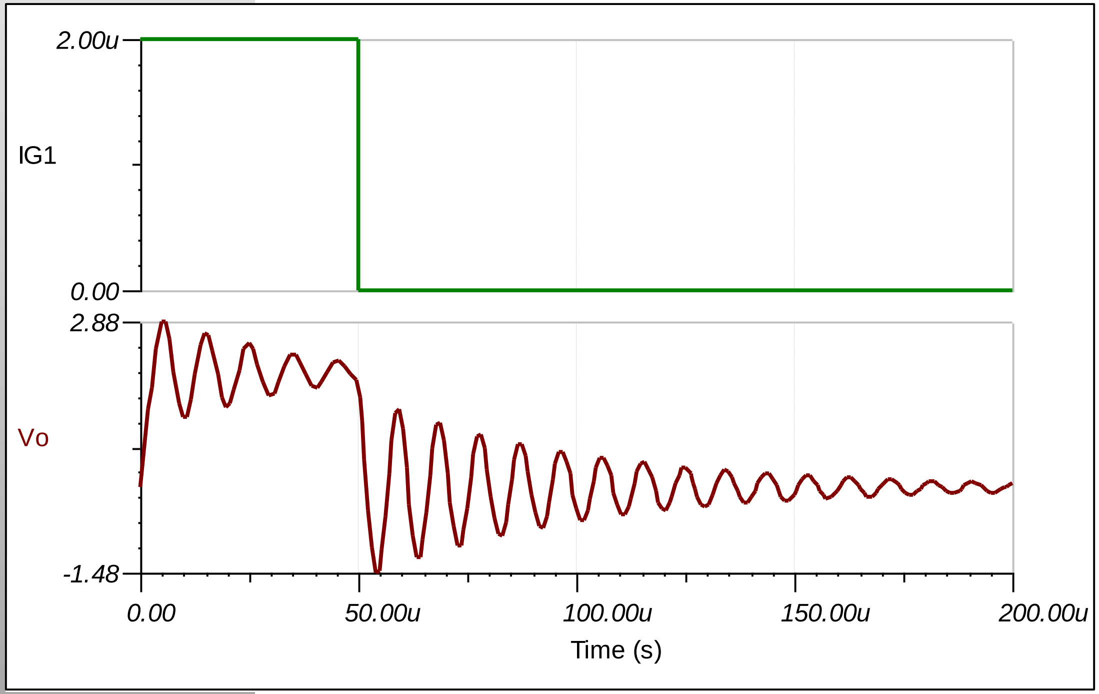
- Noise Gain is key to stability
- Also called 1/Beta (in stability analysis)
- ROC = Rate of Closure
- ROC = (Aol slope) – (1/Beta slope)
- Unstable when ROC > 20dB/decade



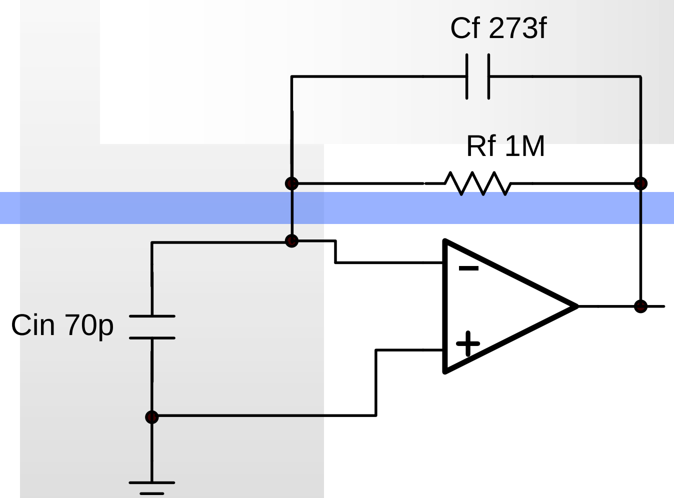
Feedback Capacitance Required for Stability

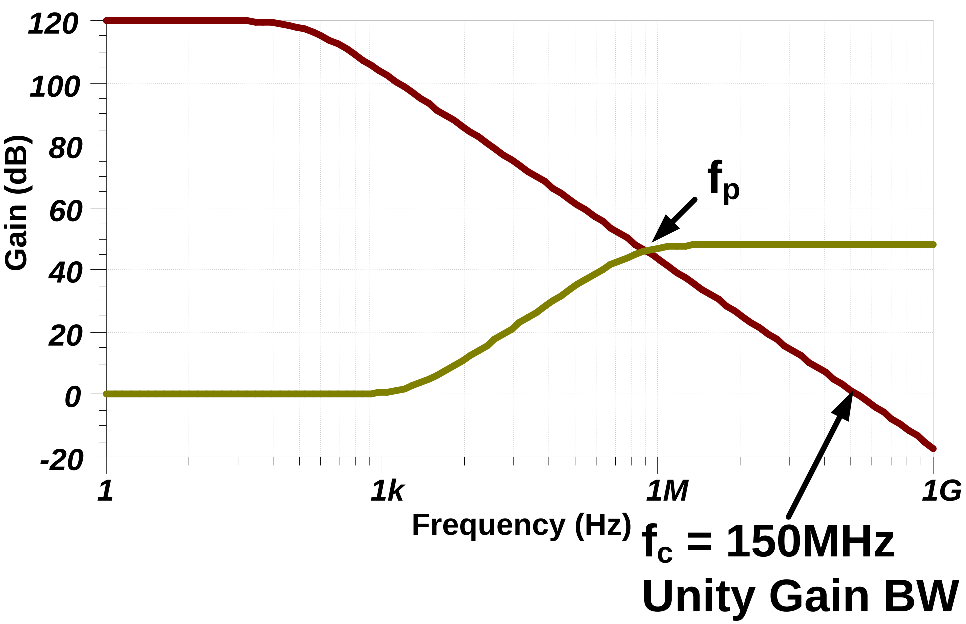


Applying a Step Input shows instability at output



Choosing a Minimum Cf for Stability





$f_c = 150\text{MHz}$ — Op-amp Unity Gain Bandwidth

$C_{in} = 70\text{pF}$ — Total input capacitance

$R_f = 1\text{M}\Omega$ — Feedback resistance

$$C_f = \sqrt{\frac{C_{in}}{2\pi \cdot R_f \cdot f_c}} = 272.5\text{fF}$$

Simplified equation for minimum feedback cap
Assumes Cin >> Cf

$$C_c = \frac{1}{2\pi \cdot R_f \cdot f_c}$$

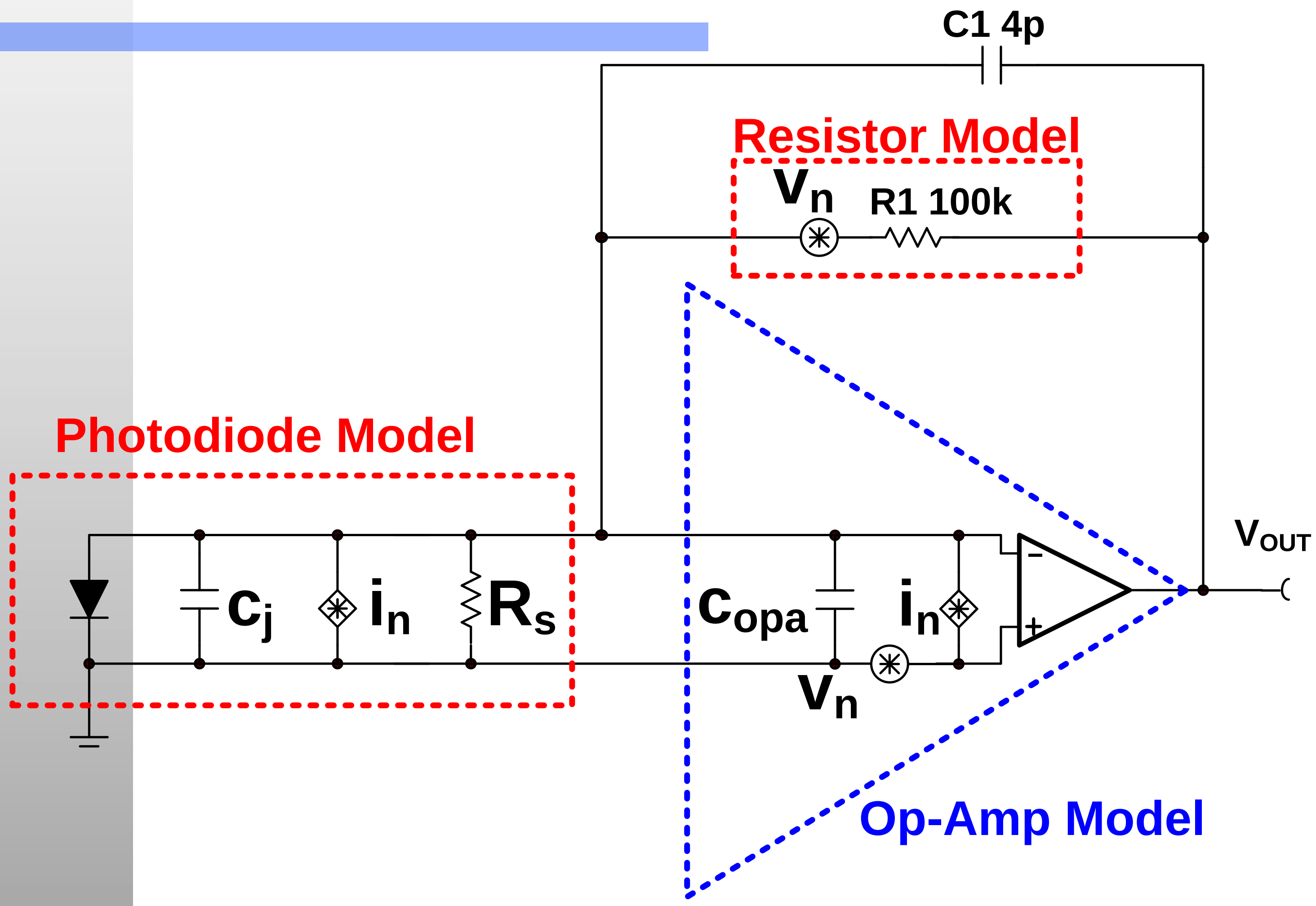
Intermediate calculation used in more exact formula

$$C_{fe} = \frac{C_c}{2} \cdot \left(1 + \sqrt{1 + \frac{4C_{in}}{C_c}}\right) = 273.1\text{fF}$$

More exact formula for feedback capacitance

Op Amp Calculations

Noise Model for Simple Transimpedance Amp



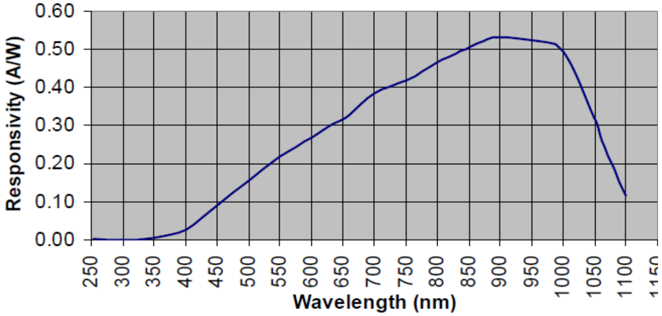
Example Photodiode: PDB-C158

ABSOLUTE MAXIMUM RATING (TA)= 23°C UNLESS OTHERWISE NOTED

SYMBOL	PARAMETER	MIN	MAX	UNITS
V_{BR}	Reverse Voltage		50	V
T_{STG}	Storage Temperature	-40	+100	°C
T_O	Operating Temperature	-40	+80	°C
T_S	Soldering Temperature*		+260	°C

* 1/16 inch from case for 3 seconds max.

SPECTRAL RESPONSE



ELECTRO-OPTICAL CHARACTERISTICS RATING (TA)= 23°C UNLESS OTHERWISE NOTED

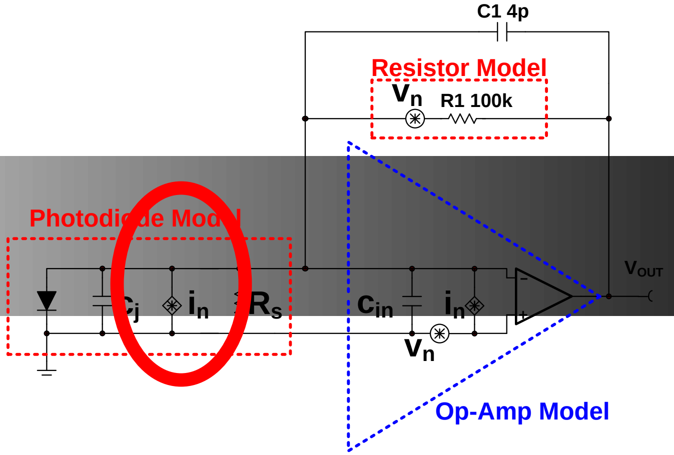
SYMBOL	CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
I_{SC}	Short Circuit Current	H = 100 fc, 2850 K	100	145		μA
I_D	Dark Current	V_R = 10 V		2	30	nA
R_{SH}	Shunt Resistance	V_R = 10 mV	100	150		MΩ
C_J	Junction Capacitance	V_R = 10 V, f = 1 MHz		10	25	pF
λ range	Spectral Application Range	Spot Scan	400		1100	nm
V_{BR}	Breakdown Voltage	I = 10 μA	30	75		V
NEP	Noise Equivalent Power	V_R = 10V @ λ = Peak		4.4×10^{-14}		W/ $\sqrt{\text{Hz}}$
t_r	Response Time	RL = 1KΩ, V_R = 10 V		50		nS

**Response time of 10% to 90% is specified at 660nm wavelength light.

Cj is not specified at Vr=0V.

Cj=70pF for Vr=0V

Calculate Diode Current Noise



Thermal (Johnson Noise)

$$\sqrt{\frac{4k_b \cdot T_n}{R_{sh}}} = 10.472\times 10^{-15} \frac{A}{\sqrt{Hz}}$$

Shot noise (dark)

$$\sqrt{2q \cdot I_D} = 25.314\times 10^{-15} \cdot \frac{A}{\sqrt{Hz}}$$

Shot noise (w. Light)

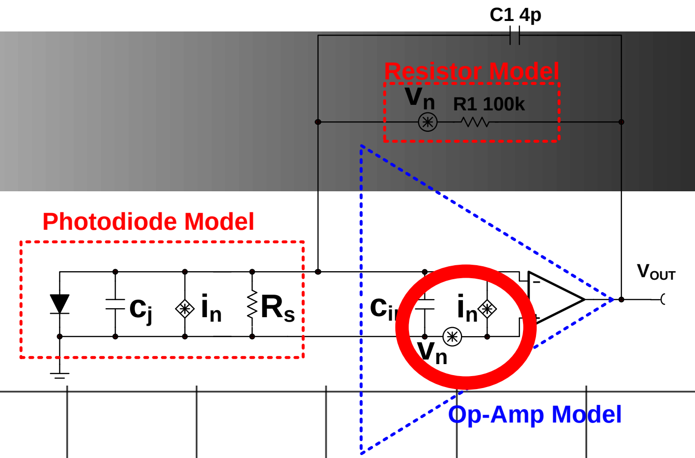
$$i_{sL} := \sqrt{2q \cdot I_L} = 0$$

Total Diode Current Noise

$$\sqrt{i_j^{2} + i_{sD}^{2} + i_{sL}^{2}} = 27.395\times 10^{-15} \cdot \frac{A}{\sqrt{Hz}}$$

$k_b := 1.38 \cdot 10^{-23} \frac{J}{K}$	Boltzmann constant
$q := 1.602 \cdot 10^{-19} C$	One electron Charge
$T_n := 298 K$	Temperature in Kelvin (25C)
$f_p := 397.887\times 10^{3}\ Hz$	Transconductance bandwidth
$R_{sh} := 150 \cdot 10^{6} \Omega$	Shunt Resistance in photodiode
$I_D := 2 \cdot 10^{-9} A$	Dark Current in photodiode
$I_L := 0A$	Photo current in photodiode (our measurements are dark)

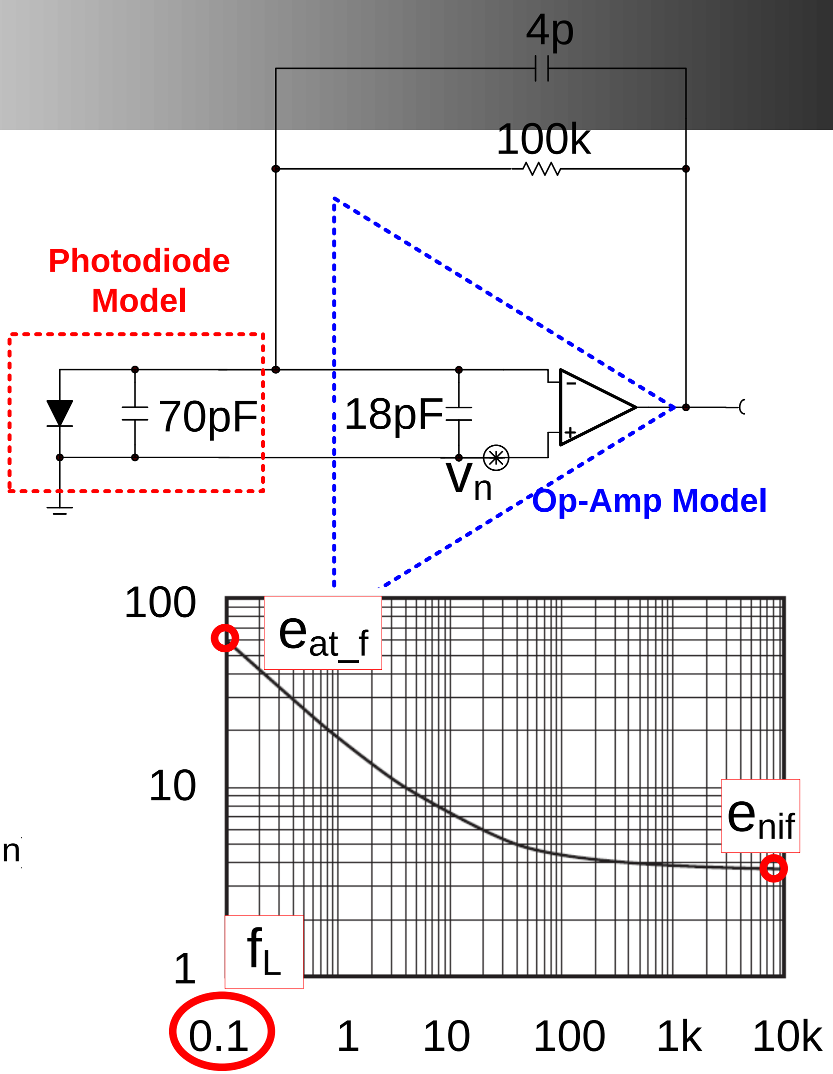
OPA827 Noise Calculation (key numbers)



NOISE									
Input Voltage Noise:									
f = 0.1Hz to 10Hz	e_n	$V_S = \pm18V$, $V_{CM} = 0V$		250			250		nV_{PP}
Input Voltage Noise Density:									
f = 1kHz	e_n	$V_S = \pm18V$, $V_{CM} = 0V$		4			4		$nV/\sqrt{Hz}$
f = 10kHz	e_n	$V_S = \pm18V$, $V_{CM} = 0V$		3.8			3.8		$nV/\sqrt{Hz}$
Input Current Noise Density:									
f = 1kHz	i_n	$V_S = \pm18V$, $V_{CM} = 0V$		2.2			2.2		$fA/\sqrt{Hz}$
INPUT IMPEDANCE									
Differential				$10^{13} \parallel 9$			$10^{13} \parallel 9$		$\Omega \parallel pF$
Common-Mode				$10^{13} \parallel 9$			$10^{13} \parallel 9$		$\Omega \parallel pF$
OPEN-LOOP GAIN									
Open-Loop Voltage Gain	A_{OL}	$(V-)+3V \leq V_O \leq (V+)-3V$, $R_L = 1k\Omega$	120	126		120	126		dB
Over Temperature		**$(V-)+3V \leq V_O \leq (V+)-3V$, $R_L = 1k\Omega$**	**114**			**114**			**dB**
FREQUENCY RESPONSE									
Gain-Bandwidth Product	GBW	G = +1		22			22		MHz

OPA827 Noise Hand Calculation

$C_j := 70pF$	Photodiode Junction Capacitance (from photodiode manufacturer)
$C_{opa} := 18pF$	Opamp input capacitance (OPA827 Data Sheet)
$C_i := C_j + C_{opa}$	Total input capacitance
$f_c := 22MHz$	Unity Gain Bandwidth (OPA827 Data Sheet)
$R_f := 100k\Omega$	Feedback resistance
$C_f := 4pF$	Feedback capacitor
$e_{nif} := 3.8\frac{nV}{\sqrt{Hz}}$	Broadband Noise Spectral Density (OPA827 Data Sheet)
$f_L := .1Hz$	Lower bound on frequency (1/f region) (arbitrary lower bound of frequency)
$e_{at\_f} := 60\frac{nV}{\sqrt{Hz}}$	Flicker noise measured at f_L (OPA827 Data Sheet Noise Curve)

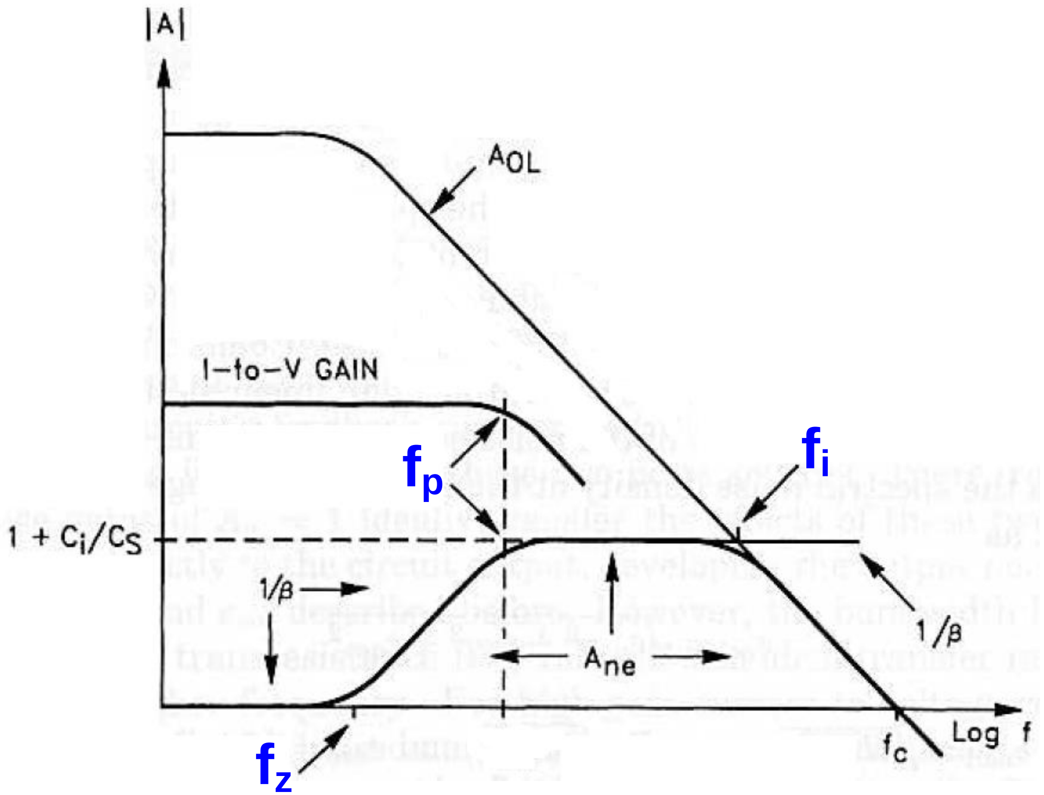


Poles and Zeros in Noise Gain Curve

$$f_z := \frac{1}{2\pi\, R_f \cdot (C_i + C_f)} = 17.299 \times 10^3\ \text{Hz}$$

$$f_p := \frac{1}{2\pi\, R_f \cdot C_f} = 397.887 \times 10^3\ \text{Hz}$$

$$f_i := \frac{C_f}{C_i + C_f} \cdot f_c = 956.522 \times 10^3\ \text{Hz}$$



Output Noise from OPA Noise Voltage

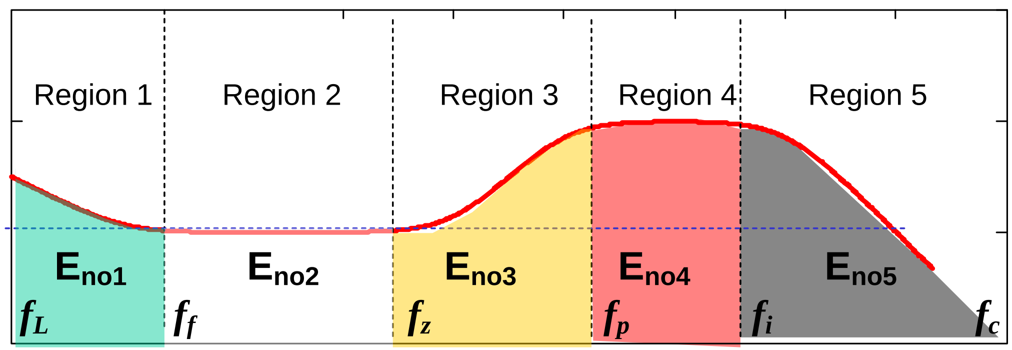
$$E_{noe1} := \sqrt{e_{nif}^{2} \cdot f_f \cdot \ln\left(\frac{f_f}{f_L}\right)} = 44.573 \times 10^{-9}\,V$$

$$E_{noe2} := \sqrt{e_{nif}^{2} \cdot \left(f_z - f_f\right)} = 499.444 \times 10^{-9}\,V$$

$$E_{noe3} := \sqrt{\left(\frac{e_{nif}}{f_z}\right)^{2} \cdot \frac{f_p^{\,3} - f_z^{\,3}}{3}} = 31.828 \times 10^{-6}\,V$$

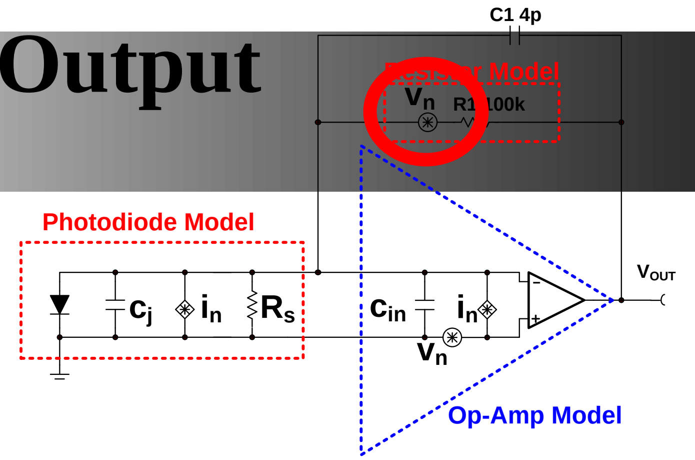
$$E_{noe4} := \sqrt{\left(e_{nif} \cdot \frac{C_i + C_f}{C_f}\right)^{2} \left(f_i - f_p\right)} = 65.324 \times 10^{-6}\,V$$

$$E_{noe5} := \sqrt{\frac{\left(e_{nif} \cdot f_c\right)^{2}}{f_i}} = 85.479 \times 10^{-6}\,V$$



$$\boxed{E_{noe} := \sqrt{E_{noe1}^{\;2} + E_{noe2}^{\;2} + E_{noe3}^{\;2} + E_{noe4}^{\;2} + E_{noe5}^{\;2}} = 112.193 \times 10^{-6}\,V}$$

Thermal (Resistor) Noise at Output



$R_f := 100 \cdot 10^3 \Omega$ Feedback Resistance

$k_b := 1.38 \cdot 10^{-23} \frac{J}{K}$ Boltzmann constant

$T_n := 298K$ Temperature in Kelvin (25C)

$f_p := 397.887 \times 10^3 \text{ Hz}$ Transconductance bandwidth

$K_n := 1.57$ Noise Current from OPA827 data sheet

$BW_n := K_n \cdot f_p$ Noise bandwidth (brick wall filter)

$e_{n\_r} := \sqrt{4k_b \cdot T_n \cdot R_f \cdot BW_n} = 32.056 \times 10^{-6} V$ Thermal noise at output

Current Noise to Voltage Noise at Output

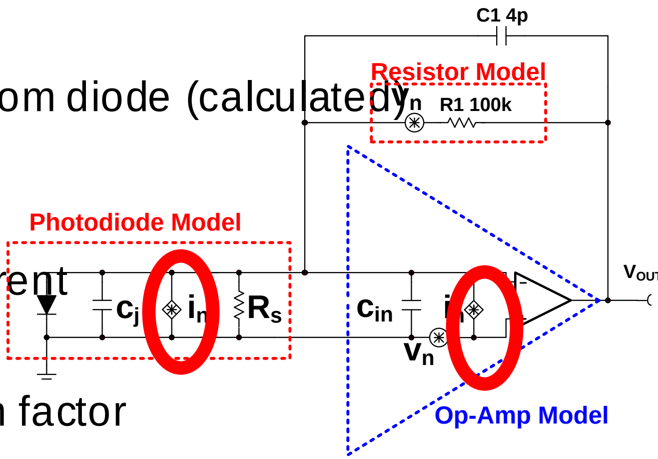
$R_f := 100 \cdot 10^3 \Omega$ Feedback Resistance

$f_p := 397.887 \times 10^3 \text{ Hz}$ Transconductance bandwidth

$i_{n\_opa} := 2.2 \times 10^{-15} \frac{A}{\sqrt{Hz}}$ Noise Current from OPA827 data sheet

$i_{n\_diode} := 27.395 \times 10^{-15} \frac{A}{\sqrt{Hz}}$ Noise Current from diode (calculated)

$i_{n\_total} := \sqrt{i_{n\_opa}^{\,2} + i_{n\_diode}^{\,2}}$ Total Noise Current



$K_n := 1.57$ Noise bandwidth factor
1st order filter

$BW_n := K_n \cdot f_p = 6.247 \times 10^5 \text{ Hz}$ Noise bandwidth (brick wall filter)

$E_{n\_I} := i_{n\_total} \cdot R_f \cdot \sqrt{BW_n} = 2.172 \times 10^{-6} \text{ V}$ Current noise at output

The Final Total Noise

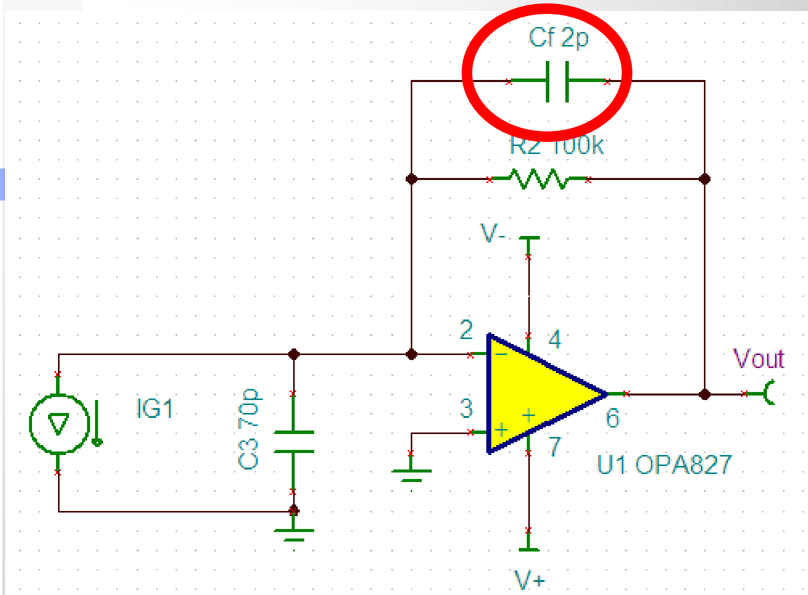
$E_{noe} := 112.193 \times 10^{-6}\,V$ Op-Amp Voltage Noise

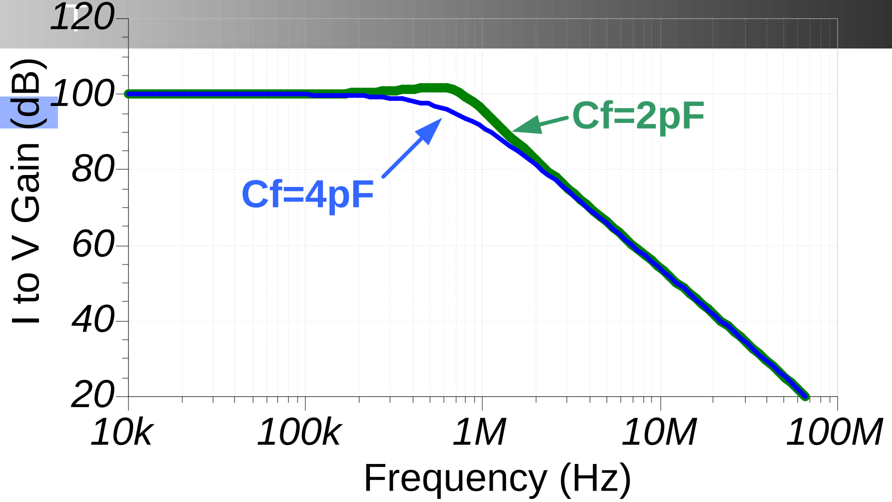
$E_{noR} := 32.056 \times 10^{-6}\,V$ Resistor Noise

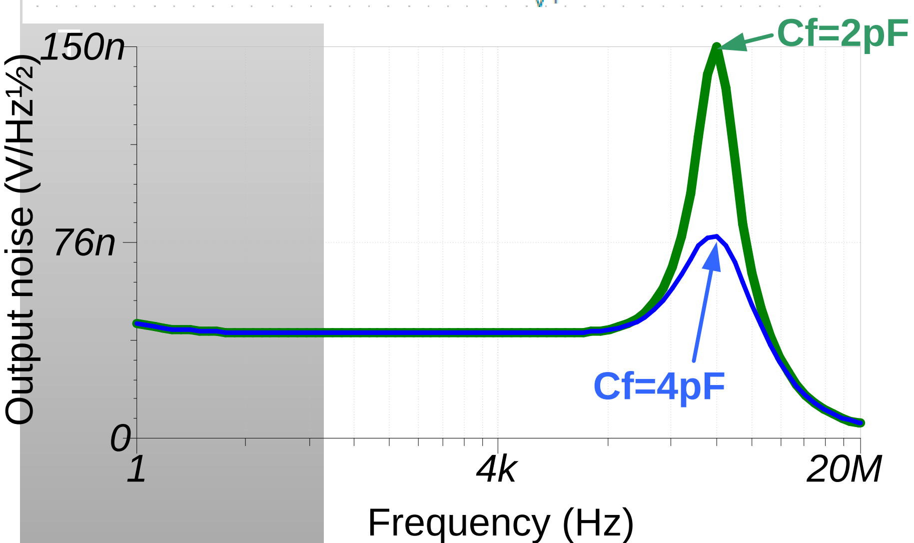
$E_{noI} := 2.172\,10^{-6}\,V$ Op-Amp Current Noise

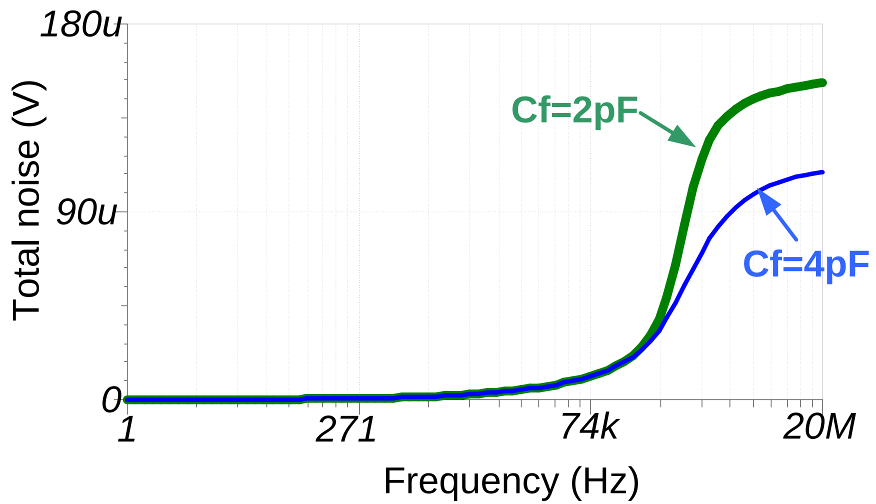
$E_{no} := \sqrt{E_{noR}^{2} + E_{noI}^{2} + E_{noe}^{2}} = 116.703 \times 10^{-6}\,V$ Total Output Noise for OPA827 Transimpedance Amp

Reducing Noise (Higher Cf = Lower BW Noise)



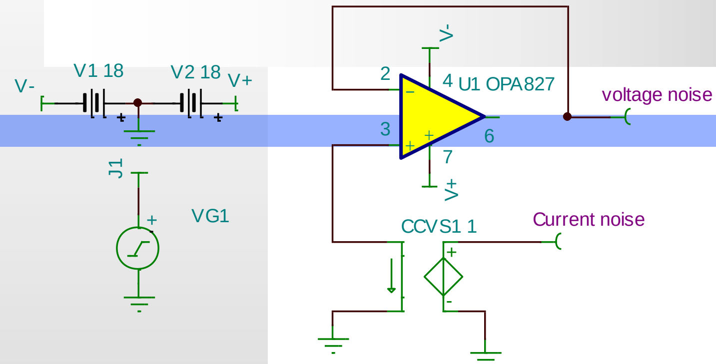






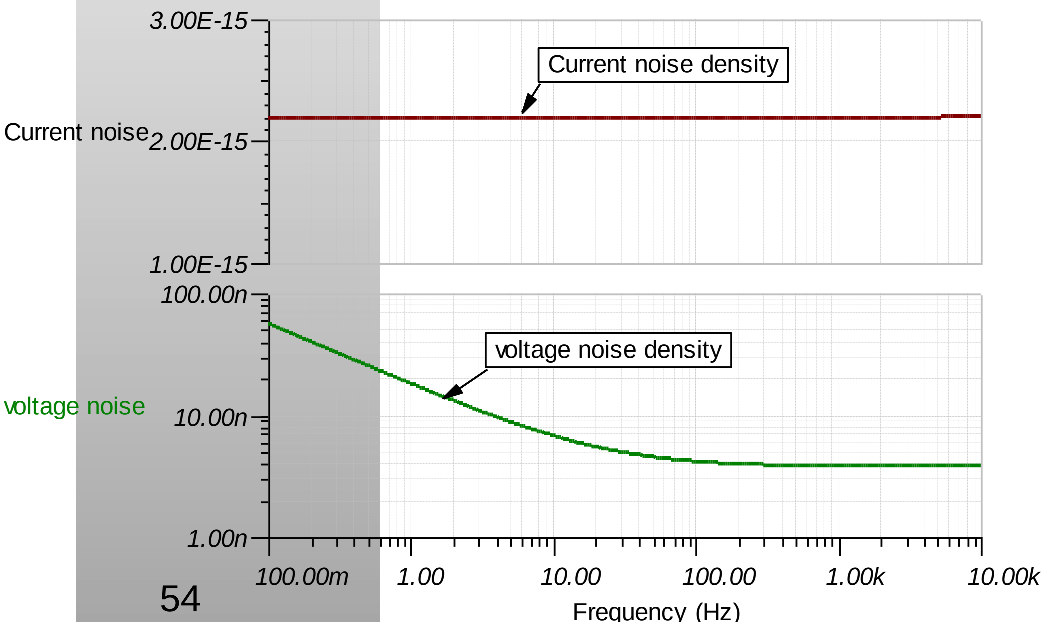
OPA827 Spice Analysis

OPA827 – test the model



- **Low Noise : 4nV/√Hz at 1kHz**
- **Low Offset Voltage: 150µV max**
- **JFET Input: I_B= 15pA typ**
- **Wide Bandwidth: 22MHz**

The voltage noise performance is the same as datasheet.



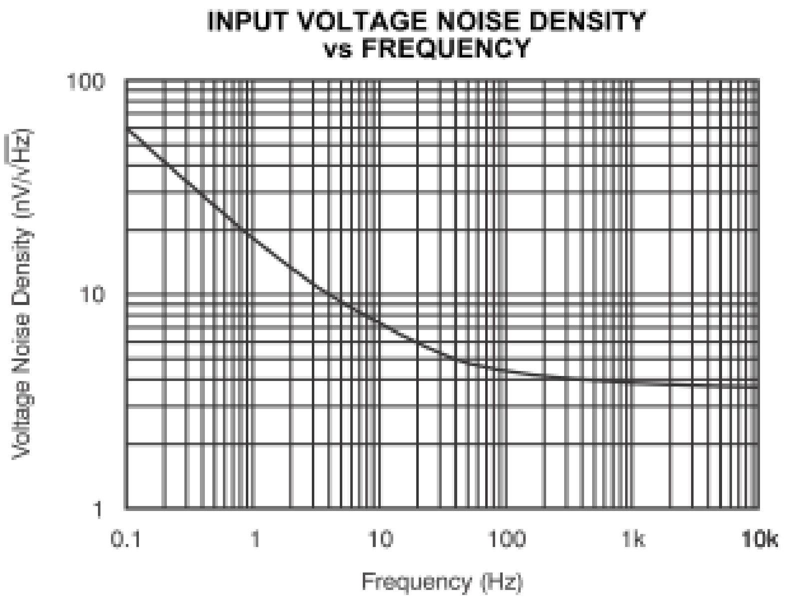
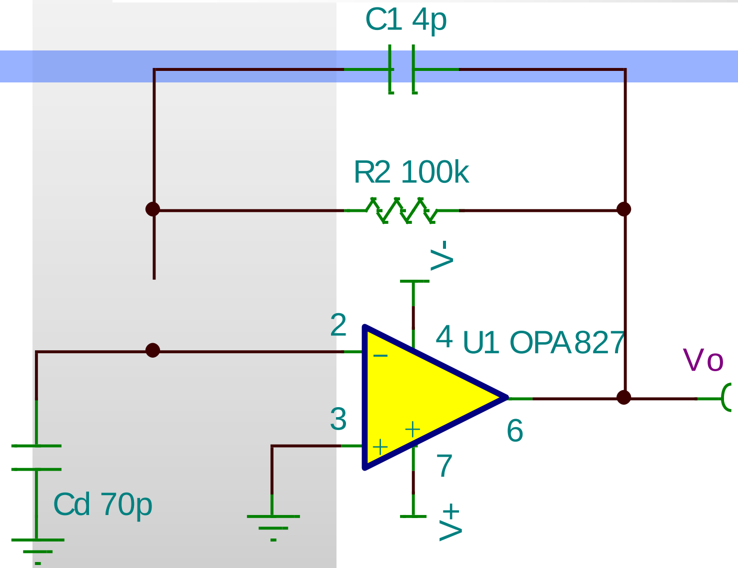
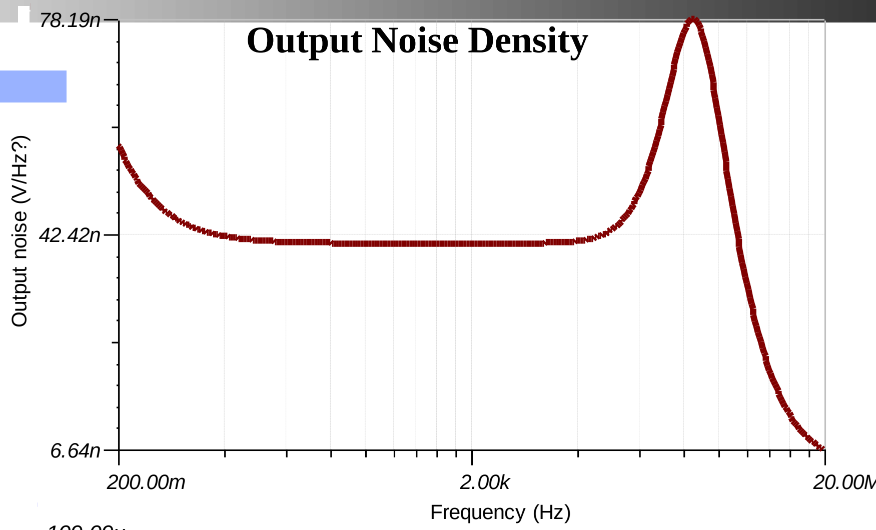
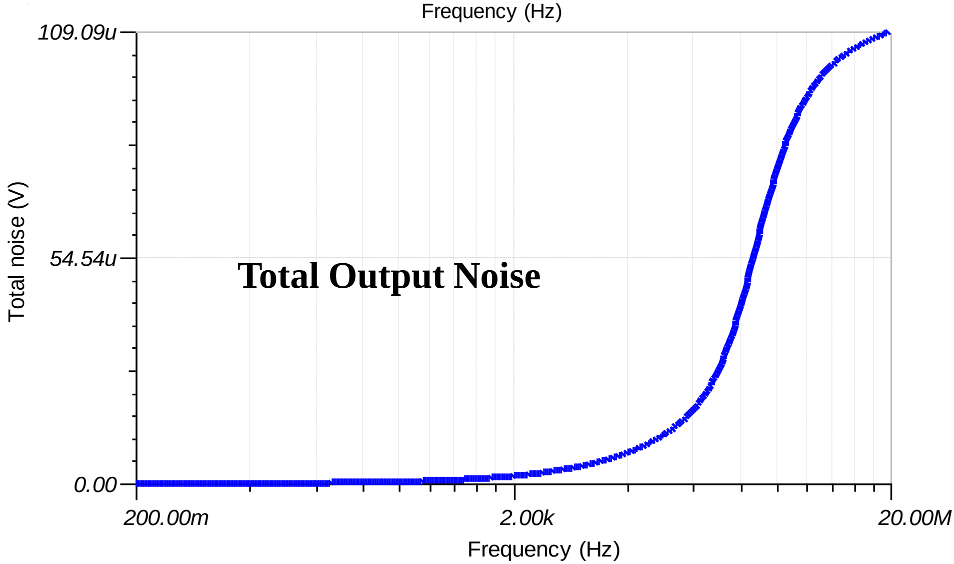


Figure 1.

Simulated Spectral Density and Total Noise



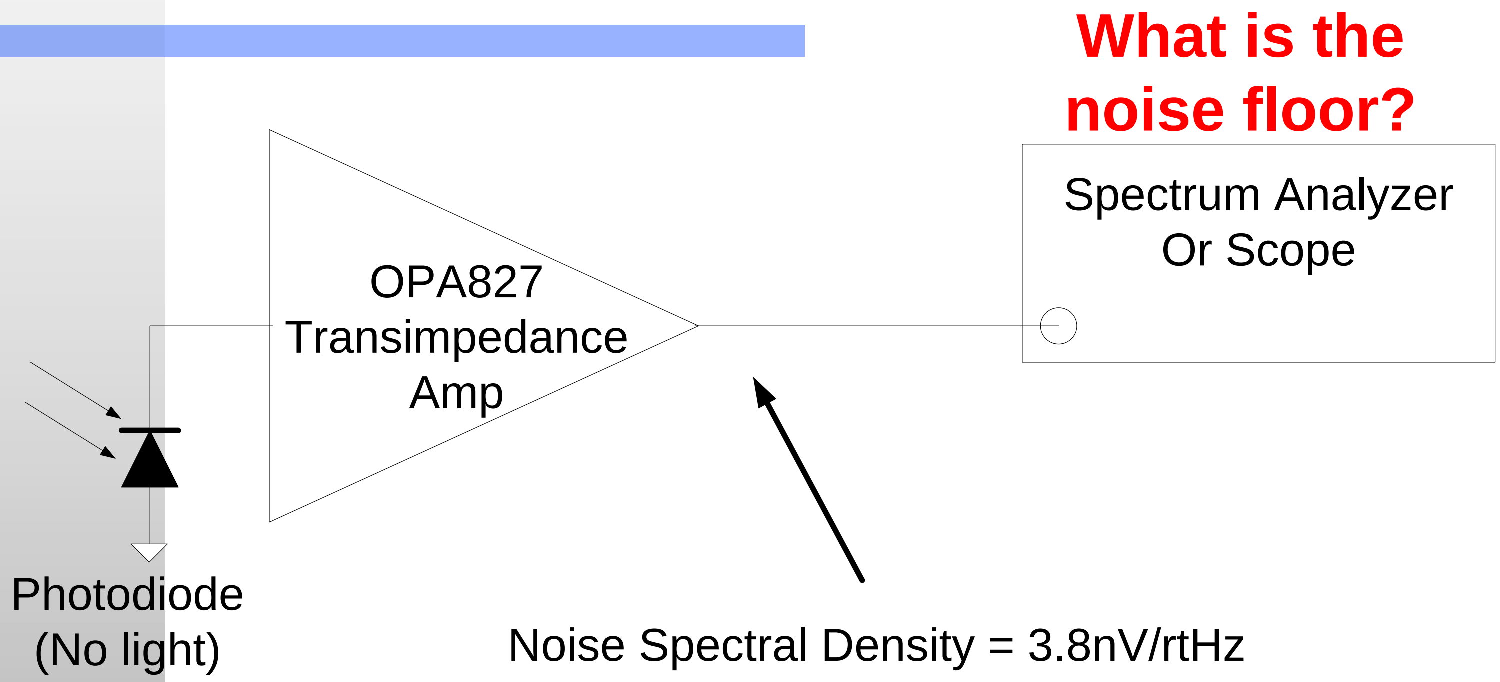




Calculated (rms)	Simulated (rms)
116.7uV	109.1uV

Op Amp Measurement Example

Validating Test Equipment Capability

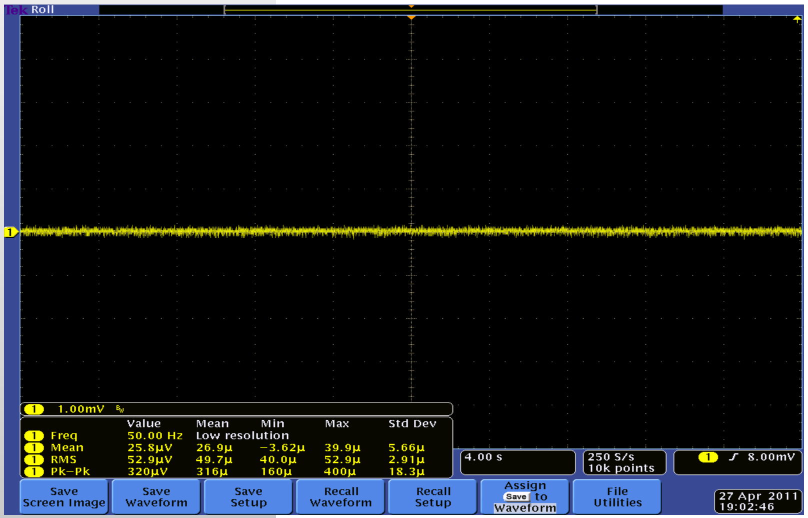


Noise Spectral Density = 3.8nV/rtHz

Total Noise = 109.1uVrms

= 654.6uVp-p

Tektronix DPO 4034 Oscilloscope

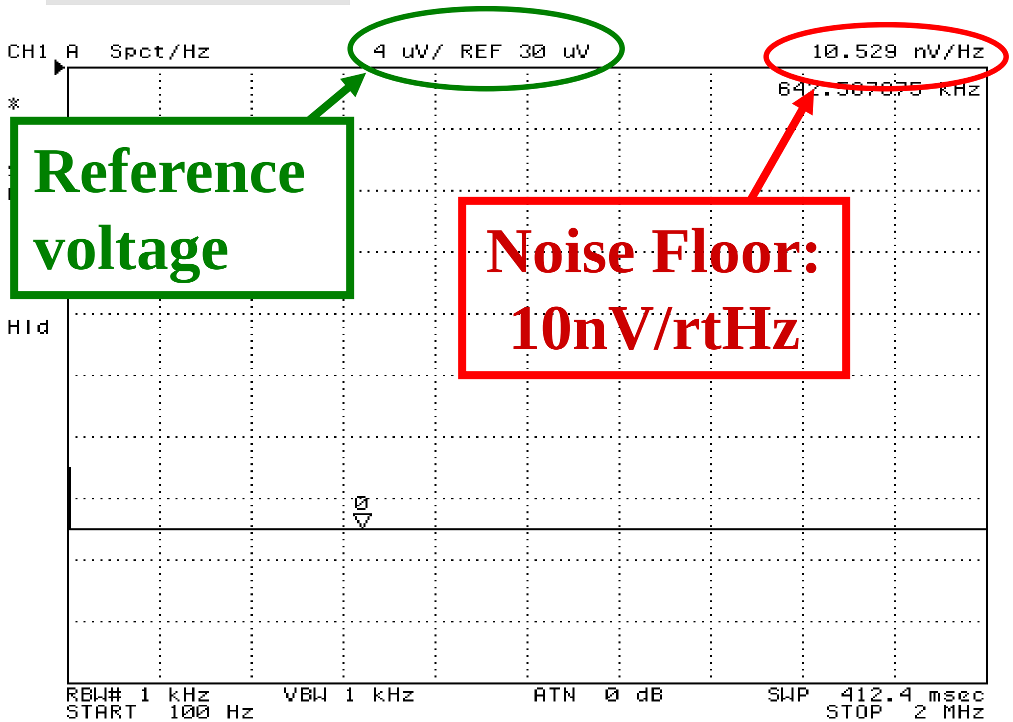


STDEV: 48uV (same as RMS)
P-P: 6.6*STDEV=319uV
40s P-P: 320uV

1) Set DC couple, 20MHz bandwidth limit
2) Short input channel to measure noise floor

Agilent 4395A Spectrum Analyzer

1. Frequency Range: 10Hz~500MHz
2. Noise floor: 10nV/rtHz
3. Input Impedance: 50Ω

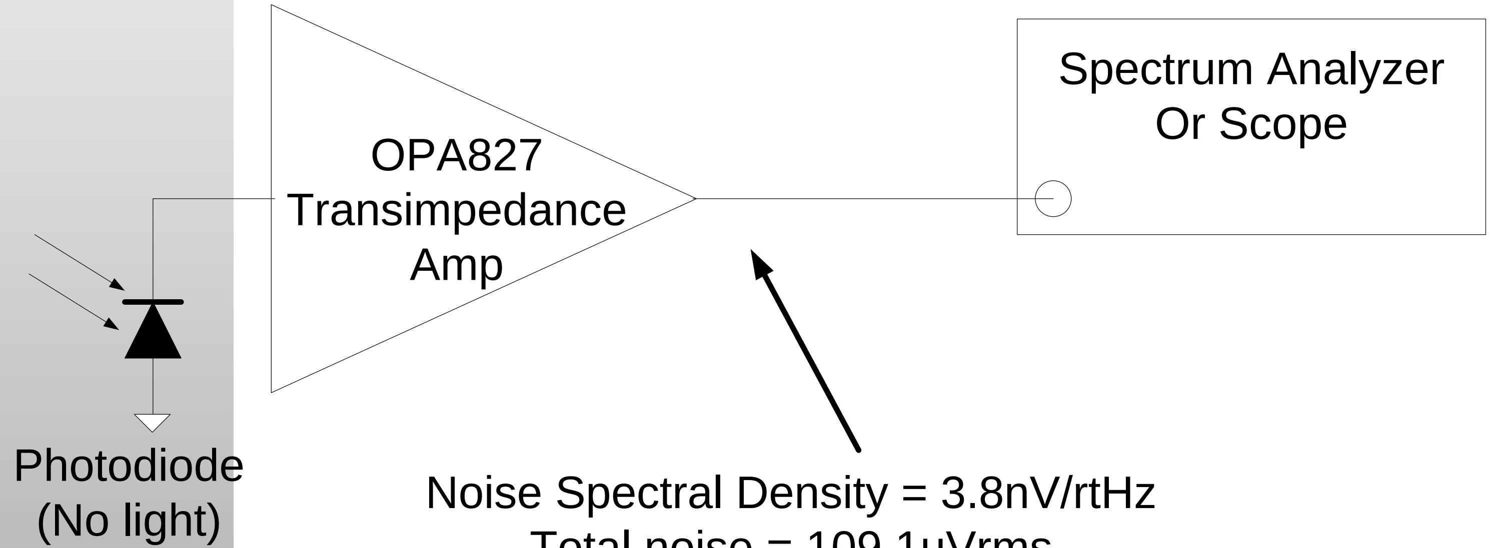


The Noise Floors are Not Good Enough

Noise Floors:

Scope (1mV range)= 48uV rms =320uVpp

4395A Spect. Analyzer = 10nV/rtHz

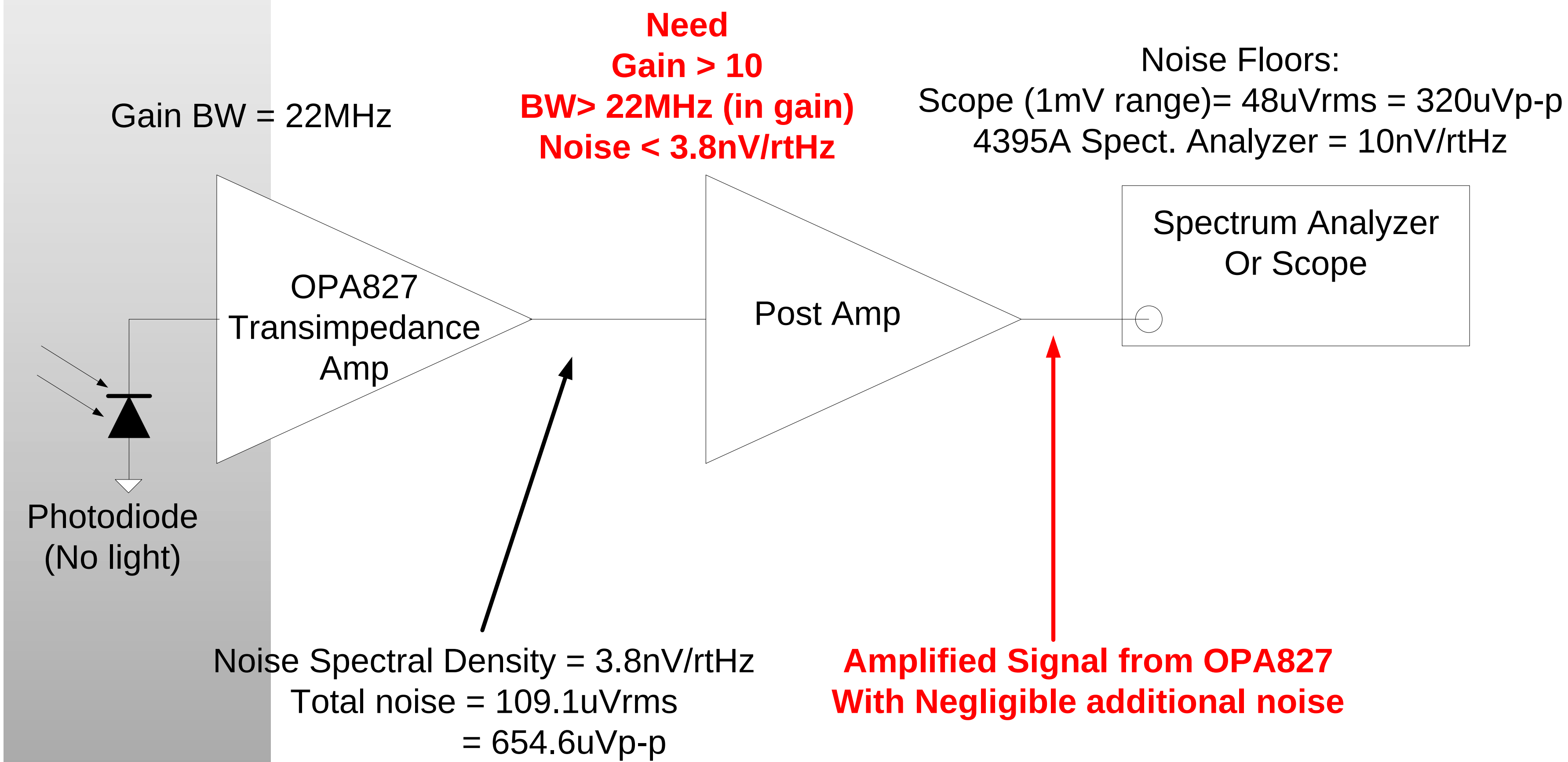


Noise Spectral Density = 3.8nV/rtHz

Total noise = 109.1uVrms

= 654.6uVp-p

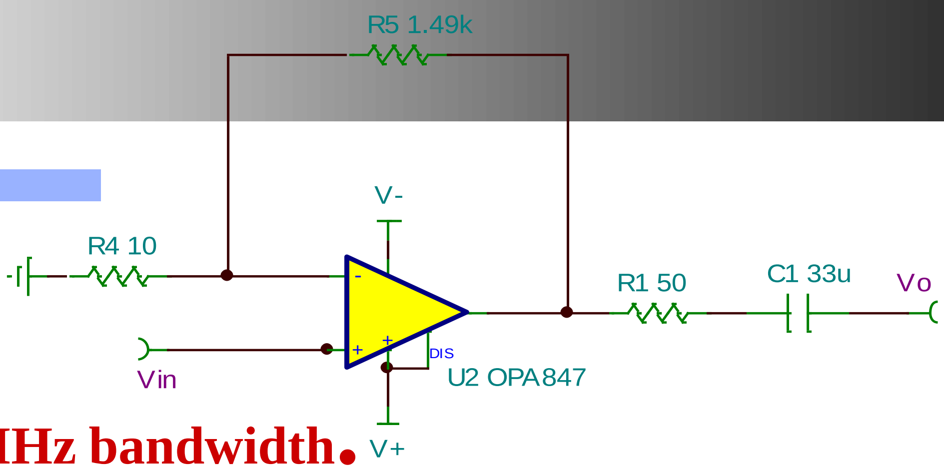
Solution: Use A Post Amp
What amp do we Choose?



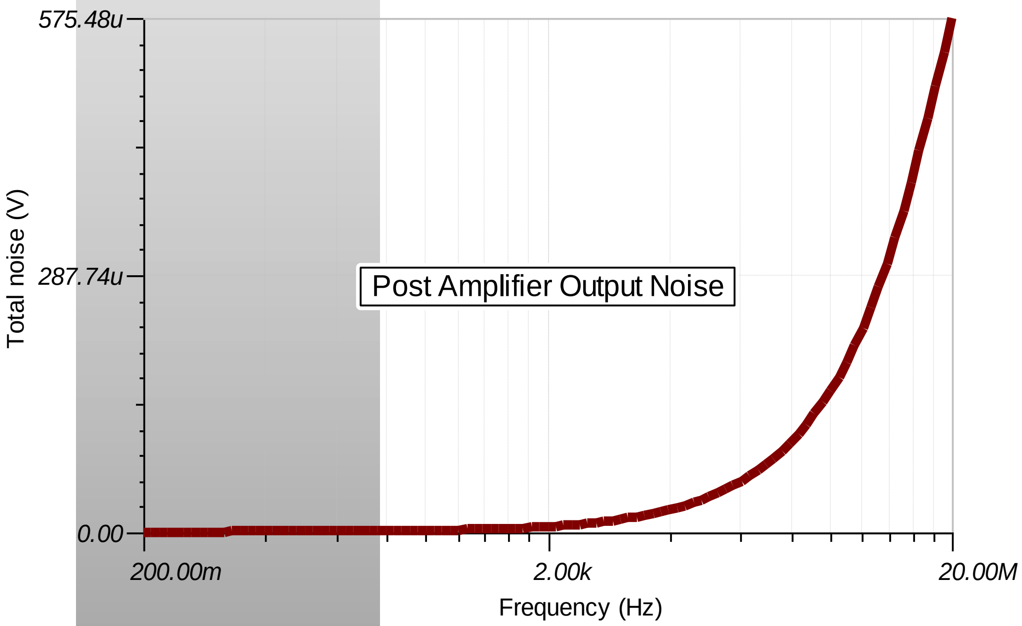
OPA847 as post amplifier

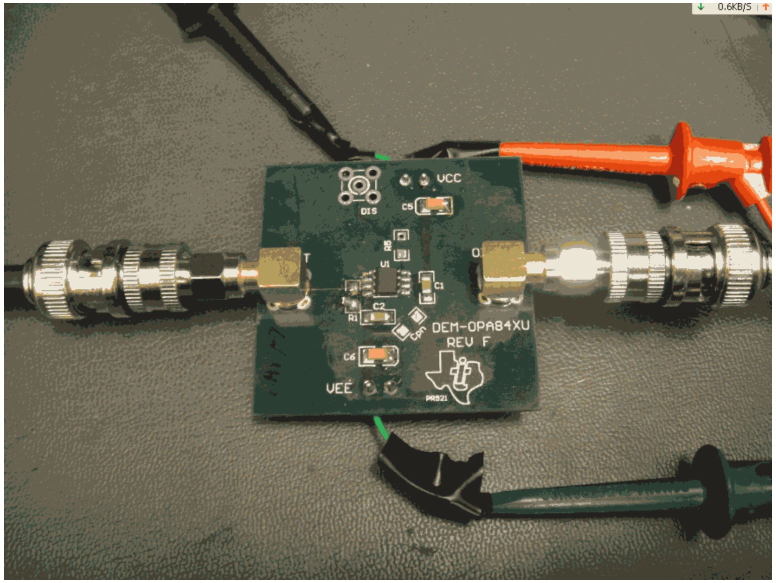
Wideband, Ultra-Low Noise, Voltage Feedback, Operational Amplifier

- **At the gain of 150, the bandwidth is 26MHz**
- **0.85nV/√Hz Input Voltage Noise**
- **2.5pA/√Hz Input Current Noise**
- **±100uV Input Offset Voltage (Typical))**



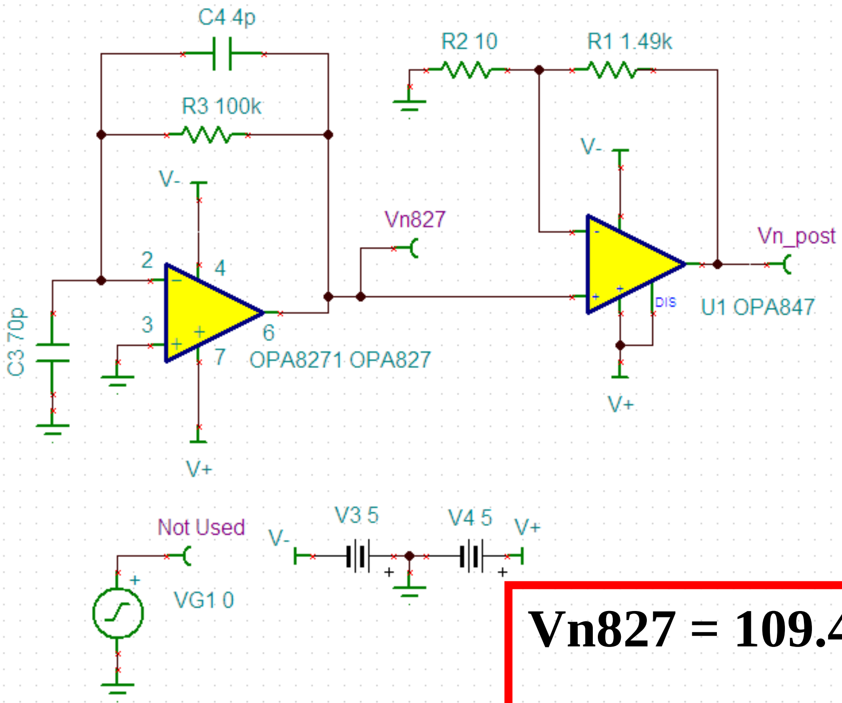
575uVrms post amplifier noise in 20MHz bandwidth.

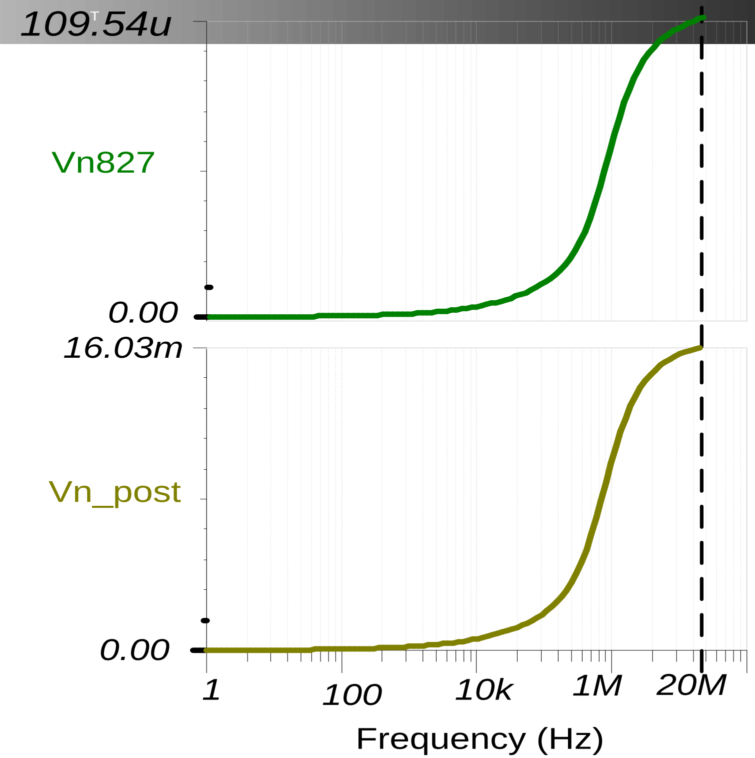




Post Amplifier Relatively small error!

Gain=150



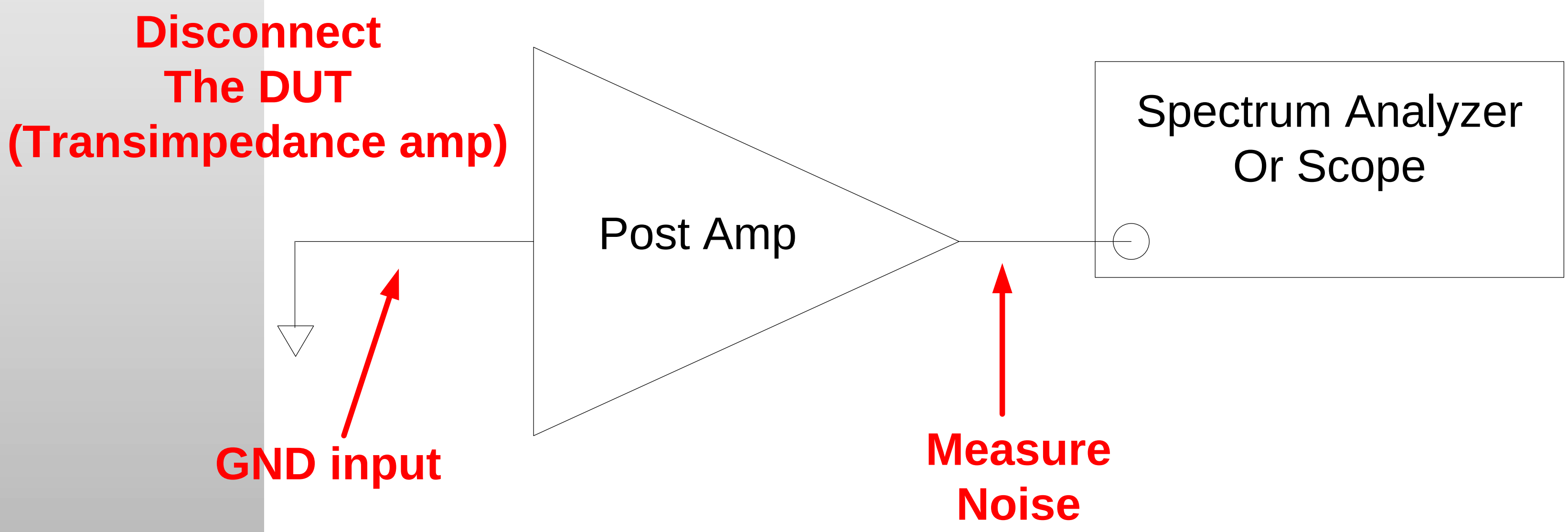


Vn827 = 109.4uV rms

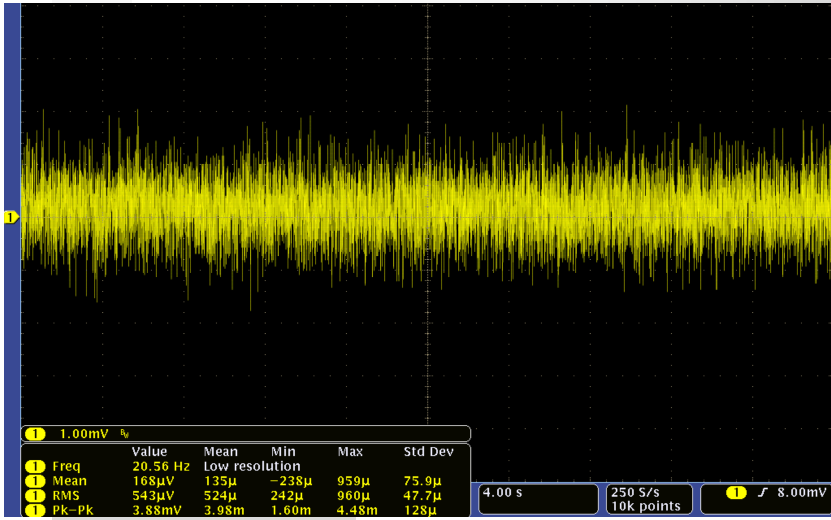
Vnpost = 16.03mV rms

Vnpost/Gain = 16.03mV/150 = 106.8uV rms

Test the Noise Floor



Test The Noise Floor – Post Amp Noise

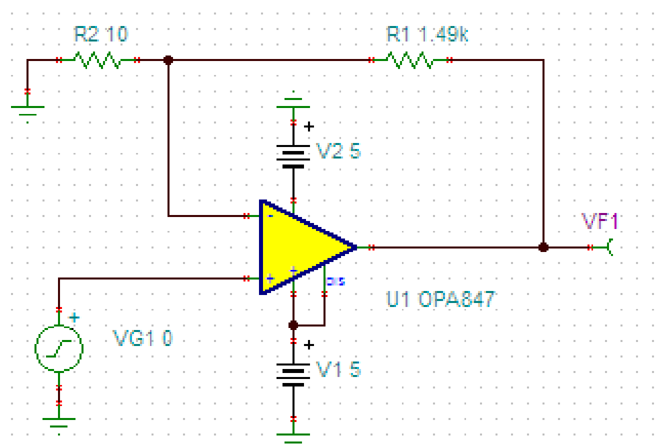


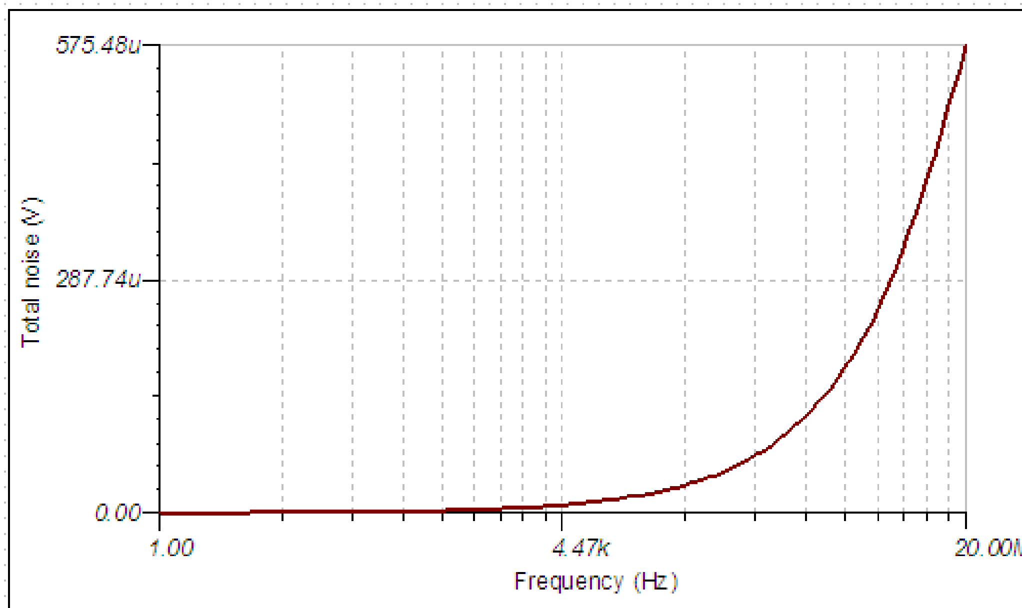
Simulated (rms)	Measured (rms)
575uV	518uV

STDEV: 518uV

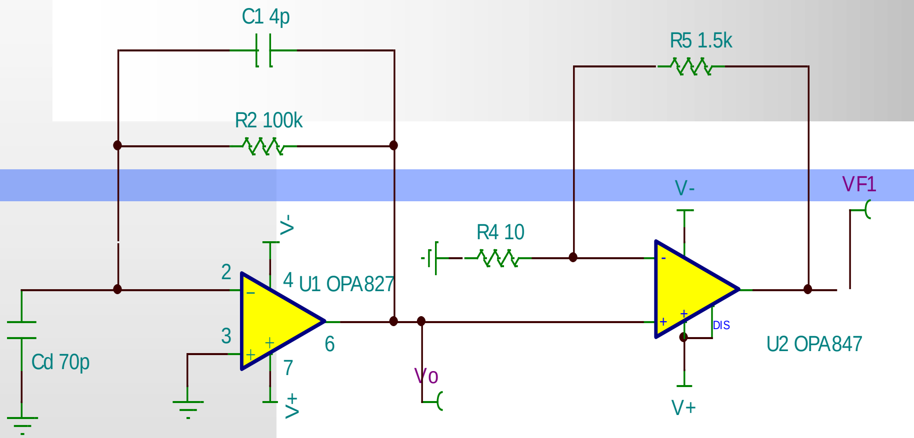
P-P: 6.6*STDEV=3.4mV

40s P-P: 3.88mV

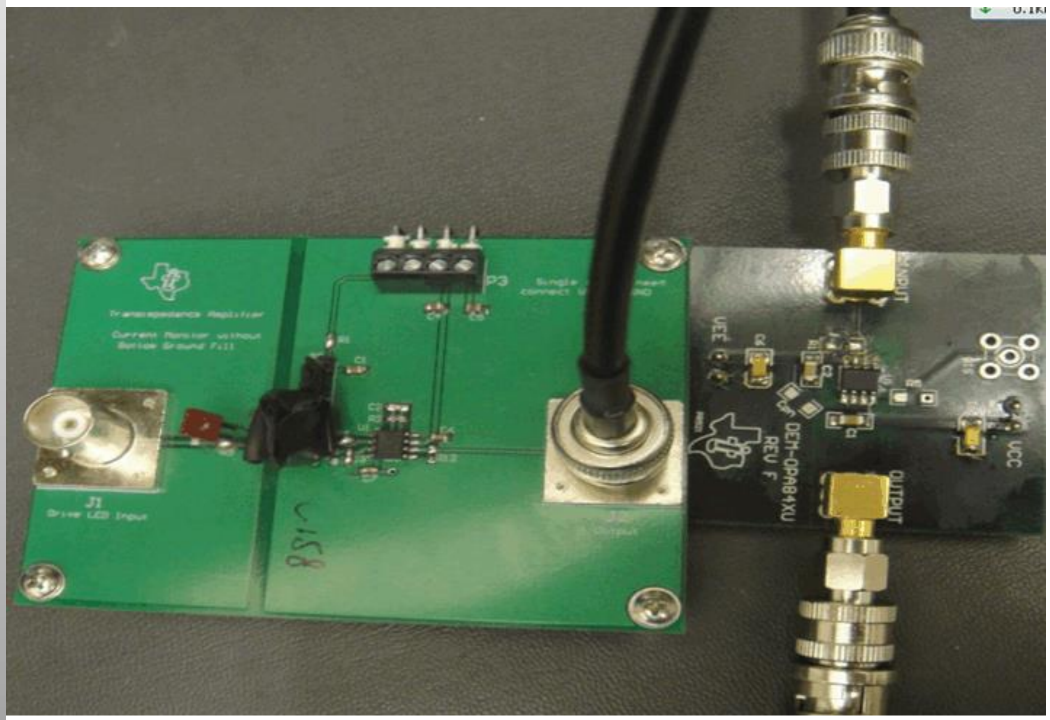




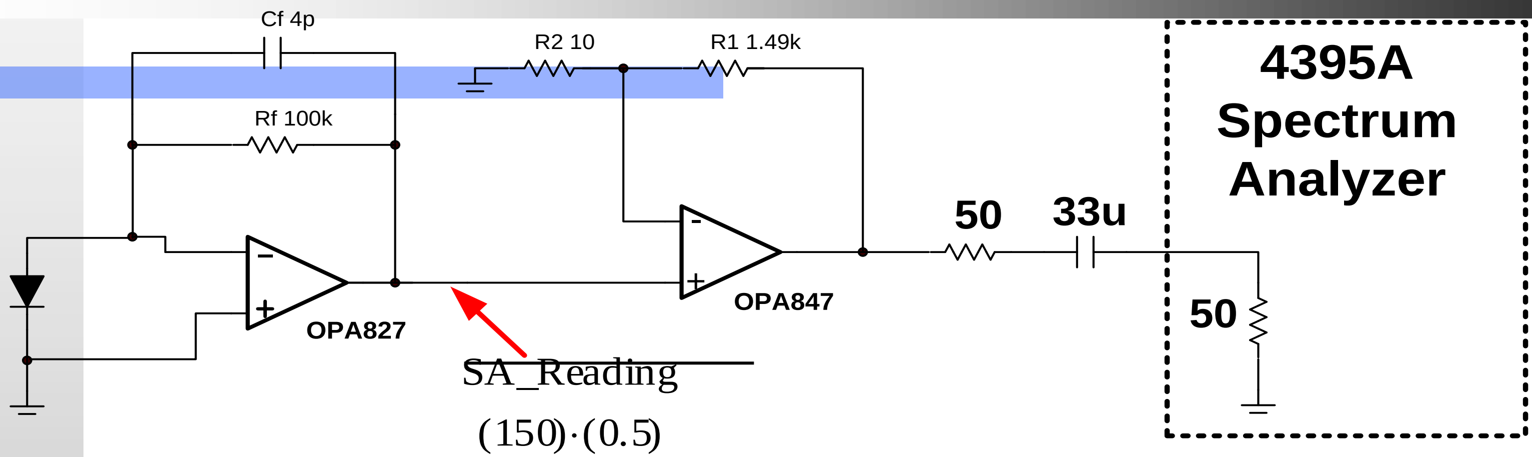
Hardware Connections

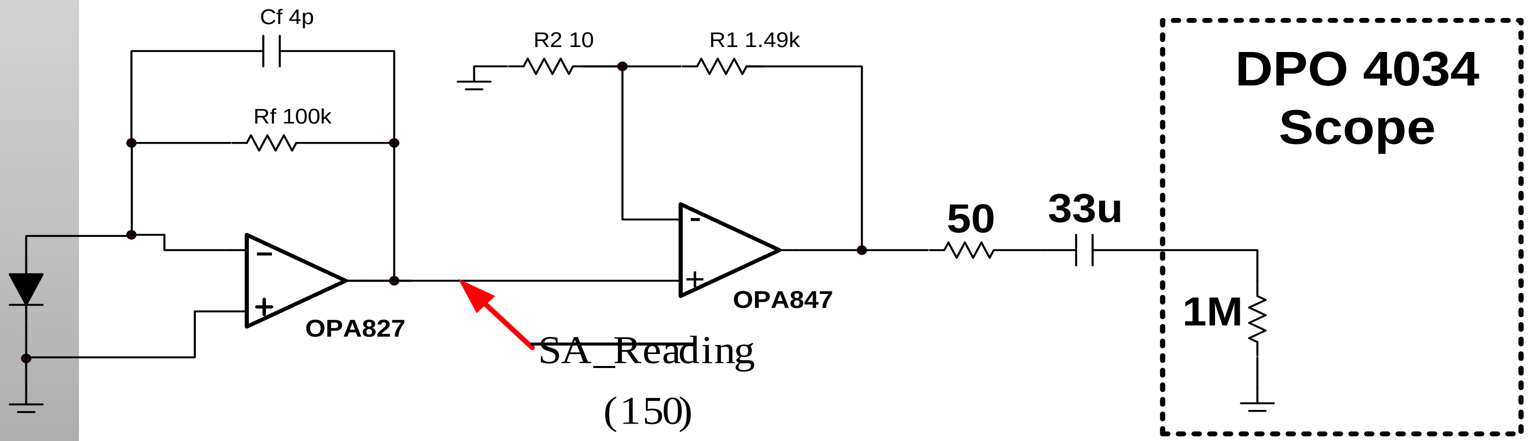


1. PDB-C158-ND photodiode
2. 70pF junction capacitance at Vr=0 V
3. 100dB I-V gain
4. 4pF compensation capacitor
5. ±5V power supply.

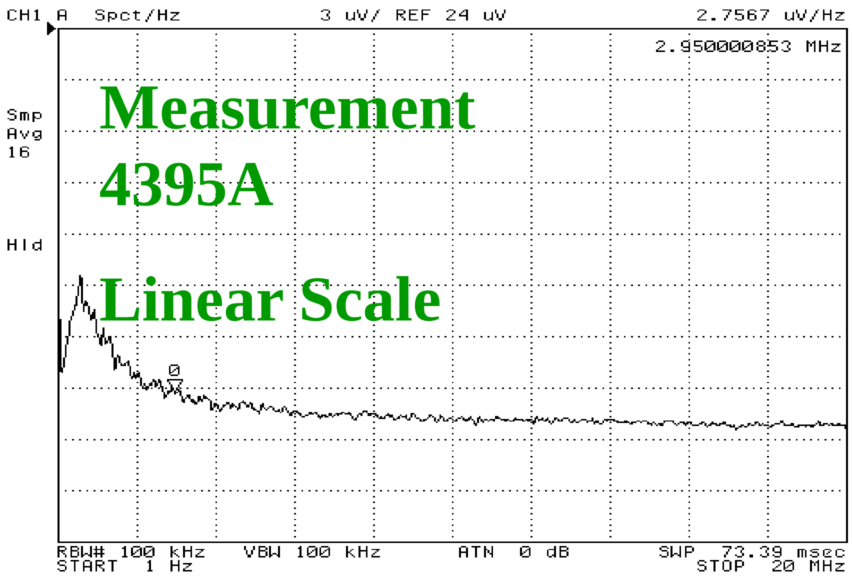


Divide by Gain for OPA827 Output Noise

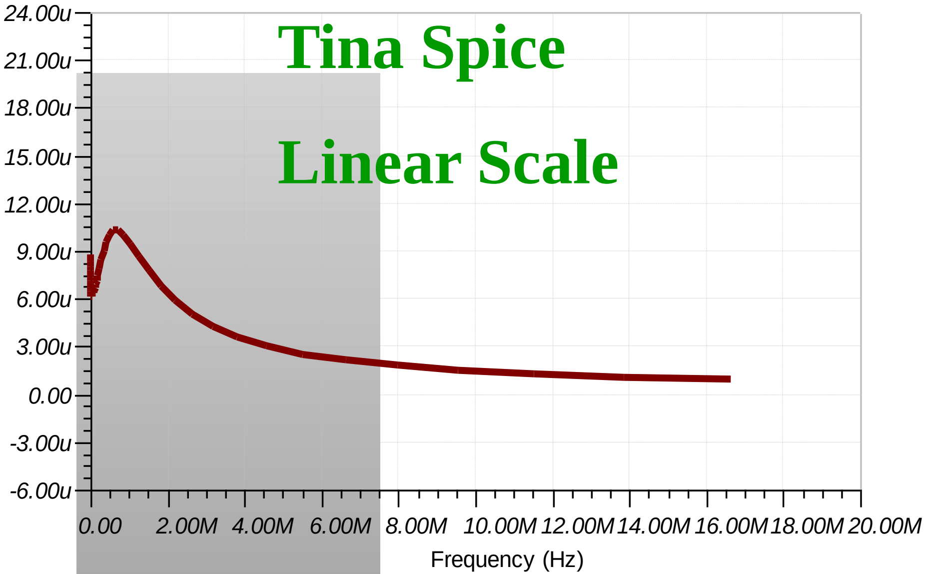


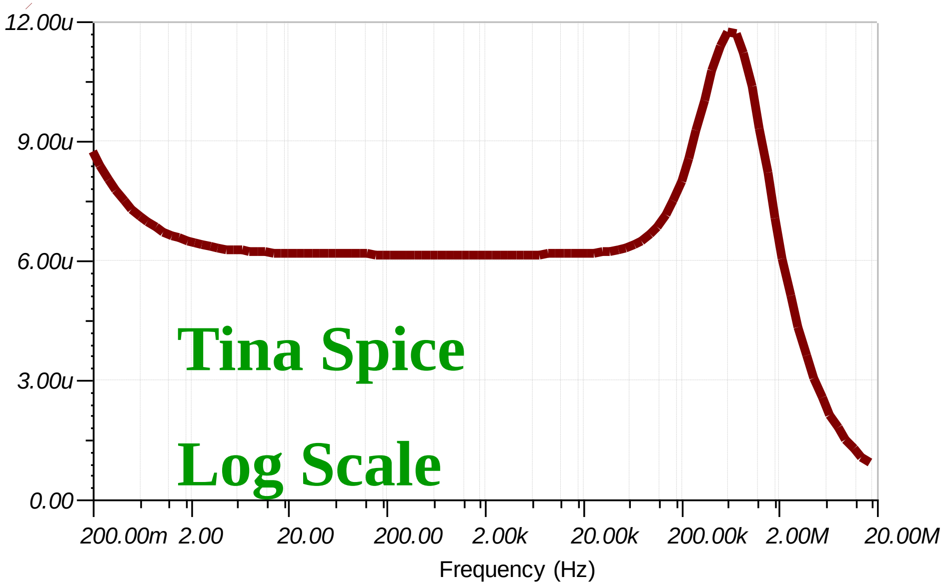


Measured Spectral Density 4395A Spectrum

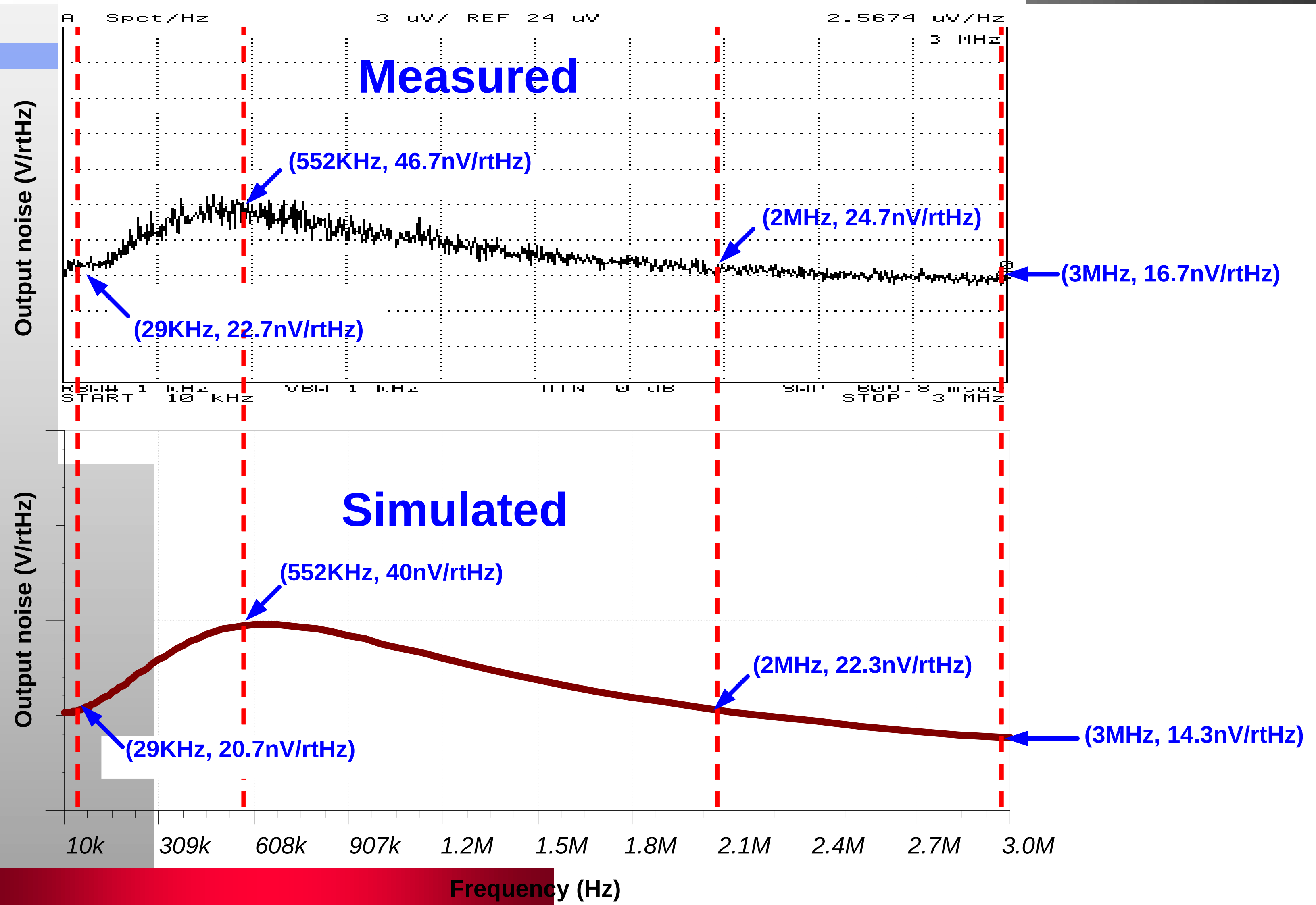


1. Agilent 4395A Spectrum Analyzer test 1Hz~20MHz span, 3uV/div, REF=24uV.
2. The tested noise density curve shape is the same as simulation.





OPA827-Noise Density 4395A Spectrum Analyzer



Thank you Gen-Probe Staff

- **Nick Nickols (AKA S.E Nickols)**
- **Science.dmr@gmail.com**
- **925-256-0161**

References

http://www.radio-electronics.com/info/data/semicond/photo_diode/structures-materials.php

http://www.rp-photonics.com/photodiodes.html

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http://home.sandiego.edu/~ekim/photodiode/pdtech.html

http://sales.hamamatsu.com/assets/html/ssd/si-photodiode/index.htm

Appendix

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Low-Noise, High-Precision, JFET-Input OPERATIONAL AMPLIFIER

FEATURES

- INPUT VOLTAGE NOISE DENSITY: 4nV/√Hz at 1kHz
- INPUT VOLTAGE NOISE: 0.1Hz to 10Hz: 250nV$_{PP}$
- INPUT BIAS CURRENT: 15pA
- INPUT OFFSET VOLTAGE: 150µV (max)
- INPUT OFFSET DRIFT: 1.5µV/°C
- GAIN BANDWIDTH: 22MHz
- SLEW RATE: 28V/µs
- QUIESCENT CURRENT: 4.8mA/Ch
- WIDE SUPPLY RANGE: ±4V to ±18V
- PACKAGES: SO-8 and MSOP-8

APPLICATIONS

- ADC DRIVERS
- DAC OUTPUT BUFFERS
- TEST EQUIPMENT
- MEDICAL EQUIPMENT
- PLL FILTERS
- SEISMIC APPLICATIONS
- TRANSIMPEDANCE AMPLIFIERS
- INTEGRATORS
- ACTIVE FILTERS

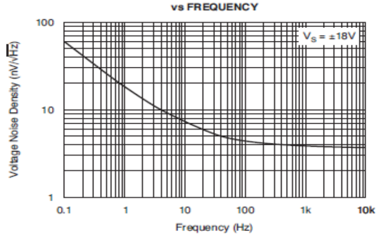
DESCRIPTION

The OPA827 series of JFET operational amplifiers combine outstanding dc precision with excellent ac performance. These amplifiers offer low offset voltage (150µV, max), very low drift over temperature (1.5µV/°C, typ), low bias current (15pA, typ), and very low 0.1Hz to 10Hz noise (250nV$_{PP}$, typ). The device operates over a wide supply voltage range, ±4V to ±18V on a low supply current (4.8mA/Ch, typ).

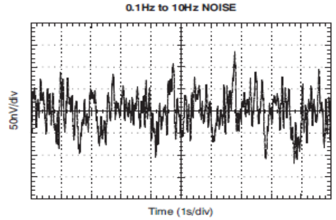
Excellent ac characteristics, such as a 22MHz gain bandwidth product (GBW), a slew rate of 28V/µs, and precision dc characteristics make the OPA827 series well-suited for a wide range of applications including 16-bit to 18-bit mixed signal systems, transimpedance (I/V-conversion) amplifiers, filters, precision ±10V front ends, and professional audio applications.

The OPA827 is available in both SO-8 and MSOP-8 surface-mount packages, and is specified from –40°C to +125°C.

INPUT VOLTAGE NOISE DENSITY vs FREQUENCY



0.1Hz to 10Hz NOISE



Photodiodes Technologies

- ***Types of photodiodes:***

- **Although the term photodiode is widely used, there are actually a number of different types of photodiode technologies that can be used.**

PIN photodiode: This type of photodiode is one of the most widely used forms of photodiode today. Although the PIN or p-i-n photodiode was not the first type of photodiode to be used, it collects the light photons more efficiently than the more standard PN photodiode, and also offers a lower capacitance.(Lot's of application and manufacturers)

PN photodiode: The PN photodiode was the first form of photodiode to be developed and used. It is not as widely used as other types which are able to offer better performance parameters. (Solar Cells)

Avalanche photodiode: Avalanche photodiode technology is used in areas of low light. The avalanche photodiode offers very high levels of gain, but against this it has high levels of noise. (Laser range finders)

Schottky photodiode: As the name indicates, Schottky photodiode technology is based upon the Schottky diode. In view of the small diode capacitance it offers a very high speed capability and is used in high bandwidth communication systems.(Telecom/Fiber optics)